STOWARZYSZENIE GEOMORFOLOGÓW POLSKICH

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WARSZTATY GEOEKOLOGICZNE

FUNKCJONOWANIE EKOSYSTEMÓW AZJI POŁUDNIOWO-WSCHODNIEJ

INDOCHINY 2008

5.02 – 20.02. 2008

Organizatorzy:

Wydział Geografii i Studiów Regionalnych Uniwersytetu Warszawskiego
Stowarzyszenie Geomorfologów Polskich

FUNKCJONOWANIE EKOSYSTEMÓW AZJI POŁUDNIOWO-WSCHODNIEJ

INDOCHINY 2008
Tajlandia & Laos & Kambodża

5-20 luty 2008

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PROGRAM

Indochiny umożliwiają poznanie niezwykle zróżnicowanego pod względem ekosystemów obszaru. Zróżnicowanie to wynika przede wszystkim z odmiennej rzeźby, klimatu, szaty roślinnej, jak również znacznego wpływu działalności człowieka na środowisko przyrodnicze. Program skonstruowany został w taki sposób, aby uczestnicy mogli zapoznać się z różnymi ekosystemami.

Ekosystemy dolin rzecznych; silnie przekształcona przez człowieka dolina rzeki Kwai; Mekong – królowa Indochin, którą poznamy w kilku miejscach, zróżnicowanych pod względem cech morfodynamicznych; okresowe, krótkie potoki górskie, które podczas pory deszczowej powodują spustoszenie zmieniając, niekiedy bardzo gwałtownie, przebieg koryta.

Ekosystemy gór średnich, w tym krajobrazy związane z bardzo intensywnymi procesami krasowymi. Zapoznamy się z funkcjonowaniem 3 parków narodowych *(światowe dziedzictwo przyrody UNESCO)* położonych w zachodniej Tajlandii oraz w Laosie. Są to obszary, w których człowiek w ograniczonym zakresie wpłynął na zmiany w środowisku przyrodniczym (miejscami występują nawet lasy uznawane za pierwotne). Mimo tych ograniczeń są to obszary, w których występują bardzo intensywne procesy stokowe (głównie osuwiskowe). Można się przekonać, że w tych warunkach morfoklimatycznych nawet nieznaczna ingerencja człowieka może być bardzo groźna dla ekosystemu (procesom stokowym sprzyja oczywiście rodzaj podłoża oraz warunki klimatyczne). Góry te zbudowane są głównie ze skał węglanowych, co doprowadziło do rozwoju rzeźby krasowej, z przepięknymi formami krasu powierzchniowego (mogoty, doliny i leje krasowe) oraz podziemnego (jaskinie z bogatą szatą naciekową).

Ekosystemy nizinne (w bardzo szerokich, wypełnionych osadami aluwialnymi ujściowych odcinkach dolin) mogą być bardzo zróżnicowane, zależnie od intensywności działalności człowieka. W Tajlandii obszary nizinne wykorzystywane są od wieków do uprawy ryżu, z zastosowaniem kiedyś tradycyjnego, a obecnie bardzo nowoczesnego systemu irygacyjnego. W nizinnej Kambodży, mimo podobnych warunków klimatycznych i dominacji równie żyznych jak w Tajlandii gleb aluwialnych, z powodu wyniszczającego kraj reżimu *Czerwonych Khmerów*, uprawy prowadzi się na bardzo nielicznych obszarach, mimo iż znaczna część ludność kraju jest niedożywiona. Nawet obecnie miejscowa ludność nie kwapi się, aby zagospodarowywać rolniczo nadające się do uprawy obszary z uwagi na ... około 1 milion min, które są pozostałością po czasach reżimu. Paradoksalnie, dzięki temu wiele obszarów pozostaje nietkniętych przez człowieka. Umożliwia to naturalny rozwój ekosystemów i stanowi znacznie lepszą barierę dla ingerencją człowieka niż granice parków narodowych!

Ekosystemy nadmorskie to głównie wybrzeża mangrowe, wśród których będzie przebiegać trasa naszej wyprawy. Można będzie ocenić, jak ekosystem ten wrażliwy jest na zanieczyszczenia w pobliżu dużych miast, np. Sihanoukville, z których wlewa się do morza dużo nieoczyszczonych ścieków.

Ekosystemy jeziorne (zarówno jezior naturalnych np. Tonle Sap, jak i bardzo dużych zbiorników zaporowych występujących w zachodniej Tajlandii) są również niezwykle interesujące. Podstawowym zagadnieniem rozpatrywanym w funkcjonowaniu tych ekosystemów jest bardzo szybka akumulacja materiału mineralnego, jak również (być może dużo groźniejsza dla funkcjonowania zbiorników) akumulacja materii organicznej i zanieczyszczeń związanych z działalnością człowieka, które są tam głównym czynnikiem sprzyjającym intensywnemu zarastaniu jezior.

Indochiny to również obszar, w którym poznamy zróżnicowanie przyrodnicze w zakresie innych cech środowiska przyrodniczego, m.in. gleb, szaty roślinnej, fauny itd. Obszar ten jest także zróżnicowany pod względem kulturowym. Wynika to z odmienności religijnej i kulturowej zamieszkującej tam ludności, a w Laosie i Kambodży również z wpływu francuskich kolonizatorów. Zobaczymy Indochiny bardzo nowoczesne (Bangkok), tradycyjne świątynie i klasztory (wpisana na listę światowego dziedzictwa kultury UNESCO królewska stolica Luang Prabang, świątynie Angkor w Kambodży) oraz tradycyjne wiejskie obszary w Laosie i Kambodży.

1. dzień

Przelot na trasie Warszawa – Bangkok

TAJLANDIA

Kraj drapaczy chmur i autostrad, które nawet przybysza z Europy zaskakują nowoczesnością – jeden z najbogatszych w południowej Azji. Kraj paradoksów, w którym dawna kultura przetrwała w niemal nienaruszonym stanie współistniejąc z najnowszymi osiągnięciami cywilizacji. Dawny, legendarny Syjam.

2. dzień

Bangkok

Miasto składa się z kilku odrębnych, niezależnych dzielnic. Każda z nich ma do zaoferowania odmienną atmosferę, każda nastawia się na inny typ turystów. Jest Bangkok biznesowy, Bangkok królewski, Bangkok nocnych uciech, Bangkok obieżyświatów. Po tajskiej stolicy można pływać kanałami jak po Wenecji. Najbardziej przyciągają jednak majestatyczne złote, świątynie. Odgłosy modlitw, słodki zapach kwiatów i kadzideł sprawiają, że miejsca te na długo zapadają w pamięć.

Świątynia Złotego Buddy - Wat Trimitr, Świątynia Leżącego Buddy Wat Pho, Świątynia Szmaragdowego Buddy - Wat Phra Kaeow, Wielki Pałac.

Wycieczka po kanałach (khlongach) Thonburi.

3. dzień

Bangkok, Kanczanaburi (most na rzece Kwai), dolina rzeki Kwai, Park Narodowy Sai Yok i Khao Laem, Sanghla Buri - granica z Myanmarem (Birmą)

Wojenna historia kolei tajlandzko-birmańskiej ze słynnym mostem budowanym na rzece Kwai przez 60 tysięcy alianckich jeńców wojennych. Przejazd pociągiem przepiękną krajobrazowo trasą w dolinie rzeki Kwai do końca torów (Nam Tok). Wodospady Sai Yok Noi i największa jaskinia stalaktytowa na tym obszarze - Tham Lawa, do której można dostać się jedynie łodzią. Przejazd drogą wzdłuż dalszej części doliny rzeki Kwai przez porośnięty lasem monsunowym (las tekowy) Park Narodowy Sai Yok *(światowe dziedzictwo przyrody UNESCO)*. W parku tym można również spotkać najmniejszego ssaka na świecie – nietoperza o wadze 1,75g i rozpiętości skrzydeł 1,6cm. Następnie wzdłuż zbiornika Khao Laem przez park narodowy o tej samej nazwie do Sanghla Buri.

4. dzień

Sanghla Buri - granica z Myanmarem, Park Narodowy Erwan, Jaskinia Phrahat, zbiornik Nakharin, Kanchanaburi

Przełęcz Trzech Pagód – jedno z zaledwie dwu przejść lądowych z Tajlandii do Myanmaru, słynne od wieków jako szlak przemytników opium, szlachetnych kamieni, a obecnie... drewna tekowego. Wodospad Erwan (słoń) ukształtowany został przez wietrzenie chemiczne i mechaniczne w 7 trawertynowych tarasów. Dzięki otoczeniu, w którym dominują bambusy, ratany i drzewa tekowe jest jednym z największych i najpiękniejszych w Tajlandii Z kolejnych poziomów roztacza się niezapomniany widok na góry porośnięte gęstą dżunglą. Powstanie jaskini Phrahat, w której wnętrzu można zobaczyć bogatą szatę naciekową, związane jest z główną linii uskoku, który wykorzystuje rzeka Kwai Yai. Nad jednym z największych, sztucznych zbiorników w Tajlandii – Nakharin położonym wśród gór znajduje się wodospad Huay Khamin, do którego można dostać się łodzią. Przejazd do Kanchanaburi.

5. dzień

Kanchanaburi, Ayutthaya, Park Narodowy Khao Yai

Ayutthaya (światowe dziedzictwo kultury UNESCO) – druga stolica państwa syjamskiego, założona w XIV wieku sprawia wrażenie skansenu wysoko rozwiniętej kultury buddyjskiej. O dawnej świetności świadczą klasztory, świątynie oraz liczne, monumentalne rzeźby.

Park Narodowy Khao Yai położony jest 120 km na północny-wschód od Bangkoku. Tworzą go wapienne, gęsto porośnięte tropikalnym lasem góry, w których występuje 300 gatunków ptaków i ponad 20 dużych ssaków lądowych, m. in. gibony białorękie, lapundery, słonie, tygrysy, lemury oraz cztery gatunki dzioborożców. Park charakteryzuje się również urozmaiconą rzeźbą krasową – jaskiniami oraz licznymi dolinami rzecznymi z malowniczymi wodospadami.

6. dzień

Park Narodowy Khao Yai, Prasat Hin Phimai, Udon Thani, Nong Khai (granica z Laosem), Vientiane

Prasat Hin Phimai – khmerskie ruiny świątynne, jedne z największych tego typu świątyń w Tajlandii, zbudowane zostały około 1000 roku z ciemnoróżowego i szarobiałego piaskowca. W pobliżu rośnie jeden z największych na świecie indyjskich figowców, którego korona zajmuje powierzchnię 2300m². Przejazd przez Udon Thani i Nong Khai do Vientiane – stolicy Laosu.

LAOS

Przez wielu uważany za najpiękniejszy i najbardziej egzotyczny kraj południowej Azji. Laos to głównie wapienne, bardzo urozmaicone pod względem rzeźby, porośnięte tropikalnym lasem góry co sprawia, że za każdym zakrętem możemy się spodziewać niezapomnianych widoków. Laos to spokojne obecnie tereny rolnicze, z dominacją w krajobrazie tarasów ryżowych oraz krytych strzechą domów, w których mieszkają gościnni i spontaniczni mieszkańcy. To ciągła obecność potężnego Mekongu. Do niedawna Laos był dla turystów zamknięty. Granice otwarto niespełna 5 lat temu i niemal natychmiast rozwój turystyki stał się bardzo dynamiczny.

7. dzień

Vientiane - Van Vieng

Vientianne – stolica Laosu. Najmniejsza i najspokojniejsza ze stolic Azji (liczy zaledwie 133000 mieszkańców).

Świątynie Wat Ong Teu Mahawihan, Wat Hai Sok; Spacer po Parku Buddy

Przejazd do Van Vieng

Van Vieng – przepiękna górska okolica przecięta rzeką ... W krajobrazie dominują strzeliste, wapienne skały (mogoty), pomiędzy którymi znajdują się pola ryżowe. Van Vieng słynie zwłaszcza z krasowych jaskiń. Niektóre z nich, jak Tham Jang, zostały w pełni zagospodarowane turystycznie.

8. dzień

Van Vieng – Luang Prabang

Droga z Luang Prabang do Van Vieng należy do najbardziej malowniczych w całym Laosie. Mijamy malownicze górskie krajobrazy, plantacje drzewa tekowego i bananów. Miejscami stoki porośnięte są gęstą, dziewiczą roślinnością. Dachy domów okolicznych wiosek (tradycyjna, kryta strzechą zabudowa) wręcz dotykają asfaltu – płaskiego miejsca jest tak niedużo, że wykorzystano każdy centymetr. Wybudowanie w 2002 roku drogi spowodowało prawdziwą rewolucję w życiu okolicznej ludności.

9. dzień

Luang Prabang i okolice

Luang Prabang (światowe dziedzictwo kultury UNESCO) – położone w górach, nad Mekongiem, malownicze postkolonialne miasto, znane przede wszystkim z przepięknych świątyń. Buddyjska tradycja *i laotańska architektura królewska łączą się tutaj z francuskim stylem kolonialnym. Mimo "wielkości historii" Luang Prabang jest ciche i spokojne. Świątynie Wat Xieng Thong, Wat Mai, Wat Aham.*

Mekong – magiczna, legendarna rzeka. Najdłuższa w Azji. Przepływa przez Chiny, Laos, Birmę, Wietnam. Przełomy w okolicach Luang Prabang uznawane są za najpiękniejsze w całym jej biegu. Wioski nad Mekongiem zamieszkiwane są przez mniejszości etniczne i kulturowe słynące z rękodzielnictwa. Do niedawna rzeka była jedynym środkiem transportu.

Część Mekongu, którą będziemy płynąć słynie również z połowu ryb – np. paa beuk, która w Bangkoku osiąga cenę 5000 USD za sztukę (!!!).

Wycieczka łodzią. Po drodze zwiedzamy malownicze wioski (produkcja papieru czerpanego, produkcja lokalnej whiskey) oraz jaskinię Pak Ou pełniącą rolę buddyjskiej świątyni.

KAMBODŻA

Kraj położony w samym centrum Indochin. Po Francuzach pozostała tu wspaniała kuchnia i atmosfera romantycznych bulwarów, nie spotykana nigdzie indziej w Azji. Kraj został zniszczony i wytrzebiony w czasach reżimu Czerwonych Khmerów. Dziś jest tu bezpiecznie. Kambodża to przede wszystkim magiczne ruiny Angkor Wat, to mili i gościnni mieszkańcy. Kambodża to kraj, który z powodu swojej niedawnej historii nikogo nie pozostawi obojętnym.

10. dzień

Luang Prabang (Laos) – Siem Reap (Kambodża) - przelot

Wieczorem podziwiamy najbardziej spektakularny zachód słońca w świątyni Angkor Wat.

11. dzień

Siem Reap

Starożytne miasta Angkor Wat i Angkor Thom (światowe dziedzictwo kultury UNESCO) to największy kompleks świątynno-pałacowy na świecie (zbudowany w okresie od IX do XIV wieku). Ponad 100 świątyń ozdobionych zostało, zależnie od wiary panującego władcy, posągami Buddy lub motywami znanymi z wierzeń hinduistycznych. Cały kompleks porzucono w XV wieku, kiedy dwór Khmerów przeniósł się do Phnom Penh. Dopiero w XIX wieku zarośnięte dżunglą wspaniałe budowle zostały odkryte i opisane przez Europejczyków.

Świątynie Angkor można opisać tylko jednym słowem – magiczne! Wielu uważa je za najpiękniejsze na świecie. Położone wśród gęstej, tropikalnej roślinności na przestrzeni kilkudziesięciu km^2, po obaleniu reżimu Czerwonych Khmerów na powrót stały się ważnym miejscem kultu. W niektórych obiektach

czujemy się jak odkrywcy, którzy w środku dżungli znaleźli cenne, zarośnięte jeszcze skarby. Konary i pnie drzew dosłownie splatają się z murami budynków stanowiąc jednolitą, niepowtarzalną całość.
Świątynie: Angkor Wat, Angkor Thom, Preah Khan, Ta Prohm, Preak Nean Pean, Ta Som i inne.

12. dzień

Siem Reap – Phnom Penh

Rejs wodolotem po jeziorze Tonle Sap, a następnie rzeką do Phnom Penh .
Phnom Penh – kambodżańska stolica: Pałac Królewski, Srebrna Pagoda, Pomnik Zwycięstwa, odpoczynek i pożegnanie Mekongu.

13. dzień

Phnom Penh – Sihanoukville – Trat –Ko Chiang (Tajlandia)

Poranny wyjazd do Sihanoukville, przejazd przez dziewicze lasy deszczowe (dziewicze z powodu min, które się w nich znajdują, w związku z tym za daleko zapuszczać się nie będziemy...). Z Sihanoukville płyniemy po Oceanie Spokojnym (oby!!!) wzdłuż bardzo interesujących wybrzeży mangrowych. Po przekroczeniu granicy udajemy się na zasłużony wypoczynek na wyspę Ko Chang.

14. dzień

Ko-Chang – Bangkok

Wypoczynek na przepięknej wyspie – podziwiamy rzeźbę litoralną wysp tropikalnych (czyt. plaża).
Późnym popołudniem przejazd na lotnisko w Bangkoku, odlot do Polski.

15. dzień

przelot Bangkok – Warszawa

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I N F O R M A T O R

Uczestnikiem może być osoba która:

- dokona wpłat w następującej wysokości i terminach:

I wpłata - do 01.11. 2007 - 5000 PLN

II wpłata - do 15.01. 2008 - 4300 PLN (dla członków SGP); 4600PLN (dla osób niezrzeszonych w SGP)

- posiada paszport ważny co najmniej do 30.09.2008
- posiada legitymację Teacher (można ją wyrobić np. w biurze Almatur, zawiera ubezpieczenie PZU do końca 2008 roku – cena około 80 PLN), lub będzie ubezpieczona u innego ubezpieczyciela

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W ramach opłaty organizatorzy zapewniają:

- Zakwaterowanie w hotelach 3*** , pokoje 2-osobowe z łazienkami
- Pełne wyżywienie
- Transport lotniczy: Warszawa – Bangkok – Warszawa (przez jedno z miast europejskich); przelot na trasie Luang Prabang-Siem Reap (wraz ze wszystkimi opłatami lotniczymi).
- Transport wewnętrzny**:** minibus lub autokar, pociąg, statek, wodolot, łódź motorowa
- Opłaty wizowe
- Wstępy do parków narodowych i zabytków
- Usługi przewodnickie na obszarze zabytków (w języku angielskim)
- Mapy...

Informacje dodatkowe:

- ostateczny termin wylotu zostanie podany w późniejszym terminie (wylot nastąpi między 02-06 luty, czas pobytu 15-16 dni)
- informujemy, że organizatorzy zastrzegają sobie możliwość dokonania zmian w programie związanych z przyczynami niezależnymi organizatorów.

Uprzejmie zapraszamy:

W imieniu Komitetu Organizacyjnego
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Prezes Stowarzyszenia Geomorfologów Polskich
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Environmental geology in Thailand – programs and strategies

N. Mantajit

Abstract The paper describes the activities and objectives of the Department of Mineral Resources in the field of environmental geology. This approach is still a comparatively new for Thailand and presently comprises different programs: environmental geology for regional planning, seismic hazards, flooding/landslides, coastal management and geosites conservation. The Environmental Geology Section of the Department is the relevant administrative unit. The technical work and the related documentations focus on rising public awareness and integration of geo-information into land-use planning and land development.

Key words Environmental geology · Seismic hazards · Flooding/landslides · Coastal management · Geosites conservation

Introduction

The demand for environmental protection and natural resources conservation has grown considerably in Thailand, especially as a consequence of the rapid economic growth during the past decade. As the geological environment describes a major part of our physical environment, geology can play an important role in environmental planning and management. The Department of Mineral Resources (Geological Survey of Thailand Fig. 1) took this fact into account and established in 1990 the Section for Environmental Geology (EGS) under the Geological Survey Division.
The EGS has the task of compiling and assessing environmentally relevant geo-information in an integrated manner and to provide this information to authorities responsible for land-use planning and land development.
A Major tool for the transferring of environmentally relevant geo-information to planning authorities or other data users are thematic maps which focus on the availability, quality and vulnerability of the geological resources and provide recommendations for land-use planning from a geoscientific point of view. Included is also the risk assessment of natural hazards which might pose a threat to human life and property. This approach is supported by the set-up of a computerized data base for storage, processing and presentation of technical data.
After its establishment, the EGS initiated environmental geological work in the Lampang area in northern Thailand (Hinthong 1992). Since 1996, the Department of Mineral Resources (DMR) and the German Federal Institute for Geosciences and Natural Resources have carried out a Technical Cooperation Project, which focuses on environmental geological recommendations for the Chiang Mai-Lamphun Basin in NW Thailand (Tantiwanit and Lietz 1998).

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Scope of environmental geological programs

Environmental geology for regional planning

Work objectives in this field are directed towards fast growing regions in the surroundings of major urban centers. These regions are characterized by high exploitation rates of the geological resources (mineral raw materials, groundwater, soil) as well as by increasing competing demands with regard to the use of the available land. If, under such circumstances, land-use planning and land development is not supported by relevant geo-information, serious environmental impacts are likely to occur: groundwater overuse, loss of fertile soil, groundwater and soil pollution as well as destruction of the landscape.
The EGS has targeted under this program the surroundings of 11 major cities in different administrative regions of Thailand. Within the framework of the Thai-German Technical Cooperation Project "Environmental Geology for Regional Planning" the Chiang Mai-Lamphun Basin in NW Thailand was selected as a pilot area. Chiang Mai, Thailand's second largest city, is situated in the basin center. The area covers four topographic map sheets of scale 1:50000. Co-operation partners are, on the local level, the Provincial Planning Offices in Chiang Mai and Lamphun and, on the central level, the Department of Town and Country Planning in Bangkok. Moreover, the

Fig. 1
The new building of the Department of Mineral Resources

project co-operates closely with the Department of Land Development, which is the national authority in all soil matters.

Environmentally relevant geological information is provided in a set of thematic maps as well as in a synthesis map. The synthesis map summarizes the most important information from different technical disciplines and gives recommendations for land-use planning and land development from the geoscientific point of view. All maps are displayed in the scale of 1:100000, while field surveys and data compilation are carried out in the scale of 1:50000. The environmentally relevant technical disciplines are: groundwater, soils, search areas for waste disposal sites, mineral resources and natural hazards.

The project has set up a GIS Arc/Info for storage, processing and display of the spatial data. Compilation and production of thematic maps including the application of various overlay techniques are the main GIS tasks. This work is supported by a central EGS database under client/server technology (Windows NT, SQL Server).

Seismic hazards

The danger of seismic hazards is evidenced in Thailand most visibly by the historical earthquake in 1545 which destroyed parts of the pagoda “Chedi Luang” of Wat Chedi Luang in Chiang Mai. More recent is the record of an earthquake which occurred on 11 September, 1994 with a magnitude of 5.0 on the Richter scale. The epicenter was about 20-km SE of Amphoe Phan in northern Thailand. The earthquake destroyed the newly designed district hospital, which was built using reinforced concrete.

The seismic risk along active faults in northern Thailand has already been studied by various authors (e.g. Singharajwarapan 1982; Nutalaya and others 1985, Lukkunaprasit and Warnitchai 1994; Warnitchai and Lisantono 1996, Fenton and others 1997). Intensity, acceleration and displacement values have been calculated as well as estimated for the return period of surface rupturing (2500–15000 years). Empirical relationships between rupture length and earthquake magnitude indicate that the faults are capable of generating earthquakes as large as Mw7.

The Department of Mineral Resources is a member of the National Earthquake Committee. Accordingly, it has assigned the Environmental Geology Section with the task of participating in the Earthquake Hazard Reduction Program and to study active fault zones in Thailand. Hinthong (1995, 1997) proposed an overall review on the ongoing active fault programs in Thailand. His papers highlight the importance of a better understanding of active fault systems as well as the need for the development of relevant concepts and classification schemes. Research work of the EGS focuses on an assessment of the status of fault movement, on movement rates and on possible periods of return. A draft map (1:1000000) already shows 12 major active fault systems in Thailand. Further studies shoud provide a Seismic Risk Map as well as a Seismic Zonation Map. The final target is the establishment of relevant building codes to be elaborated in close co-operation with the Department of Public Works.

Landslides and flooding

Flooding of habitat areas due to riverbank overflow frequently occurs in different parts of the country. Most damaging was the event in August 1994, when newly developed residential areas in the southeastern outskirts of Chiang Mai were flooded by the Ping River. Damage costs were calculated to be about 40 Million US dollars. Intensive rainfall periods can also cause devastating landslides. The most destructive event in Thai history occurred in November 1988 near to Ban Kathun Nua in southern Thailand also involving a great number of casualties (Tantiwanit 1992). Detailed investigations showed that the mass-movement was triggered by a combination of several critical factors: rainfall intensity, slope steepness, soil stability and land use.

The EGS continues to study landslides and flooding events on a case by case approach. Its objective is to study and determine the critical parameters and their interrelationships in more detail, to integrate the information in relevant hazard maps and to make them available for the purpose of sustainable land-use planning and land development.

Coastal zone management

Thailand’s shorelines along the Andaman Sea and the Gulf of Thailand amount to about 2600 km. Geological and historical records indicate that the coastlines have considerably changed over time. They describe extremely dynamic environments and can pose serious threats to human life and property.

Processes of coastal erosion and their monitoring play an important role within the framework of environmental geological investigations (Sinsakul 1992). Aspects of sea level change, structural geology, stratigraphy, tectonic movement and climatic change are among the natural factors which have to be considered in this context. If not controlled and directed by safe concepts and strate-

gies, human encroachment can also contribute significantly to coastline destruction. This process in turn endangers human life and property.
With this background the EGS has the task of compiling and assessing the relevant geo-information from the coastal zones of Thailand and making this information available as thematic maps, including geomorphological, coastal hazard and coastal change aspects. The superior objective is to contribute to an integrated management concept for the coastal regions which focuses on their protection, and envirknmentally sustainable utilization.

Geosites conservation

Objects of special geological / geomorpholocical importance or beauty ("geosites" or "geotopes") are increasingly recognized as unique environments highly worthy for conservation and protection (Ad-hoc Geotope Conservation Working Group 1996).
In Thailand such geosites also occur. While some of them are already within the boundaries of protected national parks, others have been declared natural heritage sites and placed under conservation status. Several agencies and organizations are charged to enforce the existing laws with relevance to nature conservation.
The DMR is the government organization that compiles, registers and evaluates sites of special geological interest and provides recommendations for their protection and conservation. In this context it is not only takes into account the wish for the preservation of scientific research objects, but also the public interest in the geological heritage and its educational importance.
Geosites in Thailand may be generally divided into three groups: rock exposures, geomorphological features and geothermal phenomena. Rock exposures or outcrops are generally related to exceptional and rare mineral or fossil occurrences or to important stratigraphic or tectonic/structural features. Here, the DMR is involved in a systematic inventory and description of such sites. Distinguished geomorphological landforms resulting from geological processes are found in Thailand in several national parks and are hereby protected under the forest laws of the Royal Forestry Department. The DMR provides, in some cases, geological background information which explains the origin of these landforms to the public. Research work on the occurrence of natural hot springs and recommendations for their use are a further sector of DMR's activities in the field of nature conservation.
A future important aspect in geosite conservation and protection will be the necessity to iiprove the relevant legal framework. Adequate changes to the existing Mineral Act shall serve the DMR as a suitable tool to achieve this goal.

Conclusion

The Department of Mineral Resources has developed concepts and strategies for environmental protection and sustainable use of the geological resources. This is in reply to the obvious impact of rapid economic development in the past and in recognition of the important role which geology can play in this context. An inventory and assessment of the physical environment becomes increasingly important for a meaningful utilization of the natural resources. It is the task of geoscientists to unravel the complex geoscientific evidences and their interrelationships and to provide this geo-information in suitable formats to authorities for sustainable land-use planning and land development. While working in this fashion the DMR will also play in accordance with related environmental agencies an active role in the elaboration and implementation of laws, guidelines and regulations aiming at the protection of the geological resources.

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VARIABILITY OF FLOW AND SOLUTES IN THE RATTAPHUM CATCHMENT (SONGKHLA LAKE BASIN), THAILAND

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Abstract. Pesticides can have a number of adverse impacts on crops, soil and water. In this paper, we focus on the physical and hydraulic properties of soils controlling the leaching of pesticides into the shallow groundwater of the Rattaphum Catchment in Thailand. Results from an analysis of soil physical properties, hydraulic conductivity, dye tracer and bromide tests show that the top 10–30 cm of soils in the three agro-ecosystems (vegetables, fruits and rubber) have a high clay and organic carbon content and are relatively impermeable with very low hydraulic conductivity (15–40 cm/day). Most of the dye and bromide were retained in the top clayey layer; the bromide forming a miniature bulge below 30 cm in two profiles which dissipated after 30 days, while the pesticides were mainly confined to the top 10 cm.

Keywords: bromide and pesticides leaching, dye tracer test, groundwater, soil properties

1. Introduction

The Rattaphum Catchment is a predominantly agricultural region, of 9100 km^2, in southern Thailand. It is one of the fastest growing (GNP > 6 %) regions in Thailand and supports a population of 1.25 million with over 75% of the labour force engaged in agricultural activities (SLBPS 1985). The Basin has a tropical monsoon climate. The rainfall is highly seasonal, resulting in flooding in the wet season and pronounced water deficits in the dry season. Over 75% of the rain falls between October and January, while February and March are very dry. Average precipitation is about 1900 mm/yr, while average Class A pan evaporation is about 1400 mm/yr (MD, 1994).

The provincial, small town and rural public scheme water reaches a rather small percentage of the total population, with more than 75% being served by private shallow wells. Shallow groundwater also provides much of the public domestic water demand, as deeper aquifers have been largely unexploited. Private wells dug into the shallow aquifer are the primary source of domestic water supply for the majority of the rural population.

The three main groups of agricultural agro-ecosystems consist of rubber, fruits, rice and vegetables (Kamnalrut *et al.*, 2001). Of the total cultivated area, paddy rice occupies about 50%, rubber about 40% and the intensive agriculture (fruits, vegetables and field crops) about 10%. However, the economic return per unit land area is highest from the intensive agriculture. The main vegetables grown are:

cauliflower, kale, onion, petasi, lettuce, egg plants and chillies. It is estimated that the fruit and vegetable industry in the Rattaphum Catchment (part of the Songkhla Lake Basin (SLB)) region is worth about 30 million dollars/yr and engages a workforce of about 35,000 (Dept Agriculture, 2000).

The Songkhla Lake Basin is characterised by three broad topographic units (Panapitukkul and Chatupote, 2001). A narrow range of mountains lie to the west and south of the Basin and are covered by native forest. Parts of the foothills and terraces are used for growing tropical fruits but much of this part of the landscape is used for rubber agro-ecosystem. The broad plains are used for rice production in the west, while in the east near Songkhla Lake land is mostly used for intensive agriculture (e.g. vegetable agro-ecosystem).

During the last decade, the use of fertilisers has been increased linearly, while the official import and application of pesticides has increased almost exponentially (Chatupote and Panapitukkul, 2001). The greatest use of fertilisers and pesticides is in intensive agriculture (e.g. vegetable), followed by the fruit agro-ecosystem. The smallest use is in the rice and rubber agro-ecosystems. Generally, vegetable growing is associated with light to medium-textured soils; therefore the potential of leaching of agrochemicals is likely to be highest. The organic input is through chicken or cow manure. In most cases three crops of vegetables are grown in a year. The rate of fertiliser application varies with the crop type and to some extent on the farmer, thus the exact amounts used remain largely unknown.

A wide variety of insecticides and fungicides are used in crop production (Pipithsagchan *et al.*, 1994). The intensity of use is the highest in the vegetable agro-ecosystem followed by the fruit agro-ecosystem. The most common insecticides used include carbosulfan, carbaryl, methamidophos, prothiophos, fenvalerate, permethrin and teflubenzuron. Fungicides include benomyl, mancozeb, diuron, captafol, chlorothalonil and copper oxychloride.

The majority of villagers use wells dug into the top of the shallow aquifer for drinking water supply as well as for irrigation. Overall the depth of the shallow aquifer varies from a couple of metres to 50 m. In the vegetable growing area the depth to the water table is less than 5 m. In the majority of cases ($>70\%$) the farmer's home is surrounded by vegetable farms. In many instances, the household toilet is located in close proximity (within 10 m) of the drinking supply well. In general, the results of a coliform bacteria count show that all water samples from the three agro-ecosystems are highly contaminated with coliform bacteria, with most of the water samples highly contaminated with fecal coliform bacteria (Panapitukkul *et al.*, this issue).

Due to the heavy application of fertilisers, nitrate-nitrogen (NO_3–N) and ammonia nitrogen (NH_3–N) are the main chemicals of concern in the study area. A high percentage of water samples analysed from the agricultural areas especially in the vegetable agro-ecosystem, exceeded World Health Organisation standards. As a general trend, the nitrogen concentrations were found to be highest in the vegetable agro-ecosystem, lower in the fruit agro-ecosystem, with the lowest concentrations in rubber agro-ecosystem (Panapitukkul *et al*., this issue).

In this paper the mobility and penetration of pesticides through surface soils to the groundwater is assessed for the various farming systems of the Rattaphum Catchment area. Many activities were carried out to address this, including:

- quantification of the physical and hydraulic properties of soils;
- tracer tests to study infiltration characteristics; and
- investigation of the leaching characteristics of bromide and selected pesticides under site specific conditions.

This allowed a more holistic assessment of the fate of the chemicals of concern.

2. Background Information

2.1. Landform and Geomorphology

The Rattaphum Catchment is characterised by a narrow range of mountains to the west and south. These slope eastward through the foothills and flood plain to Songkhla Lake. There are four main landforms comprising mountains, hills, plains and a lake system with associated inland wetlands (Panapitukkul *et al.*, this issue).

The lake system and the inland wetlands include the lake and fringing swamps and marshes. The wetland areas were formed by silting caused by recent inundation and consist mainly of very soft silt and clay.

The coastal plain was formed by the marine deposition of clay and low sand ridges in a sequence of a several regressions. During pauses in a period of relative movement, clay sediments were deposited in shallow seas and sand ridges were formed along the coastal front.

The flood plains are of fluvial origin and occur in the east of the catchment. They were formed by the continued deposition of clays and silts brought down by the river. At the river mouth shoals and shallows form offshore. Marine clay deposits consisting of very soft clay and silt are covered by fluvial flood deposits.

The footslope and terraces form a relatively narrow band along the east side of the mountain range, with slopes ranging from 5–25%. They are generally composed of gravel, sands, silts and laterite. The high plains in the west, which lie at an altitude ranging from 80–120 m above mean sea level (MSL), form the transition between the hills and the flood plain. This transitional landform is composed of Mesozoic sedimentary rock, covered in places with terraces of Pleistocene deposits.

The hills and mountains at the boundary of the project area to the west form an uplifted crest of rocks with steep slopes. The mountains (of an average height of 500 m above MSL) are formed by erosion-resistant granite.

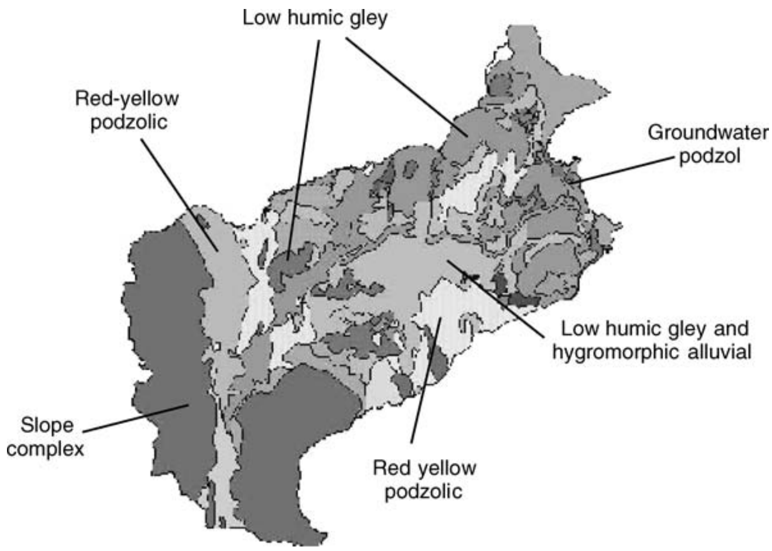

Figure 1. Major soils in Rattaphum Catchment.

2.2. Soil Types

There are six major soil types within the SLB (Figure 1). They include Humid Gleys (occupying 20% of the total area), Hydromorphic Alluvial (15%), Podzol (16%), Humid Gley/Podzols Association (21%), Lithosols/Podsols Association (7%), and slope complex soils (17%) (Dept of Land Development, 1981).

Humid Gleys soils are developed on the old flood plain and lowlands and are found throughout the rice growing areas and swampy land. They range from sandy loams to silty clays, and are moderately suited to rice production and a few field crops which can tolerate the heavy blocky structure of the subsoil when it dries out. Poor drainage, low phosphorous and potassium levels are their main limiting characteristics.

Hydromorphic Alluvial Soils are mainly associated with inland wetlands and the coastal plain of recently deposited beach sands. Poor drainage and flooding, along with local acid sulphate character and relatively high-saline salt content are some of the main limiting characteristics of these soil types. They commonly need substantial applications of N and P fertiliser to achieve good rice yields, or dry season crops.

Podzols are found on the foothills and dissected terraces along the western and southern boundaries of the basin and are used mainly for rubber plantations. Cation Exchange Capacity is usually low as are the nutrients P and K, resulting in low fertility, which is their main limitation for cropping.

Slope Complex Soils are shallow recent soils on the upper foothills and mountainous areas. They are well drained with poor fertility, and have a high

TABLE I
Major characteristics of soil units

Soil unit	Soil name	Slope (%)	Effective soil depth	Texture profile	Drainage	Ground water level	Organic matter
6	Humic gley	<2	very deep	Loam or silt loams or clay loam over silty clay or clay with plinthite of more than 50% in any subhorizon with 1.25 m.	Poor	Saturated during 4–5 months of the year	Medium (1.75%)
6sp	Low humic gley	<2	very deep	Sandy loam over loam or clay loam or sandy clay loam which occurs at a depth between 60–85 cm from the surface and accompanied with plinthite that form a continuous phase or constitutes more than half of the matrix of some sub horizon	Poor	Saturated during 3–4 months of the year	Low (0.7%)
17	Red yellow podzolic	2–5	v. deep	Sandy loam throughout but sandy clay loam may occur below 80 cm.	Good	Below 1 m throughout the year	Low (0.85%)
23	Ground water podzols	0–1	v. deep	Sandy clay loam over sandy loam over loamy sand or sand accompanied with soft iron concretion or iron pipe	Poor	Saturated during 3–4 months of the year	Moderately low (1.4%)
34	Humic gley	<2	very deep	Loam or clay loam over clay loam or clay with plinthite of more than 50% in any sub horizons within 1.5 m.	Poor	Saturated during 4–6 months of the year	N/A
45	Red yellow podzolic	6–30	v. shallow to shallow	Sandy loam or loam over very gravelly loam, very gravelly clay loam or very gravelly sandy clay loam or rock	Good	Below 1 m throughout the year	Moderately low (1.4%)

erosion hazard if cleared of trees. They are moderately suited to rubber plantation development. Some of the major characteristics of the soils developed in the catchment are summarised in Table I.

3. Materials and Methods

3.1. General

Investigations were focused on three agro-ecosystems: vegetables (BP15), fruit (KP1) and rubber (TP2), and their associated soil types (soil units No. 17, 34 and

45, respectively) to provide data on water movement in the major soil types of the area. Some physical and chemical properties of these soils are given in Table I. Hydraulic conductivity tests were conducted in the field using a disc permeameter at the soil surface and at 50 cm depth.

At the beginning of the rainy season the soils were rather moist and the water tables were high. Thus sites were selected where the water table was at depths greater than 1 m below the ground surface.

3.2. Experimental Setup

Three test sites were established, and consisted of a field plot approximately 2 × 2 m in dimension. The initial soil moisture content for the three sites is shown in Table II. Two days before the beginning of the tracer experiment, the crop and its residues were removed, and the soil surface was prepared with a spade. (This work was undertaken by the farmers).

3.3. Tracer Experiment

3.3.1. *Bromide and Pesticides*

Bromide and two commonly used pesticides, Parathion-methyl and Profenophos, were used in the tracer experiment. The application rates were about 4 g m^{-2} for Br^- and 1250 mg m^{-2} for Parthion-methlyl and 2500 mg m^{-2} for Profenophos. Bromide was added as potassium salt. The pesticides were mixed and then applied to the soil surface, using a hand-driven spray bar device commonly used for the application of pesticides. The plot was irrigated with 20 mm of 200 ppm Br^- using a local hand watering pot. During the first day, all plots received an irrigation volume equivalent to 20 mm. This corresponds to the average daily rainfall in the wet season. The amount of rainfall and irrigation were recorded every day from the

TABLE II

Initial soil moisture content at the three test sites

	Experimental sites (% by weight)		
Depth (cm)	Bp	Kp	Tp
0–5	17.6	14.8	13.8
5–10	11.8	14.7	11.1
10–20	12.3	13.3	9.9
20–30	11.3	13.5	11.0
30–50	12.1	16.0	10.8
50–75	10.5	11.3	8.5
>75	–	25.4	16.2

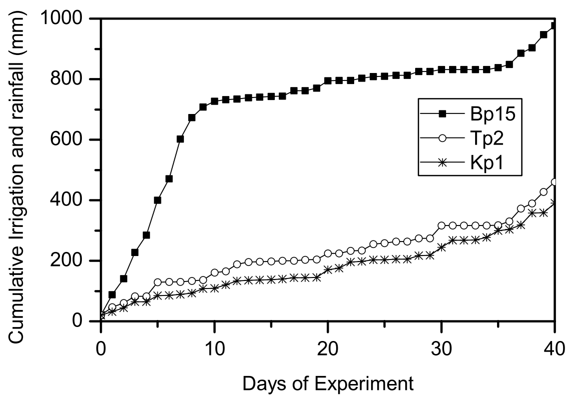

Figure 2. Cumulative irrigation water and rainfall during the experiment.

first day of chemical application until the 40th day. Figure 2 shows the cumulative amount of water applied versus time.

Soil core samples were taken by driving a 50 mm diameter, 100 cm long PVC pipe into the soil along a central line transecting the test plot. The soil core and pipe were sectioned into equal intervals, such as 0–10, 10–20, 20–30, 30–50, 50–70 and 70–100 cm. Coring occurred immediately after the chemicals were applied and 1, 3, 5, 10, 20, 30 and 40 days after chemical application.

3.3.2. *Brilliant Blue Dye Tracer Test*

A dye tracer test was conducted after the rainy season during January 2002 when the soil moisture was relatively low and the water table below 1.5 m from the surface for all sites.

At each field site the plot was irrigated with a solution containing 1 kg Brilliant Blue. A total of 20 mm of irrigation water was applied within 8 h. One day after the application of the solution, a trench was dug to a depth of 1.0 m. A vertical soil profile was monitored and photographed with a calibrated wire mesh grid to help follow and calculate the distribution of the dye. Three profiles were photographed from the same trench in the same day and the distribution of the dye was then calculated using a 10 $\times$ 10 cm wire grid.

3.3.3. *Chemical Analysis*

Bromide The Br in soil was extracted by distilled water at a ratio of 1:5, soil to water. An Orion bromide electrode model 9635 was used to measure bromide concentrations. The standard solutions used for the calibration curve ranged between 0.5 to 100 ppm.

Pesticides Organophosphorus pesticides were extracted from the water samples with 150 ml hexane by mixing vigorously for 2 min using a high speed homogeniser.

The volume of extract was reduced and injected into a gas chromatograph (HP 6890) equipped with an NPD detector and a split-less injection system. A HP–5 capillary column (30 m × 0.32 mm ID) was programmed to resolve the analytes. The temperatures of the injector and detector were kept at 260 and 290 ° C, respectively. The overall recovery from spiked samples ranged from 73 to 100%. Data presented in this paper were not corrected for differences in the recovery.

Organophosphorus pesticides were extracted from 10 g of soil sample with 30 ml of 1:1 hexane/acetone in microwave. Similar procedures were followed for reduction and analysis in the case of water samples.

4. Results and Discussion

4.1. Soil Properties

4.1.1. *Lowland Soil No 6 at Bp 1 and Bp 4 and Bp15 Sites*

In the lowlands the soil textures from three sites ranged from loams, clay loams and sandy loams. The soils had very low hydraulic conductivity (15.1 cm/day) at the top of the profile. A clay layer occurred 25–30 cm below the soil surface. Organic matter averaged 1.75% in the top 30 cm of the soil, and the pH of the soil become mildly alkaline. Soil bulk densities were high and varied with soil texture and soil compaction Table III). Water content varied from 5 to 9% by weight.

TABLE III

Soil properties of the three experiment sites (SL: sandy loam; CL: clayey loam; SCL: sandy clayey loam)

Soil	Depth (cm)	Bulk density gm/cm^3	Gravel (%)	Clay (%)	Silt (%)	Sand (%)	Texture	Conductivity Ks (cm/day)
Bp15	0	1.68	1.84	0.27	0.33	0.41	SL	15.1
	20	1.72	0.00	0.39	0.28	0.34	SL	
	50	1.78	0.00	0.24	0.34	0.43	CL	108.0
	60	1.60	0.00	0.53	0.22	0.25	L	
	130	1.77	0.00	0.53	0.26	0.21	CL	
Tp2	0	1.57	3.36	0.23	0.05	0.72	SCL	32.6
	10	1.65	3.98	0.24	0.08	0.68	SCL	
	20	1.57	5.07	0.18	0.12	0.70	SL	
	50	1.47	8.87	0.20	0.11	0.68	SCL	343.2
	100	1.68	42.61	0.29	0.13	0.58	SCL	
Kp1	0	1.64	2.01	0.18	0.24	0.58	SL	40.8
	20	1.52	10.15	0.20	0.19	0.60	SCL	
	30	1.63	10.63	0.20	0.15	0.65	SCL	
	70	1.78	41.30	0.26	0.16	0.59	SCL	175.4

4.1.2. *Lowland Soil No 17 at Bp 8 Sites*

Soil textures from the lowland soils at site Bp8 varied from loam, sandy loam to loamy sand. These soils have medium hydraulic conductivity throughout the profile (40–50 cm/day). Organic matter is very low (<1.0%) throughout the soil profile and pH of the soil varies from strongly acid to very strongly acid. Soil bulk densities follow soil textures. Available water capacity is from 8 to 13% by weight.

4.1.3. *Fruit and Rubber Plantations Sites*

Soil textures in fruit and rubber plantation sites varied from loam to clay. Soils had medium hydraulic conductivity at the top of the profile (32–40 cm/day) and a relatively higher hydraulic conductivity at depths of more than 50 cm (175–340 cm/day). Clay content increased with soil depth and changed to sandy loam after 50 cm. Organic matter is moderately low (1.0–1.5%) within 15 cm of the soil surface and low to very low below this depth (<1.0%). The pH of the soil is very strongly acidic at site Tp2 and slightly acidic at Kp1 site. Measured soil bulk densities were high and were linked to soil texture. Water content for the soil at site Kp1 is higher than that for soil site Tp2. This may be related to the high gravel content of soil site Kp1.

4.2. Dye Tracer Test

During the dye tracer experiment three profiles were taken from each trench on the same day. The results indicate that water flow pathways at all sites were relatively uniform for the three profiles in each trench. The dye was mostly limited to the top 20–30 cm of the profile, however deeper penetration occurred in places. The penetration of the dye decreased rapidly with increasing depth down to about 60 cm (Figure 3). This was due to the adsorption of most of the dye in the top clayey layer. At the Bp site, there were more irregular flow pathways in the soil. This behaviour was determined by the soil moisture content, repellency and the preferential wettability potential of the soil during the experiment.

However, at the other two sites the flow path was more uniform albeit at different rates, and this was related to the variability of the hydraulic conductivity of the soil.

4.3. Bromide and Pesticides Leaching Characteristics

4.3.1. *Bromide*

Bromide movement was related to saturated moisture content of the soil (Figure 4). Most of the Br (30–50%) was confined to the top 20 cm layer characterized by a low hydraulic conductivity following the first few days of water application (Figure 4). After 3 days bromide recovery was 30–40% at a depth of 65 cm and 30% at 90 cm. In most profiles a bulge was formed after 3 days and seemed to dissipate slowly downward, becoming greatly reduced after 40–50 days.

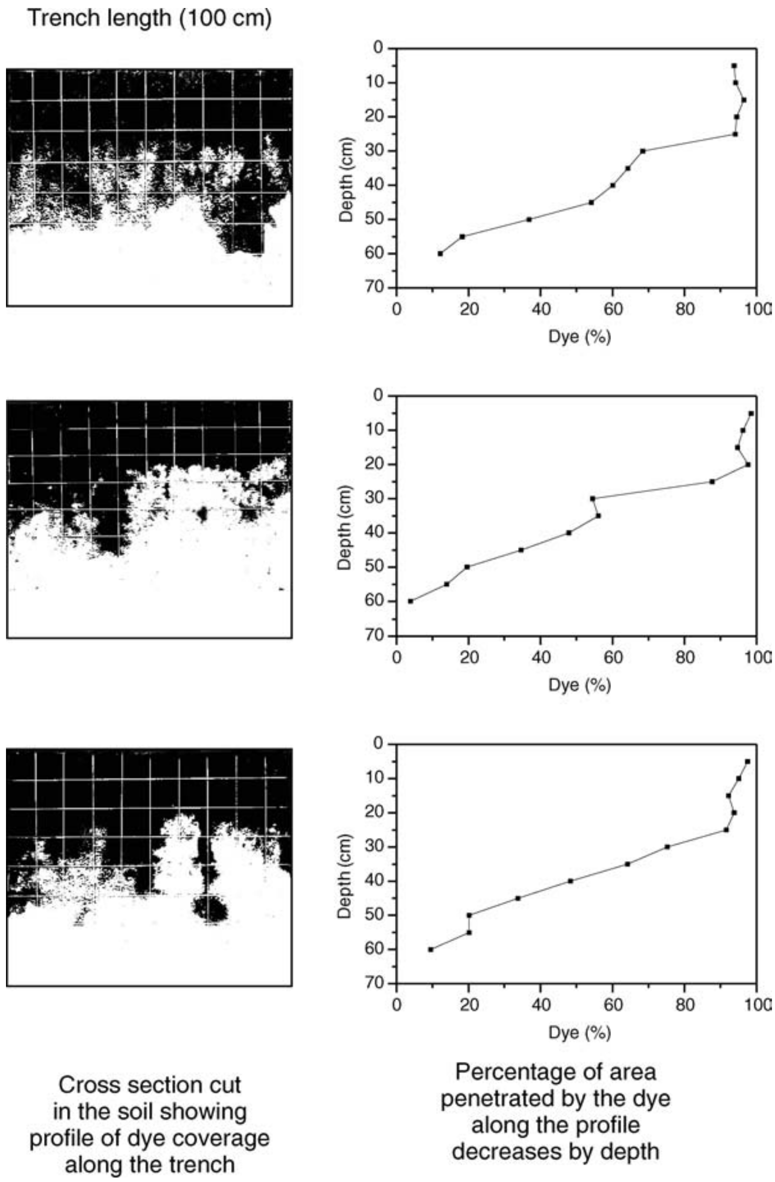

Figure 3. Vertical infiltration patterns of Brilliant Blue FCF and one-dimensional profiles of dye coverage after application of 20 mm coloured water in vegetable area (Bp15), Rubber plantation (Tp2) and fruit area (Kp1) (from top respectively).

4.3.2. *Pesticides*

Pesticides were mainly confined to the top 10 cm of the soil layer in contrast to the Br results which moved to below 50 cm during the experiment. However, the percentage recovery of the pesticides was relatively low and showed a relatively

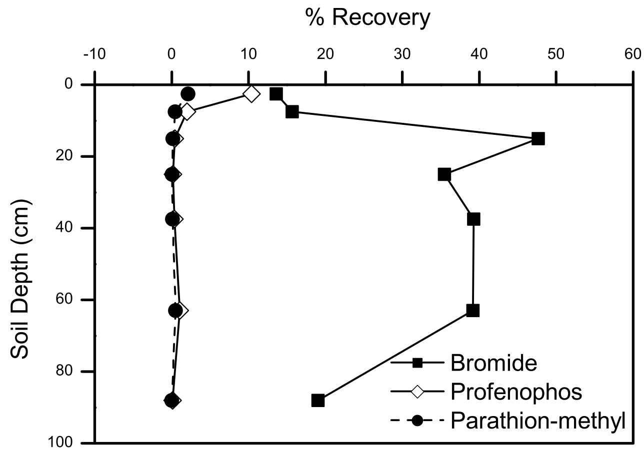

Figure 4. Bromide, profenophos and parathion-methyl after 30 days.

high variation between the different dates of sampling. This was attributed to the spatial variability of the soil core samples and the relatively short half life and high K_{oc} values of the pesticides.

5. Discussions and Conclusions

Pesticides have long been used for pest control throughout the world; hundreds of different compounds are in use. In Thailand the increasing reliance on pesticides for pest control has led to the degradation of soil and surface and groundwater quality in many areas. A detailed study has been conducted during the last 4 years in Rattaphum Catchment in southern Thailand to study possible contamination of surface and groundwater resources. The physical characteristics and hydraulic conductivity of the soils indicate that the top 0–30 cms are mainly clayey and silty loams of high organic carbon content and low hydraulic conductivity. Dye tracer test showed that most of the dye was adsorbed and retained in the top 0–30 cm of the topsoil. Similar results were also obtained from the pesticides which were retained in the top 10 cm with insignificant amounts passing to the 30 cm level. The conservative bromide formed a miniature bulge below 30 cm in two profiles; however, this was greatly reduced after 30 days by downward infiltration.

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ORIGINAL ARTICLE

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2001 debris flow and debris flood in Nam Ko area, Phetchabun province, central Thailand

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Abstract The factors of the debris flow and debris flood (debris flow-flood) occurrence on 11 August 2001 on the active Nam Ko alluvial fan in Phetchabun province, central Thailand, were studied. Evidences of past activity registered in the alluvial fan, and the debris flow-flood event were reconstructed. The disastrous debris flow-flood event was not the work of the unusual high amount of rainfalls alone, as previously theorized, but is a work of combined factors from the terrain characteristics with specific land covers to the time delay for accumulation of debris and sediments. This combination of factors could lead to a debris flow-flood after a high amount of precipitation. The process could also be worse if a landslide formed a natural dam, then the dam was destroyed under the weight of impounded water. After such a disastrous event, it would take time for more plant debris and sediments in the sub-catchment area to accumulate before the next debris flow-flood.

Keywords Debris flow and debris flood · GIS and remote sensing · Nam Ko · Phetchabun · Thailand

Introduction

On 11 August 2001 (8/11) at 3:30 a.m., a disastrous debris flow and associated debris flood (debris flow-flood) severely damaged Nam Ko Yai village on the alluvial fan just below the canyon mouth of the Nam Ko Yai stream (Fig. 1), a major tributary of Pa Sak river in Lom Sak district, Phetchabun province, central Thailand. The floodwater, full of debris and fallen trees, destroyed several houses on the stream banks and claimed 136 lives with over 5 million US dollars in property damage. This is one of many severe tragedies caused by the debris flow-flood in Thailand in the past few decades.

A complete understanding of the processes and the factors that influenced this incident in Nam Ko Yai sub-catchment and the alluvial fan below in terms of action, source areas and run-out zones, as well as the identification of the potentials for hazards has never been accomplished. Expected frequency of such a debris flow-flood in this area is yet to be evaluated. However, a case study analysis of this event will provide essential basic information to mitigate future debris flow-floods under similar geographical conditions.

This study identifies the relationship of influencing factors of the debris flow-flood occurrence, defines the evidences of past activity registered in the alluvial fan, and determines the potential for future disastrous events in this area. The results will provide planners and decision-makers with adequate and understandable information for more effective planning with the appropriate strategies to reduce and mitigate debris-flow hazards and related phenomena in a long-term risk analysis that could occur in areas of similar geographical conditions, and particularly, along the western flank of Phitsanulok-Phetchabun mountain range.

General concepts

Debris flows and related sediment flows are fast-moving flow-type landslides composed of slurry of rock, mud, organic matter and water that move down drainage-

Fig. 1 **a** Two oblique aerial photographs perceivably illustrating the characteristics and extension of a large volume of deposited sediments; and **b** four closed-up photographs illustrating the seriously battered structural damage of houses, orchard trees and other infrastructures in Nam Ko Yai village caused by the fast-moving debris flow-flood occurrence on 11 August 2001 (8/11)

basin channels onto alluvial fans. Debris flows are generally initiated by one of the two processes, by land sliding or by sediment bulking of surface water flows from intense rainfall or rapid snowmelt on steep slopes or in channels. When flows reach an alluvial fan and lose channel confinement, they spread laterally. In addition to being debris-flow-deposition sites, alluvial fans are also often favored sites for settlement. Debris flows pose a hazard different from other types of landslides and floods due to their rapid movement and destructive power. In addition to threatening lives, debris flows can damage buildings and infrastructure by sediment burial, erosion, direct impact and associated flooding.

Beverage and Culbertson (1964), Pierson and Costa (1987) and Costa (1988) describe the following flow types that build alluvial fans based on generalized sediment–water concentrations and resulting flow behavior: stream flow (less than 20% sediment by volume), hyperconcentrated flow (20–60% sediment by volume) and debris flow (greater than 60% sediment by volume). All three flow types can occur during a single event. The U.S. National Research Council (1996) also considers stream, hyperconcentrated and debris-flow types in alluvial-fan flooding. The term debris flood has been used to describe hyperconcentrated flow (Wieczorek et al. 1983), waterfloods with large sediment load (Costa and Jarrett 1981), sediment flow (Miyajima 2001) and mud flood (National Research Council 1982).

Understanding the processes that govern a debris flow-flood initiation, debris- and water-transport action in the drainage basin, sediment bulking and deposition on the alluvial fan is vital to hazard evaluation. The guidelines for such geologic evaluation are necessary for safe and appropriate land use to prevent loss of life and property damage. The general technique used address debris flow-flood hazards is to evaluate past flows on the alluvial fan and the drainage basin, as well as channel sediment-supply conditions (Cannon 1997; National Research Council 1996; Giraud 2002).

Investigation methods

Three data inputs were used: thematic data preprocessed from geographic information system (GIS) and remote sensing techniques, field observation and mechanical testing of soil and rock samples. Scar-scouring locations in Nam Ko Yai sub-catchment and deposition locations in the alluvial fan were detected and interpreted from multi-temporal satellite images, aerial photographs and rectified orthophotographs. Field visits were performed to determine the nature of some debris. The univariant probability analysis method of Dai et al. (2001) was used to present the spatial relationships between the detected scar-scouring locations and major debris flow-flood factors. To define the evidence of past debris flow-flood activity recorded in the alluvial fan, the geologic evaluation and age determination were used in a two-step procedure. This procedure (National Research Council 1996) consists of an initial delineation of the active depositional area and a subsequent detailed site-specific analysis of the hazard within the active depositional area.

The digitally based inventory of important input data themes in the study area was also preprocessed and compiled from secondary data, field investigation and interpretation of the multi-temporal rectified orthophotographs (1:25,000 and 1:50,000 scales), as well as satellite images of medium resolution (Landsat TM) and high resolution (IKONOS). These important input data themes were provided a basis for detailed analysis of initial terrain and damage sites using GIS and remote sensing techniques of Varnes (1984) and Westen (1994). These input data themes (Table 1) were primarily used for defining the evidence of past debris flow-flood activities, analyzing the factors affecting flow-flood processes and identifying the potential for flow-flood hazards.

Description of the study area

The study area (Fig. 2) is in the northwestern corner of the main upper Pa Sak catchment at the feet of Khao Ko

Table 1 Overview of the important input data themes discussed

Main theme	Sub theme	Made through
A. Debris flow and debris flood inventory map	A1. Scar-scouring and depositional locations	Multi-temporal image interpretation, multi-temporal image classification, field investigation
B. Geomorphological map	B1. Digital elevation model (DEM)	Topographic map, existing photogrammetric-elevation data
	B2. Slope	With GIS from a DEM
	B4. Topographic shape	With GIS from a DEM, image interpretation, field investigation
D. Geological map	D1. Rock unit	Existing geological map, image interpretation, field investigation
E. Soil map	E1. Soil unit	Existing soil properties map, field investigation
	E2. Soil thickness	Existing soil properties map, field investigation
F. Land cover map	F1. Land cover	Multi-temporal image interpretation, multi-temporal image classification, field investigation
G. Hydrological map	G1. Sub-catchment characteristics	Topographic maps, DEM extraction, field mapping
	G2. Drainage network	Topographic maps, DEM extraction
	G4. Rainfall intensity	Existing information, inflow hydrograph analysis
H. Elements at risk map	H1. Settlement area	Image interpretation, field investigation

and Phu Hin Rong Kla Mountains in the Phitsanulok-Phetchabun range. Nam Ko Yai village is situated on the alluvial fan. The sub-catchment area is 14 km long and 5 km across. The upstream rims are bounded by the steep slopes to a maximum altitude of 1,746 m in the northwestern part, down to the gentler slopes; then flat rolling sub-catchment terrain and the alluvial fan is at an altitude of 160 m.

Various rock units ranging from the uppermost Paleozoic and Mesozoic sedimentary and volcanic rocks to younger unconsolidated sediments occur in the study area. Stratigraphically, the lowest rock unit generally exposed in the eastern part of the study area is Permian Lom Kao (Lk) Formation. It consists of folded limestone, massive shale and slaty shale. Unconformably, above is the Triassic Lom Sak (Ls) Formation that is a volcanic complex, plus siltstone, shale and slate. Ls Formation covers most of the study area, especially adjacent to the central stream channel. Ls Formation is subsequently angular-unconformably overlied by the gently westerly dipping Khorat Group that is mainly exposed on the steepest and highest western and northern rims, near the tops of a flat highland away from the study area. This Khorat Group consists of Phu Kradung (Pk) Formation (red siltstone, conglomeratic sandstone, tuffaceous sandstone and siltstone) and Phra Wihan (Pw) Formation (gray sandstone, tuffaceous siltstone and red shale), both Jurassic in age, and Phu Phan (Pp) Formation (pebbly sandstone) of Cretaceous period. The younger unconsolidated sediments (Qa) of quaternary age are mainly stream deposits, composed of river sands and gravels, silts, clays and gray soils along the drainage system. The Qa sediments also include those that form the alluvial fan from the canyon mouth to the southeastern limit of the area.

The Nam Ko Yai sub-catchment is covered by dense forests on the western and northern high steep-slopes. Within the undulating valley floor along Nam Ko Yai

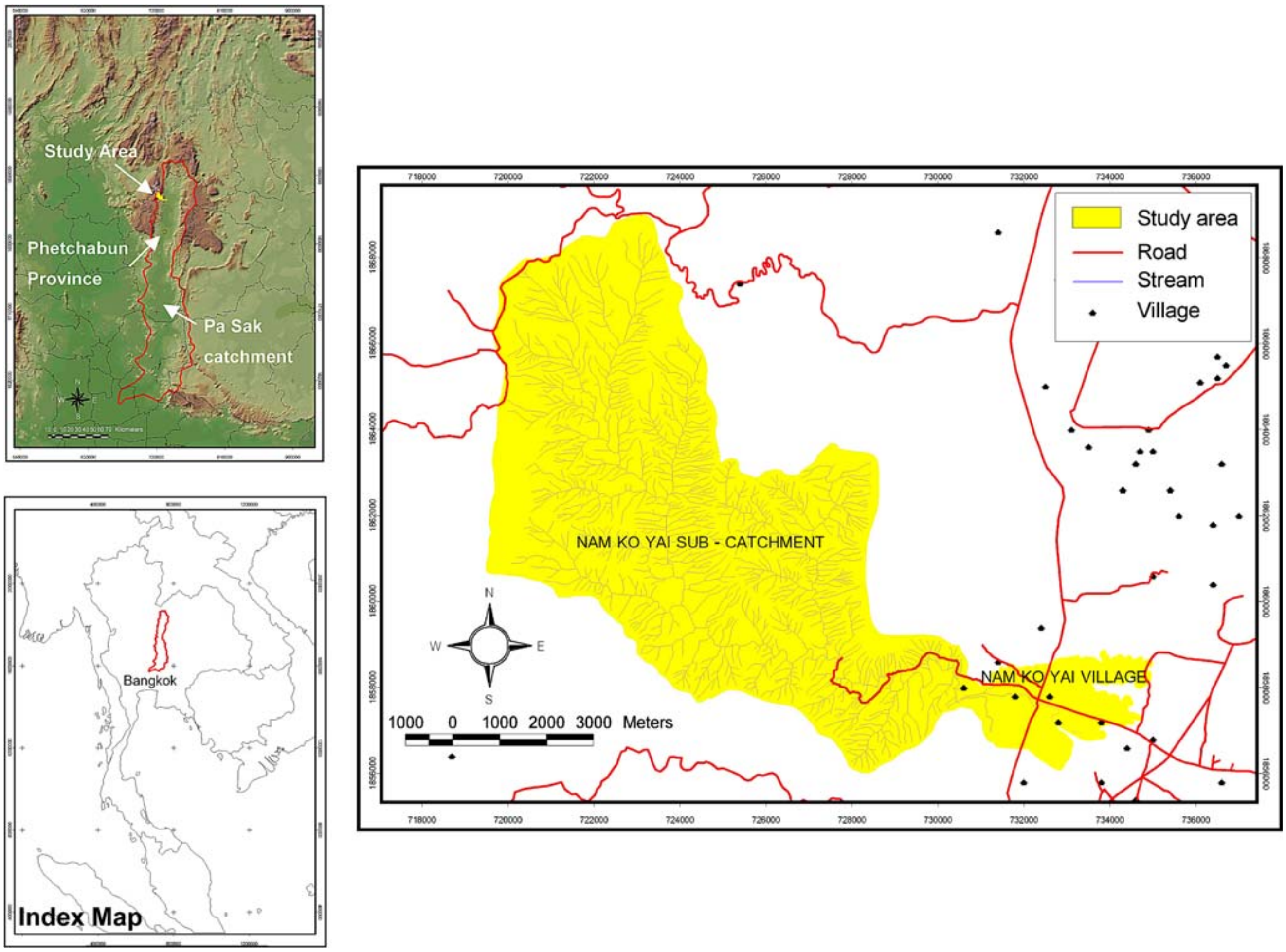
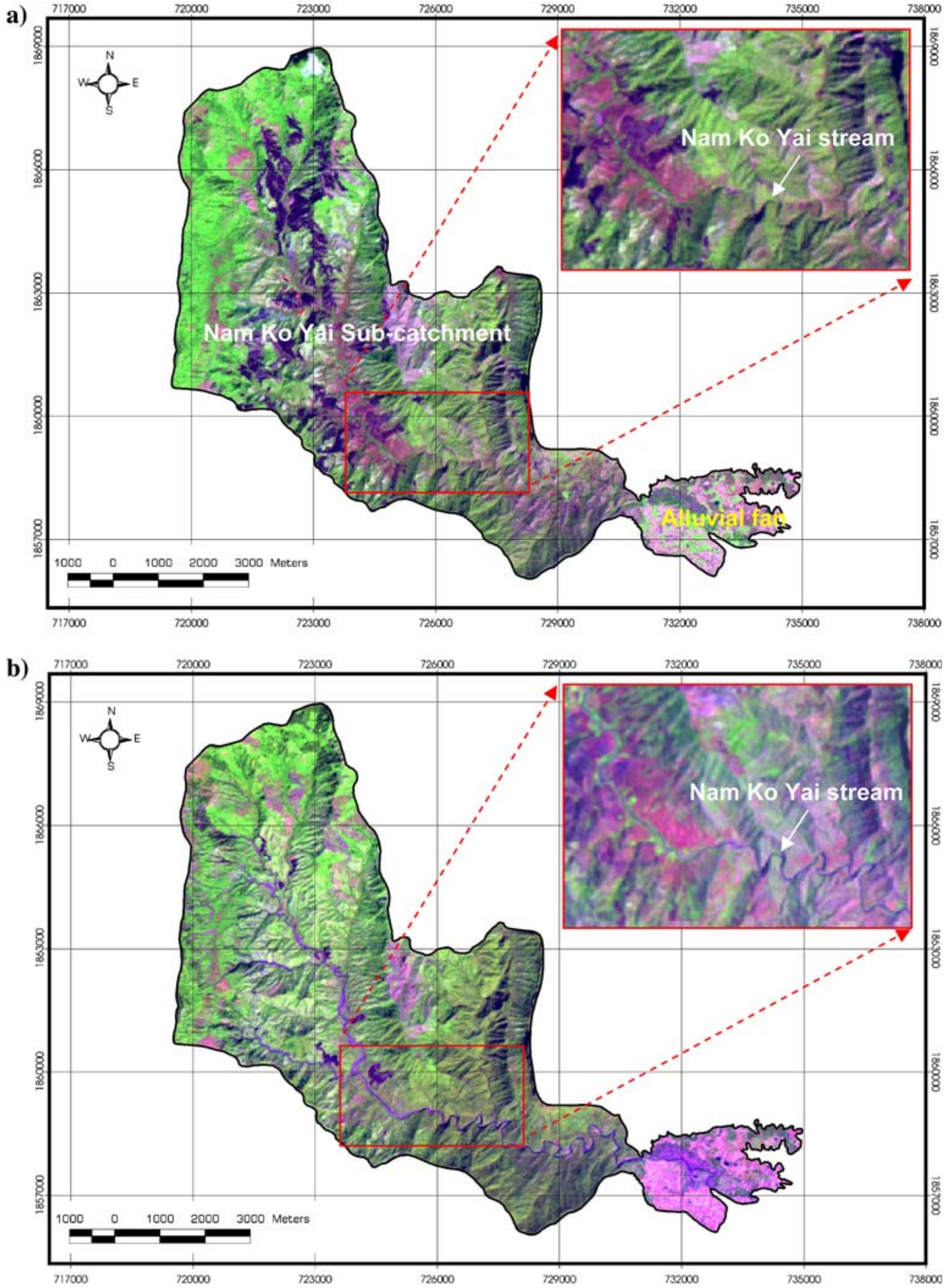


Fig. 2 Geographical location map of the study area in Pa Sak catchment, central Thailand. The coordinates are according to the Universal Transverse Mercater projection with 47 North Zone in Indian 1975 ellipsoid

Fig. 3 **a** False color composite of Landsat 7 ETM + (R = 5, G = 4, B = 3) of the study area acquired on 5 January 2001 (before the debris flow and debris flood occurrence); and **b** false color composite of Landsat 7 ETM + (R = 5, G = 4, B = 3) of the study area acquired on 21 November 2001 (after the occurrence) that show the distinctively changed features, especially in the main channels of Nam Ko Yai stream and its alluvial fan just below the canyon mouth



stream in the central part of the sub-catchment, deforestation preceded agricultural usage. Erosion includes sheet and rill, mass movement, gullies and badlands, which are widespread across the sub-catchment area. In the eastern extreme of the sub-catchment and on the alluvial fan, there are irrigated orchards and densely populated settlements.

In this upper Pa Sak region, the average annual rainfall normally exceeds 1,000 mm. The climate is tropical, occasionally with tropical storms in the early and middle periods of rainy season (June–October). The tropical storm ''Usa-ngi'' that passed through during the first 2 weeks of August 2001 was blamed for the 8/11 tragedy.

Evidence and factors affecting debris flow-flood processes in Nam Ko Yai sub-catchment

Factors affecting the 8/11 event included landforms, slope gradient, underlying materials, land cover and unusual amount of rainfall. Evidence of the 8/11 occurrence were scar-scouring and depositional locations from the flow/flood. A key assumption is that the potential (occurrence possibility) of the debris flow-flood processes is the same as the actual frequency of those processes.

Landsat 7 ETM+ imageries data and geomorphometric data (e.g. slope, terrain aspect, topographic shape, etc.) were derived from a digital elevation model (DEM) and combined to determine and classify newly formed distinctive scar-scouring and depositional locations in the sub-catchment and alluvial fan areas. These characteristics were detected in the Landsat imageries, aerial photographs and rectified orthophotographs. Brief field traverses were carried out locally. The ground-truth information was used to verify and adjust the accuracy of Landsat imagery classification, as well as aerial photograph and rectified orthophotograph interpretation.

Two sets of multi-spectral Landsat imageries of different periods, one on 5 January 2001 (before 8/11) and the other on 21 November 2001 (after 8/11), were classified (Fig. 3). Preprocessing of the six spectral bands of these Landsat imageries involve an atmospheric correction based on the standard atmospheric-model approach. Orthorectification was accomplished using GIS vectors of road- and stream data, as well as a DEM interpolated from contour vectors (1:25,000 scale). Slope and terrain aspect were calculated from the DEM. A normalized different vegetation index (NDVI) was created from the red and infrared spectral bands. NDVI was used to establish a threshold of vegetated and unvegetated pixels in the images for change detection at the scar-scouring and depositional locations (Fig. 4).

The classification scheme used to detect the scar-scouring and depositional locations utilized a user-specified hierarchical structure to eliminate non-relevant image objects. The first level was a division between the vegetated and unvegetated objects based on their NDVI value. The choice of 150.00 NDVI value (ratio) was empirically based on an inspection of the objects from the ground-truth information. Those objects with NDVI value below 150.00 were considered as unvegetated objects, and those above 150.00 as vegetated ones.

The scar-scouring and depositional locations were identified and validated. Classification accuracy was determined by comparing a sample of classified pixels with ground-truth information derived from the rectified orthophotographs and field observation (Fig. 5). The validity of the classified results was tested through the identified ground-truth information of the scar-scouring and depositional locations.

The univariant probability analysis was used to present the spatial relationship between the detected scar-scouring locations and each of the flow-flood related factors. Factors were the rock units (lithology), geomorphology (elevation, slope and topographic shape), soil thickness, land cover and hydrological data (catchment characteristics and rainfall intensity). The spatial data revealed the correlation between the scar-scouring locations and those influent factors. For this, the spatial data were converted to a 10×10 m grid or

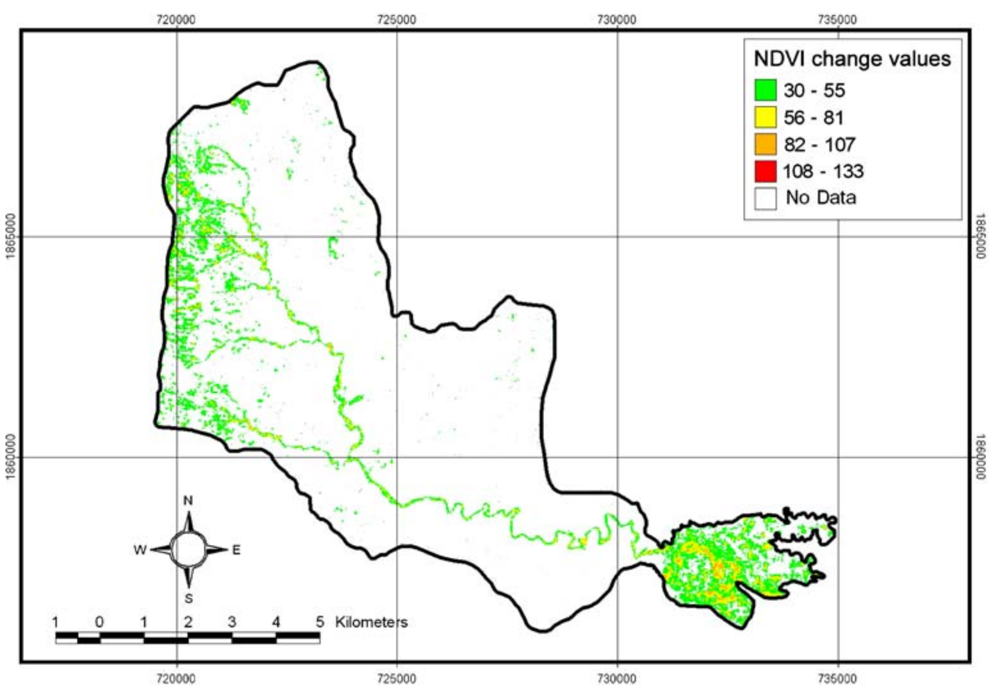


Fig. 4 The resulted significant change detection of NDVI showing scar-scouring and depositional locations in Nam Ko Yai sub-catchment and its alluvial fan that are caused from the 8/11debris flow-flood occurrence

cell (ARC/INFO GRID type) then further converted to ASCII data for a use with a general statistical program. In the study area, the total number of cells was 753,423 while the detected scar-scouring number of cells was 50,935. The correlation ratings were performed on the relationship between the detected scar-scouring locations and each factor's range, i.e., the ratio of the number of cells where scar-scouring was not detected to the number of cells where scar-scouring was detected. The relationship analysis is based on the ratio of the area of detected scar-scouring to the total area. A value of 1 defines an average value. The value greater than 1 means a high correlation, and less than 1 a low correlation. A high correlation indicates a high probability of the scar-scouring occurrence.

For slope configuration (Fig. 6), it was concluded that the steeper the slope, the greater the landslide probability was. For the slope inclination of 35–40° and

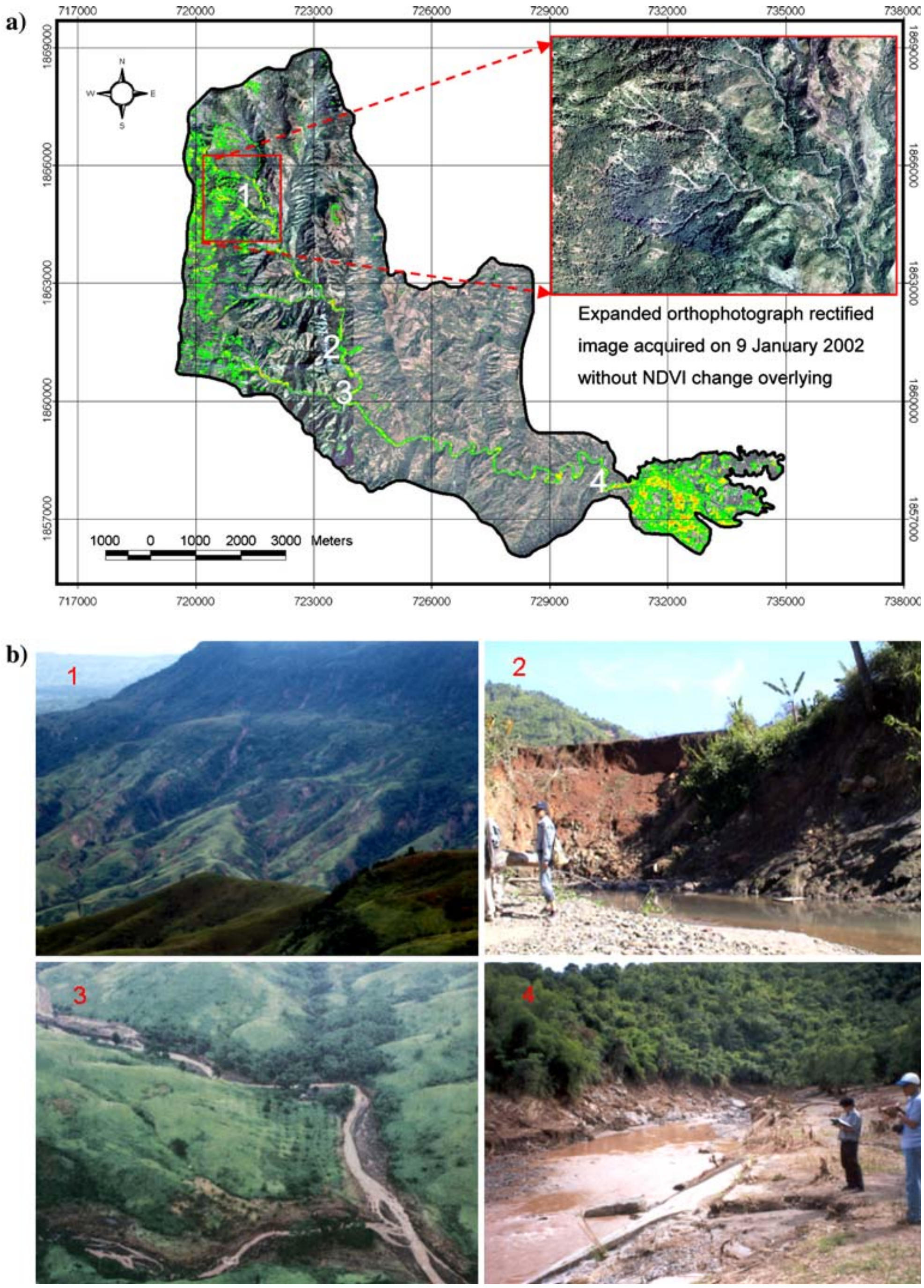


Fig. 5 **a** The significant change of NDVI (from Fig. 4) overlain on the orthophotograph rectified image acquired on 9 January 2002 (after the debris flow-flood occurrence); and **b** the photographs of four locations (number referred to the location in the map) taken a few days in Nam Ko Yai sub-catchment after the 8/11 event showing the ground truth evidences

more than 40°, the ratios were 1.57 and 1.70, respectively, indicating a slightly high probability for the scar-scouring occurrence in both cases.

For elevation above mean sea level (Fig. 7), the higher elevation, the greater the scar-scouring probability. For elevations between 1,000 and 1,100; 1,100 and 1,200; 1,200 and 1,300; and 1,300 and 1,400 m, the ratios were 3.16, 3.41, 3.99 and 2.54, respectively, indicating a very high probability for scar-scouring. Similar elevation ranges were observed in the steep-cliff areas.

The different topographic units, peak, ridge, saddle, flat, ravine, pit, convex hillside, concave hillside, slope hillside, inflection hillside, saddle hillside, seemed to be less significant. The frequencies of scar-scouring locations for any specific topographic shape were varied.

The frequencies of scar-scouring as related to the lithologic groups (Fig. 8) were determined for the different stratigraphic units. In the alluvial deposits (Qa1), Phra Wihan (Pw), Phu Kradung (Pk) and Lom Sak (Ls) Formations, the ratios were 3.188, 3.079, 2.302 and 2.713, respectively, indicating very high probabilities for scar-scouring occurrence in all units.

A relationship between the frequencies of scar-scouring and topsoil thickness was also attempted. Ranges of less than 50 cm, between 50 and 100 cm, and more than 100 cm were defined. Topsoil thickness was insignificant. Perhaps the scar-scouring occurrence was more directly related to the underlying basement rocks than to topsoil thickness.

Lom Sak (Ls) Formation is the most wide-spread rock unit in the study area and supplied the most debris of all sizes for deposition along the channel bank of the stream system. The debris were further transported downstream toward the alluvial fan, and perhaps formed a significant temporary landslide dam along the way. Special interest was paid to engineering properties of the weathered products of this rock formation. Six weathered samples from this rock unit were collected along a tributary from the main Nam Ko Yai stream channel to the toe of the steep slope just below the exposures of Khorat Group. Geotechnical studies performed included grain size analysis, determination of Atterberg limits and indices, natural moisture content and shear strength (Table 2). All specimens were non-uniform clay to clayey sand, with natural water content of 21–50%, with the plastic limit and liquid limit between 17 and 31, and 24 and 55%, respectively. The clayey soils also illustrate a low permeability value of about 10^{-2} to 10^{-7} m/s. This indicates that the natural moisture could hardly be drained out of the soils, which staying close to the liquid limit. If the soils receive more water, their weight increases while the shear strength decreases, thus the soils would easily flow. These soils had varied shear strength values from about 10 to 100 kPa. Ls Formation soils, however, had shear strength values lower than other common soils thus were highly movable.

The relationship between the scar-scouring and different types of land cover (Fig. 9) was also determined. The study revealed a high probability value on the banks close to the stream course and in forest areas further away, but lower in the cultivated flat areas. This is con-

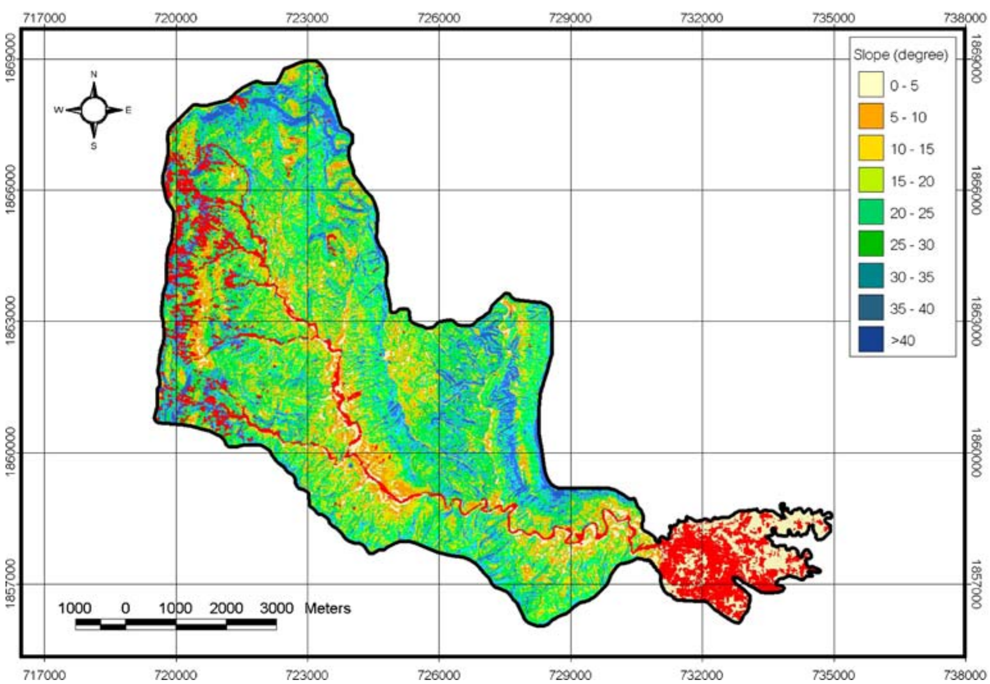


Fig. 6 Slope map overlain with scar-scouring and depositional locations (in *red*) in the study area

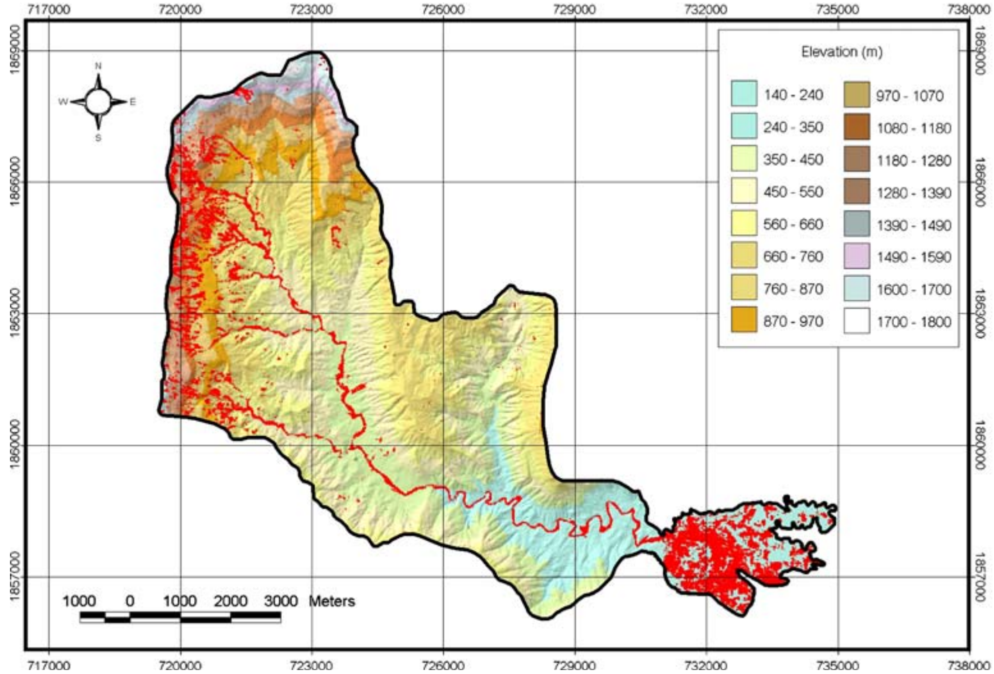


Fig. 7 Elevation map overlain with scar-scouring and depositional locations (in *red*) in the study area

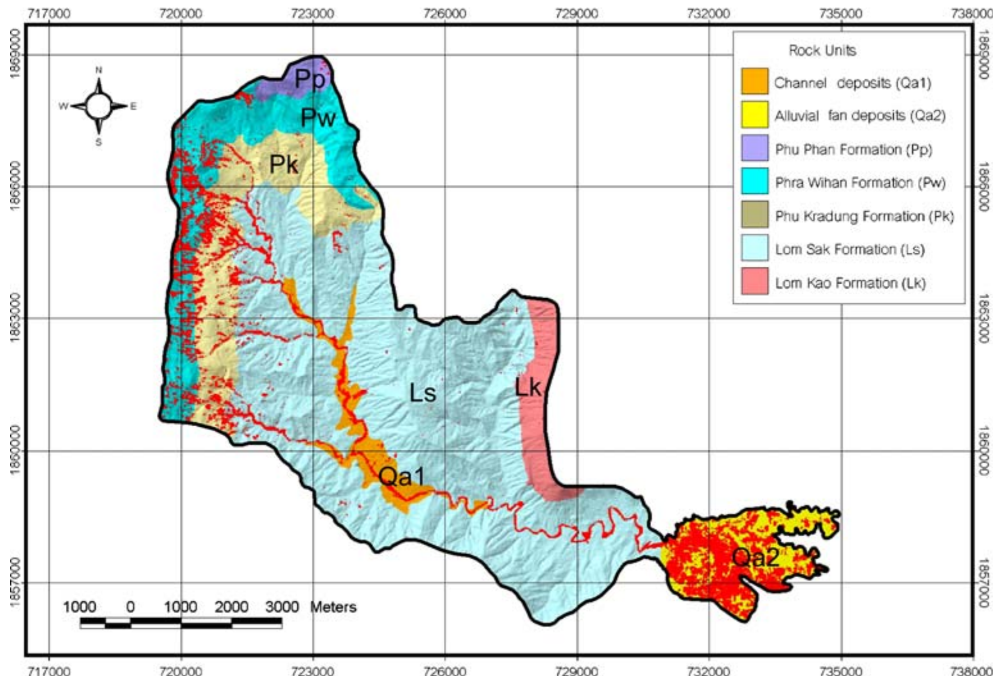


Fig. 8 Rock unit map overlain with scar-scouring and depositional locations (in *red*) in the study area

trary to a general belief that cultivated lands played a major role in this event. The explanation could be that the debris flow-flood occurred close to the main stream where there was high energy for erosion and transportation of sediments, and in the forested areas where water could be accumulated and retained to introduce more effective transport when the catastrophic event occurred.

The rainfall records during 1–10 August 2001, a period of 10 days before the 8/11 occurrence, were collected from seven surrounding rain-gauge stations (Fig. 10). The frequency of scar-scouring was determined by counting the scar-scouring locations in each isohyet range of rainfall accumulation. The results revealed a high probability value of scar-scouring locations

Table 2 The analytical results of some important soil engineering properties of the six soil samples collected from the weathered natural zone of volcanic complex of Lom Sak Formation (Ls) in the study area

Sample no.	Location	Percent finer #200 (% clay and silt)	Natural water content, w_N	Plastic Limit, w_P	Liquid Limit, w_L	Plastic index, $PI = w_L - w_P$	Activity, A = PI/% (clay)	Liquidity Index, $LI = (w_N - w_P)/PI$	C_u	Soil type			Shear strength (kPa)
										1[a]	2[b]	3[c]	
2-B	47 Q 0723290/ UTM 1860028	67.6	27.0	20.8	40.5	19.7	0.76	0.31	> 5	Clay	CL	A-7-6 (clayey soils)	40
3-B	47 Q 0723164/ UTM 1860126	87.1	44.9	29.2	54.6	25.4	0.53	0.62	> 5	Clay	CH	A-7-6 (clayey soils)	10
6-B	47 Q 0722980/ UTM 1860132	87.4	33.8	30.6	54.9	24.2	0.53	0.13	> 5	Clay	CH	A-7-6 (clayey soils)	93
7-B	47 Q 0722937/ UTM 1860140	77.3	34.4	25.4	45.6	20.2	0.67	0.44	> 5	Clay	CL	A-7-6 (clayey soils)	22
10-B	47 Q 0722609/ UTM 1860196	62.0	26.7	24.7	38.4	13.7	0.62	0.15	> 5	Clay sand	CL	A-6 (clayey soils)	87
1-A	47 Q 0728840/ UTM 1858259	38.1	21.8	17.4	24.20	6.8	0.31	0.65	> 5	Clay sand	ML	A-4 (silty soil)	9

CL inorganic clays of low to medium plasticity, gravelly clay, sandy clays, silty clays, lean clays; *CH* inorganic clays of high plasticity, fat clays; *ML* inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity

[a] Classification of the Mississippi River Commission

[b] Classification of unified soil classification system

[c] AASHTO soil classification system

in the western areas where the rainfall accumulation was over 150 mm during this period (Fig. 11).

In addition, the rainfall data and the inflow hydrograph from rainfall data of 1–10 August 2001 (pre-8/11 period) in related to the configuration of sub-catchment and channel characteristics were analyzed. The result was used as one of the most critical factors to identify the potential for the debris flow-flood. The graph of rainfall measurements in August 2001 from seven surrounding locations (Fig. 10) is presented in Fig. 12. The average 24-h rainfall value of pre-8/11 period was 12.98 mm. The two highest values of about 60 and 100 mm recorded on 10 August 2001 at the Ban Lao Ya station (southwest of the study area) and Ban Hin Hao station (northeast of the study area), respectively. The pattern of rainfall during 1–11 August 2001 recorded in most stations was the same as that of continuous rainfall during 2–14 August 2002.

The debris flow-flood may have begun before 11 August 2001 when the storm was in progress. Soils may have reached critical saturation at an earlier point, especially in the mountainous areas in the western and northern parts of the sub-catchment where the strongest intensity of rainfall was noted.

Evidence of the channel configuration and proposed natural dam location in the central part of Nam Ko Yai sub-catchment

From field investigations and rectified orthophotograph interpretation at a point along the course of Nam Ko Yai stream in the middle of the study area, the stream here issues from a flat open land to a very narrow V-shape channel with a sudden change of elevation at Tad Fa waterfall (Fig. 13). It could be hypothesized that this specific location is suitable for an accumulation of sediments composed of plant debris, soils and rock boulders to form a natural dam. A field check revealed fallen trees and vegetation traces. This probably indicated that the temporary natural dam was broken, sending the debris and water to flood further downstream, eroding the channel along the way, and finally dropping its load on the alluvial fan at the canyon mouth. The evidences of 8/11 event could be observed where Nam Ko Yai stream had a steep V-shape cross-section. The traces of the erosional feature in the outer curving bank were common. Some huge logs or intertwined bamboo clumps were left in the channel. Newly deposited large boulders were found in the channel where the gradient of stream bed changes from steep to flat. Eroded soil banks were also common.

Topographically, the area of Nam Ko Yai sub-catchment immediately upstream from this proposed natural dam location is a basin shape of about 100,000 square meters. This flat terrain is of a very

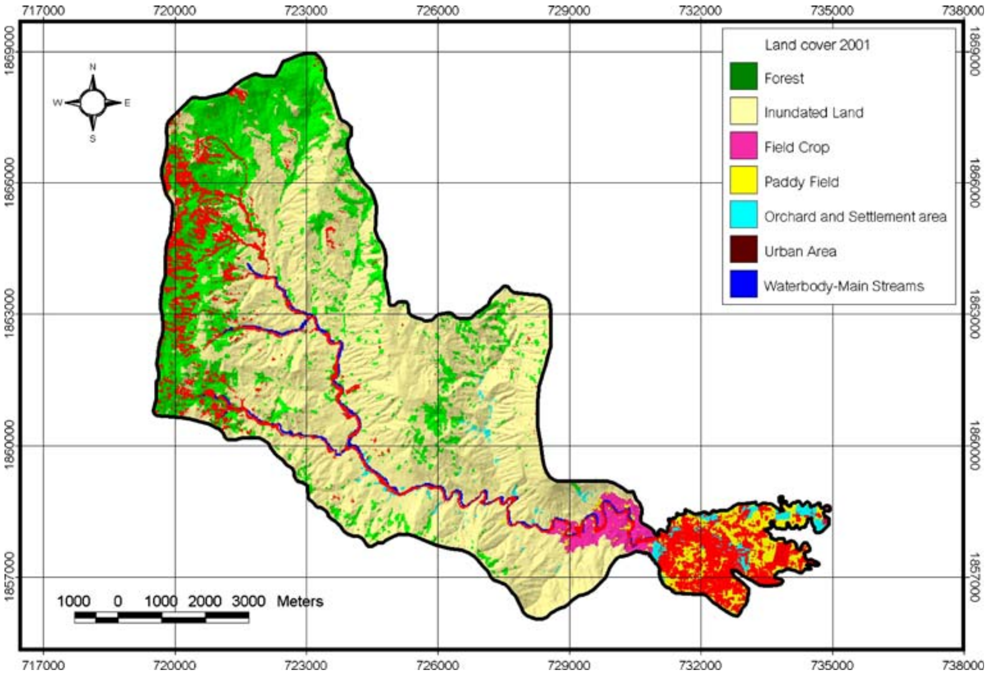


Fig. 9 Land cover map overlain with scar-scouring and depositional locations (in *red*) in the study area

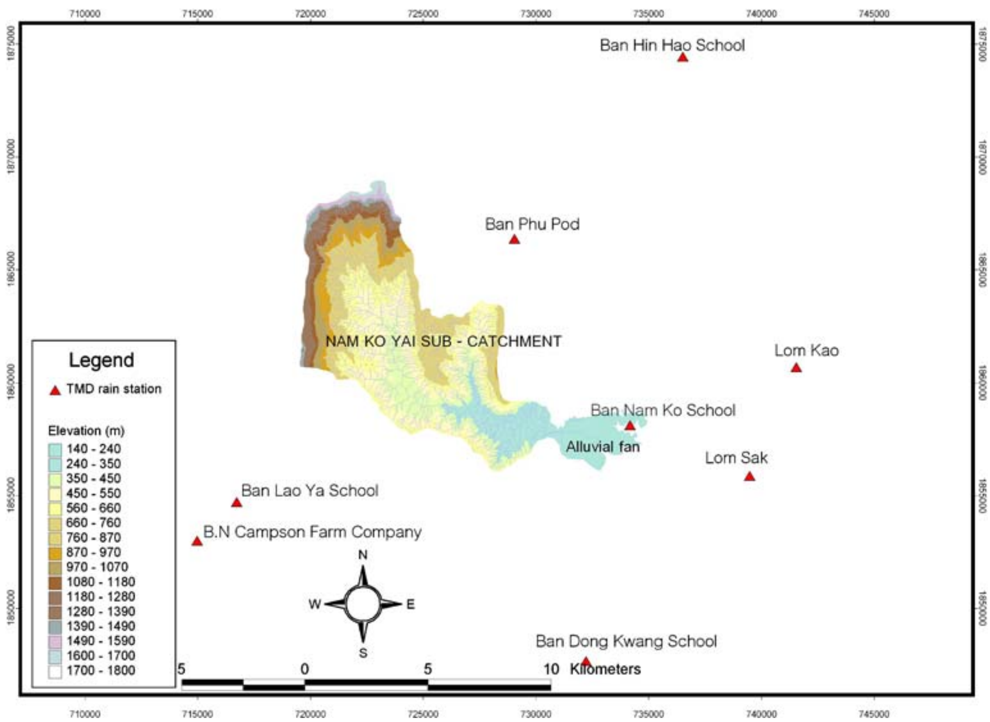


Fig. 10 Location of seven TMD (Thai Meteorological Department) rainfall measurement stations (*red triangles*) near the study area

gentle slope, less than 5°, surrounded by sloping walls with abrupt change in elevation. The stream here was of a wide U-shape and was straight for about 2,500 m. The area is suitable for forming a reservoir if a dam was built at the location. Downstream from the waterfall, the stream changes to a narrow V-shape with strong sinuosity for about 8,000 m to the canyon mouth area. This narrow V-shape and strong sinuosity channel is accompanied by increasing energy of torrent stream flow. This destructive form of mass movement was certainly not caused by the 8/11 alone, but indicates repeated strong debris flow-flood in the past.

From the field evidences and the oblique aerial photographs taken immediately after the 8/11 occurrence, the plant debris and soils transported from the sinusoidal stream banks (Fig. 14) were spread out onto the

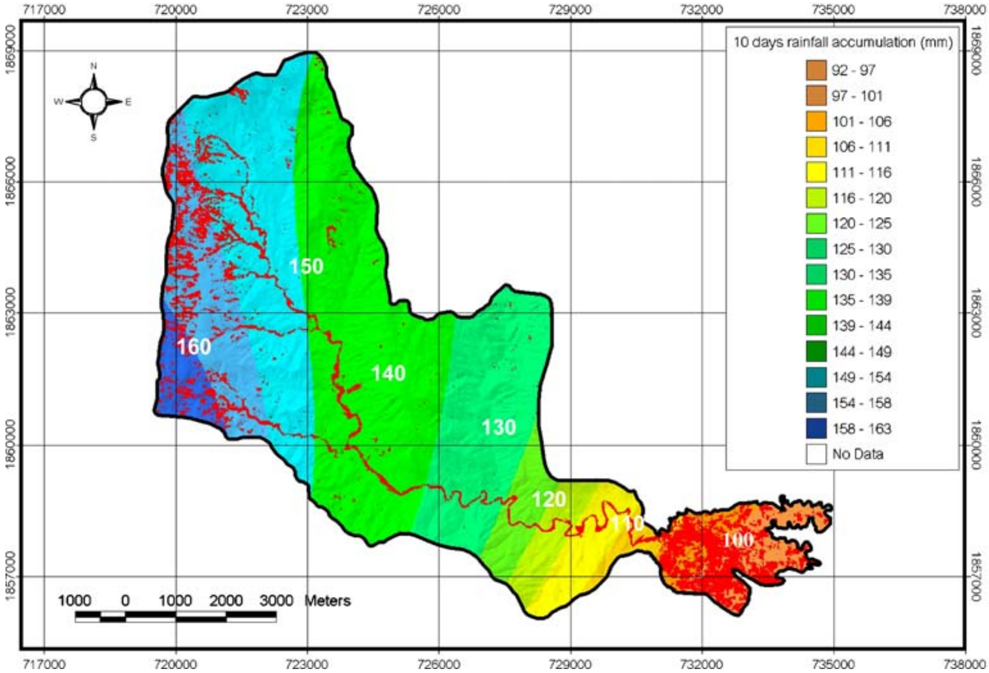


Fig. 11 Rainfall accumulation in the period of 1–10 August 2001 (before the 8/11 debris flow and debris flood occurrence) overlain with scar-scouring and depositional locations (in *red*) in the study area

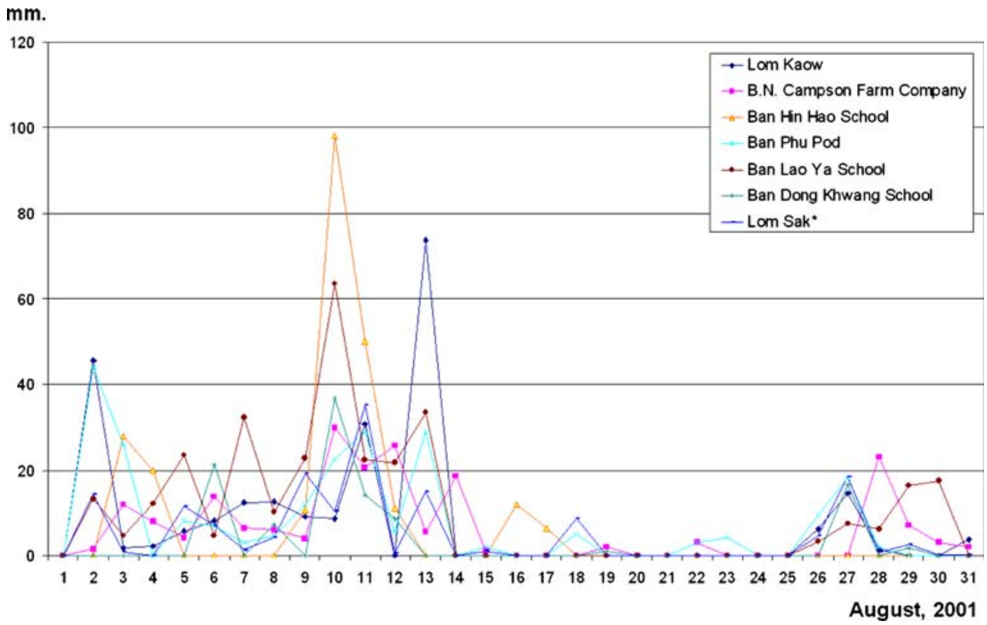


Fig. 12 The graph showing the pattern distribution of rainfall measurements in August 2001 recorded from the seven locations (Fig. 10) near the study area

alluvial fan at the toe of the mountain front. This fan was concluded that it has been formed by several similar debris flow-flood activities in the past.

Evidence of past debris flow-flood activity in the alluvial fan

The stratigraphic characteristics of the alluvial fan deposits are essential for evaluating past flows. A two-step geological evaluation was performed, consisting of an initial delineation of the active depositional area and a subsequent detailed, site-specific analysis of hazards within the active depositional area as suggested by the National Research Council (1996).

In step 1, which was to define activeness, multi-temporal aerial photographs, rectified orthophotographs and Landsat 7 ETM+ imageries were interpreted and integrated with topographic characteristics for preliminary identification of location and morphology. Detailed investigation of past representative sedimentary sequences and resistivity investigation were also

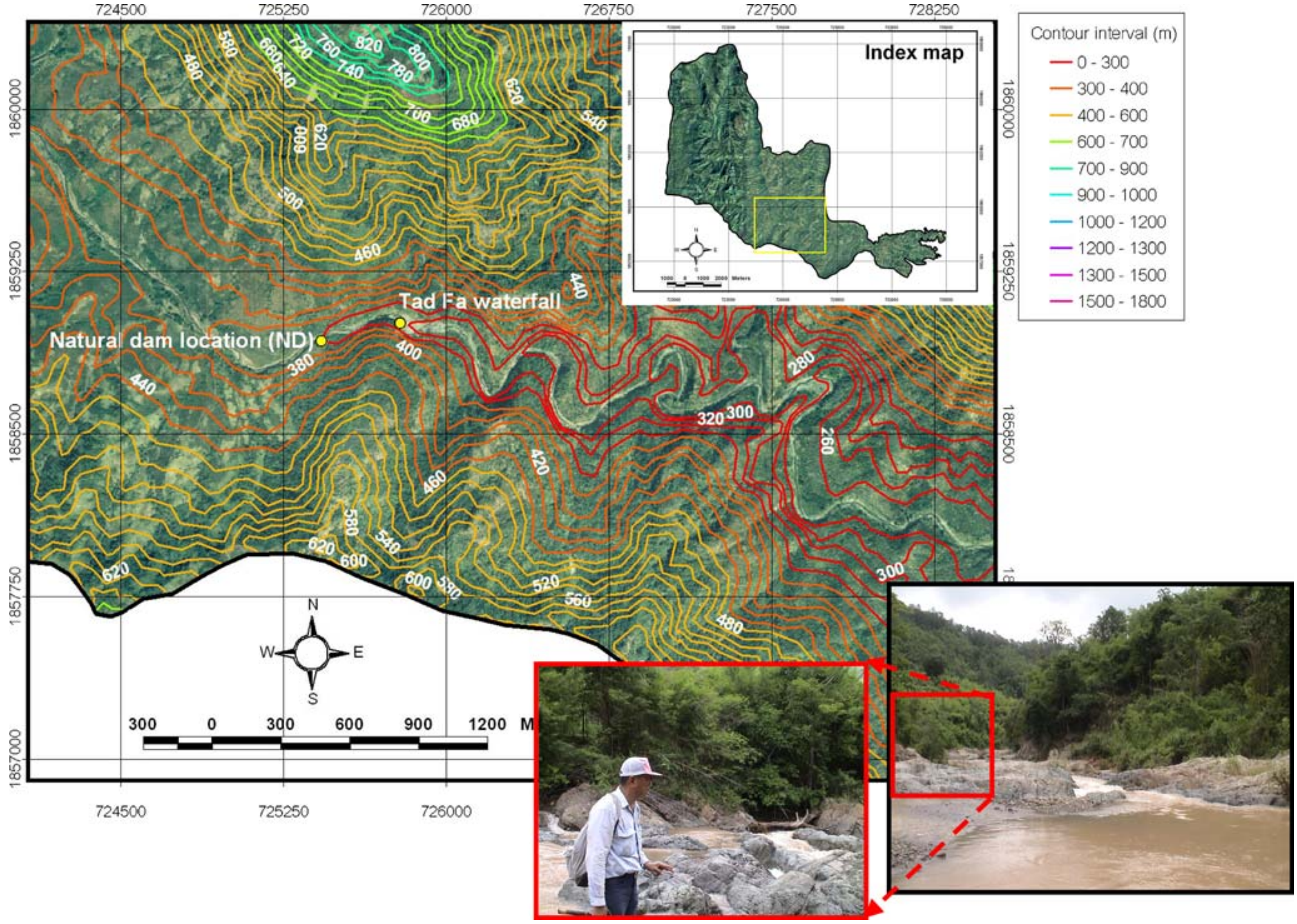


Fig. 13 The orthophotograph rectified image (1:25,000 scale, January 9, 2002 after the 8/11 event) overlain with the contour intervals (20 m) showing the specific configuration of Nam Ko Yai stream located in the lower central part of the study area proposed to be the natural dam location (ND) in front of the location of Tad Fa waterfall

conducted to determine the criteria for alluvial fan activeness.

The available multi-temporal low-altitude images of aerial photographs (1:15,000 scale) taken on 24 December 1974, rectified orthophotograph (1:50,000 scale) taken on 6 January 1996, and rectified orthophotograph (1:25,000 scale) taken on 9 January 2002 (Fig. 15) were used to characterize the Nam Ko Yai canyon mouth and its downstream depositional fan before and after the 8/11 event. The topographic apex of Nam Ko Yai alluvial fan had only minor changes between 1974 and 1996. A clear activeness of erosion and deposition was presumed to be from the 8/11 flow-flood event.

The expanded features of rectified orthophotographs (1:25,000 scale) taken on 9 January 2002 in Figs. 15 and 16 clearly show current traces and tracks of debris flood evidenced from the distinct and active alluvial fan deposit. The deposits mainly occurred on the northern bank of the alluvial fan area where the flood severely damaged houses and orchards dominantly seen in the

Fig. 14 The oblique aerial photograph (taken on 22 August 2001, 11 days after the event) along the channel of Nam Ko Yai stream with the high sinuosity characteristic illustrating the debris flow-flood track along plant debris and soils had been strongly eroded and transported from its banks before reaching the canyon mouth outlet of the stream

1974 aerial photograph and 1996 rectified orthophotograph.

In the multi-spectral Landsat 7 ETM+ imageries analysis, evidences of the alluvial fan deposit from the 8/11 event were analyzed using NDVI value. NDVI value was also used to detect the depositional locations on the alluvial fan (Fig. 16). Oblique aerial photographs taken after the flood were used to characterize the extent of the deposit and validate analyzed result. The high value of NDVI change (56–107) in Fig. 16 generally conformed the areas of the most serious damage in Fig. 17.

The oblique aerial photographs of the severely damaged settlement areas (Fig. 1) illustrate characteristics and extent of a large volume of an active alluvial fan deposit. The flood levels were established from mud traces on house walls and trees. The highest level of the debris flood, 190–200 cm above the ground level, was located in the most severely damaged zone at locations A and B (Fig. 17). The two locations faced the straight course of Nam Ko Yai stream before the channel changed direction abruptly further downstream. Here, the flood jumped over-bank to destroy houses and orchards and claim lives.

In step 2, a subsequent detailed and site-specific analysis of the hazard within the active depositional area was characterized. The multi-temporal aerial images and oblique aerial photographs clearly illustrate the typical morphology of an alluvial-fan landform where the village is situated. The landform is a section of stream gradient where long-term channel migration and sediment accumulation became markedly less confined than upstream. Below, gradients of the lower part of the older alluvial fan are gentler than those at the fan apex, as was noted from the wider spacing of contour lines in Figs. 15 and 16. The topographic apex of this active alluvial fan was located at the point where the flow in the stream

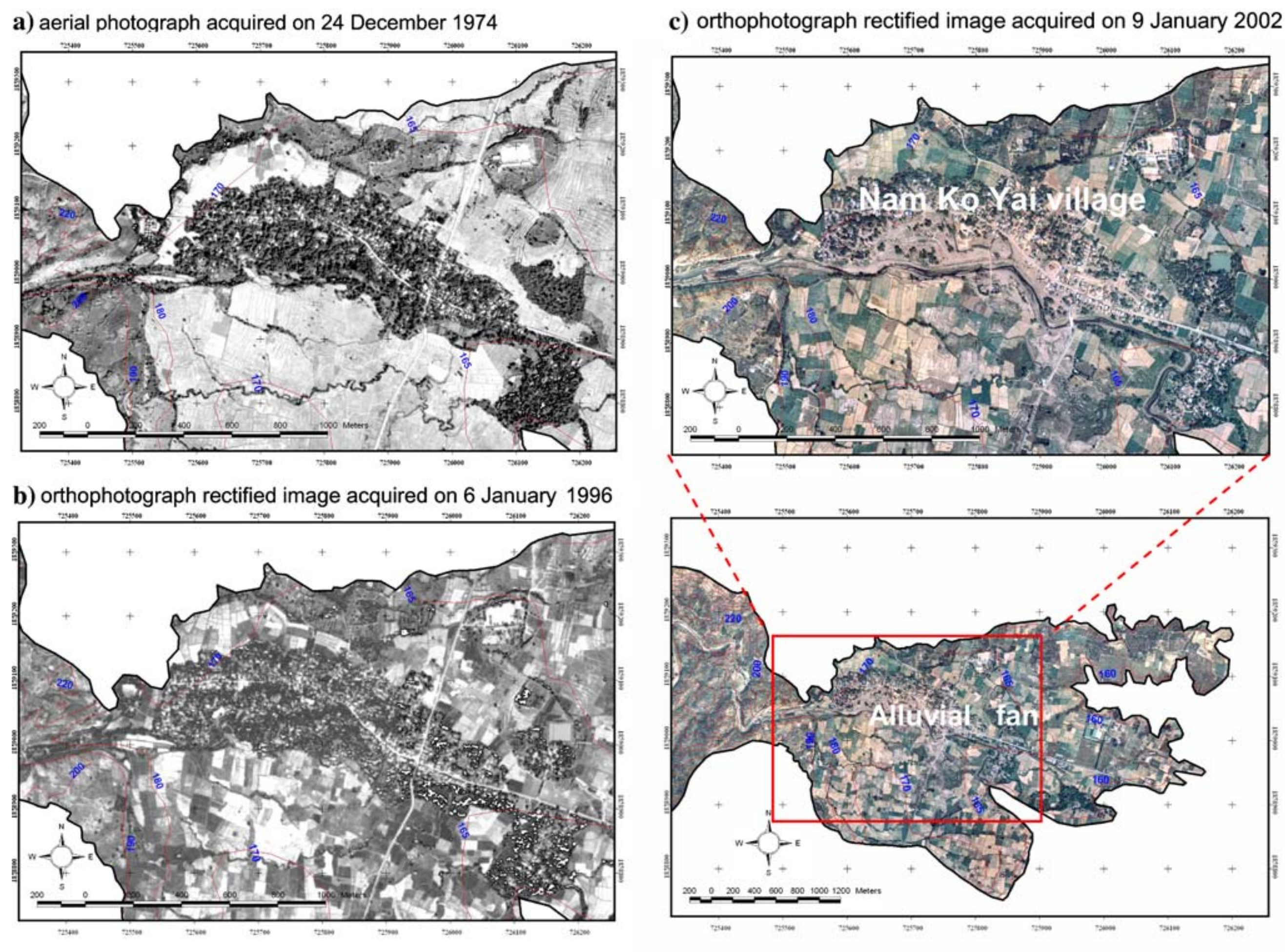


Fig. 15 The multi-temporal low-altitude images of aerial photograph and orthophotograph (with contour intervals in *red line*) acquired on three different periods: **a** 24 December 1974, **b** 6 January 1996, and **c** 9 January 2002 showing the distinct identification of the topographic apex of Nam Ko Yai stream in the alluvial fan that was slightly modified from 1974 until 1996. Pronounced and still active changes are evident following the 8/11debris flow-flood

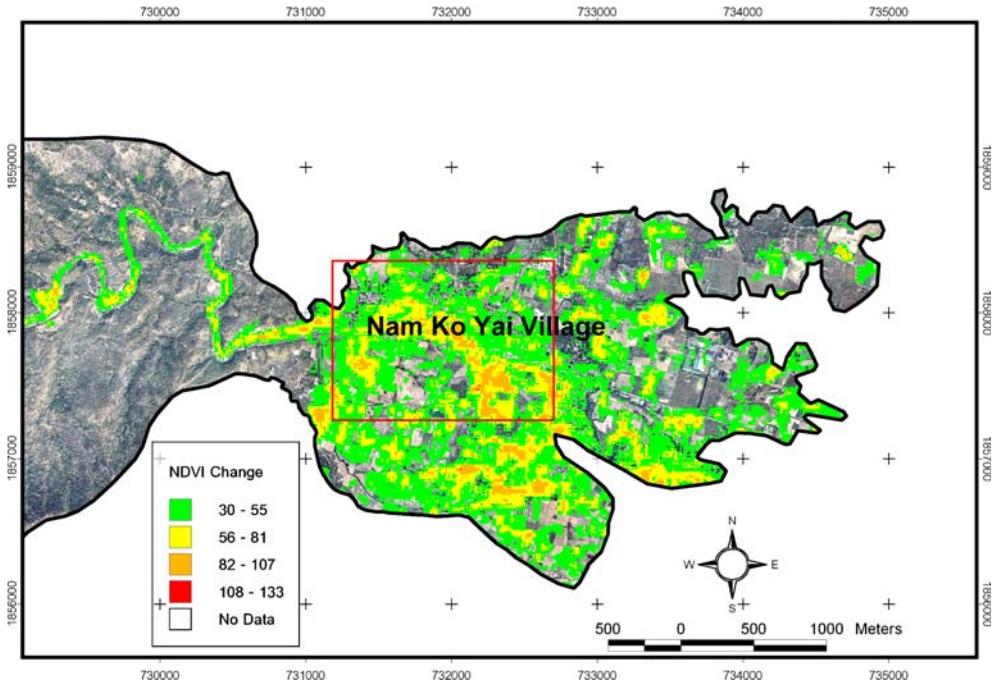


Fig. 16 The detection change of NDVI in the depositional location of the alluvial fan (expanded from Fig. 4) overlain on the orthophotograph rectified image (1:25,000 scale) acquired on 9 January 2002. The *brown-colored zones* are new traces of fan deposit after 1996

channel become unconfined and less certain, and thus is coincident with the hydrological apex.

The results of the resistivity survey investigated along the lines NK 01–NK 05 (Fig. 18) to identify the local three-dimensional geology (thickness and depth of the older alluvial deposits), revealed four sedimentary units at a total depth of less than 100 m below the ground surface. The lowest unit was semi-unconsolidated sediments or weathered rocks of at least 70 m thick to the west with the bed top at a depth of about 30 m below ground surface (Fig. 18), and much thinner, less than 10 m to the east, with the bed top be noted at a depth of about 80 m below the ground surface. The overlying second unit was semi-unconsolidated sediments with trapped water in the bed openings. Thickness was 25–70 m and increased to the east. Its shallow horizon was 5 m below ground surface in the west to about 10–20 m to the east. These two lower units are never exposed near the site, but are at surface in the surrounding hills. The third unit was unconsolidated sediments with trapped water. Thickness was in the range of 5–30 m. The thickest part of this third unit was near the NK 03 line in the central part, where the depth to the top of the unit was from a few meters down to 15 m below the ground surface further to the east. The fourth and uppermost unit was of unconsolidated sediments with a thickness of a few meters in the west to 10 m in the east. The fourth unit was commonly exposed on the ground surface along all survey lines, except in the east where it was completely covered by recent topsoils.

A detailed field study of the previous alluvial fan deposits in the fourth unit was conducted along a 5×70 m eroded bank of Nam Ko Yai stream near where the resistivity survey had been performed. Seven stratigraphic profiles were studied to reveal sedimentary sequences in both terms of vertical and lateral stratigraphic correlation. The location map of the measured stratigraphic columns and the line of resistivity survey points are shown in Fig. 19 and the actual profiles in Fig. 20.

In the observed sections, the lowest sedimentary unit of the older alluvial fan deposits was a debris flow unit of floating texture, unsorted and unstratified material that was exposed in the stream-bed only in the eastern part. The coarse-grained fluvial unit of clast-supported texture and fining-upward graded bedding was transitionally deposited on top of the debris flow unit, especially in the middle part, and extended westward (upstream). This coarse-grained fluvial unit was the thickest in the western part and became thinner to the east. The uppermost part of this eroded-bank profile was a fine-grained fluvial and debris flood unit that was dominantly deposited to form a sharp contact on top of the coarse-grained fluvial unit. The uppermost unit is thicker to the east, especially in the eastern part. The representative and complete detailed sedimentary and stratigraphic characteristics in vertical succession are shown in Fig. 21, from bottom to top, the debris flow unit, the coarse-grained fluvial unit and the fine-grained fluvial and debris flood unit, respectively.

The overall interpreted subsurface characteristics of resistivity survey lines generally conformed to the normal alluvial fan deposits. The third sedimentary sequences unit repeated in the resistivity survey should be

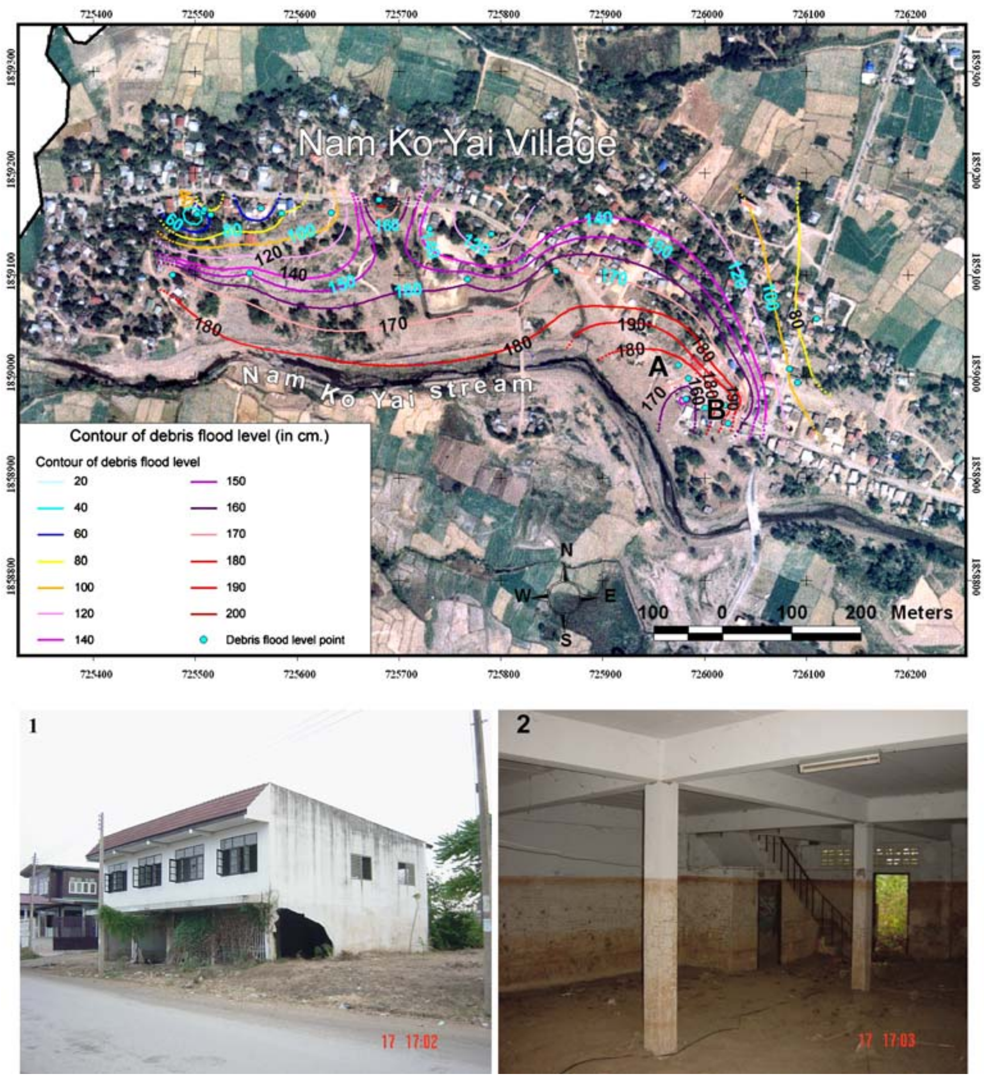


Fig. 17 The expanded orthophotograph rectified image (1:25,000 scale) acquired on 9 January 2002 (*red outline* in Fig. 16) showing the contours of debris flood levels (in cm) above the ground surface (detected from the thin brown film left at house-walls and trees) in the strongly damaged area of Nam Ko Yai village caused by the 8/11 debris flow-flood

the same as the older alluvial fan deposits in this eroded bank profile as evidenced from the depth and thickness variation from the west to the east. The upper part of the third unit is clearly of the older fan deposits composing of the coarse-grained fluvial unit, debris flow unit and fine-grained fluvial and debris flood unit.

Significant evidences of the previous debris floods found in the eastern part of uppermost fine-grained fluvial and debris flood unit were two preserved wooden debris fragments, one at the lower part (location PLW) and the other at the upper part (location PUW) as shown in Fig. 22. These preserved wooden debris were dated by radiocarbon dating method to have the absolute ages of deposition between 2,618 +/−35 years before present and post-1950, respectively. From these radioactive dating results, it is strongly confirmed that this is an active alluvial fan and that debris flow-flood process had occurred at least twice before the 8/11 disastrous event.

Debris flow-flood event reconstruction

The results of the study methods were used to reconstruct the 8/11 event as follows.

The debris flow probably began as a shallow circular landslide on the western and northern steep mountain slopes of Nam Ko Yai sub-catchment after a continuous heavy rainfall period for at least 10 days (before 8/11) that weakened the material with the increasing weight. It thus became highly movable down-slope. The colluvial soils and rock debris of Pw Formation and Pk Formation flew down the forest-covered 30° (or steeper) slopes from a high elevation (800–1,500 m) during the peak of heavy rainfall. This could be the primary source area for the debris (Fig. 23). The debris flow continued further over the central undulated valley area to the main channel of Nam Ko Yai stream. As Nam Ko Yai sub-catchment plain was extensively deforested during the

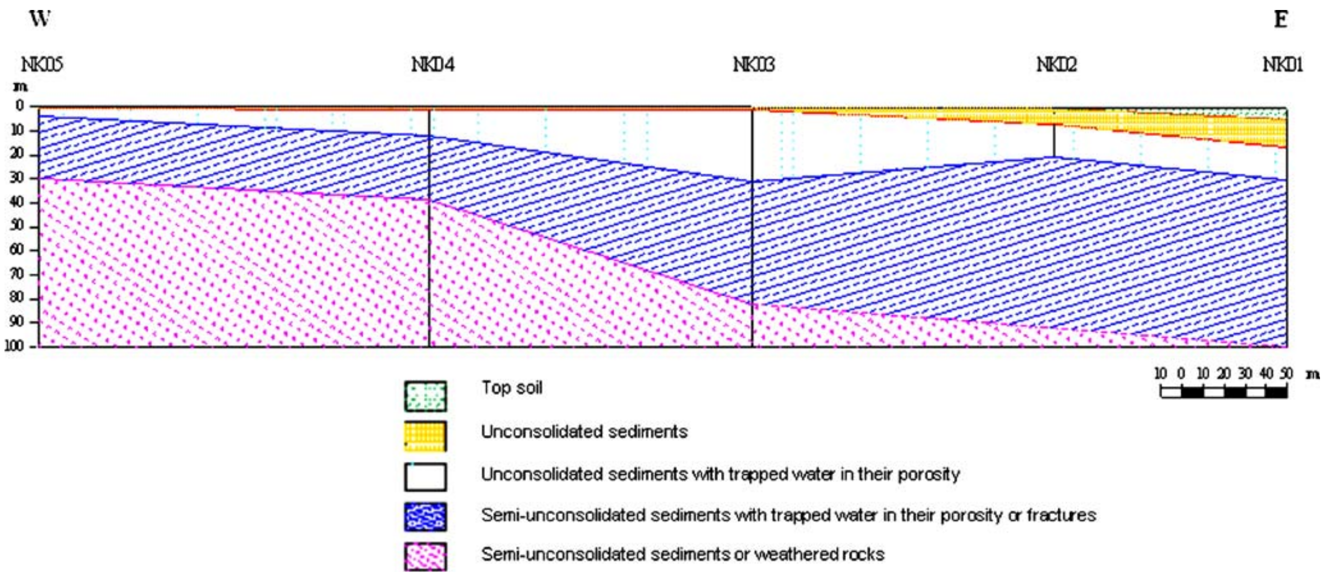


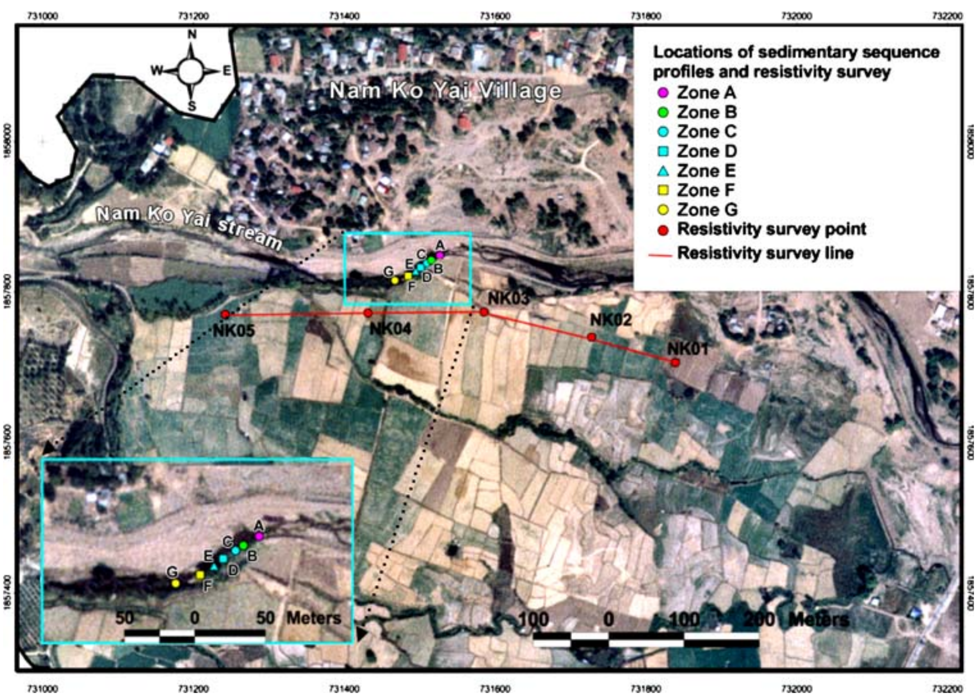
Fig. 18 The cross-section of the resistivity survey interpreted from the five survey points (NK 01–NK 05 as shown in Fig. 19) that revealed four sedimentary units lying less than 100 m below ground surface

last decade with only few trees left over its overbank flat land, the large quantity of plant debris observed must have come from the upslopes. The debris flow was capable of exerting tremendous lateral forces on obstruction in the flow path, as evidenced from the impact of entrained, large boulders in the highest velocity along the main channels of the first-order and second-order sub-catchments in the steep slope areas.

These high velocity flows severely snapped off a large number of trees, removed trunks from hillsides and over channels, and mixed with re-eroded soils of the detached-landslides at the steep banks down along the main channels to the central area of moderate-to-gentle slope. This could be the potential secondary source area (Fig. 23) where debris incorporated into the primary debris flows to form a significant volume through the run-out zone or transport zone of the sub-catchment.

With supporting study results on the soil engineering properties, the highly weathered rocks of Ls Formation with its thick residual or colluvial soils appeared to

Fig. 19 The location map of seven measured stratigraphic profiles (A, B, C, D, E, F, G) along the eroded bank of Nam Ko Yai stream, and a line of five resistivity survey points (NK01–NK05) used for investigating the stratigraphy, sedimentology and subsurface geology of the older alluvial fan deposits



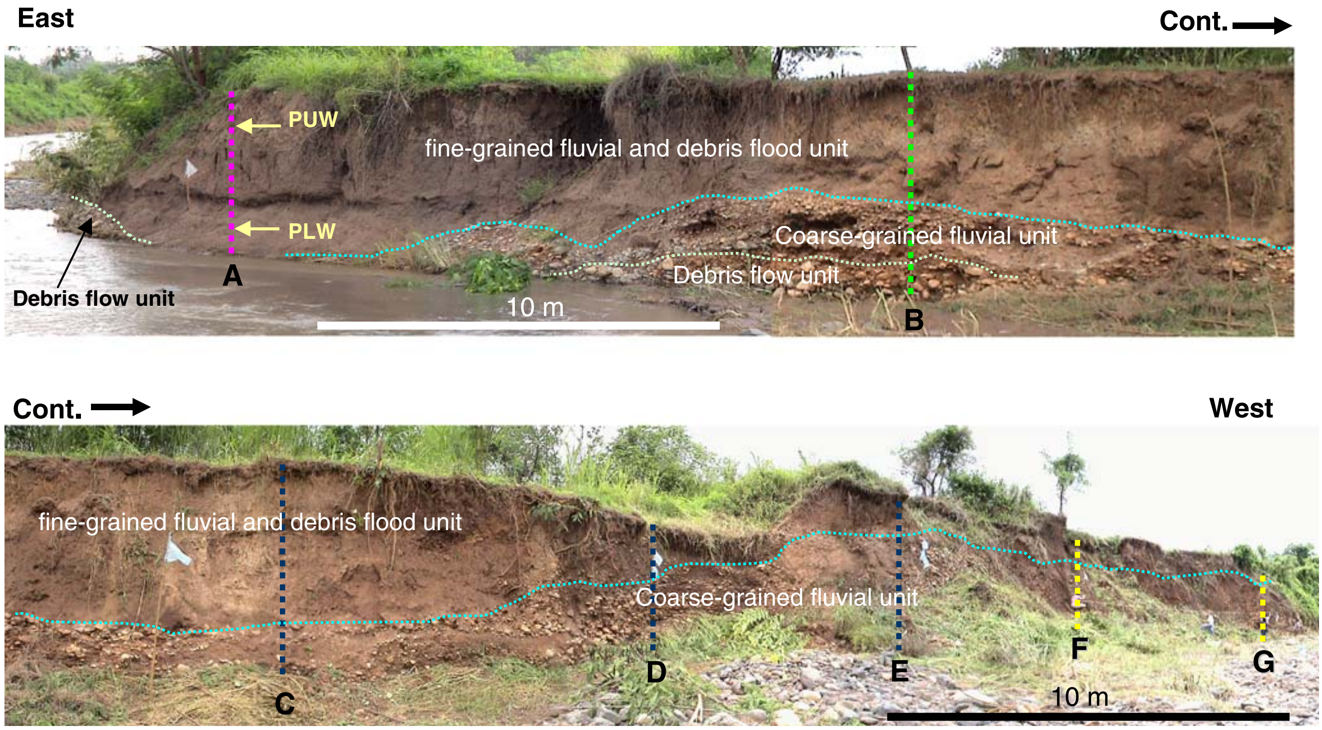


Fig. 20 The lateral and vertical stratigraphic characteristics of debris flow and debris flood deposits of older alluvial fan along the eroded bank of Nam Ko Yai stream with the locations of those seven measured stratigraphic profiles (A, B, C, D, E, F, G)

influence the slope failures on the hillsides and debris flows in the channels. These almost undrained clayey soils with increasing load pressure and less internal shear strength would have caused the mass movement beyond the critical load pressure.

Additionally, the previously mentioned physical nature of the source areas and run-out zones to the flow-flood occurrence, the amount and intensity of precipitation falling, steep hill slopes and long-running sinusoidal stream channel were key factors as well. Ten days of continuous rainfall to the cumulative peak on 8/11 triggered the landslides and flow-flood in these zones of weak materials.

During these landslides and the flow-flood processes, a temporary natural dam might have built up somewhere in the causeway of this stream, most probably near Tad Fa waterfall. The temporary natural dam could have been formed when debris of plant remains, trees, soils and boulders both from several previous and the 8/11 events were locked at this specific location, forming a reservoir upstream. Then another powerful debris flow-flood followed to break this dam, perhaps with surges up to 10 m high to send water and debris flowing further down to destroy the village on the alluvial fan.

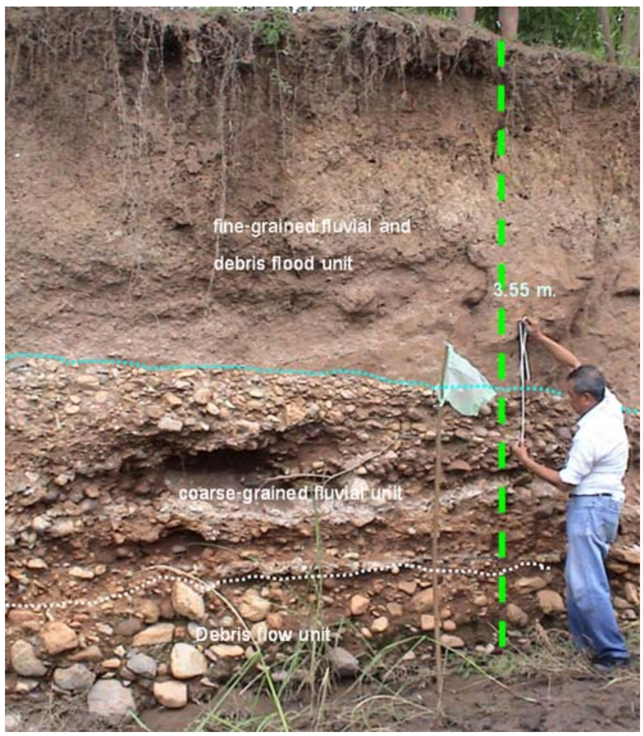


Fig. 21 The measured stratigraphic profile B showing the debris flow unit underlain by the coarse-grained fluvial unit with the transitional contact, and the uppermost fine-grained fluvial and debris flood unit overlying on top of the coarse-grained fluvial unit with a sharp contact

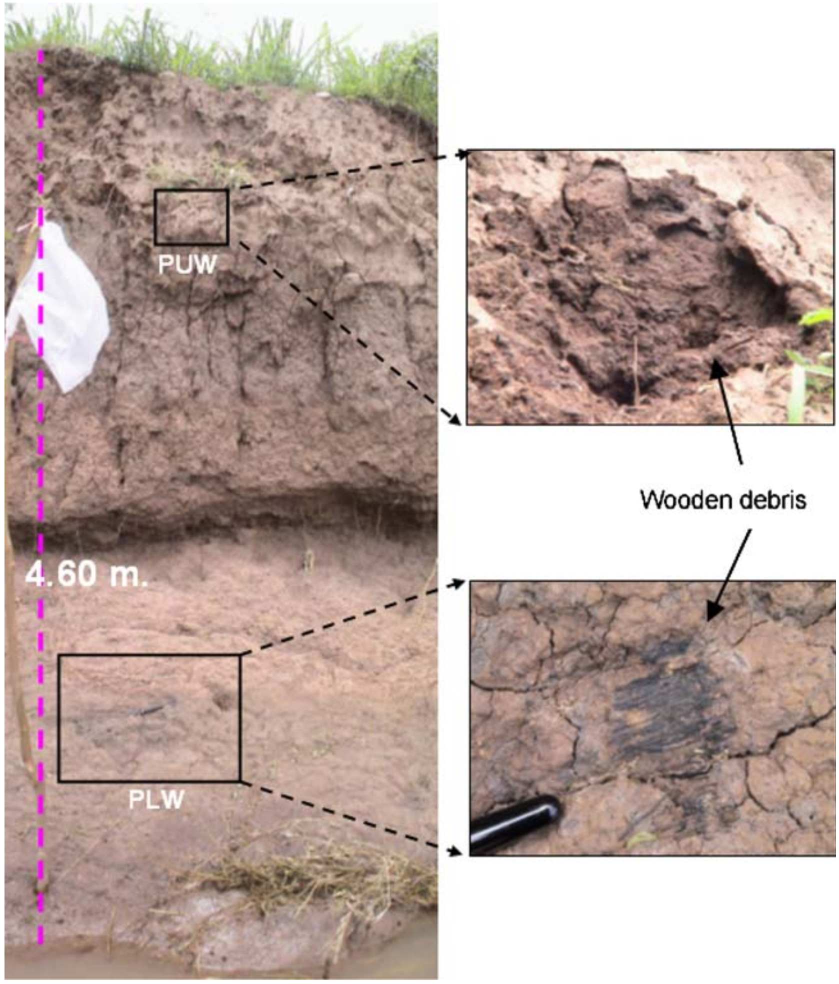


Fig. 22 The measured stratigraphic profile of the uppermost fine-grained fluvial and debris flood unit illustrating its general characteristics and two locations of preserved wooden debris at the *lower part* (location PLW) and *upper part* (location PUW)

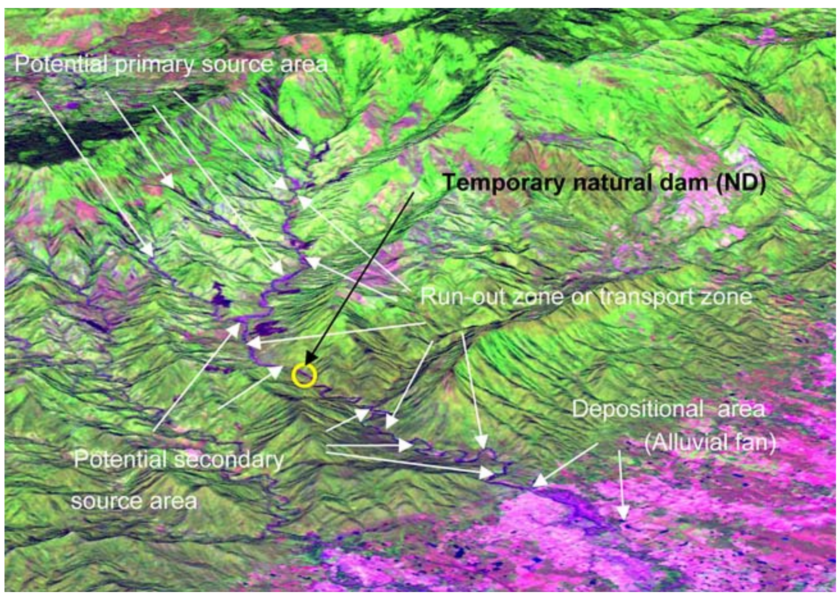


Fig. 23 Three-dimensional view of Nam Ko Yai sub-catchment and its alluvial fan modeled by overlying the false color composite of Landsat 7 ETM + (R = 5, G = 4, B = 3) acquired on 21 November 2001 through the base-scale DEM showing the main features after the debris-flood occurrence with identified potential hazard zones of the potential primary and secondary source areas, the run-out zone or transport area, the proposed location of a temporary natural dam and the depositional area

After this serious debris flow-flood occurrence in the year 2001 that completely traversed and removed the former sediments along the channels, it should take many more years to let the factor conditions to build up again. The plant debris and sediments are reduced at present. The relatively higher amount of rainfall in the following year 2002 in the same area did not result in a serious flow-flood event except a mild flash flood.

Conclusion

The disastrous 8/11 debris flow-flood event was not the work of the unusual high amount of rainfall alone, as previously theorized. Instead it was the work of combined factors from the steep terrain characteristics underlain by specific soils with natural moisture close to the liquid limit that could not be drained, and with specific land cover with time delay for accumulation of debris and sediments. This combination of factors could also cause debris flow-flood accompanied with a high amount of precipitation. The damage could be made greater by a temporary natural landslide dam forming at locations within the stream course, followed by destruction of the dam under the weight of impounded water. The areas down below, especially the settlements on the distinctive alluvial fan, will always be in danger if no proper caution or pre-investigation is employed.

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ARTICLE

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Study on structure and function of an earthen bund irrigation system in Northeast Thailand

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Abstract In Northeast Thailand, which overlaps with an erosional plain that is not suitable for irrigation because of poor water resources and terrains that prevent efficient water distribution, farmers have long supplied water to surrounding paddy fields by blocking rivers completely with earthen bunds. Although such a traditional irrigation system fits well with the characteristics of Northeast Thailand, those who are concerned with modern irrigation development projects in Northeast Thailand seem to have been paying little attention to it. The present study was performed to facilitate development of more appropriate irrigation systems in Northeast Thailand by providing information regarding traditional irrigation methods. We investigated the traditional irrigation methods with earthen bunds at three study sites, and our results indicated that styles of irrigation vary with riverbed slope. The traditional irrigation system that is used in most of Northeast Thailand is different from ordinal weir irrigation, in that paddy fields are not irrigated by gravity flow but by backwater of earthen bunds. Our results suggest that the development of more successful irrigation systems would be possible through improvement of the design ideas of traditional irrigation methods.

Keywords Earthen irrigation bund · Irrigation by backwater · Gravity irrigation · Topography · Erosional plain

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Introduction

Background

A traditional irrigation system in Northeast Thailand is unique in its form. It supplies stream water to fields in a way that is quite different from weir irrigation in several regards: i.e. (1) it blocks river courses completely with earthen bunds that are higher than both banks, (2) it mostly has no diversion canals and serves water to surrounding paddy fields directly, and (3) in some cases it causes serious damage to a percentage of the paddy fields[1] (Fukui and Hoshikawa 2003). Such features are mainly a result of the terrain of Northeast Thailand. Traditional gravity irrigation is mainly practiced in areas in which the land surface is covered with alluvial deposits, such as alluvial basins, alluvial valleys, and alluvial plains. On the other hand, Northeast Thailand roughly overlaps with an erosional plain that is covered with thick soil formed by deep weathering of base-rocks (Budel 1982). Conditions for irrigation are quite different between areas with these two kinds of geography.

First, erosional plains have much poorer water resources than alluvial lands, which have large percentages of mountainous areas from which water and alluvial deposits are supplied at relatively constant levels, while erosional plains such as Northeast Thailand have little mountainous land and large plains. Furthermore, most of the plains are covered with paddy fields. The combination of a paucity of water resources and excessive paddy field cultivation together result in serious water shortages. In addition, the surface of alluvial land is covered with alluvial deposits and inclines downstream with little irregularity, while erosional plains have undulating sur-

[1] In addition, farmers supply water to paddy fields using several kinds of traditional instruments. One such instrument, called a *kaso*, is used to scoop up farm ponds and shallow wells. However, these were used only for limited purposes, such as making nurseries and transplanting, because of their limited ability to supply water. Therefore, we will deal only with earthen bund irrigation in this study.

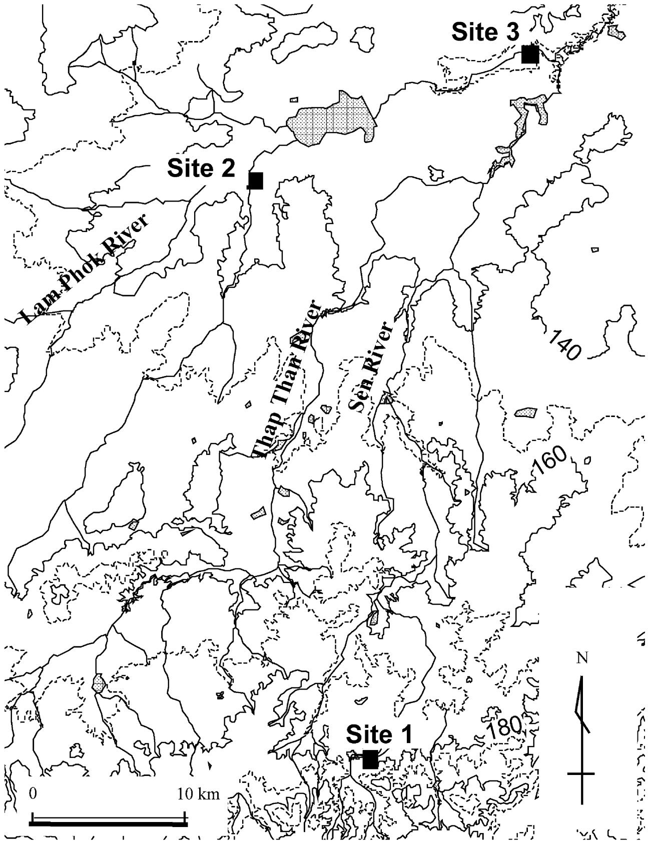

Fig. 1 Research sites. Contours are based on maps made by the Royal Thai Survey Department in the 1980s

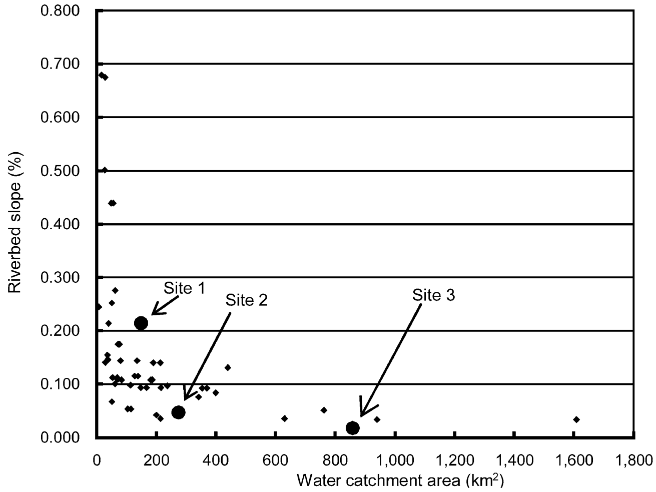

Fig. 2 Relation of riverbed slope and water catchment area at villages with traditional irrigation systems in the Thap Than River basin. The three study sites are indicated with the *large points*

faces reflecting the relief of the base rocks. Such undulating surfaces prevent efficient water distribution.

To adapt to the topographic conditions of Northeast Thailand, the irrigation system in Northeast Thailand should implement the above unique features. Therefore, common irrigation practices, such as those in alluvial lands, are ineffective for agricultural development in Northeast Thailand, and it is essential to pay attention to the traditional irrigation system[2]. This study was performed to: (1) clarify the structures and functions of the traditional irrigation system, which will be referred to here as "earthen bund irrigation" and (2) contribute to the appropriate development of irrigation systems in Northeast Thailand.

Methods

From 1999 to 2001, we conducted a survey in 193 villages in the basin of the Thap Than River, which is a branch of the Mun River in Northeast Thailand, and found that 53 villages used traditional irrigation bunds. For this study, we selected three villages that have topographical features representative of Northeast Thailand. For the present study, three villages in which farmers are still practicing irrigation with earthen bunds were selected in the Thap Than River Basin: D village (site 1) around the Sen River, TK village (site 2) and NB village (site 3) around the Lam Phok River (Fig. 1).

Figure 2 shows the relationships between the distribution of weirs and topographical features in the Thap Than River basin. The three sites represent various topographical features. Site 1 has a steeply sloping riverbed (0.214%) with a small stream having a catchment area of 148 km^2, site 2 has a gentle riverbed slope (0.048%) with a medium-scale stream (270 km^2), and site 3 has a very gently sloping riverbed (0.019%) with a large river (860 km^2).

A leveling survey was carried out at these three study sites, and detailed topographical maps with a contour interval of 0.5 m (supplemental contour, 0.25 m) were drawn to describe detailed topological features, structure, and earthen bunds for irrigation[3]. Next, the water condition of paddy plots, growing conditions of rice plants, damming of upstream water etc. were observed during the paddy rice growing period (May to December) in 2001. In addition, the level of rice production was investigated by interviewing each cultivator.

Features of the irrigation system

The traditional irrigation system in Northeast Thailand has three distinguishing features: (1) the earthen bunds for

[2] If systems that deliver water are constructed on major rivers with pumps and canals, a considerable percentage of the rice fields in Northeast Thailand may be irrigated. However, this is unlikely to happen because of the high costs of construction and the low market price of rice.

[3] Elevation is based on contours in 1:50,000 topographical maps of the Royal Thai Survey Department. Consequently, relative errors of contours in the maps of the study sites are less than 0.5 m, while absolute errors of elevation from the MSL should be 10 m at most.

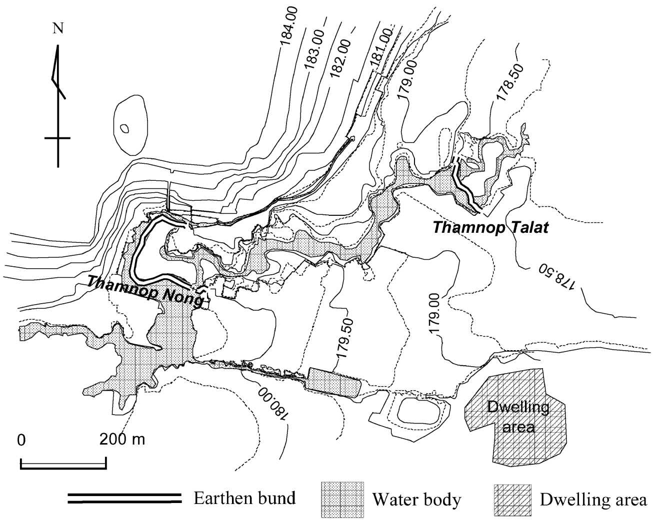

Fig. 3 Topography of site 1

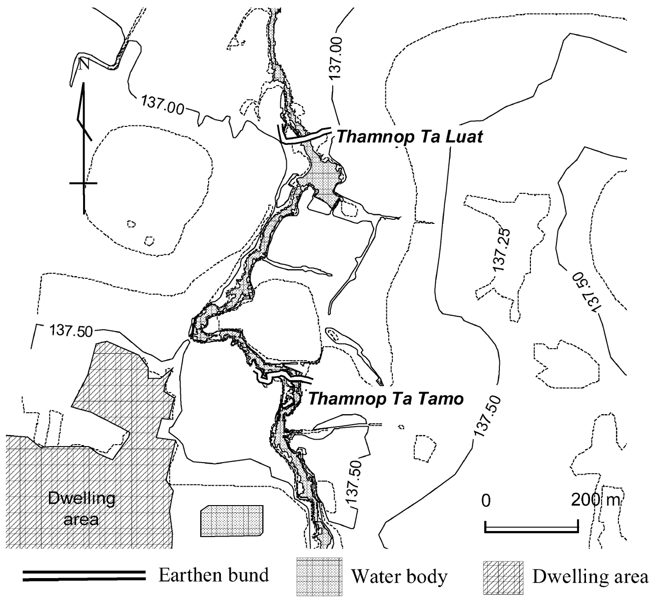

Fig. 4 Topography of site 2

irrigation are higher than the banks, blocking off the river completely, (2) most of them have no diversion canal and supply water to adjacent plots directly, and (3) some cause damage to a percentage of the plots. We noted by how much the crests of the bunds were higher than the riverbanks, how the river water flowed into the paddy fields, how the water spread in the fields, and what types of small terrain were present around bunds for irrigation through which water flowed into the fields.

There are two earthen irrigation bunds to supply water to paddy fields on the Sen River, which is a branch of the Thap Than River (Fig. 3). One is called "*Thamnop*[4] *Nong*" and the other, located 230 m further downstream, is "*Thamnop Talat*." None of the villagers know how many years ago these irrigation bunds were originally constructed. Both of these bunds were constructed along the inside of meandering curves and cross their neck-cutoffs. The crest length of *Thamnop Nong* is about 400 m and that of *Thamnop Talat* is about 170 m. These two bunds at site 1 have spillways with stop-logs that were constructed in 1997 with a budget for sub-district development to prevent the bunds from breaching. Differences in elevation between the crests of the spillways of the two bunds and both banks are not more than 0.25 m. Due to these spillways, the water level merely reaches crest elevation of the bunds crossing the river. Headwater levels at the two bunds are dependent on elevation of the crest of these sluices. Before these spillways were constructed, excess water was released through paths to the side of the banks. However, the bunds were often breached, as the ability to release water was insufficient.

As shown in the large-scale topographical map in Fig. 3, the land at site 1 can be classified into two types: valley bottom plain and hillside. The former is irrigated, and paddy fields outside of the irrigated area were newly reclaimed after the 1970s. The land surfaces of both banks of the Sen River have an almost constant slope of 0.25% downstream with few remarkable irregularities. The terrain around this site is similar to that seen in alluvial valleys rather than erosional plains.

Water is supplied through intakes and canals, and spreads plot-to-plot due to the steeply inclined land surface. There is no trouble or conflict regarding water distribution among farmers as they can easily adjust the amount of water intake and the river has a rich and stable water supply. Irrigated areas are clearly divided from non-irrigated areas. The bunds irrigate only the land of the valley bottom plain below the elevation of the crests of the concrete sluices. An area of about 105 ha is irrigated by these two irrigation bunds. According to local farmers, the stream flow in the Sen River is so stable that there has never been a single drought year in which the irrigation bunds could not supply water to the paddy fields. Indeed, some plots are filled with water from *Thamnop Nong* and *Thamnop Talat* even during the dry season.

There are two irrigation bunds on the Lam Phok River at site 2 (Fig. 4). One, *Thamnop Ta Tamo*, was constructed about 300 m West of the village around 1970. The other, *Thamnop Ta Luat*, was constructed 520 m North (downstream) of *Thamnop Ta Thamo* in the mid-1980s. Elevation from the banks and crest length of *Thamnop Ta Tamo* are about 0.5 m and 50 m, respectively, and the bund blocks the stream completely. The headwater level at *Thamnop Ta Tamo* is dependent on the elevation of the top of the bund. Elevation from the banks and crest length of *Thamnop Ta Luant* are about 0.5 m and 100 m, respectively. However, this bund has a breach in its left side due to a flood a few years ago. The

[4] Earthen bunds crossing streams are called "thamnop" especially in areas where the Khmer language is spoken in Northeast Thailand. In two of the three study sites, people speak Khmer.

elevation at the breach is almost the same or slightly lower than those of both banks. As this breach does not cause the water level to rise too high, the farmers have not repaired it. Some water is released through the breach, but the headwater level reaches the top of the bund and floods the surrounding land in the middle of the rainy season because of the large amount of water and gentle riverbed slope.

As a whole, the land on which the Lam Phok River runs has a gradual v-shape around site 2. The mean slope of the streambed is approximately 0.08%. However, the land surface has numerous irregularities that are much more remarkable than the slope downstream: i.e., defects due to water flow and convex areas of several tens of centimeters.

At site 2, when the water level of the Thap Than River reaches the tops of the bunds of *Thamnop Ta Tamo* and *Thamnop Ta Luat*, paddy fields over an area of about 20 ha are filled with stream water. As a result of the gentle downstream slope and irregularities on the land surface, water cannot spread from plot-to-plot. Water is served to the paddy land only when the water level is high enough to flood the whole surface of the paddy fields, including the bunds between paddy plots. To serve water to high places, such as convex areas in plots, low places are inundated by more than 1 m, and in most of the irrigated areas, bunds between plots are also submerged. Ditches in paddy fields are dug for discharge, damming them up with grass and soil. Farmers adjust the amount of discharged water to maintain a steady water level in the paddy fields. The paddy fields begin to be flooded at the end of July or early August, and the depth of the water increases until the end of the rainy season. After construction of the bunds for irrigation, farmers dug numerous ditches in the paddy fields to drain excess floodwater from the bunds. However, these do not have sufficient capacity to discharge excess water and avoid flooding.

The irrigation bund *Thamnop Nonburi* at site 3 (Fig. 5) is constructed on Lam Phok River in a meandering plain, 14 km downstream of site 2, and 9 km downstream of the Lam Phok Reservoir. The irrigation bund crosses the stream just downstream of a meander cut-off. The designer of this earthen irrigation bund should have aimed to make use of a meander scar with an ox-bow lake as a reservoir. The crest length of *Thamnop Nonburi* is about 570 m. When *Thamnop Nonburi* was constructed in the 1940s, there was little paddy field along the river, and rice was cultivated mainly around dwelling areas on hills. As the lowest crest elevation of *Thamnop Nongburi* is 0.5–1.0 m higher than the right bank, river water flows into the right bank and is discharged downstream. In addition, there are hume-pipes and culverts to discharge stream water. However, the water level rises up to the crest elevation because the riverbed slope is gentle, and the pipes and culverts do not have sufficient ability to discharge the water of the large river.

At site 3, at the beginning of the rainy season, water merely goes into paddy plots along the river. However,

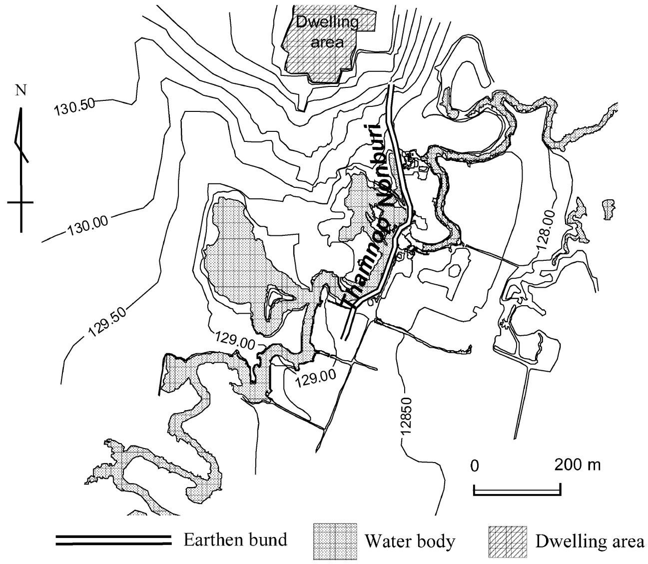

Fig. 5 Topography of site 3

from the middle of the rainy season (the end of July–August), when the water level of the river rises rapidly, tens of hectares of paddy fields on the upstream side of *Thamnop Nonburi* are flooded until the end of the rainy season. When the water level reaches the crest elevation, an area of more than 25 ha of paddy fields upstream of the bund is flooded and the lowest plot is submerged under more than 1 m of water. In addition, downstream of the bund is also flooded by water causing detouring of the right bank of *Thamnop Nonburi.* Although farmers dug farm drains on the right bank to drain water to the original river channel downstream, paddy fields on the right bank are flooded as they do not have sufficient ability. In total, more than 100 ha of land are flooded by this bund.

Effects on rice growing

The yield of rice is dependent on various factors, such as hydrological conditions, type of soil, amount of fertilizer applied, varieties of rice, treatment by farmers, etc. Weed problems are among the major factors that cause a decrease in the yield of paddy rice in direct-seeded plots, the percentage of which is increasing at present in Northeast Thailand. In this section, we describe the effects of irrigation at the three sites while also considering the effects of fertilizer, and method of planting rice. As rice varieties cultivated in the study sites were mostly government-recommended non-glutinous rice varieties, KDML-105 (*Khao Dok Mali* 105) and RD-15[5], difference

[5] Some traditional varieties are also cultivated in the study areas. However, the percentage of area given over to the traditional varieties is so small that the difference in variety should hardly affect average yield.

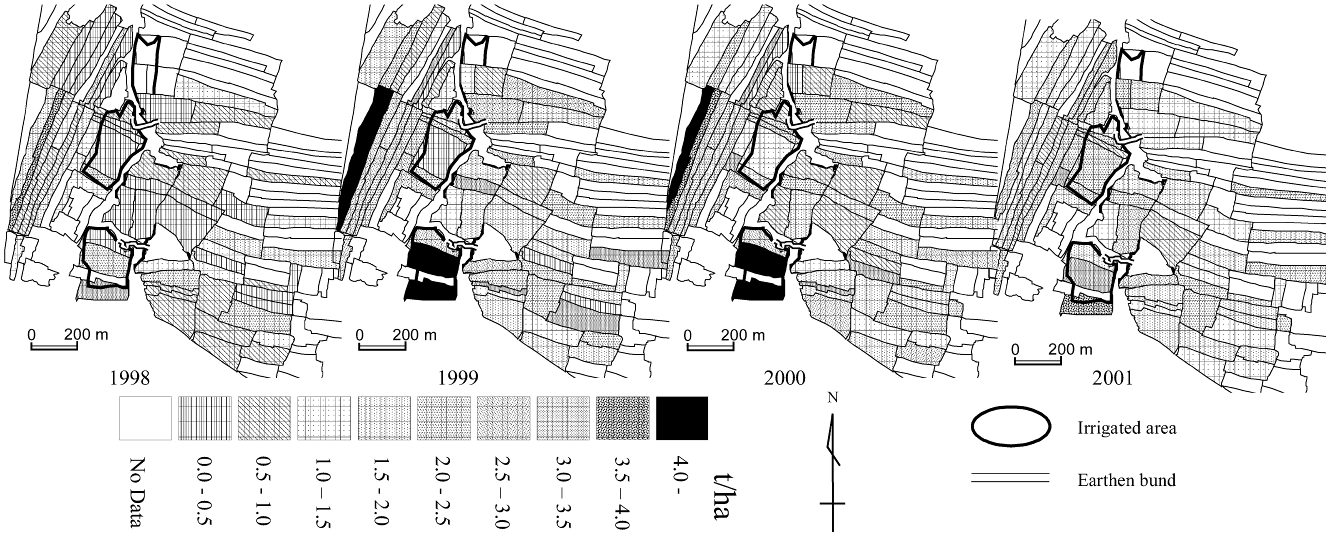

Fig. 6 Yield of rice at site 2. Boundaries of irrigated areas are shown by *bold lines*

in varieties as factor of yield will be excluded from the following analysis[6].

At site 1, farmers start transplanting rice in the middle of June almost every year in the bottom of the valley, while transplantation in non-irrigated plots is dependent on rainfall condition, which is unstable, and in some years it starts late in August. Although paddy fields on the valley bottom plain are sometimes submerged by floodwater from the Sen River, this flooding recedes quickly and does not damage the rice. Average yield in irrigated plots was significantly higher than those in other plots at the 5% level of significance every year (Table 1). Amount of fertilizer used clearly indicate that farmers invest more in plots that promise high and stable yields (Table 1). The differences in amount of fertilizer applied may also contribute to higher yields in irrigated plots[7].

Farmers at site 2 use two methods to plant rice: transplantation and direct seeding. Farmers adopted direct seeding in 1996 mainly because of a labor shortage. In direct-seeded plots, weeds tended to grow so much that average yields of rice in transplanted plots were significantly higher than those in direct-seeded plots at the 5% level of significance in 2000 and 2001, and at the 10% significance level in 1999 (Table 2). In addition, only weak correlations were seen between the amount of fertilizer used and annual yields of rice (correlation coefficients in 1999–2001 were 0.46, 0.44, and 0.33).

Table 1 Differences in average yield and average amount of fertilizer used between irrigated and non-irrigated plots in 2001 (site 1)

Samples	Irrigated 35	Non-irrigated 12
Average yield (kg/ha)	3,978	1,903
Variance	5,688,389	1,465,385
Significant at	0.05%	
Average amount of fertilizer used (kg/ha)	221	111
Variance	11,787	6,503
Significant at	0.50%	

The irrigation bunds at site 2 start to serve water to plots after sufficient rainfall, and at the same time non-irrigated plots are also filled with rainwater. Yields in the irrigated plots are not always higher and stable. On the contrary, the average yield in irrigated plots is significantly lower than other plots in some years, including 2000 (Fig. 6 and Table 3). The areas that are supplied with water from the bunds are also indicated in Fig. 6. However, as other plots outside the irrigated areas are also filled with water that flows down from land with higher elevation, the boundaries of the irrigated areas are indistinct. The effect of irrigation should be much less than other factors. However, farmers who cultivate rice in the lands along the stream regard *Thamnop Ta Tamo* and *Thamnop Ta Luat* as indispensable to keep water in the paddy plots.

Immediately after its introduction in the early 1990s, all the households at site 3 adopted direct seeding. Because farmers use pesticides for weed control, there was no weed problem. According to the farmers, the yield of rice was improved with the introduction of direct seeding. There is a positive correlation between the elevation of the plots (elevation of the centroid of each plot) and yield of rice (Table 4). This indicates that yields

[6] Average yield of RD-15 is about 10% higher than that of KDML-105 (Bunduang and Uchin 1990). However, this difference is much less than the difference in yield among plots.

[7] All except three of the households transplanted rice at site 3. The method of planting may also affect on yield of rice, however, it is difficult to evaluate the effect, as there are only few cases of direct seeding. Regardless, the average yield of irrigated plots was significantly higher even if the yields in direct-seeded plots are excluded from the analysis.

Table 2 Difference in yield between transplanted and direct-seeded plots (site 2)

	1999		2000		2001	
	TP	DS	TP	DS	TP	DS
Average (kg/ha)	2,468	1,908	2,275	1,745	2,236	1,681
Variance	745,617	610,781	988,987	665,343	450,596	235,115
Samples	41	10	36	23	14	44
Significant at	10%		5%		5%	

TP transplant; *DS* direct seeding

Table 3 Difference in yield between irrigated plots and non-irrigated plots (site 2)

	1999		2000		2001	
	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated
Average (kg/ha)	2,023	2,365	1,648	2,413	1,960	1.843
Variance	1,054,026	801,690	937,048	1,815,816	484,952	370,903
Samples	18	44	18	44	18	44
Significant at	–		5%		–	

Table 4 Correlation coefficient matrix (yield, fertilizer, elevation) (site 3)

		Yield	Elevation	Fertilizer
2001	Yield	1,000		
39 samples	Elevation	0.480	1,000	
	Fertilizer	–0.466	0.568	1,000
2000	Yield	1,000		
39samples	Elevation	0.528	1,000	
	Fertilizer	0.614	0.579	1,000
1999	Yield	1,000		
31 samples	Elevation	0.693	1,000	
	Fertilizer	0.528	0.531	1,000

from plots along the stream that are flooded most deeply are low, while plots in the hillside around the dwelling area beyond the reach of the river water have high yields. The farmers along the stream directly sow rice seeds just after first plowing and use little fertilizer, which indicates that they do not expect a certain harvest. This is also indicated by the relationship between elevation and amount of fertilizer used (Table 4). The farmers along the stream assure at least a minimum harvest by cultivation of rice in other places, such as on the hillside. The farmers who feel that they earn a profit from *Thamnop Nonburi* are those who cultivate plots that are on the upstream side of the earthen bund and flooded to a depth of less than 0.5 m when the water level reaches the top of the crest[8] (Fig. 7). That is, the area that shows the greatest benefit from this irrigation system lies along the shallows of the backwater of *Thamnop Nonburi*. Plots at elevations that are too high cannot benefit from the backwater as they are beyond reach, while those that lie too low are damaged by floods. It is interesting that *Thamnop Nonburi* contributes only to rice transplantation in low fields on the right bank upstream at the beginning of the rainy season. These plots are flooded too deeply in the mid-rainy season. They no longer gain profit from the irrigation system as rice is no longer transplanted but is seeded directly.

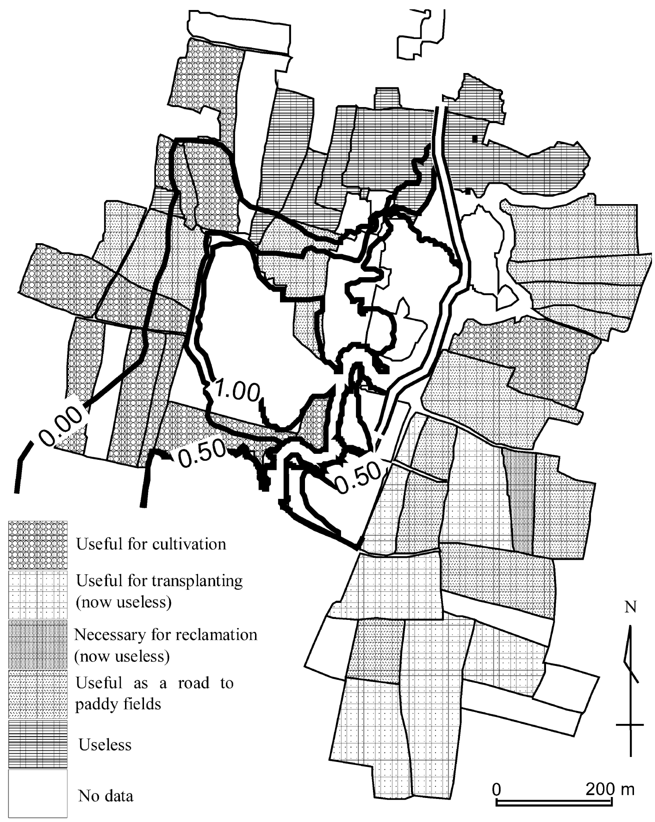

Fig. 7 Utilities of *Thamnop Nonburi*

[8] The elevation at the top of the crest is about 129.50 m.

Discussion on the function of the earthen bund irrigation

In general, diversion works, including weirs for irrigation, are constructed upstream of the command areas. Water is distributed through long canals by gravity, and it is not necessary to raise the headwater level above the height of the banks. However, the diversion works in Northeast Thailand have to raise the stream water level above the height of the banks because it is difficult to construct long canals to divert the water due to the undulating land surface. So, the water flows into the paddy fields directly from the headworks. This is the main reason why the bunds for irrigation in Northeast Thailand[9] were constructed higher than the banks. We observed curious concrete weirs whose sluices are higher than the banks. These weirs, originally designed by the KKU-NZ weir project, are fixed. According to the original design, a fixed crest of the weir should be set to block at most 60% of the cross-sectional area of the channel (Bruns 1990). However, local people adapted and installed them, viewing them as a traditional irrigation facility made of modern techniques and materials. Farmers in Northeast Thailand have a good understanding of how to build irrigation facilities from them.

The irrigation method at site 1 is intermediate in form between methods designed for alluvial terrains and for erosional plains. The crests are higher than both banks similarly to those at sites 2 and 3. Indeed, it is not necessary to raise the water level much higher than the banks, and the water can spread efficiently by gravity as in irrigation systems in the alluvial plains. About 20% of all earthen irrigation bunds in the Thap Than River basin have steep riverbed slopes, and they are of the same type as that at site 1.

On the other hand, in areas in which the riverbed slope is gentle and the land surface is undulating to a greater extent than the downstream slope, water cannot flow by gravity but spreads by the backwater from bunds crossing the rivers. The irrigation method at site 3 is representative of such a backwater irrigation scheme. At site 2, water spreads both by gravity and by backwater, which can be regarded as intermediate in form between the irrigation methods at site 1 and site 3. The bunds often cause floods and floodwater is influenced by gravity. As it is difficult to regulate water intake at the river, farmers try to regulate the water level in their fields through drainage. However, this effort is not successful because of the gentle slope of the land[10].

Here, the slope is the most important factor in determining the type of irrigation system to be used. The type of irrigation system changes from gravity irrigation to irrigation by backwater as the slope of the land becomes gentler. A steep slope can facilitate water distribution but this is not the only reason. The paddy fields in the steep areas are located mainly at the foot of the mountains, where sedimentation from the mountains has formed alluvial terrain, as can be seen at site 1. In addition, the ratio of catchment area to paddy fields is relatively large, which contributes to stable irrigation. Most of the lands in Northeast Thailand have terrains similar to site 2 or 3.

[9] Sites 2 and 3 indicate that it is not necessary to block a river course completely if the river has sufficient water.

[10] However, these features of earthen bund irrigation systems may prevent salt accumulation as they supply water to fields only when a river has a plentiful water that washes salt away.

Conclusions

In this paper, we discussed both the function and structure of the traditional irrigation system with earthen bunds, in Northeast Thailand. This type of irrigation system is similar to flooding because of the topographical characteristics of the areas involved. This system does not guarantee a stable and high yield, and in addition, the significance of the system has decreased because of the adoption of direct seeding of rice. As most of earthen irrigation bunds supply water only when rivers are flooded, it is inevitable that some part of the rice in low plots will be damaged. However, farmers have maintained the irrigation bunds for various purposes in addition to irrigation for rice cultivation, for example as reservoirs for securing water for livestock and as bridges to cross rivers (Fig. 7).

The irrigation system with earthen bunds is well suited to the socioeconomic conditions of Northeast Thailand. Rice cultivation in Northeast Thailand is now greatly affected by the economy of Bangkok and the rest of the world, with which farmers always have to keep pace. Agriculture is requested to be more flexible. Despite their low efficiency, earthen irrigation bunds, most of which have comparatively low cost of construction, will not lose their significance as flexible agricultural methods. Farmers can construct such facilities immediately according to their need for low cost. It is necessary to have a deep understanding of this system prior to the development of modern irrigation systems. A successful irrigation system can be attained through the application of modern technology and materials to improve the traditional irrigation system.

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ORIGINAL ARTICLE

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A new technique for rapid assessment of mangrove degradation: a case study of shrimp farm encroachment in Thailand

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Abstract A new technique (Aerial Video Manta Analysis) was developed for the rapid assessment of mangrove degradation due to logging and conversion for shrimp aquaculture. Video recordings were made of mangroves along the Andaman Sea coastline, Thailand, during a 2-day aerial survey (16–17 September 1997) in a small Cessna 206 aircraft at an altitude of 800–1,000 feet and flying speed of 100 knots/h. The video recordings were analysed following a modified Manta-Tow technique, originally developed for coral reef surveys. The percentage cover of good mangrove stands, mangrove areas degraded by logging, and mangrove areas converted into shrimp farms, was estimated for each consecutive 1-min interval of video playing time. The analysis revealed that 9.9±2.2% of the mangroves along the Andaman coastline were severely degraded by logging and 23.3±1.9% had been converted for shrimp farming (a total of 3,255±370 shrimp ponds were counted). The encroachment for shrimp farming was most severe (34%) in Krabi Province, while Phang-nga Province had the most (75%) good mangroves. These results demonstrate that illegal development of new shrimp farms along the Andaman Sea coast has been substantial in recent years. The results obtained by four independent observers using this new method were remarkably close (SD≤25% of mean). The new method allowed cheap, rapid and accurate evaluation of the status of the mangrove resources over a long stretch of coastline within a time-span of a few days. Aerial Video Manta Analysis is a valuable tool to support coastal conservation and management efforts.

Keywords Andaman coast · Mangrove degradation · Rapid assessment · Shrimp farming · Thailand

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Introduction

After a long history of neglect, there is now widespread recognition of the ecological, economic and socio-economic importance of mangrove forests among governments, international development agencies, non-governmental organisations and the general public. Intensive field studies have established that mangrove forests sustain highly productive fisheries, support a significant biodiversity, play a vital role in protecting riverbanks and shorelines against erosion and storms, and are valuable in sustaining the needs and livelihoods of many coastal communities (Field 1995). Nevertheless, mangrove forests around the world are under significant and increasing threats from degradation, pollution, conversion to other land uses, and various other anthropological impacts (Kathiresan and Bingham 2001). Whilst efforts are being made in many countries to restore degraded mangroves and to conserve the remaining healthy stands, conservation and management still lag far behind the destruction (Kathiresan and Bingham 2001).

As a result of this ongoing degradation and other major disturbances of mangroves, there is a continuous need to survey, map and monitor changes in their status as part of mangrove management efforts (Spalding et al. 1997). An accurate and objective assessment of mangroves and other coastal resources, which allows comparisons on regional and global scales, is only possible through the repeated use of standardised methodologies for the collection and analysis of data (English et al. 1997). Aerial photography has been used since the 1940s and allows high-resolution mapping using stereo image preparation techniques. Satellite imagery has been available since 1972 and despite limited resolution enables digital processing of data from very large areas and incorporation into geographic information systems (GIS). When remote sensing materials of different years are compared, it is possible to make calculations concerning changes in mangrove area (e.g. due to degradation or conversion for other land uses) or to assist scientists in studies aimed at understanding large-scale and long-term dynamics in the mangrove ecosystem. However, most of these remote sensing techniques are usually expensive and time-consuming, and all rely on the availability of high-technology equipment, data processing facilities, and advanced interpretation skills (Spalding et al. 1997).

For the day-to-day management of mangrove areas, subject to illegal logging, encroachment and other human activities, there is a need for rapid assessment techniques, which can give a reliable picture of the status of the resources. To meet the challenges of management reality of the largely inaccessible mangrove habitat, often under financial and time constraints, there is an urgent need to develop easy, rapid and cheap methodologies. The present study was undertaken as part of a 3-year EU-funded conservation project of mangrove forest resources in southern Thailand (Erftemeijer 1999), where mangroves are under threat from degradation by logging and illegal encroachment for the establishment of shrimp aquaculture ponds (Plathong 1998). The study aimed at rapid assessment of the status of mangrove forest resources along the Andaman Sea coastline in Thailand using a cost-effective and simple technique.

Materials and methods

Study area

The study was carried out along the west coast of the Thai Peninsular along the Andaman Sea, Thailand (9°50′ N, 98°30′ E – 6°24′ N, 100°10′ E). This coastline reportedly has 75–80% of the country's remaining mangrove forests (Spalding et al. 1997). Whereas up to 83% of the mangrove forests along Thailand's East coast (Gulf of Thailand) have been lost over the past 3–4 decades mostly owing to illegal encroachment for conversion into shrimp farms (Plathong 1998), the Andaman coast is widely believed to have remained largely unaffected. The aerial survey covered most of the approximately 710-km-long coastline. However, due to bad weather the upper 80-km stretch near the border with Myanmar (Ranong Province) was not covered. The island of Phuket, which has only limited mangrove resources, was also omitted from this survey. Hence, the present study covered the four main provinces of Phang-nga, Krabi, Trang and Satun in southern Thailand.

Aerial survey

The aerial survey was carried out in a small high-winged single-engine Cessna 206 G aircraft (suitable for six persons), from which the side-door had been removed. The survey was conducted on 16–17 September 1997 and consisted of a total of approximately 8 flying hours (Anonymous 1998; Erftemeijer 1998). The aircraft had an average flying speed of approximately 100 knots/h (equivalent to 185 km/h) and flew at an altitude of about 800–1,000 feet. The aircraft flew in a straight line following the coastline and made an effort to position itself in such a way that most of the mangrove forest along the coastline was visible through the open door of the plane. The status of the mangroves along the coastline was recorded with a hand-held Sony Handicam ccd-tr3400e video camera pointed through the open door of the aircraft. The zoom lens of the video camera remained unchanged during most of the recording (the few recordings made by zooming were omitted from further analysis). Stretches of coastline without mangroves were not recorded on tape, while no recordings were made during the return flights to avoid double recording of the same mangrove areas. This resulted in final edited video recordings amounting to a total of 80 min of mangrove-covered coastline. It was possible to determine the approximate position of the aircraft at any given moment during the video recordings with the help of the timer function of the camera, topographical maps and notes made during the flight.

Video analysis

The video recordings of the mangroves were analysed using a new method called Aerial Video Manta Analysis, described here for the first time. This method was adapted from the manta tow survey method, originally developed for surveys of large areas of coral reefs (Kenchington 1978; Done et al. 1982), critically reviewed for possible bias (Fernandes et al. 1990), and standardised to allow comparison of data on regional and global scales (English et al. 1997).

In the Aerial Video Manta Analysis, video recordings of the mangroves were played to four independent observers. The recordings were broken down into intervals of 1 min, during which visual estimates (integrated over time interval) were made and noted on the status of the mangrove forests, as follows: percent good mangrove, percent degraded mangrove, and percent converted to shrimp farms (each expressed as a percentage of the total mangrove area, excluding large water masses). The total number of individual shrimp ponds, located in the mangrove area and visible on the video recordings, was also recorded. The records of the observers were later sub-divided and averaged according to the four provinces covered during the aerial survey.

Results

The analysis of the aerial survey video recordings using the newly described technique revealed that 23.3±1.9% of the area covered by mangroves along the Andaman coast had been encroached upon and converted into shrimp farms, and an additional 9.9±2.2% was severely degraded (mainly from logging activities). A total of

Table 1 Results of the Aerial Manta Video Analysis of video recordings made during an aerial survey along the Andaman coastline, Thailand (16–17 November 1997). Data show average estimates (±SD) by four independent observers of the status of mangrove resources by province (expressed as percentage of total mangrove area) and total number of shrimp ponds

Province	*n* (min)	Good mangroves (%)	Degraded mangroves (%)	Shrimp farms (%)	Number of shrimp ponds
Phang-nga	30	75.4±3.6	10.7±3.2	14.0±1.4	533±46
Krabi	19	57.1±3.4	9.1±2.3	33.8±3.9	999±61
Trang	17	66.1±1.2	7.3±2.9	26.5±1.9	1,175±281
Satun	13	61.7±5.8	13.0±1.7	25.3±4.6	547±46
Total	79	66.7±2.9	9.9±2.2	23.3±1.9	3,255±370

Table 2 Mangrove and shrimp farm areas (in ha) and their ratio in four provinces along the Andaman coastline (Thailand), based on interpretation of 1996 Landsat-5 remote sensing data (adapted from Charuppat and Charuppat 1997) compared with results from the present study

Province	Remaining mangrove forest	Shrimp farms in mangroves	1996, mangrove: shrimp ratio	September 1997 (this study), mangrove:shrimp ratio
Phang-nga	30,442 ha	953 ha	31.9	5.4
Krabi	28,273 ha	1,266 ha	22.3	1.7
Trang	24,095 ha	905 ha	26.6	2.5
Satun	29,344 ha	1,484 ha	19.8	2.4
Total	112,154 ha	4,608 ha	24.3	2.9

3,255±370 individual shrimp ponds were recorded during the survey (Table 1). Encroachment for shrimp farming was most severe (33.8±3.9%) in Krabi Province, while Phang-nga Province had the highest percentage (75.4±3.6%) of good mangroves. Degradation as a result of logging was most severe (13.0±1.7%) in Satun Province.

The average results calculated from the recordings of the four independent observers were remarkably close, with standard deviations of less than 5.8% in all cases. Only in 5 out of a total of 79 cases (1-min intervals) did the results of one of the observers deviate by more than 25% from the mean.

Discussion

This study showed that rapid, accurate and reliable assessment of the degree of degradation of mangroves along a 710 km stretch of coastline in Thailand could be achieved at minimal cost by conducting a 2-day aerial survey to record the coastal mangrove areas on video, and subsequent Aerial Video Manta Analysis of the recordings. Comparison of the results obtained by four independent observers using the new technique to analyse the same video recordings demonstrated a good level of precision, with less than 6% of the individual 1-min interval results deviating by more than 25% from the mean.

Where the major goal is to provide a rapid, cost-effective and reliable assessment of the status of mangrove forest resources, Aerial Video Manta Analysis provides coastal managers with an easy, cheap and rapid alternative to conventional remote sensing techniques, such as aerial photography and satellite imagery interpretation. Whilst not dismissing the value of these latter methodologies (Klemas 1976; Howard 1991) they are costly and time-consuming, and rely heavily on the availability of high-technology equipment, data processing facilities and advanced interpretation skills. The aerial survey and data analysis of nearly 700 km of coastline reported here took only 4 days and cost less than US $1,800 (excluding the purchase of video camera and staff salaries).

A possible source of inaccuracy and bias in the present method is found in the interpretation of areas along the margin between mangroves and dry land. This is particularly true for the estimates of mangrove areas converted into shrimp farms. Such potential over-estimation of shrimp farms in the mangrove area, however, was more than compensated for by the fact that most of the video recordings concentrated on the mangrove zone proper. As a result, more often than not shrimp ponds located along the dry-land margin of the mangroves were not visible on the video, hence introducing a potential under-estimation of shrimp farms in the mangroves. The present study was not accompanied by ground-truthing. However, studies of the accuracy of the original manta tow technique used in coral reef surveys demonstrated a good correlation between manta tow results and data obtained with detailed line-transect methods (Alcala 1991; English et al. 1997). Video technology has also been successfully applied in studies on the status of coral reefs (Carleton and Done 1995), deep-water seagrasses (Anderson 1994) and benthic algae (Leonard and Clark 1993). The results of such video transects were found to correlate well with line intercept and point quadrat estimates (Osborne and Oxley 1997).

The findings of the present survey clearly demonstrate that the illegal encroachment on mangroves for the establishment of new shrimp farms along the Andaman Sea coast has been substantial in recent years, despite official claims and a widespread belief that this coastline had remained relatively unaffected (Plathong 1998). Charuppat and Charuppat (1997) reported only 4,608 ha of shrimp farms in former mangrove areas, compared with 112,154 ha of mangroves for the four provinces surveyed during the present study, based on Landsat-5 remote sensing data of 1996 (Table 2). Comparison of these data with the results of the present survey (notably the 8-fold decrease in the mangrove: shrimp farm ratio) indicates that recent expansion of shrimp farms in mangrove areas along the Andaman coastline must have been substantial.

There is considerable controversy in Thailand concerning the reliability of statistics on mangrove forest coverage and shrimp farm expansion as reported by government departments and associated scientists on the one hand, and by environmental pressure groups and associated scientists on the other. According to the official figures of the Royal Forest Department (RFD) for the year 1993, the total combined area of mangrove forest and shrimp ponds (in mangroves) along the Andaman Sea coast was 118,287 ha (Charuppat and Ongsomwong 1995). In that same year, the shrimp farms contributed only 3% (or 3,549 ha) to that combined total area. The official RFD reports also make mention of an additional loss of 48,851 ha of the original cover of mangroves along this coastline (during 1961–1993) to urbanisation and other forms of land development. If the same total combined area of mangroves (including degraded mangroves) and shrimp farms still applies as in 1993, then this would mean that the total area of shrimp ponds in mangrove areas in September 1997 (based on the results of the present study) would be in the order of 27,500 ha while the mangroves (including degraded areas) would then have made up the remaining 90,787 ha. The RFD does, however, state in unpublished reports (see Plathong 1998) for 1997 that they had reforested more new mangroves than were destroyed during that same period, claiming that by 1997 the total mangrove area along the Andaman coast had increased by approximately 37,280 ha.

Discrepancies between figures most likely arise from the following factors: (1) not all shrimp farms observed during our aerial survey were actually situated in (former) mangrove areas; (2) some or many of the new shrimp ponds were not established in pristine mangroves but rather in areas that had already been degraded or converted earlier by other land-use developments, thus not contributing to a reduction of the mangrove statistics, but rather to a reduction of other land use categories (e.g. urbanisation); (3) large areas replanted recently with mangrove propagules may have been classified as mangrove forest and included as such in the official mangrove forest statistics; (4) the flight path of the aircraft (present study) may not have yielded video imagery that could be considered perfectly representative of the true state of the mangroves along the Andaman coast; and (5) differences between resolution and scale contributed to a possible source of error in the comparison between the results of the aerial survey and those obtained through interpretation of satellite imagery.

While governments (RFD in this case) may want to present statistics that reflect better management performance or rehabilitation results than reality, environmental pressure groups and NGOs may tend to overstate the seriousness of environmental degradation. The present methodology has provided a cheap and easy tool to enable rapid and unbiased assessment of the status of coastal mangrove resources. The method eliminates the need for time-consuming ground surveys in an often poorly accessible habitat, and enables quick but accurate assessment of large areas of coast.

The good results obtained with Aerial Video Manta Analysis in the present study make this an attractive technique for wider application in other assessments of land-use changes in areas to which access is difficult, such as seasonally flooded wetlands and freshwater swamp forests. The method could also be tested for general application in tracing and monitoring illegal logging, forest fires, flooding in river floodplains, and in monitoring the impacts of management programmes and the success of rehabilitation efforts.

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SPECIAL FEATURE: REVIEW

Diversity of ecological restoration in East Asia

Rehabilitation of degraded forests in Thailand: policy and practice

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Abstract Thailand has suffered from severe deforestation during the last century. Forest cover has declined drastically both in terms of area and quality, mostly due to the expansion of human activities. Much of the deforested area has been used for agricultural purposes, but much has also been left in a degraded condition. In late 1980s, the forest declined to a point where the nation decided that the remaining forest should be kept for conservation rather than further exploitation. Consequently, forest policy has shifted its focus from exploitation to sustainable management and protection. Thailand has set a goal of increasing its forest area to 40% of the total land area, while at present, forests occupy around 28.9% of the land. With the intention to retain most of the remaining forest as protected areas and, at the same time, achieve the goal set, several reforestation and rehabilitation initiatives have been implemented, especially on those lands in a degraded condition. This paper focuses on the significant issues affecting both the policy and practice of forest rehabilitation. Given that the large number of people whose livelihood depends on the forests for subsistence and other purposes normally has been excluded from the decision-making process in forest management, most important among these issues are the integration of the socio-economic and environmental needs into rehabilitation initiatives together with the active participation of local communities in the rehabilitation program. Case studies of reforestation and rehabilitation initiatives are also discussed.

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Introduction

Thailand has suffered severe deforestation during the past 4 decades. Forest cover is continuing to be lost at an alarming rate together with an unknown area of forest that was left in a degraded condition as a result of a range of human activities. Accessible forests have been logged to maximize the commercial output and short-term financial gain as can be seen from the establishment of the Royal Forest Department (RFD) in 1892 to regulate forest exploitation and to enable the central government to look after all logging (Gilmore et al. 2000). Additionally, a great deal of illegal encroachment has taken place. The expanding population places additional demands on forests for both subsistence and market goods. Forests are often seen as appropriate places to absorb people from overpopulated parts of the country and at the same time to increase agricultural production. This perception remained prevalent until the late 1980s, when the forest declined to a point where the nation decided that the remaining forest should be kept for conservation rather than further exploitation.

Consequently, forest policy has shifted its focus from exploitation to sustainable management and protection. Several measures and initiatives have been implemented in order to regenerate the forest area and at the same time to protect and manage the remaining natural forest areas for the sustainability of the forest services. The two common measures used are the development of a protected area system and reforestation programs.

However, the problem is that the protected areas are often too degraded to meet the need for healthy, natural forest that is capable of supporting viable populations of wildlife. When most of the protected areas are designated, there often have been some means of utilization going on within the protected areas. Consequently, parts of the newly declared protected areas are degraded areas. It is becoming increasingly apparent that attempts to protect the remaining forest are not enough (Blakesley and Elliott, undated). As for the reforestation program, there is common agreement that some form of rehabilitation should be carried out on these degraded lands. However, there is much less agreement over how this should be done. Most programs implemented initially involve two choices: restoring the biological diversity in a small area by planting a large number of species or, alternatively, restoring just productivity over a large area by planting a large numbers of individuals of a single species for commercial purposes. Satisfactory methods of restoring biodiversity to degraded areas have not been developed (Lamb 1999).

Given that there have been almost 20 years of policy shift, this paper aims to evaluate existing forestry policies with special focus on the issues affecting the successfulness of both the policy and practice of forest rehabilitation.

A history of forest exploitation in Thailand

Thailand's forest areas declined from 53.33% of the total land area in 1961 to 22.8% in 1999 (FAO 1999). The annual deforestation rates were in excess of 3% for much of the period (FAO 1998). In 1997, FAO estimated that 329,000 ha of Thailand's forest areas were being removed annually, equating to 2.6% annual forest loss. Researchers and other involved parties agree that there are several direct causes of deforestation in Thailand, for instance, legal and illegal logging, land encroachment and shifting agriculture. In general, Thai forestry has undergone four stages as follows (FAO 1998):

1. *Early exploitation stage (the mid-1890s to the early 1930s)* Logging for commercial purposes started when teak was in demand here and abroad.

2. *Forest exploitation and management stage (the 1930s to the early 1960s)* Logging became an important economy-building activity. RFD, as the government agency responsible, attempted to put forest exploitation under management by enacting important forest laws, opening a school to train foresters and putting them to work to implement forestry laws and regulations.

3. *Peak exploitation decline stage (the 1960s to the mid-1980s)* Logging peaked, export-oriented agriculture expanded, and the national economic development gained momentum. As the forests diminished, a growing awareness of the link between the forest and national well-being emerged.

4. *Exploitation closing stage and the beginning of a new forestry era (from the late 1980s)* People developed a high awareness of the adverse effects of forest exploitation. The forest had declined to a point where the nation had to decide that what remains of it must be kept for conservation rather than for further exploitation.

Strategies to combat deforestation and forest degradation

To address deforestation problems, RFD has been working with different programs in land settlement, agro-forestry, reforestation and land entitlements in reserve forest areas. These activities are supplemented by other site-specific projects in watershed conservation in highland agriculture, mini-watershed development and village woodlot programs. The main objectives of the programs are to encourage tree planting on large to medium scales in order to increase forest plantation areas to compensate the loss of national forest land. At the same time, it aims to organize forest and forest margin populations to include appropriate agricultural technology and increase domestic production for a better quality of life. Programs can be grouped into three main categories.

Policy amendment

The National Forest Policy that required Thailand to have forest cover at 40% of the total land area was also changed to incorporate the rising awareness into its tasks. Within the 40% of the country land area, the ratio of conservation and commercial forest, which used to be 15:25, was changed to 25:15, respectively.

To fulfill the goal, the National Reserved Forests, with an area of 23.52 million ha or 45.9% of the country's land area, were re-categorized into three zones: the conservation zone (C), economic zone (E) and agriculture zone (A) (RFD 2005).

The conservation forest zone (zone C) is the area covered by natural forest areas that have been undisturbed and/or have been minimally affected by human activity, and it is made up of the areas identified as being ecologically sensitive, such as habitats of endangered species and watershed areas. This zone normally covers existing protected forest areas and those nominated to be so. Zone C encompasses an area of 14.1 million ha, or 27.5% of the total land area. However, some of these areas have already been occupied by human settlement, with the people carrying on their rotating or permanent cultivation.

The economic forest zone (zone E) covers arable land suitable for commercial tree plantations for distribution to landless farmers. The E-zone is often devoid of forest, and some of the land has been under cultivation. Some of the E-zone is in degraded forest areas. Zone E covers 8.3 million ha, or 16.18% of the total land area.

The agricultural zone (zone A) covers the deforested areas suitable for agriculture, which will be allocated to landless farmers through the agricultural land reform process. In 1993, the RFD transferred 70,848 km^2 of zone A to the Agricultural Land Reform Office (ALRO) for issuing forest dwellers the title that will guarantee their right to cultivate the land. This title is not salable and only transferable to descendants. After the transfer of land management, ALRO became the responsible agency for zone A. In 2002, a small portion of zone A, which is unsuitable for agriculture, was legally returned to the RFD for forest rehabilitation. Zone A makes up 1.15 million ha, or 2.25% of the total land area.

This policy was launched with the expectation of clarification of where good and degraded forest was and how to best manage and improve its condition, by whom and using what mechanisms.

Reforestation initiatives

To achieve the reforestation target, a number of schemes have been introduced and carried out by government agencies (the Royal Forest Department, Forest Industry Organization and the Thai Plywood Company), the private sector, non-governmental organizations (NGOs) and people's organizations. In addition to these schemes, a major reforestation program was activated in recognition of the Royal Golden Jubilee (the 50th Anniversary of H.M. the King's ascension to the throne). The program's total target, approximately 800,000 ha, was allocated to various parts of Thailand with the major emphasis on the northern region (65.4%).

The cumulative area planted under various initiatives reached 10,640.49 km^2 in 1998 and 11,923.18 km^2 in 2004, respectively (Table 1).

Based on the area planted, the four most important tree species are teak (*Tectona grandis*), followed by two local pines (*Pinus kesiya* and *P. merkusii*) and a eucalypt (*Eucalyptus camaldulensis*) (Uthaiwan 1995). However, a growing number of people have become concerned about the long-term sustainability of the existing monoculture planting systems. The arguments mainly mention the impact on the ecological, social and cultural aspects and the long-term economics, which may look either suitable or unsuitable. Alternatives to monoculture plantation have been developed by several NGOs; the Forest Restoration Research Unit at Chiang Mai University, for instance, emphasizes the matching of species to the site and working in partnership with local communities (Elliott et al. 1998). The Faculty of Forestry of Kasetsart University has also conducted research for developing and testing techniques in reforestation for both economic and conservation purposes.

Table 1 Annual reforestation by sources (in km^2)

Item	From beginning to 1998	1999	2000	2001	2002	2003	2004
Afforestation by government budget	6,579.79	92.83	54.77	42.08	55.92	39.36	56.00
The Royal Golden Jubilee Program	3,403.64	153.48	129.72	160.05	168.31	23.86	49.90
By the Forest Industry Organization (FIO)	270.25	59.24	7.10	NA	NA	NA	NA
By the Thai Plywood Co. Ltd.	24.94	6.94	3.78	3.41	5.72	1.22	2.80
Reforestation according to ministry regulations	137.69	13.37	14.78	19.14	4.50	4.68	5.66
Reforestation by concessionaire budget	224.18	0.40	0.54	1.38	24.00	48.69	29.06
Total	10,640.49	326.26	210.69	226.06	258.45	117.81	143.42

Source: Royal Forest Department (RFD 2004)

NA Not available

Community forestry initiatives

Apart from the concern over reforestation programs, there is also a division of opinion over who should now be put in charge of rehabilitating the land—the government (who has long been in charge of the forest resource), the local people (who need to earn a living) or the industrialists (who want to prosper by supplying the country and its growing economy with wood-based products).

The eighth National Social and Economic Development Plan (NSED) (1996–2001) outlines proposed activities for the forest sector and is probably the best indicator for the current focus of policy. The plan encourages people's participation in reforestation and forest management; especially those in the economic zone may receive support in terms of loans and crop insurance for reforestation with fast-growing species. It also encourages the private sector to develop large-scale forest plantations. For the conservation of the remaining forest, the plan called for the continuation and extension of protective forest boundaries together with the promotion of community forestry in buffer zones by providing loans for farmers in buffer zones to develop agro-forestry programs.

Meanwhile, development NGOs tend to emphasize community forestry as a potential answer to forest conservation problems and as an important tool to achieve sustainable land use and rural development (Mingsarn et al. 1995).

The growing interest in community involvement in forest management led to the drafting of a Community Forestry Bill (CFB) in 1996. However, there is considerable opposition from various sections of society concerning the permission for communities to live in and use of forests, and the bill has so far failed to pass through Parliament.

What was done in order to attract people's involvement in forest management was the reformation of forest management national institutions in 2002. The reformation aims to increase the people's participation and also includes a system for collaborative natural resources. This in particular involves the establishment of the Ministry of Natural Resources and the Environment, which is comprised of the following key departments (RFD 2005):

- RFD supports and facilitates the executing of people's rights in forest management via the establishment of a community-managed forest. RFD has a Community Forest Management Office to carry out support activities and implementation. In general, this office is responsible for (1) CF implementing under CFB (when ratified) and other relevant decrees, (2) conducting research and development in community forestry as well as agro-forestry, and (3) developing linkages with other parties involved in community forest management. The RFD has invested in promoting and supporting local communities to manage their nearby forest patches since 1987, and the statistics of implementation are shown in Table 2.
- The Department of National Park, Wildlife and Plant Conservation has initiated a project called Pilot Park Management, which promotes and encourage people's participation in national park and wildlife management. Starting in 2001 (as the RFD) with only six pilot parks, the number of testing parks has increased steadily from 6 to 12 and to 18 parks in 2003 and 2004, respectively.
- The policy of the Department of Coastal and Marine Resources emphasizes people's participation in mangrove forest conservation and management.

Table 2 Statistics of community forest project implemented as of January 2004

No. of community forests established	No. of villages with legal founding status	No. of managed forest patches	Total area of managed forest (km^2)
10,848	5,285	4,761	1,947

Source: RFD (2005)

Reforestation options: analyses and case studies

Option 1: Industrial and private forest plantation of single species

The high demand for eucalyptus encouraged local people to expand the plantation area drastically. It has been reported that the area increased from 60,000 to 350,000 ha between 1985 and 1995, while the planting of indigenouse species has stagnated. The expansion of the eucalyptus area, however, raises some concerns about sustainable wood production in the region as well as the ecological impacts on water supplies and soil quality that may arise (Shimamoto et al. 2004). Consequently, the government enacted the Forest Plantation Act of 1992, which aimed to encourage the private sector to plant more indigenous species, including protected tree species such as teak, eagle

Table 3 Operational result under subsidy scheme

Fiscal year	No. of grower (person)	Area planted (ha)
1994	49,600	115,003.73
1995	65,596	151,558.30
1996	27,537	65,805.82
1997	17,177	38,512.28
1998	2,807	6,644.44
1999	2,218	5,155.52
2000	3,465	7,298.24
Total	168,400	389,978.44

Source: RFD (2004)

wood and iron wood. However, the program was not successful due to the complicated procedures and red tape involved from the planting to cutting stages (Makarabhirom 1998).

On the other hand, the government interpreted this lack of response as being the result of expensive planting and tending costs, and responded by introducing a subsidy system in 1994 for the planting of indigenous tree species. Growers signed up for this program will be granted a subsidy of 3,000 baht per rai (equivalent to US$ 750/ha in 1994) for the initial 5 years. Table 3 shows the number of farmers who have entered the subsidy scheme as well as the area of plantation.

The plantation area in the official report increased to almost 400,000 ha during the period from 1994–2000, but the actual area planted was likely much lower than this figure, because of widespread corruption in this scheme. Besides this shortcoming, there are many cases of cancellation because of the low survival rate of the planted trees. Some farmers failed to tend the planted trees, which led to the deterioration of the planted trees, because of their perception that no market existed for them to sell their logs if they planted indigenous tree species (Ubukata and Jamroenpruksa 1997).

Table 4 Imports of timber by species, 2000–2004

Species	Amount of timber imported (m^3)				
	2000	2001	2002	2003	2004
Tectona sp. (Teak)	94,823	91,622	340,816	128,497	120,641
Pinus sp.	133,679	135,259	150,474	191,057	147,792
Dipterocarpus sp.	171,144	247,388	152,534	141,824	109,683
Lagerstroemia sp.	59,507	67,658	106,408	100,181	78,713
Pterocarpus sp.	13,831	14,762	25,722	29,842	10,073
Afzelia sp.	10,352	19,619	21,113	21,276	34,163
Hopea sp.	44,496	35,092	23,550	35,458	26,779
Dalbergia sp.	1	323	49	929	917
Shorea sp.	6,449	12,492	11,587	13,276	15,567
Heavea sp.	236	67	65	2,050	3,120
Total	534,518	624,282	835,318	664,390	547,448

Source: RFD (2004)

Despite the report concerning the market for indigenous logs, the Thai government reduced log import tariffs and opened borders to timber imports (Pragtong and Thomas 1990). Therefore, the import of some indigenous species of timber has remained high, as shown in Table 4 (RFD 2004). As a result, the market for domestic logs, which are not competitive with foreign logs, is not secure.

In case markets for locally grown timber did exist, the profitability was, as expected, highly sensitive to changes in the growth and yield rate, and to timber prices. Thus, even slight changes in either the timber prices or in the growth and yield rates affect the profitability of reforestation considerably (Niskanen 1998). In addition, other factors also contribute to the level of profit gained. Factors include the selection of the plantation area, selection of planting species and labor costs, especially for industrial plantation. Economically, forest plantations should only be established on sites with a low opportunity cost to maximize the profit since better growth and yield rates for trees on more fertile sites could probably not compensate for the increased opportunity cost of more productive land. Profitability analyses from the same study found that teak plantations yielded higher profits than those of eucalypt plantations. It can be assumed that a better selection of agricultural species could substantially improve the profitability of commercial reforestation programs.

As a result of the difficulties discussed, together with the cut in budget allocations for subsidy schemes, the program was terminated in 2004.

Option 2: Community forest management

Most community forests (CFs) in Thailand occur naturally all over the country where ethnic and other local Thai communities still practice traditional and sustainable forms of forest management. Although CFs have long been used by rural communities, they were only recognized as a tool for sustainable forestry about 2 decades ago (Pagdee 2006).

In general, the community develops a set of rules and regulations, both formal and informal, and enforces these rules and regulations to ensure that the user rights and benefits are fairly distributed among the members and are not reaped by outsiders or noncontributing members. Although the CFB has not yet passed the Parliament, the RFD has established procedures for a community forest designation. The process of granting approval for CFs has to follow 15 steps (Table 5). Currently, over 5,000 villages have registered their CF programs with the RFD. In fact, a

Table 5 The steps for the proposal and approval of a community forest designation from RFD under the National Reserve Forest (NRF) Act BE 2507

Steps	Procedure and activities
1	Interested groups and the sub-district headman or village headman propose a CF by submitting the proposal form (*PCC1 form*); this should be supported by half of the villagers who are over 18 years old. The form is then submitted to the chief of the district office. *PCC stands for Po Cho Cho, which is the abbreviation of community forest in Thai
2	The document must be approved by the District Forestry Office and submitted to the Provincial Forestry Office (PFO)
3	The PFO receives the document and copies it for the Regional Forestry Office (RFO). Two officers from the PFO and one officer from the RFO survey the proposed community forest
4	The three foresters and the sub-district headman or village headman go to survey the proposed community forest area and then complete the details of the report by filling out the *PCC2* form
5	The sub-district headman or the village headman together with the representatives of the village draft the community forest project proposal by following the PPC3 form under the supervision of the PFO and RFO. Then the draft is submitted to the Tambon Administrative Organization (TAO) for their consideration and comments related to implementation. The officers from the PFO and RFO report the results of the survey and submit the proposal
6	The PFO considers the report of the survey of the community forest area, compile the relevant documents and submit them to the central RFD for approval; they propose the names of officers who will participate with the sub-district and the village headman
7	The Community Forestry Division submits all documents to the director of the RFD; if approved, the letter of acceptance (or permission of grant) will be made; if not, then the community forest project proposal will be terminated
8	If the RFD does not accept the proposal, a letter is sent to the district to inform the sub-district headman or the village headman who submitted the project proposal. When the RFD accepts the proposal, step 9 is followed
9	The Director of the PFO will announce the demarcation of the community forest area under article 15 of NRF Act BE 2507. All documents and the project that has been approved will be sent to the district; they will then inform the sub-district headman and the village headman. A copy of the community forest project will be sent to the provincial office of the Ministry of Agriculture and Cooperatives (MOAC) for the monitoring and evaluation of the project
10	The boundary of the community forest is demarcated and a notice board prepared
11	The rules and regulations of the conservation, management and utilization of the community forest are set up under existing laws
12	Project activities that have been approved by the RFD are implemented under the supervision of forestry officers
13	The provincial MOAC officers cooperate with the RFO and the district to monitor and evaluate the project and report the results using the PCC4 form to the provincial office. After the provincial office considers the report, then they submit it to the director of RFD
14	The director of RFD considers the report; if the implemented activities have damaged the community forest, the project will cease, and the provincial office will inform the sub-district headman and village headman of the decision
15	If the community forest project is to be extended, the community can follow steps 1 to 12, 6 months prior to the end of the existing project

Source: Maneekul (2002)

greater number of villages is managing CFs that have not yet been approved, meaning that greater forest areas are under community protection.

With or without legal establishment status, in most cases, the successfulness of community forests depends on certain elements: (1) the community's direct experience with natural disaster (drought, landslide and flood, for instance) or severe environmental changes, (2) the associative capacity of the community, (3) awareness of people in the community to obey the rules set, and (4) support from government agencies. A review of cases in community forest management reveals that these elements are the key factors influencing a community's ability to manage their natural resources.

The conclusion drawn can be seen clearly from the case taken from the northern region, the management of CFs in Huay Pong Village located in the Mae Khan watershed (Kanjan and Kaewchote 2004).

The Mae Khan watershed project was an attempt to develop a watershed management network among several community-managed catchments within a larger watershed. Huay Pong Village, one of the communities in the watershed area, was once densely forested, until the beginning of a timber concessionaire, which changed the forest landscape and turned villagers into hired hands for tree felling and extraction. When the timber company left the area, the communities began felling smaller trees to expand their farmland. Gradually, the communities started to suffer the adverse impacts of the degraded forest: surface water runoff and increased erosion during the rainy season, decreased spring water during the dry season, an altered microclimate, and a drastic decease in wild animals.

CFs in Huay Pong entail the establishment of protected forest and communal woodlands. The village established in 1992 had a 400-ha protected forest and utilized forest. Rules were subsequently laid down in 1992 and revised in 2000.

The 1992 rules state that people illegally felling trees, setting fires, opening new fields for agriculture and hunting within the protected forest will be fined from B100 to B20,000 depending on the type and magnitude of the offense committed. However, the collection of non-timber forest products (NTFPs) including bamboo shoots and mushrooms is allowed.

The revised version in 2000 requires approval from the village committee of all timber felling for household construction. Further, persons who destroy the forest will be charged by the Community Forestry Committee of Ban Huay Pong in accordance with the Forestry Law. The CF Committee is also in charge of other aspects of forest management such as the maintenance of firebreaks that separate protected forest from the utilized forest.

Despite the successfulness of some community forests, the area of forest protected under this management scheme is still lower than it should be. One factor contributing to this problem is the complication of the procedure of obtaining legal status set by the RFD as shown earlier in Table 5.

While noticing this shortcoming, on the other hand, the RFD has sufficient reason to be extra careful when granting forest managing authority to local communities since pressure from the public concerning forest conservation issues and the conflicts over the Community Forest Act are so intense.

To simplify the complications, a new approach, Criteria and Indicators (C&I) for sustainable forest management, was developed for assessing trends in forest conditions and management. They go well beyond an assessment of the sustained yield of timber to an assessment of forests as well as economic functions. C&I provides a common framework for describing, monitoring and evaluating progress towards sustainable forest management and implicitly defines it (Prabhu et al. 1998). For Thailand, it was introduced in 1998, and the first C&I frameworks for Thailand were approved in 2002, resulting in a set of 7 criteria and 67 associated indicators. The seven criteria are: (1) enabling conditions for sustainable forest management, (2) forest resource security, (3) forest ecosystem health and conditions, (4) the flow of forest produce, (5) biodiversity, (6) soil and water, and (7) economic, social and cultural aspects (Markopoulos 2003).

Moving from the national C&I frameworks, there were attempts to formulate C&I at the local level in order to serve as a platform for dialogue and to explore its use in resolving conflict between the authorities and local people. However, the implementation of these C&I approaches is still at an early stage, and there is much more to be done in order to make them eligible to be practiced or implemented.

Blockage issues for the future

In order to improve the situation in forest rehabilitation, several measures should be taken into consideration. Some of the urgent measures are listed as follows:

- Commitment to forest rehabilitation. There should be a commitment from the agency responsible for forest management to the rehabilitation policy. In many cases when there are changes in executive members, there will also be changes in policy options, and the plantation of timber trees might be altered to plantation of native species or vice versa.
- Development of operational guidelines to turn policy into practice. The implementation of policy cannot be done properly, especially when the policy is too complicated. The development of operational guidelines may help in the creation of the same understanding and practice all over the country, which will help in realizing the policy faster than will be the case without the guidelines.
- Integration of socio-economic and environmental factors into forest rehabilitation initiatives. The local community cannot focus on environmental protection if it is poor and still cannot fulfill the basic requirements in life. Initiatives that will generate income and improve local communities' quality of life may receive more cooperation from the communities. Part of the failure in timber tree plantation was that the market for timber is not secured, and as a result, the people's future quality of life is also not stable.
- Research and development in the technological aspects. There are many constraints in terms of technological availability. Techniques used in the rehabilitation efforts such as species-site matching, the quality of seeds and seedlings, natural regeneration and harvesting systems should be improved to ensure the effectiveness of the rehabilitation program.
- Facilitate capacity building and environmental awareness of the community. The reason for unsuccessful management of forest resources can be the result of poor associative ability and low environmental awareness. Programs that can improve both aspects will allow the local community to manage their resources in a sustainable way.

Conclusion

The growing concern over the scale of deforestation and forest degradation will generate the need for stable forest policy and restoration of degraded forests. Thailand has seen the move from wood harvesting to conservation forestry. The seventh NSED Plan proposed that 25% of the country land area should be protected as conservation forest instead of 15% as stated in the previous plan. The eighth NSED Plan reinforced this shift with guidelines that emphasize protection of the remaining forest and the promotion of forest rehabilitation and reforestation.

In terms of forest plantations, the crucial factors in good plantations are the selection of suitable species, the quality of seed and seedlings and planting techniques. Additionally, the development of promising approaches that will facilitate the collaboration is urgently needed to ensure that the rehabilitation measures introduced will not be of a top-down nature.

The current emphasis on the rehabilitation of degraded forests also provides opportunities to build new relationships between the government and local communities based on collaboration rather than confrontation. Successful programs have to take into consideration the social reality of poor rural households to ensure an equitable sharing of the benefits and costs.

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ORIGINAL ARTICLE

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Contamination of tsunami sediments in a coastal zone inundated by the 26 December 2004 tsunami in Thailand

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Abstract Tsunami sediments deposited in a coastal zone of Thailand by the 26 December 2004 tsunami wave were sampled within 50 days after the event. All surface and ground waters in tsunami- inundated zone revealed significant salinity at that time. The tsunami sediments, composed mainly of fine to medium sand, contain significantly elevated contents of salts (Na^{+}, K^{+}, Ca^{+2}, Mg^{+2}, Cl and SO_4^{-2}) in water-soluble fraction, and of Cd, Cu, Zn, Pb in the bioavailable fraction and As in the exchangeable fraction in relation to the reference sample. The origin of contaminants is marine, as well as litho- and anthropogenic. The salts and Pb, Zn and Cu reveal high correlation to each other and to the mean grain size (pore size and porosity). Serious environmental hazard exists in that region because, due to gentle morphology, there is a risk of migration of the contaminants into ground waters and food chain.

Keywords Contamination · Tsunami sediments · Thailand

Introduction

Tsunami waves are known to be able to cause significant alterations in coastal systems (e.g. Dawson 1994; Bryant et al. 1996; Bryant 2001; Scheffers and Kelletat 2003). They may produce extensive changes in coastline topography: considerable erosion and subsequent deposition of substantial quantity of sediments in short time span. Tsunami also—through translation of large amount of seawater on land—introduces salt into surface and ground waters and, in consequence, does have substantial impact on coastal ecosystems.

The large tsunami, which was generated by an earthquake on the 26 December 2004, affected most of the countries around the Indian Ocean. It was the first wave of such a dimension in this region during the human-written history. The estimated tsunami death toll was about 300,000 coastal zone inhabitants. Its effects, however, are not restricted to the damages due to direct impact of the wave but they also include some long-term consequences. The latter comprise problems associated with soil contamination by seawater and tsunami sediments, which may contain some pollutants released due to damages of waste disposal storages, factories, fuel stations, etc. Only in Thailand, about 20,300 ha of land were covered by seawater during that event. Most of that area was also covered with a blanket (few to several tens of cm thick) layer of tsunami sediments (Szczuciński et al., unpublished data). In spite of a number of studies focused on contemporary tsunami sediments (e.g. Nishimura and Miyaji 1995; Shi et al. 1995; Dawson et al. 1996; Dawson and Shi 2000; Nanayama et al. 2000; Gelfenbaum and Jaffe 2003), the aspects of their contamination and possible future effects to ground waters and ecosystems were not considered.

In the present study, we aim to assess soil and water contamination in the coastal zone of Thailand after the 26 December 2004 tsunami event. The study focuses on tsunami sediments deposited on land and contaminants in easily soluble fraction (salts, heavy metals and metalloids), which may migrate into ground waters and, in consequence, may create a potential threat to the environment. Factors (morphology, sediment type, etc.) possibly controlling the degree of soil contamination in a tsunami-affected zone are also discussed.

Material and analytical techniques

All the samples were collected within less than 50 days after the 26 December 2004 tsunami event, from selected locations on Phuket island (around Patong Bay), and along the coastline between Khao Lak and Kho Khao Island, on the western coast of Thailand (Fig. 1 and Table 1). Between the tsunami and sampling dates, rainfall if any was reported; therefore, at the time of collection, the studied sediments were almost unaltered by redeposition processes. Because air temperatures were high during post-tsunami period, an intensive evaporation of water from the sampled sediments occurred. However, in many locations, the sediments were still wet. The entire tsunami-sediments layer was sampled unless it was thicker than 5 cm. Otherwise, only the uppermost few-centimetres thick layer was collected. One additional sample (16) was taken for reference from an area out of reach of the tsunami wave. Samples were packed in plastic bags and transported within 2 weeks to laboratories. They were divided into subsamples for sedimentological and chemical analysis.

To determine the grain-size distribution, the subsamples were dried and sieved into thirteen, 0.5 Φ interval, grain-size fractions ranging from gravel to mud. Fractions smaller than sand ($>4\Phi$) were analysed with optical diffractometry method on laser-diffraction-based Mastersizer 2000 Particle Analyzer. Conversion of micrometers into Φ values is based on:

$$\Phi = -\log_2 D \quad (1)$$

where D = the size in millimetres. The grain-size statistics (mean, sorting, skewness and kurtosis) were calculated using the logarithmic method of moments with Gradistat software (Blott and Pye 2001). The division into different sediment types follows Folk and Ward (1957) classification.

Salts contained in water-soluble fraction of the samples were determined by standard titration method (Greenberg et al. 1992). A water extract was obtained from 1 g of sample treated for 24 h with 100 ml of de-ionized water. In this way, soluble substances were isolated which may be easily washed from the sediments into ground waters. In the prepared extracts, Na^{+}, K^{+}, Ca^{+2}, Mg^{+2}, Cl^{-} and SO_4^{-2} were measured. The results are presented in grams per sample dry mass. The accuracy of measurements was tested by ion balance.

Heavy metals (Cd, Cr, Cu, Ni, Pb and Zn) were analysed from extracts obtained by 1 h extraction with 2 mol HCl at 80°C. In this way, all the metals, which are potentially bioavailable were separated. The metals were measured with AAS spectrometer in the flame mode. The detection limits were at a level of 0.1 mg kg^{-1} for all the determined metals.

Mercury, due to low concentrations, was determined only for the samples following *aqua-regia* digestion and was measured with CV–AFS instrumentation by Millenium Merlin (PS Analytical) spectrometer. The detection limit was 0.001 mg kg^{-1} with uncertainty below 5% for all samples.

Metalloids: As, Se and Sb, were measured in solution extracted by phosphate buffer (concentration of PO_4 about 50 mmol l^{-1} and pH around 6.0) at 80°C for 1 h. Such an extraction is believed to release exchangeable fraction of the metalloids (Orero Iserte et al. 2004). Concentrations of metalloids were measured with HG AAS equipment (220FS spectrometer by SpectrAA) with hydride generation unit VGA-77 (Varian). The detection limits were 5 μg kg^{-1} for all the determined elements and the uncertainty below 10%.

The surface waters and ground waters (in wells) in the investigated areas were examined in the field using conductivity-meter CC-101 IP 67 (range up to 19.99 mS cm^{-1}) by Elmetron.

Sampling sites

Sampling sites were located in a range of settings representing variable morphology, degree of tsunami damages and pre-tsunami human impact (Fig. 1 and Table 1). Samples 1 and 2 were collected on a narrow isthmus on the peninsula, which encompass the southern edge of Patong Bay. The isthmus was completely flooded by waves from southern and northern direction, too (Fig. 1). Both samples were taken from local small depressions/ponds. Samples 3–8 were taken from a low-lying terrain, adjacent to a small river in the southern part of Patong city. In a village Nam Khem, which was largely damaged, samples 9–13 were collected. Sample 12 was taken close to a damaged fuel station and samples 11 and 13 in low-lying wet depressions. Samples 14 and 15 were collected in the tsunami-inundated zone in the vicinity of Bang Mor village, and sample 16 was taken as a reference sample in the neighbourhood of Thung Tuk village. In Nam Khem and Bang Mor

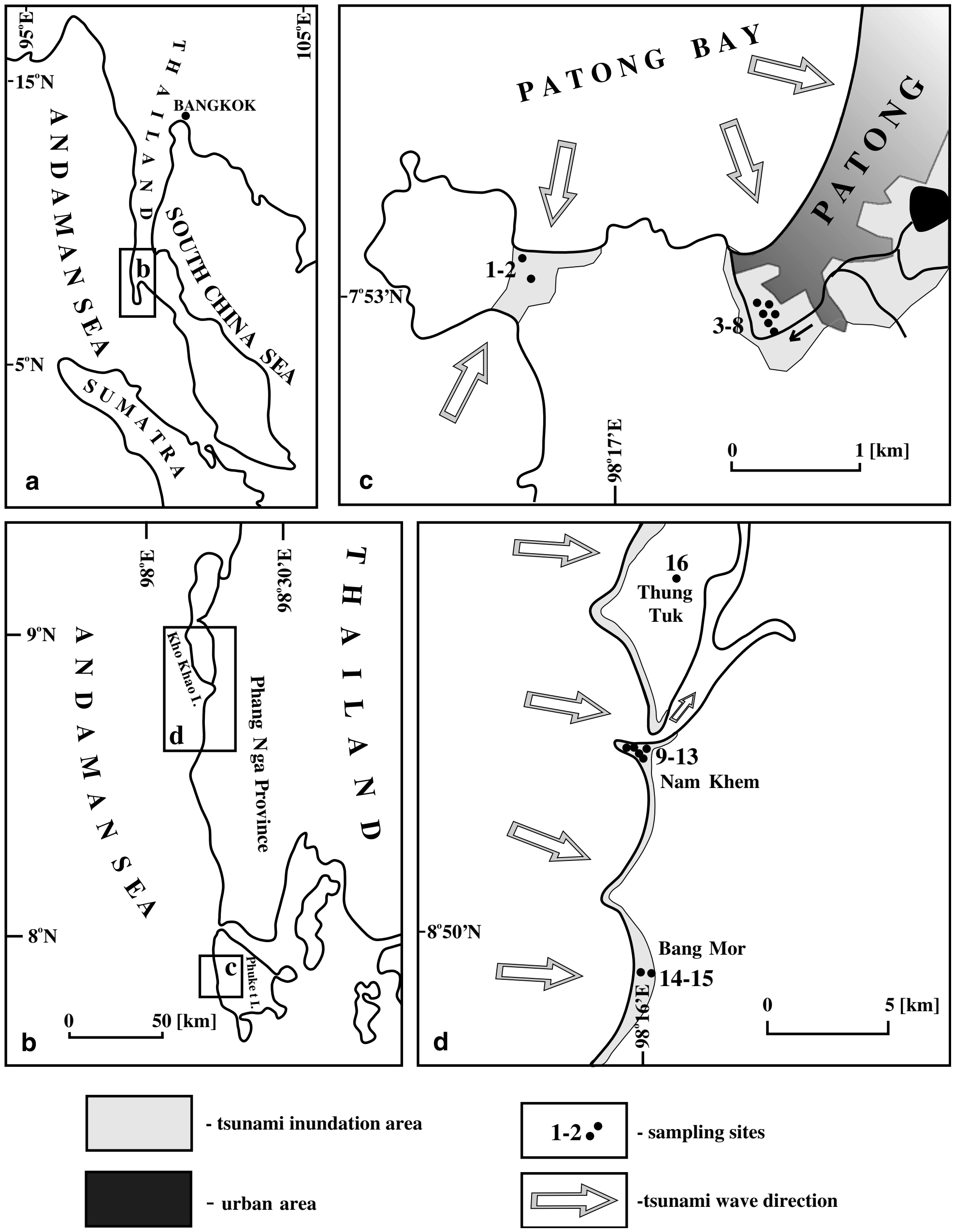

Fig. 1 Study area and sampling sites locations. The tsunami-inundation zone is marked according to remote sensing and field studies (Rachlewicz et al., unpublished data)

mining, of placer deposits for arsenic and other metals took place in former time (N. Chaimanee, personal communication).

Results

Sediment characteristics

Tsunami sediments in the studied locations are mainly in the form of continuous (few cm to few tens of cm thick), sheet of fine and medium sand. Their thickness depends on many local factors. According to grain-size analysis, the sediments are classified in range from very coarse silt to medium sand (Table 2). The clay fraction (>9 Φ) content is very low (Fig. 2)—maximum value of 6.2% was found in sample 2. The coarsest class includes gravels, which in sample 12 compose as much as 6.9% (Fig. 2). In general, most of the samples from Nam Khem and Bang Mor villages are classified as very fine sands (9, 11, 13, 14 and 15), and from Patong town as fine sands (3, 4, 5, 6 and 8). Single samples from Patong (7), Nham Khem (12) and the reference sample (16) belong to medium sand. To the finest classes are classi-

Table 1 Sampling sites locations

Sample	Location	Latitude N	Longitude E	Thickness of tsunami sediments (cm)	Distance from shoreline (m)
1	Patong Bay	7°53.088′	98°16.443′	2	75
2	Patong Bay	7°53.014′	98°16.435′	1	315
3	Patong	7°52.924′	98°17.309′	5	430
4	Patong	7°52.910′	98°17.320′	2	480
5	Patong	7°52.887′	98°17.328′	2	520
6	Patong	7°52.864′	98°17.349′	1	545
7	Patong	7°52.953′	98°17.328′	2	390
8	Patong	7°52.938′	98° 17.336′	20	410
9	Nam Khem	8°51.470′	98°15.930′	20	60
10	Nam Khem	8°51.417′	98°15.953′	15	100
11	Nam Khem	8°51.405′	98°16.310′	18	570
12	Nam Khem	8°51.553′	98°15.940′	2	50
13	Nam Khem	8°51.618′	98°16.527′	5	1,100
14	Bang Mor	8°49.973′	98°16.128′	11	300
15	Bang Mor	8°49.907′	98°16.271′	14	590
16	Thung Tuk	8°53.766′	98°16.694′	Reference sample	1,500

fied deposits (samples 1 and 2) from the isthmus on peninsula encompassing the southern side of Patong Bay (Table 2).

Most of the sediments are poorly sorted (Table 2). The best sorting represents samples from Bang Mor (14 and 15), which are moderately well sorted. The worst sorting (very poorly sorted) are samples with the highest content of clay fraction (1, 2 and 13). Skewness is a measure of grain-size distribution symmetry. Most of the samples are with excess of coarse material (coarse and very coarse skewed). Only three samples are symmetrical (2, 13 and 16), one is fine skewed (9) and two are very fine skewed (5 and 10). Kurtosis is a measure of whether the grain-size distributions are peaked or flat relative to normal distribution. Most of the analysed samples are very leptokurtic (3, 4, 8, 9, 11, 14 and 15) or leptokurtic (4, 6, 7, 10, 12 and 16). Samples 1 and 13 have mesokurtic distribution and sample 2 is platykurtic.

Salts in water-soluble fraction of sediments

In all the samples taken from tsunami sediments, content of salts (K^+, Na^+, Ca^{+2}, Mg^{+2}, Cl^- and SO_4^{-2}) dissolved with de-ionized water is significantly higher than in the reference sample (Table 3). The highest contents of all the studied ions are found in samples: 1 and 2, only SO_4 has slightly higher concentration in sample 13. These samples are taken from depressions, which were for longer time filled with seawater.

Among major ions in the water-soluble fraction, the amounts of Na^+ and Cl^- ions are found to be the highest (Table 3). Their contents vary from 29 and 300 mg kg^{-1} in the reference sample to 67,500 and 118,000 mg kg^{-1} in sample 1, for Na^+ and Cl^-, respectively. Relatively elevated values of Na^+ and Cl^- are also found in samples: 2, 3, 5, 6, 9, 10, 13 and 14.

Table 2 Grain-size statistics and sediment types of the analysed samples

Sample	Sediment type	Grain-size statistics, logarithmic method of moments (Φ)			
		Mean	Sorting	Skewness	Kurtosis
1	Coarse silt	5.62	2.21	−0.55	3.35
2	Very coarse silt	4.69	2.35	0.20	2.54
3	Fine sand	2.04	1.27	−1.80	9.19
4	Fine sand	2.01	0.97	−0.55	4.88
5	Fine sand	2.73	1.08	1.44	11.36
6	Fine sand	1.97	1.93	−0.93	6.03
7	Medium sand	1.61	1.10	−0.60	5.68
8	Fine sand	2.14	1.19	−1.70	8.73
9	Very fine sand	3.20	1.12	1.22	10.23
10	Very coarse silt	4.32	1.43	1.88	7.20
11	Very fine sand	3.77	0.93	−1.45	15.67
12	Medium sand	1.14	1.66	−1.57	5.54
13	Very fine sand	3.77	2.81	−0.29	3.47
14	Very fine sand	3.75	0.61	−2.03	25.40
15	Very fine sand	3.69	0.56	−1.57	27.12
16	Medium sand	1.24	1.05	−0.21	5.88

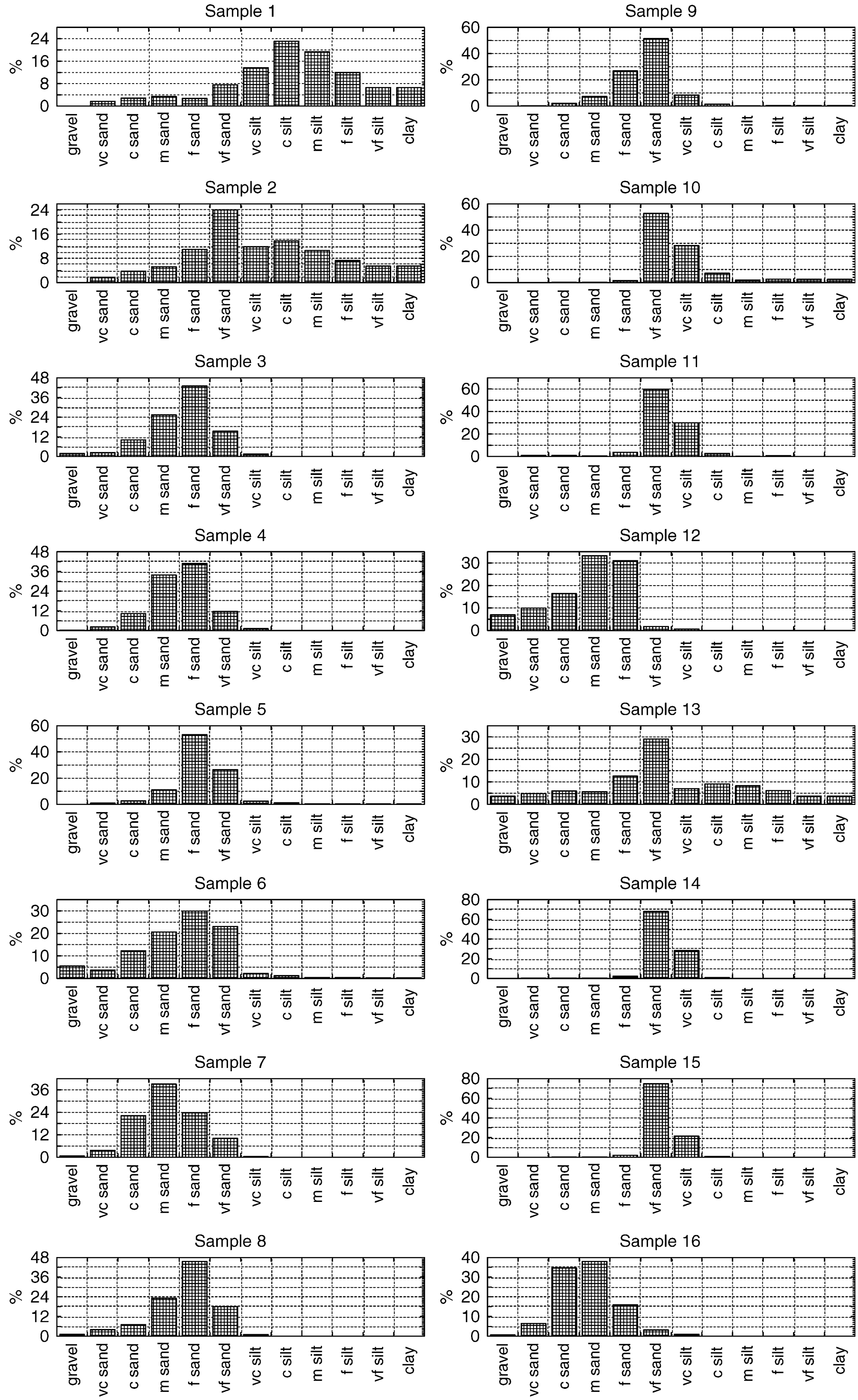

Fig. 2 Grain-size distributions of the studied samples. Explanation of abbreviations used in names of sediment fractions: *vc* very coarse, *c* coarse, *m* medium, *f* fine, *vf* very fine

Table 3 Contents of salts (K^+, Na^+, Ca^{+2}, Mg^{+2}, Cl^- and SO_4^{-2}) dissolved with de-ionized water in mg kg^{-1} of dry mass

Sample	K (mg kg^{-1})	Na (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Cl (mg kg^{-1})	SO_4 (mg kg^{-1})
1	1,558	67,500	10,600	4,600	118,000	11,200
2	620	14,210	4,710	1,910	25,200	7,800
3	368	7,915	2,570	1,130	17,400	2,800
4	95	1,996	1,570	564	4,800	300
5	520	10,770	2,500	1,860	23,600	4,200
6	415	9,619	3,280	1,040	17,400	4,300
7	113	2,593	1,930	304	5,600	1,800
8	154	3,122	1,710	608	6,200	2,200
9	330	7,208	2,070	1,260	14,200	2,600
10	666	16,920	2,430	3,040	33,000	4,900
11	207	2,887	2,210	564	4,600	1,200
12	78	2,182	1,430	434	4,600	1,700
13	323	7,270	7,570	243	13,000	14,500
14	520	8,763	2,710	121	18,800	3,200
15	118	1,210	2,000	608	2,200	< 50
16	24	29	171	61	300	< 50

Table 4 Heavy metals in bioavailable sediment fraction

Sample	Cd (mg kg^{-1})	Cr (mg kg^{-1})	Cu (mg kg^{-1})	Ni (mg kg^{-1})	Pb (mg kg^{-1})	Zn (mg kg^{-1})	Hg[a] (mg kg^{-1})
1	1.5	5.6	10.4	< 0.1	46.3	49.1	0.092
2	1.2	5.7	8.1	0.9	36.5	47.2	0.164
3	1.5	1.6	4.0	< 0.1	16.4	10.6	0.224
4	0.8	< 0.1	1.7	< 0.1	10.2	5.8	0.064
5	1.7	2.5	4.4	< 0.1	18.9	13.3	0.071
6	1.1	1.0	4.3	< 0.1	16.1	12.8	0.065
7	0.9	0.2	2.4	< 0.1	11.2	6.8	0.093
8	1.6	2.7	5.9	< 0.1	19.0	11.5	0.115
9	1.7	4.1	2.1	< 0.1	17.1	9.7	0.130
10	1.5	7.2	2.0	< 0.1	17.1	9.1	0.076
11	1.2	9.1	2.1	1.3	16.1	11.9	0.085
12	0.9	5.5	1.4	1.2	9.9	8.9	0.133
13	0.6	6.9	11.2	2.2	20.0	131	0.233
14	1.4	11.3	2.1	1.1	15.8	11.5	0.087
15	1.2	13.1	1.7	1.4	14.2	13.6	0.097
16	0.1	1.5	1.0	0.6	1.1	2.7	0.164

[a]In case of Hg, concentration was determined for bulk sample

K^+ reveals lower concentrations (Table 3), between 24 and 1,558 mg kg^{-1} for samples 16 and 1, respectively. Variations in K^+ content between samples are similar as in case of Na^+ and Cl^-.

Values of Mg^{+2} (Table 3) vary between 61 mg kg^{-1} in the reference sample and 4,600 mg kg^{-1} in sample 1. High contents of Mg^{+2} are also in samples 2, 5 and 10.

Concentrations of Ca^{+2} (Table 3) are the highest in sample 1 (10,600 mg kg^{-1}) and 13 (7,570 mg kg^{-1}), and the lowest in reference sample (171 mg kg^{-1}). The remaining samples have very similar values; only samples 2, 3, 6 and 14 have slightly higher concentrations of this element.

SO_4^{-2} amounts are very low in the samples 15 and 16 (reference sample). In the remaining samples, its content varied from 300 mg kg^{-1} in sample 4 to 14,500 mg kg^{-1} in sample 13 (Table 3).

Heavy metals in the bioavailable fraction of sediments

Among the analysed heavy metals, two groups are distinguished. The first one includes Cd, Cu, Zn and Pb, whose concentrations are higher in tsunami sediments than in reference sample (16). In particular, Pb and Zn have significantly elevated values (Table 4). In the second group are: Cr, Hg and Ni. Their concentrations are generally low and similar in tsunami sediments and in the reference sample.

The content in the bioavailable fraction of Cd in tsunami sediments is between 0.6 (sample 13) and 1.7 mg kg^{-1} (samples 5 and 9). It is relatively more than that in the reference sample, where only 0.1 mg kg^{-1} of this element was determined. There are no significant spatial changes in the concentrations of Cd between the sampling locations (Table 4).

Table 5 Metalloids in exchangeable fraction

Sample	As (μg kg^{-1})	Sb (μg kg^{-1})	Se (μg kg^{-1})
1	880	145	60
2	515	165	85
3	255	200	25
4	230	195	35
5	400	185	40
6	405	210	30
7	235	190	30
8	395	210	30
9	980	200	25
10	1,145	195	30
11	1,280	240	15
12	415	195	15
13	1,775	240	50
14	995	210	35
15	1,230	205	20
16	105	175	15

The range of Cr amount is from less than 0.1 mg kg^{-1} in sample 4, to 13.1 mg kg^{-1} in sample 15 (Table 4). Its content in reference sample is within the range observed in tsunami sediments. Elevated values are observed in samples from the southern part of Patong Bay and Nam Khem village and maximum—in samples from Bang Mor village neighbourhood.

The maximum content of Cu is found in sample 13—11.2 mg kg^{-1} (Table 4). The lowest value is determined for the reference sample—1 mg kg^{-1}, however, it is only slightly lower a value than in most of the tsunami sediments.

The content of Ni is very low (Table 4). In majority of samples (including all the samples from Patong town), its concentration is less than 0.1 mg kg^{-1}. Maximum content is found in sample 13—2.2 mg kg^{-1}. The reference sample is within the range determined for tsunami sediments.

The content of Pb in bioavailable fraction (Table 4) is much higher in tsunami sediments (between 9.9 and 46.3 mg kg^{-1}) than in the reference sample (1.1 mg kg^{-1}). The maximum values are in the samples from the peninsula on southern side of Patong Bay (samples 1 and 2). The remaining samples reveal small variations of Pb content.

Tsunami sediments have clearly a higher content of Zn in the bioavailable fraction than the reference sample (Table 4). The maximum values are noted in samples: 13 (131 mg kg^{-1}), 1 and 2. The minimum value for tsunami sediments is 5.8 (sample 4) and for the reference sample, it is 2.7 mg kg^{-1}.

Due to low concentrations, the Hg content is determined for bulk samples. The obtained values (Table 4) are from 0.064 mg kg^{-1} in sample 4 to 0.233 mg kg^{-1} in sample 13. The differences between samples are very small and the reference sample has Hg content in the same range as tsunami sediments.

Metalloids in exchangeable fraction of sediments

As, Sb and Se are analysed among the metalloids in the sediment fraction; these may be subjected to migration. The reference sample (16) has a significantly lower content of As than the tsunami sediments (Table 5). Concentration of Se and Sb are small in this sample, however, they are in the range observed for tsunami deposits (Table 5).

As content is between 105 μg kg^{-1} in sample 16, and 1,775 μg kg^{-1} in sample 13. Excepting the reference sample, the lowest values are observed in samples from Patong town. The highest are found in samples from Nam Khem and Bang Mor.

Sb concentrations are similar in the whole set of studied sediments. The lowest values are noted in samples 1 and 2 (145 and 165 μg kg^{-1}, respectively). The highest content of Sb is documented in samples 11 and 13 (240 μg kg^{-1}).

Values of Se are in the range of 15 (samples 11, 12 and 16) to 85 μg kg^{-1} in sample 2.

Water conductivity

Water conductivity was measured in standing, flowing and ground waters in the area inundated by the tsunami wave. Measurements were limited by the detection range of the used instrument (between 0 and 19.99 mS cm^{-1}). The survey was conducted in the vicinity of locations from which sediment samples were taken, and from inundated zone on Kho Khao Island. In all the cases, water conductivity was much higher than in reference measurement of water from a well which is located outside the zone impacted by the tsunami (close to location of sample 16) where values of 0.03–0.05 mS cm^{-1} were obtained. Ground waters measured in wells on peninsula on the southern side of Patong Bay (close to sampling locations 1 and 2) had a conductivity of 0.86 mS cm^{-1}. Conductivity of flowing waters was measured in five small creeks (maximum discharge about 10 dm^3 s^{-1}) along the coast. Values ranged from 1.31 (in stream with the biggest water discharge) to 15.20 mS cm^{-1}. The highest values were documented from a dozen of ponds and lakelets in the coastal zone. The lowest value was 6.2 mS cm^{-1} but in the most of these standing water bodies, the conductivity was out of scale of the instrument ($>$19.99 mS cm^{-1}).

Discussion

Tsunami sediments

The studied tsunami sediments are similar to depositional effects of the others reported earthquake-gener-

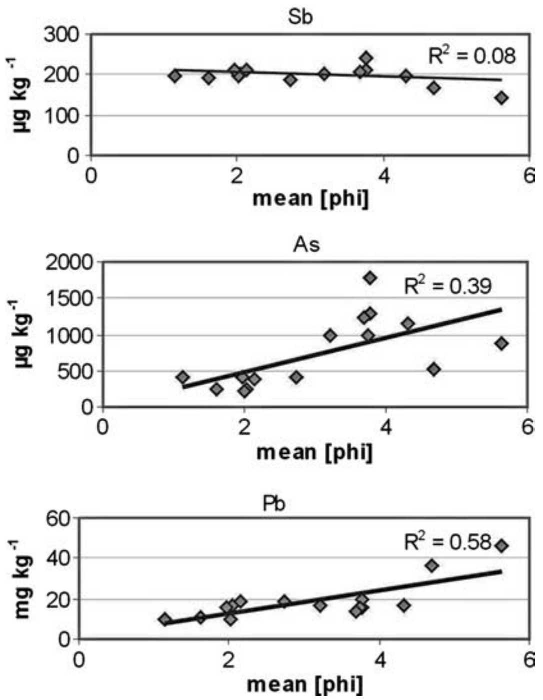

Fig. 3 Relation of elements concentrations to mean grain size. Examples of elements with no relation (*Sb*), with poor (*As*) and with moderate correlation (*Pb*)

ated tsunami waves (Dawson et al. 1996; Dawson and Shi 2000; Gelfenbaum and Jaffe 2003). They are composed mainly of very fine and medium sand fractions. The variations of grain size are not correlated to tsunami sediment layer thickness or to distance from the shoreline in the analysed set of 15 samples. Most of the sediments are delivered from erosion of nearshore and beach zone (Szczuciński et al., unpublished data). The observed differences in grain size are caused by local factors. The finest mean grain sizes are in samples 1 and 2, on a narrow peninsula next to Patong Bay. It may be related to the fact that, at least from the northern side, the peninsula is bordered by a 1-km wide shallow platform covered with corals, which could have reducing effect on the wave speed. Relatively coarser (than in the remaining locations) sediments in the Patong city are related to their location in direct neighbourhood of river channel, which served as the natural way for the tsunami-wave propagation so the speed and transporting power were stronger here. Also important is that coarser sediments (at the river bed) were available for erosion and further transport.

Tsunami can leave behind a clearly identifiable deposit (Dawson and Shi 2000; Scheffers and Kelletat 2003). If the sediment deposited by a tsunami is buried and preserved, then a geologic record of that tsunami will be created. However, unquestionable interpretation of their origin is often impossible, or require to include many diagnostic sediment properties—for example: grain-size fining trends, character of lower and upper contacts, presence of intraclasts, marine diatoms, foraminifera and other microfossils, etc. (Goff et al. 2001). Sediment chemical composition was also used as a proxy helping identification of paleotsunami sediments. Increases in concentration of sodium, sulphur, chlorine, calcium and magnesium occur in tsunami sediments relative to under- and overlying sediments indicating saltwater inundation (Minoura et al. 1994; Chagué-Goff and Goff 1999; Goff and Chagué-Goff 1999; Goff et al. 2001). As documented in present study, beside typical seawater ions, increased contents of Pb, Zn, As, Cu and Cd may also serve as indicatord in particular situations.

Table 6 Interelement relationship in the correlation coefficient matrix for the studied elements in tsunami sediments (the reference sample was not included)

	K	Na	Ca	Mg	Cl	SO_4	Cd	Cr	Cu	Ni	Pb	Zn	Hg	As	Sb	Se
K	1															
Na	0.96	1														
Ca	0.80	0.83	1													
Mg	0.90	0.88	0.61	1												
Cl	0.97	1	0.81	0.89	1											
SO_4	0.62	0.58	0.89	0.44	0.58	1										
Cd	0.40	0.30	−0.08	0.48	0.33	−0.16	1									
Cr	−0.22	−0.15	−0.18	−0.16	−0.16	−0.27	−0.38	1								
Cu	0.57	0.58	0.87	0.41	0.56	0.91	−0.09	−0.24	1							
Ni	0.21	0.25	−0.05	0.40	0.27	−0.11	0.42	0.11	−0.04	1						
Pb	0.87	0.85	0.83	0.77	0.84	0.68	0.29	−0.24	0.76	0.02	1					
Zn	0.26	0.25	0.74	0.07	0.24	0.89	−0.43	−0.13	0.83	−0.35	0.42	1				
Hg	−0.08	−0.09	0.28	−0.17	−0.10	0.47	−0.20	−0.28	0.48	−0.28	0.13	0.61	1			
As	0.15	0.11	0.38	0.03	0.09	0.45	−0.11	−0.19	0.25	−0.52	0.13	0.58	0.21	1		
Sb	−0.65	−0.67	−0.35	−0.73	−0.68	−0.16	−0.32	−0.01	−0.22	−0.35	−0.63	0.16	0.19	0.46	1	
Se	0.59	0.51	0.66	0.46	0.50	0.70	−0.03	−0.01	0.75	−0.08	0.79	0.55	0.24	0.01	−0.55	1

Relation of sediment type to contaminants content

Grain size and sorting are major determinants of pore sizes and total porosity in sediments. There are factors, which determine how fast water may infiltrate into sublayer and if capillary processes (for instance, upward migration of ground waters) may occur. Therefore, the residence time of post-tsunami seawaters in the sediments and, in consequence, the amount of bounded contaminants, may be partly related to grain-size distribution.

The studied elements revealed three types of relationships to mean grain size (Fig. 3) and are grouped into corresponding classes. The first group includes Cd, Hg, Ni, Sb and Zn with no correlation to mean grain size. The second group (As, Cr, Cu, Mg, Se and SO_4^{-2}) reveals a weak trend of rising concentration with sediment fining. The highest correlation of decreasing mean grain size with increasing elements content is revealed by Ca, Cl, K, Na and Pb. This relationship is partly caused by the ability of the finest sediments to retain water for the longest period. In conditions of continuous intensive evaporation promoting successive crystallization of salts, it may result in elevated concentrations of such ions as Na^{+}, Cl^{-}, K^{+}, Ca^{+2}, Mg^{+2} or SO_4^{-2}in structures of minerals with high water solubility. No significant correlation between elements concentrations and remaining grain-size statistics (sorting, skewness and kurtosis) is found.

Interelement relationships

Table 6 presents the correlation matrix of the analysed elements in tsunami sediments. High positive correlation is between major ions in water-soluble fraction and some heavy metals in the bioavailable fraction. Very high correlation of Na^{+}, K^{+}, Mg^{+2} and Cl^{-} suggests that the ions probably are in the sediments in form of halite (NaCl), sylvine (KCl) and carnallite ($KMgCl_3 \cdot 6H_2O$)—the most common minerals resulting from seawater evaporation. High correlation factor between Ca^{+2} and SO_4^{-2} suggests, that gypsum ($CaSO_4 \cdot 2H_2O$) or anhydrite ($CaSO_4$) may be also present in the sediments. SO_4^{-2} is also statistically closely related to Cu and Zn, which may substitute Ca^{+2} ions. Surprising is very high correlation of Pb to all the salts.

It may indicate their common sink in tsunami sediments. Most of the heavy metals have increased concentrations in samples with high salt contents.

Origin of contaminants

Relative contents of major ions in water-soluble fraction and of soluble heavy metals and metalloids were compared to the average seawater composition (Riley and Skirrow 1975; Riley and Chester 1983). The relative participation of particular ions in water-soluble fraction of sediments mimics that observed in average seawater. Consequently, elevated values of K^{+}, Na^{+}, Ca^{+2}, Mg^{+2}, Cl^{-} and SO_4^{-2} in tsunami deposits seem to be of marine origin and were probably in majority delivered in dissolved form with seawater translated on land during the tsunami.

In the case of heavy metals and metalloids, the proportions of elements in the studied fractions and in average seawater reveal much weaker correlation, however, the general trend is the same. The exception is Pb, which in seawater belongs to the least common heavy metals (Riley and Chester 1983) and in the studied sediments, its concentrations are the highest (Table 4). It would indicate distinct source of this element—lithogenic or anthropogenic. Astonishing is, however, that Pb concentrations in all the studied samples reveal very good correlation to salt content (Table 6). There are at least two possible explanations. One is that the seawater translated on land with the tsunami wave had distinctly different Pb concentrations than the average seawater. The second possibility is that high amounts of litho- or anthropogenic Pb were released during the event and were tied with salt compounds. Similarly, Cu and Zn, which are relatively well correlated to Ca^{+2} and SO_4^{-2} (Table 6), formed possibly compounds with the latter ion, although, their origin may be litho- or anthropogenic rather than marine.

In samples from Nam Khem and Bang Mor locations, where mining of heavy mineral placer deposits took place in the past, exceptionally elevated values of As are observed and are possibly related to its leaching from As-bearing minerals in this region (Williams et al. 1996). Since high contents of As are not correlated to the major water-soluble ions and are limited to one geographical region of characteristic geology, it is concluded that the elevated amounts of As are of lithogenic origin.

Possible environmental impact

During direct field survey (Rachlewicz et al., unpublished data) it was documented that most of the plants were withered in the tsunami-inundated zone. As shown by the presented results, as well as, by the recent UNEP report (unpublished), almost all the water bodies in the area inundated by tsunami reveal significant contamination due to intrusion of salt water. The previous soils are covered with a few to several tens of cm thick layer of tsunami sediments in nearly the entire inundation zone (Szczuciński et al., unpublished data). As shown in this paper, the sediments contain high amounts of salts and some other toxic elements: As, Pb, Zn and in smaller extent Cu and Cd, where elevated values are observed in easily soluble fraction and are potentially subjected to migration. These fractions are easily available to ecobiological cycle and possibly enter the food chain under suitable physicochemical conditions. Because the terrain is low lying and contains many depressions (the northern part of the studied area was a place of open cast mining of placer deposits) the salts may be washed into ground waters increasing the problem of a lack of freshwater in this area and postponing natural restoration of the flora. The mentioned heavy metals and metalloids may be washed into ground waters, as well as, assimilated by plants. In both cases, they may reach a dangerous toxic level, in certain situations. However, it is likely that, in locations with sediments of low permeability below the tsunami deposits, the contaminants will be washed away during the rainy season.

Conclusions

The studied sediments, deposited by the 26 December 2004 tsunami in Thailand, belong to poorly sorted, very coarse silts to medium sands, and are similar to depositional effects of previously reported earthquake-generated tsunami waves. They contain significantly elevated contents of salts (Na^{+}, K^{+}, Ca^{+2}, Mg^{+2}, Cl and SO_4^{-2}) in water-soluble fraction, and of Cd, Cu, Zn, Pb and As in bioavailable fraction, in relation to the reference sample. Therefore, chemical composition of sediments—particularly increase contents of salts and Pb, Zn, As, Cu and Cd, may be used as supplementary proxy to identify paleotsunami deposits. The surface and ground waters in the tsunami-inundated zone, measured within 50 days after the tsunami, were still characterized by high and very high salinity. The concentrations of major ions in water-soluble fraction and of Pb is correlated to mean grain size of the sediments, which is related to pore sizes, porosity and in consequence to possible duration of water retention in the sediments.

The origin of contaminants is complex. Major ions in water-soluble fraction of sediments (K, Na, Ca, Mg, Cl and SO_4) are highly correlated to each other and were delivered in dissolved form with seawater. Heavy metals (Cu, Pb and Zn) are also correlated to salt content and probably are tied to them in the sediments, however, their source is either litho- or anthropogenic. Arsenic has elevated concentrations in restricted area—related to mining activity, and is probably of lithogenic origin.

Because the terrain is characterized by gentle morphology with many depressions, the salts, heavy metals and metalloids contained in the sediments, may be washed into ground waters increasing the problem of a lack of freshwater in this area and postponing natural restoration of the flora. The bioavailable metals and metalloids may also reach toxic levels in food chain causing serious environmental hazard. There is, however, also possible that heavy rainfall during summer monsoon will cause dilution and removal of significant portion of the contaminants.

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Effects of Changing Environments of Mangrove Creeks on Fish Communities at Trat Bay, Thailand

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ABSTRACT / Effects of changing environments of riverside mangroves, coastal land uses, and water quality on fish communities were studied in Bangphra and Thaprik creeks, Trat Bay, Thailand. Regression analysis revealed that fish species richness in the wet season had a negative relationship with water transparency, nitrate, and phosphate and a positive relationship with zooplankton. In the dry season, species richness had a negative relationship with nitrate and phosphate and a positive relationship with salinity, pH, and zooplankton. Abundances and species richness of fish declined over distance from downstream to upstream in both creeks. Riparian mangroves and water quality also declined with distance upstream in both creeks. Results from one-way analysis of variance and Tukey's HSD test revealed that the highest zooplankton volume with the lowest amounts of nitrate and phosphate were observed at the downstream station in both creeks in each season. Low zooplankton volume with high amounts of nitrate and phosphate were found at the midstream and upstream stations of the creeks. The midstream and upstream stations of Bangphra Creek had low to moderate abundance of mangroves along the riversides, whereas shrimp farms were mainly found along the riversides at the midstream and upstream stations of Thaprik Creek. Correlation analysis results of land-use types and the significant habitat factors were discussed. This study found that mangrove degradation, shrimp farming, and residential and agricultural areas altered water quality and the health of fish habitats, causing the decreases in fish abundance and species richness.

Mangroves are one of the most productive features of coastal ecosystems across tropical and subtropical regions of the world (Baban 1997). Because of their important role in terms of carbon fixation, nutrient assimilation, and sediment stabilization (Odum 1983), mangroves are fertile habitats for foraging, breeding, and sheltering of various kinds of animal such as fish, crustaceans, birds, reptiles, and mammals (e.g., Alongi 2002). However, mangrove forests that once were abundant, particularly in tropical countries, are currently one of the world's most threatened ecosystems (Barbier and Cox 2002) due to drastic encroachment of human activities into mangrove areas, especially shrimp farming. For instance, mangrove areas in Vietnam rapidly declined from 2500 km^2 in 1943 to about 500 km^2 in 1995 (Hussain 1995), caused mainly by the invasion of shrimp farms. Likewise, In Thailand, mangrove areas along the coastal zone decreased from 3679 km^2 in 1961 to about 1687 km^2 in 1994, resulting from increasing expansion of shrimp farms and urban development (Kongsanchai 1995).

Conversion of mangrove areas into shrimp farms and urban areas not only striped away mangroves and exposed large areas of soil to erosion and oxidation but also dramatically altered runoff and drainage patterns of water (Páez-Osuna and others 2003). Effluent from shrimp ponds (e.g., nutrients and sediments) and runoff from urban areas that typically contain a variety of pollutants can cause hyper-nutrification of estuarine ecosystems (Hopkins and others 1995; Sansanayuth and others 1996; Naylor and others 1998; Smith and others 1999) and threaten natural aquatic faunae, particularly fish communities (Sudara 1997; Wang and others 2001).

Leh and Sasekumar (1991) indicated that deforestation in mangrove creeks in Selangor, Malaysia led to a reduction in species richness of fish. In addition, mangrove deforestation in Singapore caused a decrease in species diversity of mangrove fish communities (Low and Chou 1994). In Thailand, approximately

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2000 fish species from 199 families have been recorded in marine and estuarine waters. Of these, 607 species from 87 families were solely observed in estuarine habitats and adjacent waters. However, estuarine fish diversity in Thailand has been vulnerable to decline. In the last two decades, mass killings of estuarine fish species in the three major river mouths (Maeklong, Chao Phraya, and Thachin) in the Gulf of Thailand were speculated to be a consequence of water pollution (Vidthayanon and Premcharoen 2002) and mangrove deterioration (Monkolprasit 1966, 1983, 1994) due to human activities.

To preserve coastal estuarine habitats and water quality for aquatic life, shrimp farming in mangroves has been prohibited by law in Thailand. Nevertheless, illegal conversion of mangroves to shrimp farms still occurs and has become one of the most controversial topics in the country (Barbier and Cox 2002; Erftemeijer 2002). In contrast, studies about the effects of changing environments of mangroves, coastal land uses, and water quality on fish communities along the country's coastlines have been rare. The goals of this study therefore were (1) to study fish community alterations due to changing conditions of riparian mangroves, coastal land uses, and water quality and (2) to determine the influences of certain habitat factors on fish communities. Consequences from the study were proposed to reflect the health of fish habitats in two mangrove creeks with varied mangrove conditions and patterns of coastal land-use activities.

Two mangrove creeks in highly developed coastal zones of an estuary of Trat Bay, Thailand were selected for this study. The first, Bangphra Creek, runs through natural recovery mangrove forests that were banned from woodcutting by law enforcement approximately 15 years ago. The second, Thaprik Creek, runs through deteriorated mangrove forests, most of which were replaced by shrimp farms. Parts of these two creeks were drainage sites of domestic sewage from local households along the riversides and from the Trat municipality. Fish communities and habitat factors were observed at three sampling stations in each creek (i.e., at downstream, midstream, and upstream stations). Each had varied conditions of riverside land cover (e.g., shrimp farming, residential area, and mangrove forest). This study hypothesized that the sampling stations with higher degraded riparian mangroves and coastal land uses would display more impacts on water quality and poorer health of fish habitats than the sampling stations with less degraded riparian mangrove and coastal land uses.

Methods

Study Area

Bangphra and Thaprik creeks are located in the Trat province on the eastern coast of the Gulf of Thailand (between 12° 11′ 42″ N 12° 15′ N and 102° 31′ 30″ E–102° 39′ 30″ E; Figure 1). The conditions of the two creeks have been altered by uncontrolled expansion of the surrounding Trat's Muang district's urban areas and human activities during the last two decades. Bangphra Creek, 11 km long, passes through three subdistricts—Wang Krajae, Nong Samed, and Nong Khansong—of Trat's municipality before it empties into Trat Bay. Riparian mangrove density was abundant at the downstream station (ST1), declined at the midstream station (ST2), and was the lowest at the upstream station (ST3) at Bangphra Creek. Shrimp farming was not observed along the riversides of Bangphra Creek. Thaprik Creek, 9 km long, runs through deteriorated mangroves in the Thaprik subdistrict before it empties into Trat Bay. Most of the destructive mangrove areas along the riversides of Thaprik Creek were converted to shrimp farms, particularly at ST2 and ST3.

Common species of mangroves in both creeks were *Rhizophora apiculata*, *Rhizophora mucronata*, *Bruguiera gymnorrhiza*, *Ceriops tagal*, *Xylocarpus granatum*, *Lumnitzera littorea*, and *Excoecaria agallocha* (Patanaponpaiboon and others 1994). The climate in the study area is classified into two monsoon seasons: the wet southwest monsoon (April–November) and the dry northeast monsoon (December–March). Fieldwork was conducted eight times a month for 3 months in the wet season (August–October 1997) and in the consecutive dry season (December 1997–February 1998). Monthly average rainfall during the study period in the wet season was 541.1 mm, with monthly air temperature varying from 22.1°C to 34.2°C (Trat Provincial Statistics Office 1997). Monthly average rainfall during the study period in the dry season was 66.6 mm, with monthly air temperature varying from 20.0°C to 36.1°C (Trat Provincial Statistics Office 1997, 1998).

Fish Communities

At six sampling stations in both creeks, fish abundance and species richness were observed eight times/station/month in each season using a small-scale push net and a drift gill net. Of the eight observations, four were conducted during spring tide and the other four were conducted during neap tide. In each tidal period, fish were collected once a day for 2 days and once a night for 2 nights using both types of fishing gear. A push net—4 m wide at its mouth, 4.5 m long at its

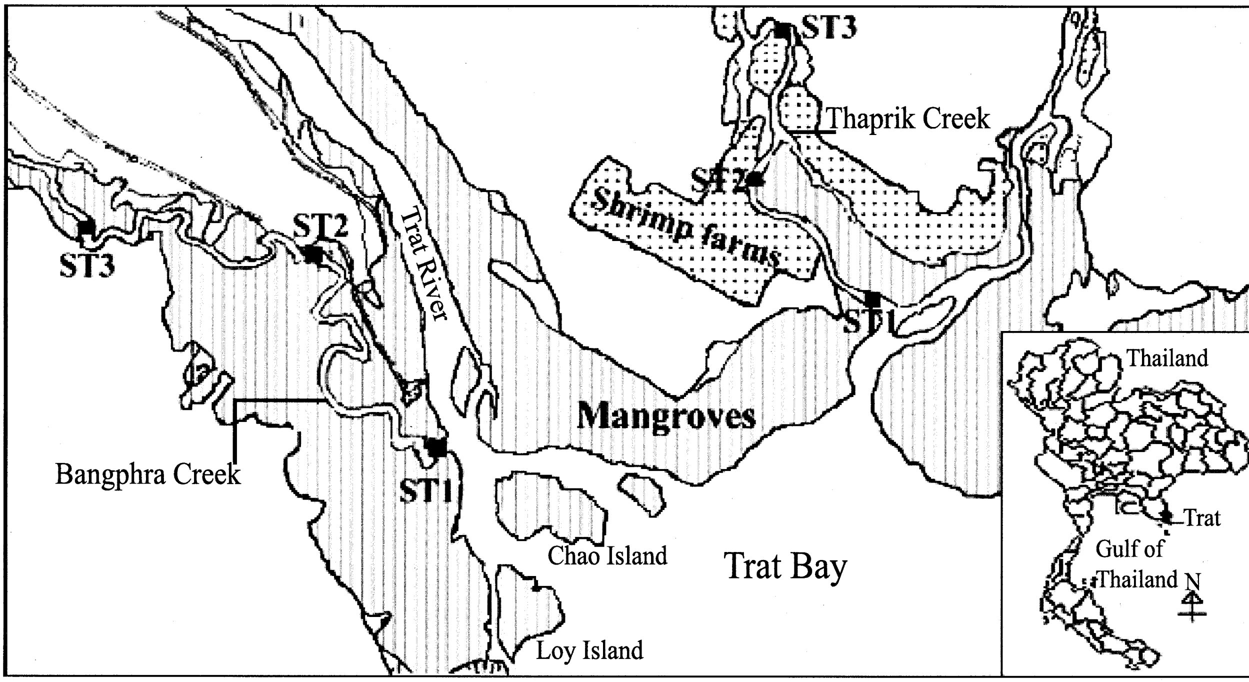

Figure 1. The study area, Bangphra and Thaprik creeks, Trat Bay, Thailand, showing three sampling stations (ST1 = downstream station, ST2 = midstream station, and ST3 = upstream station).

beam, 3- and 2.5-cm nylon mesh sizes at its mouth and neck, respectively—was operated at approximately 0.5 km upstream at each station. A polyfilament drift gill net—with mesh size of 3.5 cm, 1.5 m deep and 45 m long—was set for 30 min per station to collect pelagic fishes. Fish specimens were identified to species, enumerated, and measured for total length to the nearest millimeter. Small fish that were difficult to identify in the field were preserved in a 250-ml polyethylene bottle of 10% neutral formalin for later identification in the laboratory.

Habitat Conditions

Abundance and distribution of fish in mangrove areas are dependent on various factors such as mangrove condition (Aksornkoae 1989; Monkolprasit 1966, 1983, 1994), water turbidity (Blaber and Blaber 1980; Loneragan and others 1987; Cyrus and Blaber 1992; Satapoomin and Poovachiranon 1997), salinity of water (Najim and others 1990), and food availability (e.g., phytoplankton, zooplankton, insects, etc.). Riverside land covers and some basic habitat factors, including water depth (m), water transparency (Secchi depth, m), water temperature (°C), salinity (ppt) and pH of water, and zooplankton, were observed at all six sampling stations in both creeks. Nitrate (NO_3^-, µg/L) and phosphate (PO_4^{3-}, µg/L) were measured to determine the consequences of coastal land-use alteration, particularly shrimp farming, on water quality. These nutrients were indicated as typical major effluents discharged from shrimp farms into natural water resources causing eutrophication (Sansanayuth and others 1996; Naylor and others 1998; Wolanski and others 2000).

Land covers along the riversides at 0.5 km upstream of each station (where fish collections using the push net were conducted) were quantified using a LAND SAT-TM 1:50,000 image of Trat Bay in 1997. The image was visually interpreted using an overlay technique along with the land-use survey. In each season, all habitat factors were measured once a month during the spring tide, when water flow throughout each small creek was assumed to be well mixed. Water was randomly sampled 0.5 m below the water surface at each station to measure nitrate and phosphate using a DR/3 spectrophotometer (HACH Company 1982). Zooplankton was horizontally sampled for 5 min at each station using a plankton net with a mesh size of 330 µm and a 30-cm-diameter mouth. The zooplankton observed at each station was preserved in 5% neutral formalin and measured in terms of volume (ml/m^3 of water). The volume of water (m^3) that passed through the mouth of the plankton net was calculated from the mouth area of the net multiplied by the hauling distance, $(22/7)r^2d$, where r represents the radius of the mouth of the net and d represents hauling distance

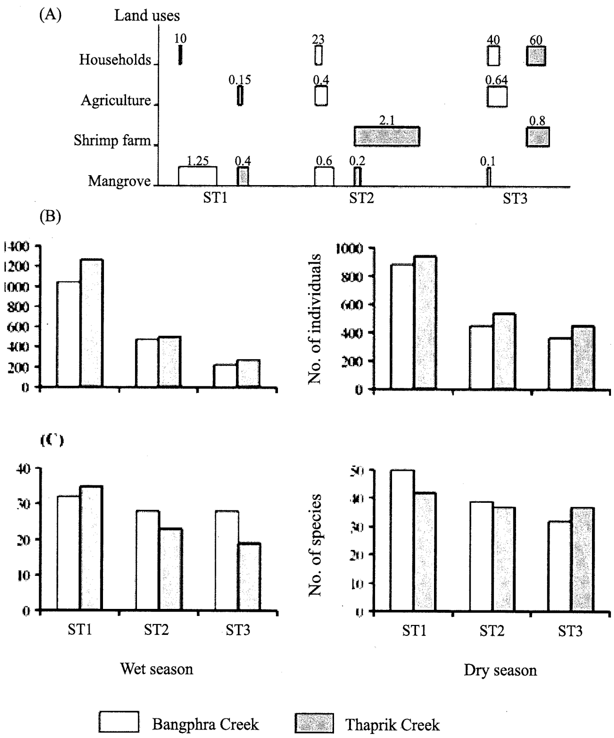

Figure 2. Comparisons of riparian land uses (A), fish abundance (B), and species richness (C) among stations (ST1 = downstream station, ST2 = midstream station, and ST3 = upstream station) in each creek in each season. All types of land use, except households (numbers), were measured in the unit of square kilometers.

recorded by the meter installed at the mouth of the net. Major taxonomic groups of zooplankton were classified in the laboratory.

Data Analysis

Species numbers of fish from eight observations/station/month were aggregated in each season. Then, the 18 values of fish species richness from all 6 stations in both creeks over 3 months (18 observed values from 6 stations × 3 months) along with the 18 average values of each habitat factor at those stations in each season were used in a regression analysis to estimate the relationship of fish species richness with each habitat factor. When significant relationships between species richness and any habitat factor were detected ($P \leq 0.05$), differences in means of that habitat factor among stations over 3 months (9 mean observed values from 3 stations × 3 months) in each creek were determined using a one-way analysis of variance (ANOVA). When mean values of habitat factors among stations were significantly different ($P \leq 0.05$), the mean differences between paired stations were compared using Tukey's honestly significant differences (HSD) test.

Results

Riverside Land Uses and Fish Communities

The visual interpretation of the LAND SAT-TM image of Trat Bay in 1997 and the land-use survey revealed about 1.25 km^2 of mangrove forest and 10 households at ST1 of Bangphra Creek. There were about 0.6 km^2 of mangrove forest, 0.4 km^2 of agriculture area (coconut plantations and rice paddies), and 23 households at ST2. About 0.1 km^2 of mangrove forest, 0.64 km^2 of agriculture area (rice paddies), and 40 households were observed at ST3 of Bangphra Creek. At Thaprik Creek, about 0.4 km^2 of mangrove forest and 0.15 km^2 of agriculture area (rice paddies) were observed at ST1, whereas about 0.2 km^2 of mangrove forest and 2.1 km^2 of shrimp farms were observed at ST2. About 0.8 km^2 of shrimp farms and 60 households but no mangrove forests were observed at ST3 of Thaprik Creek (Figure 2A).

Ninety-five species of fish were observed in Bangphra Creek in both seasons. Of these, 52 species were caught in the wet season and 65 in the dry season. A total of 75 fish species were observed in Thaprik Creek in both seasons; of these, 41 species were collected in the wet season and 58 in the dry season. The highest fish abundance and species richness were observed at ST1 in both creeks in each season (Figures 2B and 2C). Lower abundances were observed at ST2 and ST3 in both creeks in each season.

Species Richness and Habitat Factors

Results of the regression analysis revealed that in the wet season, fish species richness was significantly related to transparency ($r^2 = 0.29$, $P = 0.022$), nitrate ($r^2 = 0.28$, $P = 0.024$), phosphate ($r^2 = 0.29$, $P = 0.021$), and zooplankton volume ($r^2 = 0.70$, $P = 0.000$). Species richness tended to decrease when water transparency, nitrate, and phosphate increased, whereas it tended to increase when zooplankton volume increased (Figure 3). In the wet season, fresh water existed in both creeks (salinity of water = 0 ppt). The relationships of species richness with water depth, water temperature, and pH were not significant in the wet season. The pH in both creeks was 6.5–6.9. The depth in Bangphra Creek varied from 6.4 m at ST1 to 3.3 m at ST3, whereas the depth throughout Thaprik Creek was 2.5–2.6 m. Temperature varied from 29.3°C to 30.3°C in both creeks in the wet season.

In the dry season, species richness was significantly related to nitrate ($r^2 = 0.63$, $P = 0.000$), phosphate ($r^2 = 0.44$, $P = 0.003$), salinity ($r^2 = 0.43$, $P = 0.003$), pH ($r^2 = 0.72$, $P = 0.000$), and zooplankton volume ($r^2 = 0.60$, $P = 0.000$). Species richness tended to de-

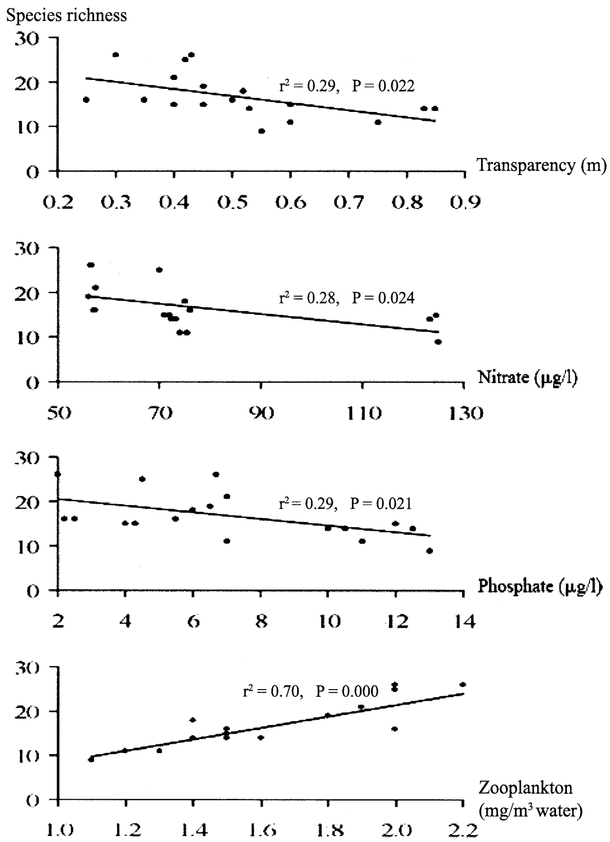

Figure 3. Relationships between species richness of fish and significant habitat factors in both creeks in the wet season.

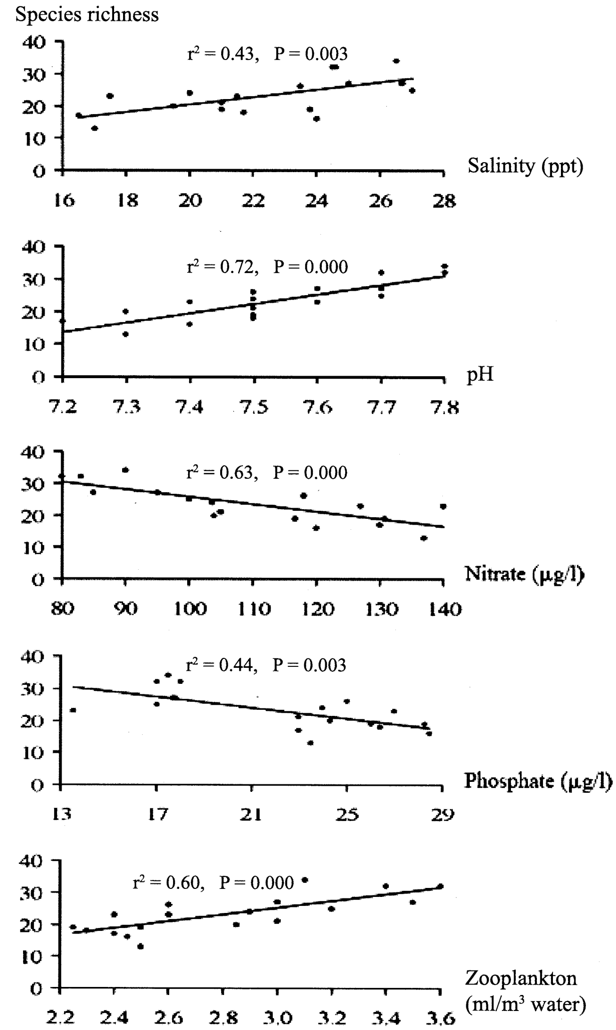

Figure 4. Relationships between species richness of fish and significant habitat factors in both creeks in the dry season.

crease when the amount of the two nutrients increased, but it tended to increase when salinity, pH, and zooplankton volume increased (Figure 4). In the dry season, species richness was not significantly related to water depth, water temperature, and water transparency. The depth in Bangphra Creek varied from 6.0 m at ST1 to 3.0 m at ST3, whereas the depth throughout Thaprik Creek was 2.4–2.5 m. Temperature varied from 29.0°C to 29.9°C in both creeks. Transparency of water was 1.2–1.6 m in Bangphra Creek and 0.8–0.9 m in Thaprik Creek.

Fish Habitat Comparisons

Habitat factors that displayed significant relationships with species richness in each season were compared among three stations in each creek. In the wet season, the mean intensities of transparency, nitrate, and phosphate and the mean volume of zooplankton among stations over 3 months in each creek were significantly different ($P \leq 0.05$, Table 1: wet season). Results from Tukey's HSD test showed significant differences ($P \leq 0.05$) in these habitat factors between paired stations in each creek. The highest transparency of water was observed at ST3, whereas the lowest transparency was observed at ST1 in both creeks. In Bangphra Creek, the highest concentrations of nitrate (75.5 µg/L) and phosphate (6.2 µg/L) were observed at ST3. In Thaprik Creek, the highest concentrations of nitrate (124.3 µg/L) and phosphate (12.5 µg/L) were observed at ST2. The lowest concentrations of nitrate and phosphate were 56.9 µg/L and 2.23 µg/L, respectively, at ST1 in Bangphra Creek and 56.7 µg/L and 6.7 µg/L, respectively, at ST1 in Thaprik Creek (Figure 5: wet season).

Major taxonomic groups of zooplankton observed in each creek were similar, but their abundances, in terms of total volume per cubic meter of water, were significantly different among the stations. Three groups—calanoid and cyclopoid copepods, and decapods (brachyuran and caridean larvae)—were ob-

Table 1. One-way ANOVA results showing mean differences of significant habitat factors

	Wet season					Dry season			
	Bangphra		Thaprik			Bangphra		Thaprik	
Factors	*F*	*P*	*F*	*P*	Factors	*F*	*P*	*F*	*P*
Transparency (m)	21.848	0.002	72.007	0.000	Salinity (ppt)	149.229	0.000	250.403	0.000
NO_3^- (μg/L)	614.152	0.000	5900.88	0.000	PH	11.200	0.000	17.333	0.003
PO_4^{3-} (μg/L)	49.047	0.000	136.976	0.000	NO_3^- (μg/L)	161.544	0.001	68.022	0.000
Zooplankton (mg/m^3 water)	9.250	0.015	8.333	0.019	PO_4^{3-} (μg/L)	2.704	0.145	62.711	0.000
					Zooplankton (mg/m^3 water)	97.000	0.000	68.808	0.000

Note. Mean difference for each habitat factor that had a significant relationship with fish species richness in each season was compared among stations in each creek (Bangphra and Thaprik). *F* is a ratio of mean squared regression (MSR) and mean squared error (MSE), and the *P*-value is a significant level of the test statistic ($P \leq 0.05$).

served throughout both creeks in both seasons. Of 15 groups observed in the wet season, 2 groups commonly found throughout both creeks were polychaete larvae and harpacticoid copepod. The highest mean volumes of zooplankton were observed at ST1 in both creeks. Lower mean volumes of zooplankton were observed at ST2 and ST3 in both creeks (Figure 5: wet season).

In the dry season, the mean intensities of pH, salinity, nitrate, and phosphate and mean volumes of zooplankton among stations in Thaprik Creek were significantly different. In addition, mean intensities of these factors, except phosphate, were significantly different among stations in Bangphra Creek (Table 1: dry season). Water in both creeks became alkaline in the dry season, resulting from elevated mixing of fresh water with marine water that provided high concentrations of HCO_3^- and CO_3^{2-}. The highest mean pH observed at ST1 in both creeks was 7.7. The mean pH at ST2 and ST3 in both creeks were similar (pH = 7.4–7.5). Water salinity was high throughout both creeks. In Bangphra Creek, the highest mean salinity was 24.7 ppt at ST1, whereas the lowest was 17.0 ppt at ST3. Likewise, in Thaprik Creek, the highest mean salinity was 26.7 ppt at ST1, whereas the lowest was 21.4 ppt at ST3 (Figure 5: dry season).

The highest concentrations of nitrate were 137.1 μg/L and 131.3 μg/L at ST3 in Thaprik Creek and Bangphra Creek, respectively, in the dry season. The lowest concentrations of nitrate were 95.0 μg/L and 82.7 μg/L at ST1 in Thaprik Creek and Bangphra Creek, respectively. The highest concentration of phosphate in Thaprik Creek was observed at ST2 (27.3 μg/L), whereas the lowest was observed at ST1 (17.4 μg/L). There were no significant differences in mean phosphate among stations in Bangphra Creek in the dry season. The observed phosphate concentrations among stations in Bangphra Creek varied from 17.6 to 23.8 μg/L.

Twenty groups of zooplankton were observed in the dry season. Of these, the three groups found commonly throughout both creeks in the dry season were medusae, ctenophore, and chaetognath. The highest mean volumes of zooplankton in both creeks were observed at ST1, wheras the lowest volumes were observed at ST3 (Figure 5: dry season).

Discussion

The abundance and species richness of fish observed in Bangphra and Thaprik creeks reflected the health of fish habitats in both creeks. The results showed that species richness of fish was related to riverside mangrove conditions, coastal land uses (i.e., shrimp farming, agricultural and residential areas), and certain habitat factors (i.e., transparency, nitrate, phosphate, and zooplankton in the wet season; pH, salinity, nitrate, phosphate, and zooplankton in the dry season).

Riparian land covers and water quality, important indicators of biotic condition (Richards and others 1996; Lammert and Allan 1999; Wang and others 2001), varied from ST1 to ST3 in each creek. Moderate–high abundance of mangroves and low riparian land uses at the downstream stations (ST1) of both creeks tended to result in less impact on water quality and the health of fish habitats, as seen in the high fish abundance and species richness observed at this station compared to those observed at the midstream (ST2) and upstream (ST3) stations in both creeks. In contrast, high mangrove degradation and riparian land uses at ST2 and ST3 altered water quality and the health of fish habitats, as seen in the lower fish abundance and species richness observed at these stations in both creeks.

Generally, water quality in a river varies over distance from upstream to downstream due to mixing,

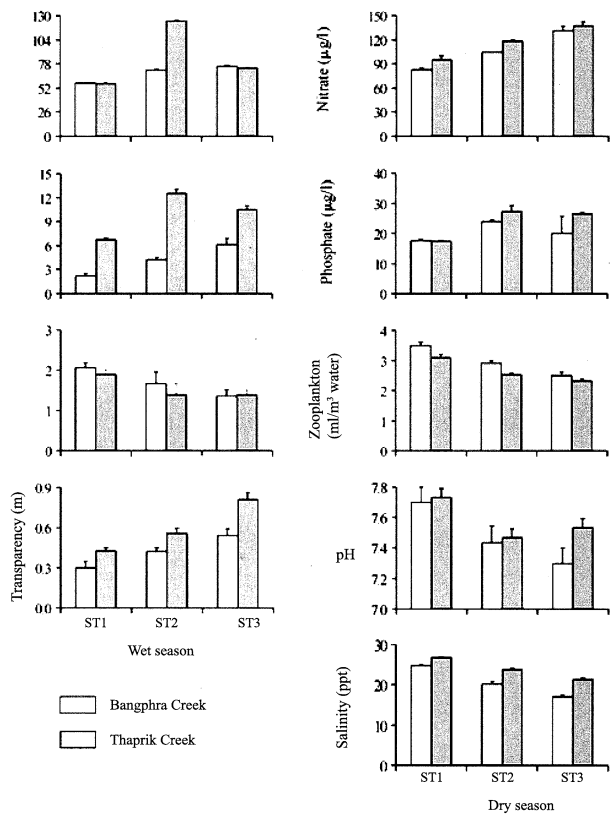

Figure 5. Mean intensities of each habitat factor that had a significant relationship with fish species richness were compared among stations (ST1 = downstream station, ST2 = midstream station, and ST3 = upstream station) in each creek in each season.

transport, and transformation processes. From these processes, dissolved inorganic nutrients like nitrate and phosphate are diluted downstream, whereas turbidity of water usually increases downstream. However, with the unique ecological conditions of the small study creeks in the estuary, the above-mentioned processes can be altered by tide (neap and spring tides), season, and the ability of riparian mangroves to filter nutrients and sediments. Thus, the observed nutrient loads in the creeks might not have appreciably altered with distance downstream during the spring tide because the water was rather well mixed throughout the creeks, causing the spatial effect to be reduced.

In this study, high nutrient concentrations observed among stations in both creeks were most likely due to effluents discharged from shrimp farms, households, and agricultural areas on the riversides. The positive correlations of shrimp farm area with concentrations of nutrients confirmed this consequence. Shrimp farming was mainly observed at ST2–ST3 in Thaprik Creek and was strongly positive correlated with concentrations of nitrate (r^2 = 0.93—wet season) and phosphate (r^2 = 0.86—wet season, r^2 = 0.69—dry season) in either season or both (Table 2). Negative correlations were found between shrimp farming and mangrove areas; and the land-use survey indicated that the shrimp farms observed at ST2–ST3 of Thaprik Creek were mainly converted from mangroves and agricultural areas (i.e., rice paddies and perennial crop plantations).

Nitrate concentrations observed throughout both creeks in each season were considerably higher than those observed downstream of Trat River. Nitrate concentrations observed at the two downstream stations in Trat River during the 6-year period 1998–2003 varied from 0.09 to 0.65 µg/L in the wet season and from 0.07 to 0.31 µg/L in the dry season (Thailand's Pollution Control Department, unpublished data). In this study, the highest concentrations of nitrate (118.2–137.1 µg/L) observed at ST2 and ST3 in Thaprik Creek in the dry season were consistent with Patanaponpaiboon and others (1994). They found that nitrate was higher (121.6 µg/L) in Thaprik Creek in the dry season than the concentrations observed in Trat River and Chao Island. Their study speculated that the high nitrate concentration in Thaprik Creek was probably due to effluents with high nitrogen content discharged from shrimp farms on the riversides.

There are currently 779 shrimp farms in Trat's Muang district. Many of them are intensive shrimp farms located around Trat Bay. Cropping practices are primarily done twice a year during June–October and December–June. Each crop takes about 4 months before harvesting (Trat Provincial Fisheries Office 2004). However, cropping and harvesting schedules of these shrimp farms vary, causing differing intensities of effluents to be discharged from the shrimp farms into natural resources over time. The periods for nitrate concentration collections in the study creeks in both seasons were coincident with the shrimp farming schedules. High amounts of nitrate observed at ST2–ST3 in Thaprik Creek, compared with those observed from the effluents of intensive shrimp farms (Table 3), were most likely due to effluent loading from shrimp farms around the sampling stations.

In areas without shrimp farming, high amounts of nitrate observed at ST2–ST3 in Bangphra Creek were mainly due to the wastewater discharged from residential and agricultural areas. In the wet season, nitrate concentrations in discharge from residential and agricultural areas were low due to high water runoff and dilution. In the dry season, with low water runoff and dilution in the creeks, the numbers of households located on the riversides tended to be a

Table 2. Correlation analysis of land-use types and habitat factors

Wet season	Mangrove	Shrimp farm	Agriculture	Households	Transparency	NO_3^-	PO_4^{3-}	Zoo. vol
Mangrove	1							
Shrimp farm	−0.415	1						
Agriculture	−0.232	−0.505	1					
Households	−0.477	−0.159	0.263	1				
Transparency	−0.820	0.453	−0.118	0.706	1			
NO_3^-	−0.450	0.925	−0.167	−0.176	0.342	1		
PO_4^{3-}	−0.777	0.860	−0.339	0.124	0.747	0.763	1	
Zoo. vol	0.763	−0.465	−0.258	−0.479	−0.687	−0.576	−0.645	1

Dry season	Mangrove	Shrimp farm	Agriculture	Households	Salinity	pH	NO_3^-	PO_4^{3-}	Zoo. Vol
Mangrove	1								
Shrimp farm	−0.415	1							
Agriculture	−0.232	−0.505	1						
Households	−0.477	−0.159	0.263	1					
Salinity	0.406	0.158	−0.762	−0.688	1				
PH	0.494	−0.159	−0.629	−0.423	0.841	1			
NO_3^-	−0.883	0.379	0.258	0.730	−0.642	−0.651	1		
PO_4^{3-}	−0.506	0.688	−0.208	0.295	−0.255	−0.466	0.602	1	
Zoo. vol	0.921	−0.519	−0.182	−0.596	0.558	0.663	−0.94	−0.697	1

Note. All types of riparian land use, except households (numbers), were measured in the unit of square kilometers. Transparency, salinity, nutrients (NO_3^- and PO_4^{3-}), and zooplankton volume (zoo. vol) were measured in the units of meter, parts per thousand, micrograms per liter, and milligrams per cubic meter water, respectively.

major source of nitrate loading at the midstream and upstream stations of both creeks, as demonstrated in the high positive correlation to nitrate concentration ($r^2 = 0.73$). Although phosphate had a rather high positive correlation to nitrate ($r^2 = 0.76$—wet season, $r^2 = 0.60$—dry season), its observed concentrations were low in the creeks (4.3–27.3 μg/L) compared with the amounts observed in the influents (20–130 μg/L) from intensive shrimp farms (Robertson and Phillips 1995) and from water resources (40–80 μg/L) near shrimp farms around Trat Bay (Pollution Control Department 2002).

Changing conditions of riparian mangroves had also altered fish communities (Monkolprasit 1966, 1983, 1994; de Graaf and Xuan 1998) in terms of abundance or species richness, or both. Wichert and Rapport (1998) indicated that although some fish species might not be affected by impaired water quality, they could decline in habitats with destructive riparian forests. In this study, a large-scale archerfish (*Toxotes chatareus*) was observed at all stations in Bangphra Creek during the wet season, but was absent from Thaprik Creek in the same season. This insectivore freshwater fish prefers living in both flowing and standing water in shaded areas with overhanging vegetation (Rainboth 1996). The large-scale archerfish feed mainly on insects and vegetable matter using their renowned habit of spitting to dislodge insectivorous prey from tree branches above the water (Allen 1991).

The occurrence of the large-scale archerfish in Bangphra Creek was related to the presence of riparian mangrove as its food source. Absence of the large-scale archerfish in Thaprik Creek thus reflected destruction of mangroves and loss of food source for this fish species. Accordingly, Tait and Perna (2001) indicated that the apparent loss of archerfish from Burdekin floodplain habitats in Australia was due to the loss of riparian vegetation and low dissolved oxygen in those habitats. *Oxygaster anomalura* (common name of this species is varied in different countries; e.g., paep in Thailand, selvang in Indonesia, trey slak russey in Cambodia) is another insectivore freshwater fish whose distribution is influenced by riparian forest conditions. Its preferred habitat is the surface of water with complete or nearly complete riparian forest canopy. Its major foods are insects and chironomid larvae (Rainboth 1996). In this study, it was observed in the wet season at only ST1 and ST2 in Bangphra Creek, where riparian mangroves and zooplankton were observed in abundance.

The distributions of fish in the creeks were also related to certain habitat factors and seasons. In the wet season, the salinity and transparency of water limited upstream distribution of some estuarine fish and all marine fish (Blaber and Blaber 1980; Loneragan and others 1987). Most fish species were found at ST1, where the lowest transparency of water (0.3–0.4 m) and the highest volume of zooplankton were observed.

Table 3. Nutrients discharged from intensive shrimp farms and in the studied creeks

Source	Nitrate (μg/L)	Phosphate (μg/L)
Tunvilai and others (1993)[a]	70–150	N/A[d]
Briggs and Funge-Smith (1994)[b]	40–110	N/A[d]
Robertson and Phillips (1995)[c]	3–100	20–130
Bangphra Creek		
ST2–ST3: wet season	71.0–75.5	4.3–6.2
ST2–ST3: dry season	104.2–131.3	20.0–23.8
Thaprik Creek		
ST2–ST3 : wet season	73.3–124.3	10.5–12.5
ST2–ST3: dry season	118.2–137.1	26.5–27.3

Note: Concentration ranges of nutrients (nitrate and phosphate) in discharged water from intensive shrimp farms (Sources [a-c]) compared with concentration ranges of the nutrients observed at the midstream station (ST2) and the upstream station (ST3) in each studied creek.
[d]N/A = Data were not available.

Freshwater fish could be observed at all stations in this season because freshwater was detected throughout the creeks (salinity = 0 ppt), whereas estuarine fish were commonly observed only at ST1 and ST2. Freshwater fish were mainly from the family Cyprinidae, whereas estuarine fish were mainly from the families Hemiramphidae, Chandidae, Eleotridae, and Gobiidae.

Only estuarine and marine fish were observed in the dry season, when water throughout the creeks became saline. Estuarine and marine fishes in both creeks were mainly from the families Mugilidae, Lutjanidae, Engraulidae, Clupeidae, Carangidae, Gobiidae, and Siganidae. More species of fish could migrate to the midstream and the upstream stations in both creeks in the dry season than in the wet season. This was likely due to the increase in water salinity throughout the creeks in the dry season, which allowed more fish species, particularly marine species, to migrate farther upstream in the creeks. The greatest abundance of fish in each creek was observed at ST1, where the highest salinity of water and the highest zooplankton volume were observed. The salinity of water decreased with distance upstream. The lowest water salinity observed at ST3 in both creeks inhibited upstream migration of some marine fish with less tolerance to low salinity, such as *Sillago sihama, Lutjanus russelli, Lethrinus semicinctus*, and *Dendrophysa russelli*. Consequently, these species were not found at ST3 in both creeks in either season.

The pH of water, which did not show a significant relationship with species richness in the wet season, did have a significant relationship with species richness in the dry season. The pH of water was strongly positive correlated with salinity ($r^2 = 0.84$). The high pH of water at ST1 and ST2 was a result of high water salinity at these stations. Meanwhile, nutrient loading from shrimp farms and other coastal land uses that can alter the pH of water (Dash 1994) were negatively correlated to pH. The positive correlations of zooplankton volume with pH and salinity (Table 2: dry season) supported the results that zooplankton was more abundant in the dry season than in the wet season. These are because low salinity and high turbidity in the wet season can lower the abundance of zooplankton (Khaosirikul 1979) by limiting the growth rate of phytoplankton, a food source of zooplankton. High nitrate and phosphate loads observed at ST2 and ST3 in both creeks might also vary zooplankton abundance at these stations as shown by their moderate–high negative correlation with zooplankton volume in both seasons (Table 2).

Summary

Abundance and species richness of fish observed in Bangphra and Thaprik creeks decreased over distance from downstream to upstream. These results were correlated with riparian mangrove and water quality conditions that declined with distance upstream. Historical studies of nitrate loads in Trat River and in effluents discharged from intensive shrimp farms supported the finding that nitrate concentrations observed midstream and upstream in Thaprik Creek were higher than would be expected by natural processes. The high concentrations of nitrate observed at the midstream and upstream stations in Thaprik Creek were thus most likely due to the effluents discharged from shrimp farms. Residential and agricultural areas were main sources of high nitrate loads observed at the midstream and upstream stations in Bangphra Creek. This study found that degradation of riparian mangroves and certain types of coastal land use altered water quality and the health of fish habitats, as shown by the decreases in fish abundance and species richness with distance upstream in both creeks.

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Heavy metals in soils and crops in southeast Asia. 2. Thailand

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Abstract

A reconnaissance soil geochemical and concomitant plant survey based on 318 soil (0–15 cm) and 122 plant samples was used for the assessment of heavy metal pollution of agricultural soils and crops of Thailand. Arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) were determined in soils using *aqua regia* digestion, and in plants using nitric acid digestion. Organic carbon (C), pH, electrical conductivity (EC) and available phosphorus (P) were determined on the soil samples using appropriate procedures. Results indicated that concentrations of heavy metals varied widely among the different regions of Thailand. Regression analysis between the concentrations of metals in soil (*aqua regia* extractable) and edible plant parts indicated a small but positive relationship for Cd in all the plants sampled in the survey ($R^2 = 0.081$, $p < 0.001$). There was also a positive relationship between soil and plant Cd concentrations in rice ($R^2 = 0.242$, $p < 0.010$), and negative relationships for Zn in rice ($R^2 = 0.385$, $p < 0.001$), and Cu ($R^2 = 0.355$, $p < 0.001$) and Zn ($R^2 = 0.122$, $p < 0.026$) in glutinous rice. Principal component analysis of the soil data suggested that concentrations of As, Co, Cr, Cu, Hg, Ni and Pb were strongly correlated with concentrations of Al and Fe, which is suggestive of evidence of background variations due to changes in soil mineralogy. Thus, the evidence for widespread contamination of soils by these elements through agricultural activities is not strong. On the other hand, Cd and Zn were strongly correlated with organic matter and concentrations of available and *aqua regia* extractable P. This is attributed to input of contaminants in agricultural fertilisers and soil amendments (e.g. manures, composts).

Introduction

Thailand has undergone considerable industrialisation and urbanisation in the past three decades. This economic growth and industrial development has been achieved at the expense of the environment and the country's natural resource base (Reutergårdh & Yen 1997) since this rapid increase in industrialisation has not been matched with a concomitant establishment of a hazardous waste treatment and disposal system. The bulk of the hazardous waste generated in Thailand is dumped into rivers, canals or drainage systems and landfills. Atmospheric pollution of soil is also increasing in Thailand as urbanisation and industrialisation proceeds, yet few data are available to assess the impact and extent of the problem (Reutergårdh & Yen 1997). The wide-ranging water contamination produced by direct waste dumping into the water system is compounded by leakage of wastewater containing heavy metals from waste dumps and waste treatment plants (Muttamara & Leong 1997). Drinking water and water for household use is accessed from deep and shallow wells, while vegetable and orchard crops are irrigated using water from streams, canals and rivers (Pipithsangchan *et al.* 1994).

The high concentrations of macro and micronutrients in biosolids (sewage sludge) combined with the increasing costs of chemical fertilisers have made biosolid application to crop and forest lands an attractive alternative for waste disposal (Parkpian *et al.* 1998). In the areas around Bangkok, the preferred method for disposal of biosolids is application to agricultural land (AIT 1995). However, biosolids contain variable amounts of heavy metals (depending on the waste stream entering the biosolids treatment plant), which might enter the food chain through plants or animals, and contaminate ground and surface waters resulting in potential health hazards.

Primary tin (Sn) deposits with attendant As mineralisation as arsenopyrite occur widely in southern Thailand. Thai authorities consider the mining of Sn to have been the principal cause of As contamination of surface and ground waters (Williams *et al.* 1996). Stream waters in the proximity of As-rich waste piles also showed enrichment of Al, Cd, Cu and Zn by two orders of magnitude relative to the regional average (Williams *et al.* 1996).

The lack of any consistent investigation into contaminants in agricultural soils and crops in Thailand has made it difficult to identify potential problem areas. Wilcke *et al.* (1998) distinguished anthropogenic contamination of urban Bangkok soils with Cd, Cu, Pb and Zn from Al, Cr, Fe, Mn and Ni attributed to parent materials using principal component analysis (PCA). These authors compared the heavy metal concentrations determined 'with those of temperate soils because no literature on heavy metal background concentrations in Thailand is available'. Thus, there is a need to define the likely extent and severity of soil and crop pollution with inorganic contaminants in Thailand.

This study was conducted with the aim of evaluating the normal ranges of heavy metals in agricultural soils of Thailand as well as the heavy metal concentrations in crops grown on these soils.

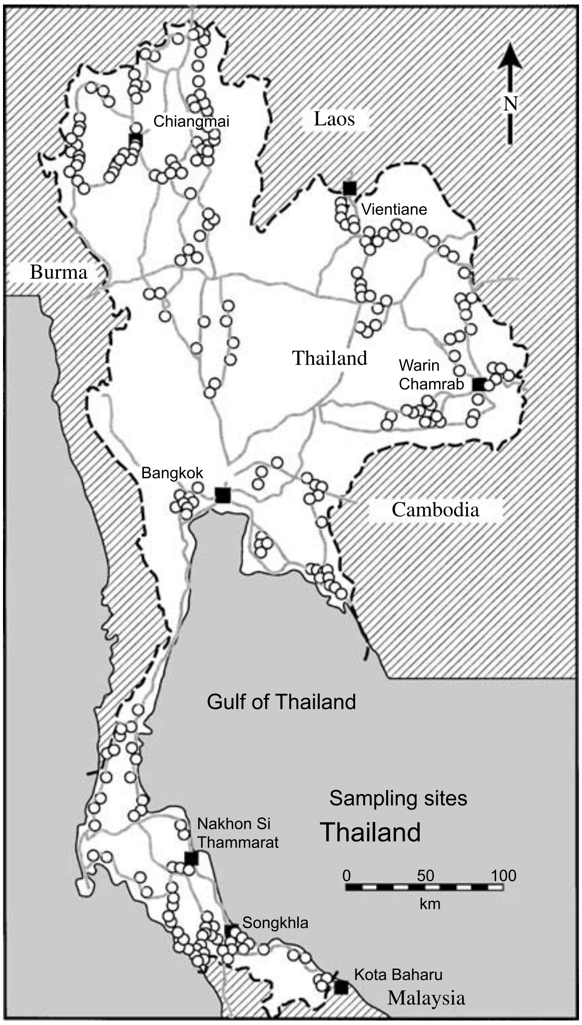


Fig. 1. Soil and plant sampling sites in Thailand.

Materials and methods

Soil and plant sampling

A soil geochemical and concomitant plant survey to assess the extent of heavy metal pollution of soils and crops in Thailand, was based on 318 soil (0–15 cm) and 122 plant samples taken from agricultural, forested and uncultivated sites in the central, eastern, northern, northeastern, and southern regions of the country (Figure 1). A reconnaissance survey approach using the main roads within a region (and not soil type) with sampling points approximately 25 km apart (Figure 1) was chosen as the basis of the investigation, since the level, source, and distribution of heavy metal pollution in Thailand was unknown. Intensive agricultural areas were sampled more rigorously.

Soils sampled from forested and uncultivated areas remote from industry were also collected and used as background values since these were assumed uncontaminated. For each soil, five core samples were taken (50 mm diameter by 150 mm depth) with a stainless steel core sampler and combined into a composite sample for laboratory analyses. All samples were taken at least 75 m from any road to minimise contamination from automobile emissions and road dust. For horticultural and orchard samples, the soil cores were taken in between plants in the rows in which the plants were growing, over the length of a row. For forest and agricultural or paddy samples, the soil cores were taken around an approximately 20 m circle. The soils were air dried at ambient temperature and crushed to pass a 2 mm stainless steel sieve.

The edible portion of at least one plant was then sampled in close proximity to each soil core where available. Plants were only sampled if they were edible. Rice and agricultural products were taken from within the soil sampling area. Many soils were sampled without paired plants as either the plants had not reached maturity or a crop had not been planted but remnant plants indicated the previous year's crop. Plant samples were washed in reverse osmosis/deionised water, combined into a composite sample for laboratory analyses, oven dried at 70 °C and ground to pass a 1 mm stainless steel sieve.

In addition, a soil core from each treatment of a long-term fertiliser and compost trial was sampled at 0–5, 5–10, 10–20, 20–30, 30–40, and 40–50 cm depth intervals. The long-term fertiliser and compost trial treatments were:

1. chemical fertiliser:
   a) 100–100–50 NPK in 1976–1979
   b) 63–63–0 NPK in 1980–1989
   c) 63–63–63 NPK in 1990–1995
2. municipal compost:
   a) 20 t ha^{-1} in 1976–1978
   b) 6.3 t ha^{-1} in 1989–1995
3. no fertiliser.

Groundnut and rice analytical values are reported on a 'dry weight' basis since they are consumed in this form, while all other plants are reported on a 'fresh weight' basis.

Chemical analyses

The soils were analysed for the following properties: available P was extracted by the Bray 2 method (0.03 N NH_4F and 0.1 N HCl, Bray & Kurtz 1945) and determined using the ammonium molybdate/ascorbic acid method of Murphy and Riley (1962). pH and EC (dS m^{-1}) were determined on a 1:5 soil:water suspension. Organic C was determined using a modified Walkley and Black procedure (Nelson & Sommers 1982). Soil Al, Fe, As, Cd, Co, Cr, Cu, Hg, Ni, Pb and Zn were extracted in boiling *aqua regia* (Zarcinas *et al.* 1996) while plant heavy metals were solubilised by digestion with nitric acid (Zarcinas *et al.* 1987). Aluminium, Fe and the heavy metals, except Cd and Hg in soils, were determined by inductively coupled plasma spectrometry (ICPS) (Spectroflame Modula, Spectro Analytical Instruments, Kleve, Germany). Cadmium in soils and plants, and Pb in plants were determined by electrothermal atomic absorption spectrometry (ETAAS), and Hg by cold vapour (CV) AAS (GBC Model 906, Melbourne, Australia).

The validity of the soil and plant digestion procedures and the ICPS operating parameters were established using internationally recognised National Institute of Standards and Technology (NIST) and National Research Council Canada certified Reference Materials (CRC-CNRC) standard materials (Zarcinas *et al.* 1987, 1996). For quality control, two in-house quality control samples (lettuce and spinach) and blanks were included in each plant analytical batch while two reference contaminated soils (State Chemical Laboratories, Victoria, Australia) and blanks were included in each soil analytical batch.

Statistical analyses

Statistical analysis and PCA, was performed using Genstat, Fifth edition, Release 4.2 (Lawes Agricultural Trust, Rothamsted, Harpenden, UK). Assessment of the normal distribution of the analytical data was based on the normal probability plot of residual log transformed data (derived from the regression analysis of log–log transformed data) versus sample percentile. Non-normal data were log-transformed to improve normal distribution and to reduce the influence of high analytical data. Correlation (r), analysis of variance (ANOVA) and regression analyses were performed on log-transformed soil analytical data.

PCA, based on the correlation matrix, was conducted for the soil chemical data set. The aim of using PCA was to ascertain any patterns in the soil samples in relation to these chemical characteristics, and hence infer possible relationships between these and other soil properties, fertiliser inputs or soil organic amendments.

Results and discussion

Data were evaluated by the comparison of heavy metals between soil Orders (Soil Survey Staff, Land Development Department (LDD) 1998), between soils sampled on different crops and between management practices. Management practices were assessed by

Table 1. Announcement of the Ministry of Health No. 98, 1986, Standard of Contaminated Food, Ministry of Health, Thailand; and Australian New Zealand Food Authority (1999, Proposal P157). Values in mg kg^{-1}. Thailand data based on produce 'as consumed'. Australian data based on 'edible content of the food that is ordinarily consumed'. If dried, based on mass of food prior to drying.

Food	As		Cd		Cu[a]		Pb		Hg		Sb[a]		Sn[b]		Zn[a]	
	Thai	Aust	Thai	Aust	Thai	Aust	Thai	Aust	Thai	Aust	Thai	Aust	Thai	Aust	Thai	Aust
General food	2	1		0.1	20		1	0.1	0.02	0.01		0.1	250	250	100	
Seafood	2	2		2	20	40	1	0.5	0.5	0.5			250		100	10

[a] Generally Expected Level (GEL).
[b] All canned food.

comparing the concentrations of metals in cultivated soils to forested or uncultivated soils. In this case, the heavy metal concentrations of forested and uncultivated areas were considered as natural background values due to minimal anthropogenic influence.

For crop quality, the maximum permitted concentration (MPC) as stated in the 'Announcement of the Ministry of Health No. 98, 1986, Standard of Contaminated Food, Ministry of Health, Thailand', was used as a reference (Table 1). The ANZFA (1999) Australian Maximum Levels (MLs) and Generally Expected Levels (GELs) are also presented in Table 1. The GELs for metal contaminants in specific commodities are based on available data and reflect the generally accepted levels in food commodities. As data for more commodities becomes available in the future, GELs will be established for these commodities.

The rationale for the selection of the 95th percentile value of the randomly selected agricultural and background soils sampled as the minimum concentration of a heavy metal for a soil to be considered contaminated is justified in Part 1 of this series of reports (Zarcinas *et al*. 2003).

Briefly, the studies of Tiller (1992), Scott-Fordsmand *et al.* (1996), Australian New Zealand Food Authority (ANZFA 1999), and Lamé and Leenaers (1998) established the percentile levels of heavy metals in order to define soil quality criteria for the protection of soil microorganisms and human health, and the maintenance of the soil resource for plant production. In this study, the 95th percentile value of the randomly selected agricultural and background soils sampled for this study were used as the minimum concentration of a heavy metal for a soil to be considered contaminated. These 'investigation levels' provide a threshold value, which can trigger further evaluation of the possible contamination. Investigation levels do not indicate a potential hazard, but rather that further investigation is needed to determine if the contamination is related to anthropogenic activity and/or could develop into a risk to the environment or human health. For comparison, the 'target' values used in the Netherlands for soil protection (Lamé & Leenaers 1998) and the Australian Ecological Investigation Levels (EILs) (NEPM 1999) are presented in Table 2. The Dutch target values are based on natural (background) soil levels and on negligible risk concentrations. The Australian EILs for urban settings are based on considerations of phytotoxicity, ANZECC (1992) B levels, and soil survey data from urban residential properties in four Australian capital cities.

Table 2. Dutch target values and Australian EIL (mg kg^{-1}).

Metal	Dutch target value	Australian EIL
As	29	20
Cd	0.8	3
Cr (III)	100	400
Cu	36	100
Hg	0.3	1
Ni	35	60
Pb	85	600
Zn	140	200

Metal distribution among soil orders

The mean, median, minimum, and maximum heavy metal and soil fertility concentrations of the soils sampled with and without separation into soil Orders (Soil Survey Staff (LDD) 1998) are reported in Table 3. From this data set, investigation levels were established based on the 95th percentile values (Table 4).

When considered by all survey soils, the background concentrations of As, Cd and Hg from non-

Table 3. Trace elements in the Thailand soils sampled in this survey as subdivided by soil Orders (Soil Survey Staff (LDD) 1998).

Soil Order	EC (μS cm^{-1})	pH	C (%)	mg kg^{-1}									
				Available P	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn
All Thailand soils ($N = 318$)													
Mean	78	5.23	2.50	59.9	7.5	0.03	6.0	25.2	14.1	0.04	13.5	17.5	23.9
Median	49	5.02	1.96	14.9	2.7	0.01	2.8	15.3	6.9	0.03	6.2	9.0	14.0
Min	9	3.45	0.06	1.9	0.08	0.01	0.1	0.14	0.16	0.01	0.1	0.1	0.1
Max	1530	8.05	14.9	1260	124	1.3	113	295	350	0.27	270	550	140
Alfisols ($N = 30$)													
Mean	99	6.10	3.20	180	11.4	0.09	10.5	31.3	20.6	0.04	21.6	18.1	41.5
Min	19	4.17	0.57	3.0	0.5	0.01	0.3	5.0	2.4	0.01	0.1	1.4	5.0
Max	283	8.05	9.90	1195	103	0.40	37.1	93.0	72.0	0.17	80.0	56.7	110
Background	*53*	*5.98*	*1.88*	*24.9*	*1.9*	*0.01*	*7.5*	*16.8*	*7.6*	*0.02*	*14.7*	*11.0*	*30.6*
Alfisols (rice) ($N = 23$)													
Mean	130	5.31	1.92	47.8	4.9	0.05	5.7	23.1	13.9	0.03	13.7	18.6	30.8
Min	33	3.45	0.63	5.5	0.5	0.01	0.7	3.5	3.6	0.01	1.5	4.6	3.0
Max	1200	7.59	3.52	300	13.1	0.13	11.5	61.2	31.6	0.09	34.2	44.4	64.7
Entisols ($N = 8$)													
Mean	64	5.96	3.70	50.6	8.4	0.03	3.4	15.4	13.1	0.05	8.8	12.6	21.7
Min	28	4.33	1.05	2.5	0.3	0.01	0.3	0.8	1.3	0.01	0.6	1.8	2.9
Max	125	7.69	11.2	170	38.6	0.08	8.9	65.9	57.0	0.27	29.0	35.8	39.9
Inceptisols ($N = 10$)													
Mean	273	5.03	3.36	45.3	9.4	0.11	6.8	22.6	24.4	0.03	17.3	33.4	49.9
Min	30	3.93	0.71	8.8	0.6	0.01	0.4	2.0	0.9	0.01	2.1	2.5	3.2
Max	1530	6.03	8.02	200	17.2	0.26	12.2	40.5	100	0.05	31.3	64.0	105
Inceptisols (rice) ($N = 7$)													
Mean	94	5.38	2.34	68.4	15.0	0.10	12.6	57.1	32.6	0.04	39.8	39.2	53.4
Min	52	4.54	1.79	20.2	1.1	0.04	4.4	18.0	18.0	0.02	11.1	18.7	19.6
Max	228	6.67	3.22	201	29.1	0.15	21.3	160	41.2	0.07	112	67.8	75.0
Mollisols ($N = 6$)													
Mean	318	7.11	3.19	110	14.6	0.12	9.5	44.9	22.8	0.03	26.1	44.4	56.6
Min	110	6.20	2.21	7.9	2.6	0.01	5.9	27.8	9.9	0.02	15.5	14.5	36.3
Max	880	7.50	3.95	195	42.2	0.40	15.9	120	37.9	0.03	55.1	105	138
Oxisols ($N = 6$)													
Mean	63	4.99	3.31	419	3.0	0.04	14.4	31.8	45.4	0.11	18.0	12.3	27.2
Min	23	4.42	1.92	8.1	1.7	0.01	4.1	19.7	20.3	0.10	11.7	7.0	13.0
Max	118	5.62	4.44	1260	5.2	0.11	26.5	47.7	73.3	0.15	30.8	16.1	47.7
Ultisols ($N = 149$)													
Mean	52	5.17	2.52	36.5	7.5	0.04	5.4	25.0	11.7	0.03	11.9	14.7	17.6
Min	9	3.82	0.06	1.9	0.2	0.01	0.1	0.5	0.2	0.01	0.2	0.1	0.4
Max	330	7.77	12.9	575	124	1.3	113	295	350	0.18	270	550	125
Background ($N = 3$)	*28*	*4.66*	*1.29*	*7.8*	*1.5*	*0.01*	*0.6*	*3.4*	*2.3*	*0.01*	*1.7*	*4.9*	*3.6*
Ultisols (rice) ($N = 75$)													
Mean	61	4.76	1.96	30.7	5.4	0.03	4.1	20.1	9.8	0.02	9.6	17.1	18.2
Min	13	3.05	0.4	3.9	0.1	0.01	0.1	0.2	0.2	0.01	0.2	0.1	0.1
Max	408	6.69	10.9	188	92.4	0.20	17.1	110	65.9	0.22	44.1	79.6	72.9

agricultural areas were significantly lower than concentrations from the agricultural soils (ANOVA, F pr. < 0.001), while Co, Cr, Cu, Ni, Pb and Zn were not. However, the number of non-agricultural soil samples was limited due to the lack of non-agricultural sites in an agriculturally dominated Thailand society. This factor, and the large variability in elemental concentrations in the agricultural soils, is most likely to have contributed to the lack of significant difference for the latter elements. Nonetheless, the very high elemental concentrations reported in Table 3 would be indicative of heavy metal contamination of many agricultural soils in Thailand due to anthropogenic activity (possibly added in fertilisers, wastes, pesticides, effluents, contaminated surface irrigation waters or atmospheric sources).

Table 4. The 95% 'Investigation Levels' determined for Thailand ($n = 318$ soils).

Element	Investigation level ($mg\,kg^{-1}$)
As	30
Cd	0.15
Co	20
Cr	80
Cu	45
Hg	0.10
Ni	45
Pb	55
Zn	70

When considered by soil order (Soil Survey Staff (LDD) 1998) (Table 3), all soil Orders had heavy metal concentrations exceeding the background values (ANOVA, F pr. < 0.001). The most contaminated soils were the Inceptisols and Mollisols followed by the Alfisols, Entisols, and Oxisols, which represent 30% of the soils sampled, while the least contaminated were the Ultisols, which represent the remainder (ANOVA, F pr. < 0.001). While the Ultisols represent the majority of the agricultural soils in Thailand, the greater part of the crops grown on these soils were not high value crops or crops grown in poorer socio-economic regions, which may reflect lower fertiliser and organic waste input resulting in the lower concentrations of heavy metal contamination. Localised excessive addition of fertilisers as chemical, and organic and industrial effluents, the use of copper oxychloride as a pesticide (Tonmanee & Kanchanakool 1999) on particular high value crops, and the use of As contaminated surface waters are likely to have contributed to the high concentrations of heavy metals in many of these soils.

Regional distribution of soil characteristics

The range of soil fertility parameter values determined for each sampling region in Thailand is reported in Table 5. The high concentrations of soil organic C reflects the high use of composts and animal manures as fertilisers for vegetable production, while the high concentrations of available P are a reflection of high value vegetable, durian and fruit crops grown in these areas. The highest available P values were determined in the sandy/sandy loam soils and are likely to be a reflection of low clay, and hence low P binding characteristics of these soils.

Heavy metals in soils and crops

The available P data reported in Table 3 indicates that the majority of cultivated soils were not well fertilised with P, and the use of P fertilisers varied between regions (Table 5). The higher rates of P addition were in the high value vegetable, durian, and fruit crops and resulted in the concomitant increase in soil Cd and Zn (Table 3). Regression analysis resulted in highly significant relationships between the log of *aqua regia* soluble soil Cd (Figure 2, $R^2 = 0.475$, $p < 0.001$) and Zn (Figure 3, $R^2 = 0.676$, $p < 0.001$) versus log *aqua regia* soluble P concentrations. The non-transformed linear *aqua regia* soluble soil Cd versus *aqua regia* soluble P concentration regression confirmed the low background soil Cd concentrations and the addition of Cd as a contaminant of phosphatic fertilisers. The non-transformed curvilinear *aqua regia* soluble soil Zn versus *aqua regia* soluble P concentration regression is indicative of the variably high background Zn concentrations (soil P values below 1000 $mg\,kg^{-1}$) and the addition of Zn as a contaminant of phosphatic fertilizers (figures not shown).

Correlation analysis between the log of the *aqua regia* soluble heavy metal concentrations for 318 soils sampled (Table 6) showed a positive correlation with log of the *aqua regia* soluble P, Al and Fe, available P, and log % soil C. These correlations imply the addition of heavy metals with phosphatic fertilisers and organic soil amendments, and an association with indigenous clay minerals in the soil.

The PCA of the soil samples from Thailand (Figure 4) show that the first two principal components of 25 assessed account for 45.2% of the overall variability in the data (PC1 – 34.8% and PC2 – 10.4%). This indicates that *aqua regia* soluble soil As, Co, Cr, Cu, Hg, Ni, and Pb are highly correlated with soil Al and Fe, while *aqua regia* soluble soil Cd and Zn are highly correlated with soil organic C and P. Therefore, either soil contamination has not occurred due to agricultural activities and therefore these elements are associated with indigenous clay minerals in the soil, or that contamination has been associated with soils types that are higher in Al and Fe. This latter hypothesis is probable, as soils high in Al and Fe have high fertiliser P requirements, so that histories of P fertiliser addition, with associated impurities, are likely to be greater on these soils. However, *aqua regia* soluble and available P concentrations were not correlated with Al and Fe, lending weight to the argument that fertiliser addition to these soils was not generally high, and the

Table 5. Fertility characteristics of soils sampled in various regions of Thailand.

Region	Soil texture	pH	Organic C (%)	Available P (mg kg^{-1})	EC (dS m^{-1})
Central	Clay	3.93–7.16	1.48–8.0	8.80–199	0.06–1.50
Eastern	Sandy loam/sandy clay loam	3.45–7.77	0.20–5.3	3.05–1260	0.02–1.20
Lower northern	Loamy sand	4.17–6.84	0.38–10.3	5.84–133	0.02–0.12
Northern	Loamy sand/sandy loam	4.32–8.05	0.84–5.3	5.46–1200	0.04–0.28
Northeastern	Loam	3.64–7.63	0.06–5.6	5.35–58.1	0.02–0.41
Southern	Loam/clay loam	4.00–7.25	0.12–12.9	1.85–86.5	0.01–0.33

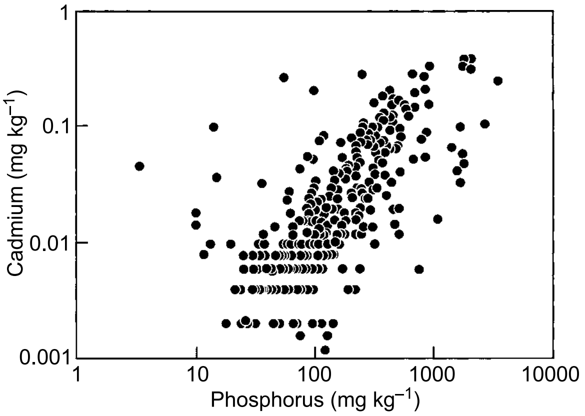


Fig. 2. Regression ($\log Cd = \log(0.8047 \times P) + \log(-3.4406)$) of log *aqua regia* soluble cadmium versus log *aqua regia* soluble phosphorus for the Thailand soils sampled in this survey ($R^2 = 0.475$, $p < 0.001$).

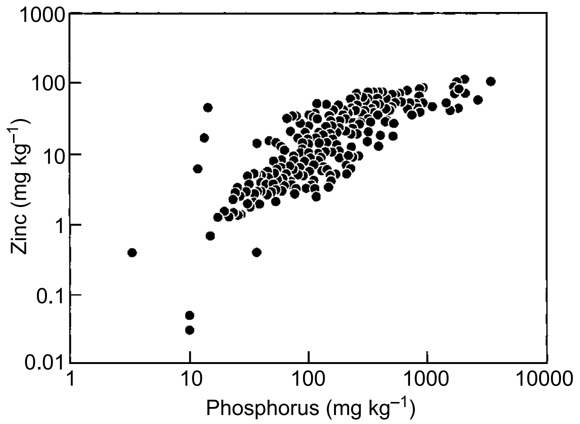


Fig. 3. Regression ($\log Zn = \log(0.9475 \times P) + \log(-0.9243)$) of log *aqua regia* soluble zinc versus log *aqua regia* soluble phosphorus for the Thailand soils sampled in this survey ($R^2 = 0.676$, $p < 0.001$).

association of As, Co, Cr, Cu, Hg, Ni, and Pb with Al and Fe concentrations was related to variations in background mineralogy. However, concentrations of Cd and Zn were enriched in many agricultural soils and were associated with soil organic matter and *aqua regia* soluble and available P, which suggests sources related to agricultural inputs.

Arsenic

The concentration of As in plant edible portions was below the Australian ML and the Thailand MPC (Table 1) for all crops except for the maximum concentrations in rice and groundnut. This is indicative of the low bioavailability of As in the soil resulting in a low transfer coefficient of As to the plant tissue (Smith *et al.* 1998). The highest soil As concentrations (ANOVA, F pr. < 0.001) occurred on those growing cabbage, corn, rice and rubber (Table 7). The rubber plantation soils were sampled in the southern region in an area with known high concentrations of As in the groundwater and alluvial soil due to the presence of arsenopyrite (Williams *et al.* 1996). The soils growing cabbage, corn and rice were sampled in the northern region, but the reason for the high concentration of soil As is not known. Using the Dutch target value (Lamé & Leenaers 1998) for soil protection and the Australian EIL (NEPM 1999) (Table 2) a large number of agricultural soils (Table 3) would be classified as contaminated due to high As concentrations.

Cadmium

Cadmium, added to the soil as an impurity of phosphatic fertiliser, is the heavy metal of most concern in soil amendments, as its transfer from soil to the edible portions of agricultural food crops is significantly greater than for other contaminant elements (McLaughlin *et al.* 1996). High concentrations of Cd occurred in the alluvial soils of the Mekong river basin (northeastern region) used for high value vegetable production (ANOVA, F pr. < 0.001). There is currently no Thai MPC for Cd in food. Groundnut and rice (Table 7) had the highest Cd concentrations of the crops sampled (ANOVA, F pr. < 0.001), and exceed the Australian ML (Table 1). Using the Dutch

Table 6. Correlation (r) matrix of the log of soil fertility parameters and the of log *aqua regia* soluble metal in the Thailand soils sampled in this survey, $N = 318$.

	Log Available P	log % C	log Al	log As	log Cd	log Co	log Cr	log Cu	log Fe	log Hg	log Ni	log P	log Pb	log Zn
log Available P	1													
log % C	*0.175*	1												
log Al	*0.191*	0.566	1											
log As	*0.159*	*0.531*	*0.581*	1										
log Cd	*0.518*	*0.424*	*0.494*	0.515	1									
log Co	*0.319*	*0.424*	*0.697*	0.492	0.614	1								
log Cr	*0.228*	*0.378*	*0.694*	0.465	0.434	0.753	1							
log Cu	*0.397*	*0.505*	*0.784*	0.616	0.646	0.847	0.783	1						
log Fe	*0.251*	*0.544*	0.811	*0.694*	*0.565*	*0.831*	*0.800*	*0.856*	1					
log Hg	*0.143*	*0.596*	*0.665*	0.590	0.494	0.427	0.366	0.569	*0.578*	1				
log Ni	*0.315*	*0.526*	*0.799*	0.591	0.632	0.860	0.807	0.864	*0.844*	0.571	1			
log P	0.671	*0.497*	*0.655*	*0.613*	*0.678*	*0.672*	*0.598*	*0.787*	*0.730*	*0.520*	*0.713*	1		
log Pb	*0.046*	*0.422*	*0.720*	0.679	0.626	0.662	0.563	0.718	*0.702*	0.565	0.704	*0.665*	1	
log Zn	*0.522*	*0.412*	*0.781*	0.646	0.710	0.798	0.713	0.872	*0.818*	0.567	0.847	*0.814*	0.835	1

Significant at the 0.05 probability level when $r \geq 0.113$.
Significant at the 0.01 probability level when $r \geq 0.161$.
Significant at the 0.001 probability level when $r \geq 0.188$.
Italic values denote significant correlations between environmentally important parameters.

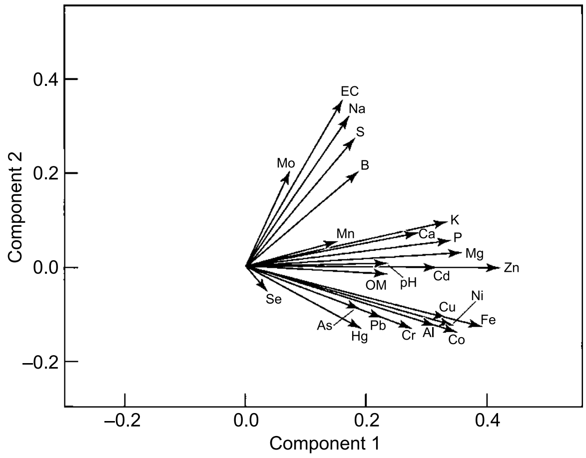


Fig. 4. PCA of the heavy metal and fertility parameters for the Thailand soils sampled in this survey.

target value for soil protection and the Australian EIL (Table 2), only one agricultural soil (Table 3) could be considered as contaminated with Cd.

Chromium

Soils from the northeast region were generally low in Cr while soils high in Cr were lateritic having a heavy texture. Chromium III is considered an essential nutrient in animal based agricultural systems while CrVI has been shown to be carcinogenic (Bagchi *et al.* 2002). There are no international guideline values for Cr in foods. Groundnut and rice (Table 7) had the highest Cr concentrations of the crops sampled (ANOVA, F pr. < 0.001). The majority of agricultural soils (Table 3) were below the Dutch target value for soil protection and the Australian EIL (Table 2).

Copper, nickel, lead and zinc

Maximum concentrations of Cu in groundnut (Table 7), although below the Thai MPC of 20 mg kg^{-1}, would violate the 10 mg kg^{-1} limit used in many other countries. Lead concentrations in all crops were generally low except for groundnut, which exceeded the Thai and Australian MPC (Table 1). Concentrations of Ni were low in all crops, and no crop exceeded the Thai MPC for Zn. Peanuts had significantly more Cu, Ni, Pb and Zn than rice, and both crops were significantly higher in these heavy metals than all other crops sampled (ANOVA, F pr. < 0.001). For Cu, the majority of agricultural soils (Table 3) were below the Dutch target value for soil protection and the Australian EIL (Table 2), except for the soils growing high value crops (Table 7). Conversely, for Ni and Pb, many soils exceeded the Dutch target value for soil protection and the Australian EIL.

Mercury

Mercury concentrations in the cultivated soils were generally higher than the background soils (forested and uncultivated) indicating the widespread contamination by Hg across all crop types and agricultural regions (Table 3). The highest concentrations of Hg were in the rubber plantation soils sampled in the south of Thailand (ANOVA, F pr. < 0.001). Although this area is known to have high As in soils and plants due to arsenopyrite in the groundwater, it is not known if Hg is associated with arsenopyrite. Mercury concentrations of crops were generally low except for rice and groundnut (Table 7) (ANOVA, F pr. < 0.001). A high Hg concentration in a corn crop soil however, did not translate into an elevated Hg concentration in the corn kernels (Table 7). Maximum concentrations of Hg in rice exceeded the Thai (0.02 mg kg^{-1}) MPC while the maximum concentrations of Hg in groundnut exceeded the Australian ML (Table 1). These occurred in samples taken in the northeast region of Thailand. The source of this Hg contamination is unknown. All soils were below the Dutch target value for soil protection and the Australian EIL (Table 2).

Heavy metal distribution in a long-term fertiliser trial soil profile

Arsenic, chromium and nickel

Soil As values did not differ between the treatments indicating As to be present as a component of the soil matrix, increasing in concentration with depth (data not shown). Chromium and Ni concentrations were elevated in the surface stratum (0–10 cm) of soils fertilised with compost, and unchanged in control and mineral-fertilised soils (data not shown). This implies Cr and Ni are present as components of the soil matrix and added to the soil as a contaminant of the compost only in the cultivated 0–10 cm soil stratum.

Cadmium, copper, mercury, lead and zinc

Cadmium, Cu, Hg, Pb and Zn concentrations were elevated in the 0–30 cm strata of the compost-fertilised soil, and remained unchanged in the 0–30 cm strata of the control and the NPK mineral-fertilised soils (Figure 5). The concentrations of these metals were very much higher in the compost-amended soil than the fertiliser and control treatments, indicating that these heavy metals were added as contaminants in the

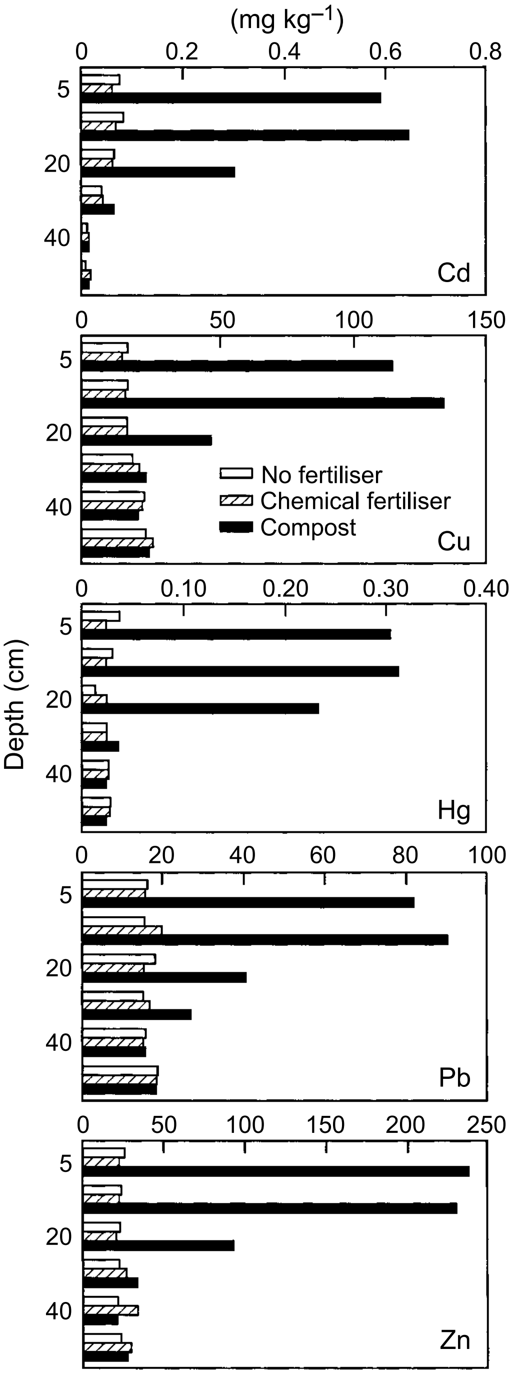
Table 7. Trace element distribution (mg kg^{-1} except Hg plant μg kg^{-1}) in soils and corresponding crops of Thailand.

Plant	As		Cd		Cr		Cu		Hg		Ni		Pb		Zn	
	Soil	Plant	Soil	Plant	Soil	Plant	Soil	Plant	Soil	Plant	Soil	Plant	Soil	Plant	Soil	Plant
Background ($N=4$)																
Mean	1.8		0.007		7.5		3.7		0.011		5.3		7.3		11.3	
Min	0.85		0.002		3.6		1.7		0.005		1.8		3.1		3.6	
Max	2.7		0.012		16.8		7.6		0.019		14.7		11.4		30.6	
Cabbage ($N=7$)																
Mean	36.4	0.083	0.39	0.01	46.1	0.04	204	0.3	0.09	0.4	55	0.08	283	0.02	110	1.4
Min	3	0.06	0.01	0.003	28.1	0.01	59	0.1	0.03	0.2	43.8	0.02	15.5	0.01	94.8	1.1
Max	69.8	0.16	0.76	0.02	64	0.07	348	0.4	0.14	0.3	68.2	0.2	550	0.04	125	2.1
Cassava ($N=25$)																
Mean	2	<0.04	0.02	0.0003	32.4	0.02	8	0.1	0.02	0.1	13.7	0.19	4.7	0.01	15.1	0.44
Min	0.5	<0.04	0.002	0.0001	2.9	0.01	1.2	0.07	0.003	0.06	0.35	0.11	0.9	0.01	1.9	0.35
Max	13.3	<0.04	0.08	0.0004	199	0.03	49.6	0.13	0.06	0.2	117	0.27	17.1	0.02	68.6	0.57
Corn ($N=19$)																
Mean	10.5	<0.04	0.07	0.0004	70	0.02	19.4	0.16	0.03	0.2	37.6	0.07	14.8	0.01	34.5	1.9
Min	0.5	<0.04	0.004	0.0001	1.6	0.01	1.73	0.1	0.001	0.1	0.63	0.05	1.5	0.01	2.9	1.3
Max	108	<0.04	0.29	0.002	295	0.04	50	0.2	0.063	0.4	270	0.09	63.8	0.01	71.9	3.2
Durian ($N=13$)																
Mean	4.8	N.S.	0.03	N.S.	22	N.S.	28.9	N.S.	0.09	N.S.	13.3	N.S.	10.1	N.S.	23.4	
Min	1.3		0.002		3		4.3		0.01		0.6		3		3.1	
Max	23.4		0.11		47.7		73.3		0.153		30.8		16.1		47.7	
Groundnut ($N=37$)																
Mean	N.S.	2.2	N.S.	0.06	N.S.	0.2	N.S.	8	N.S.	4.8	N.S.	8.8	N.S.	0.16	N.S.	42.7
Min		0.35		0.004		0.01		3.6		1		3.8		0.01		29.8
Max		3.85		0.3		0.4		13.2		10		20.6		2.4		64.5
Longan ($N=6$)																
Mean	8	N.S.	0.13	N.S.	21.9	N.S.	17.3	N.S.	0.03	N.S.	17.5	N.S.	29.2	N.S.	52.6	N.S.
Min	4.5		0.03		19.3		14.2		0.01		12.1		8		28	
Max	12.6		0.28		28.6		22.4		0.08		21.3		42.6		75.3	
Oil palm ($N=11$)																
Mean	6.1	N.S.	0.011	N.S.	7	N.S.	2.1	N.S.	0.021	N.S.	2.5	N.S.	7.2	N.S.	6.2	N.S.
Min	0.5		0.004		0.5		0.21		0.013		0.15		0.5		0.4	
Max	28.2		0.032		17.7		4.5		0.036		5.4		23.5		14.9	
Pineapple ($N=4$)																
Mean	12.1	N.S.	0.023	N.S.	11.6	N.S.	8.1	N.S.	0.046	N.S.	5.8	N.S.	14	N.S.	11.1	N.S.
Min	0.5		0.01		0.8		0.58		0.014		0.2		0.6		0.7	
Max	46.2		0.038		28.9		25.3		0.072		17.6		29.2		28.8	
Rice ($N=108$)																
Mean	6.4	<1	0.04	0.05	24.6	0.7	12.1	2	0.03	4.8	12.7	1.7	19.9	0.11	23.8	22.8
Min	0.5	<1	0.002	0.002	0.15	0.1	0.15	0.8	0.003	3.6	0.2	0.1	0.5	0.01	0.5	15.8
Max	92	<1	0.4	0.3	159	2.7	65.9	5.1	0.22	22.3	112	3.6	105	0.55	138	31.1
Rubber ($N=50$)																
Mean	11.3	N.S.	0.019	N.S.	18.6	N.S.	9.1	N.S.	0.053	N.S.	8.1	N.S.	14.3	N.S.	15.9	N.S.
Min	0.5		0.001		1.3		0.6		0.011		0.7		0.5		2	
Max	124		0.167		185		66.8		0.268		47		124		49.7	
Sugar cane ($N=25$)																
Mean	3.5	N.S.	0.05	N.S.	15.5	N.S.	10.9	N.S.	0.027	N.S.	8.8	N.S.	13.7	N.S.	20.4	N.S.
Min	0.5		0.004		1.6		1.2		0.002		0.5		0.5		2.1	
Max	15.2		0.279		40.5		40.9		0.1		33.4		91.2		73.4	
Sweet potato ($N=4$)																
Mean	1.5	N.S.	0.024	N.S.	8.8	N.S.	8.8	N.S.	0.05	N.S.	5.5	N.S.	6.3	N.S.	20.5	N.S.
Min	0.5		0.004		4.2		2		0.016		2.1		4.7		4	
Max	2.3		0.068		15.2		19.2		0.129		8.4		8.2		52.5	
Tamarind ($N=5$)																
Mean	21.3	N.S.	0.045	N.S.	40.4	N.S.	18.9	N.S.	0.029	N.S.	19.6	N.S.	15.5	N.S.	31.3	N.S.
Min	3.6		0.024		14.8		11.9		0.011		6		5.9		23.7	
Max	51.8		0.062		93		29.3		0.049		34.2		26		40.6	

Table 7. (continued)

Plant	As		Cd		Cr		Cu		Hg		Ni		Pb		Zn	
	Soil	Plant	Soil	Plant	Soil	Plant	Soil	Plant	Soil	Plant	Soil	Plant	Soil	Plant	Soil	Plant
Yard long bean ($N = 5$)																
Mean	4.5	<0.04	0.053	0.01	19.3	0.03	13.2	0.50	0.019	5.7	11.4	3.9	16.4	0.028	26.3	1.9
Min	0.6	<0.04	0.006	0.01	6.5	0.02	2.8	0.42	0.006	5.1	1.1	2.3	1.6	0.002	3.4	1.8
Max	11.7	<0.04	0.174	0.01	33.5	0.03	30.5	0.58	0.052	6.2	31.3	5.6	49.9	0.55	69.2	2.2

N.S. = not sampled.



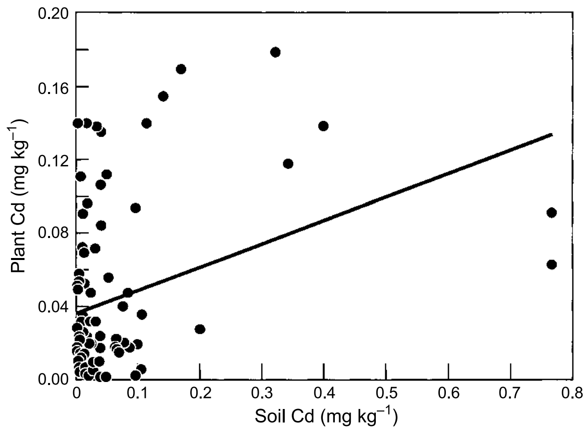


Fig. 6. Regression (Plant Cd = 0.1407 × Soil Cd + 0.04) of plant Cd versus *aqua regia* soluble soil Cd for the Thailand plants sampled in this survey ($R^2 = 0.081$, $p < 0.010$).

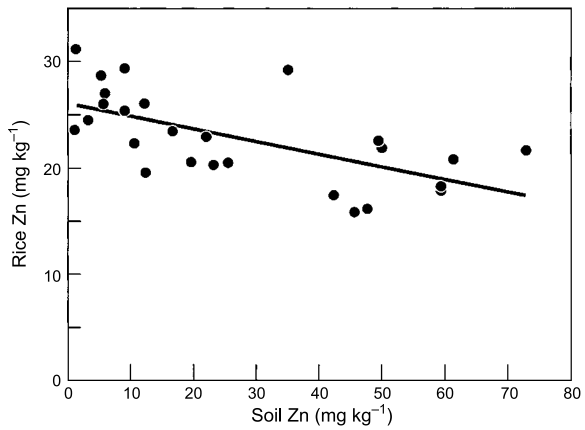


Fig. 7. Regression (Rice Zn = −0.1165 × Soil Zn + 26.0) of rice Zn versus *aqua regia* soluble soil Zn ($R^2 = 0.385$, $p < 0.001$).

←

Fig. 5. Concentrations of cadmium, copper, mercury, lead and zinc (mg kg^{-1}) in the strata of an unfertilised soil, and soils fertilised with industrial compost and chemical fertilisers.

compost but were not present in these particular chemical fertilisers. The fertiliser results are surprising, as some degree of metal contamination of the soil would be expected using chemical fertilisers. However, the main source of fertiliser-derived contaminants in soils is from phosphatic fertilisers, primarily due to impurities in the phosphate rock used for fertiliser manufacture (McLaughlin *et al.* 1996). The chemical fertilisers used in these trials were urea/potash/di and tri-ammonium phosphate blends known to be low in contaminates (Zarcinas & Nable 1992). As the organic matter associated with the addition of compost is immobile and confined to the 0–10 cm cultivation layer (data not shown), elevated concentrations of these metals down the soil profile to 30 cm is indicative of the mobility of a proportion of these metals. This would imply that the metals in the compost were present as a mixture of organically bound and ionic species. As the ionic species of metals are readily phyto- and bioavailable, they would therefore pose a substantial risk to food contamination and be present as toxic heavy metals to soil microorganisms. In addition, decomposition of the organic matter may render the organically bound species of heavy metals phytoavailable to plants and bioavailable to soil microorganisms.

Relationships between heavy metals in soils and plants

Generally, total heavy metal concentrations in a soil are poor predictors of heavy metal bioavailability. Simple regression analysis between edible plant part metal concentrations and the *aqua regia* soluble soil As, Cd, Cr, Cu, Hg, Ni, Pb and Zn concentrations indicated a weak but positive relationship of Cd in all plants sampled in the survey with *aqua regia* soluble soil Cd (Figure 6, $R^2 = 0.081$, $p < 0.001$), and of rice Cd with *aqua regia* soluble soil Cd (data not shown, $R^2 = 0.242$, $p < 0.010$). However, there were negative relationships of rice Zn with *aqua regia* soluble soil Zn (Figure 7, $R^2 = 0.385$, $p < 0.001$), of glutinous rice Cu with *aqua regia* soluble soil Cu (data not shown, $R^2 = 0.355$, $p < 0.001$), and of glutinous rice Zn with *aqua regia* soluble soil Zn (data not shown, $R^2 = 0.122$, $p < 0.03$). The positive relationship between all edible plant parts Cd sampled in the survey and rice (but not glutinous rice) and *aqua regia* soluble soil Cd indicates the high bioavailability of Cd in these tropical, generally acidic soils. The negative relationship between rice Zn and *aqua regia* soluble soil Zn, and between glutinous rice Cu and Zn and *aqua regia* soluble soil Cu and Zn is not fully understood.

Conclusions

We suggest that the 95th percentile heavy metal concentrations can be used as ‘Investigation Levels’ for metals in soils of Thailand. The concentration ranges (minimum up to 95th percentile) for all Thailand topsoils sampled were As (0.08–29.0), Cd (0.01–0.17), Co (0.10–21.1), Cr (0.14–79.4), Cu (0.16–43.6), Hg (0.01–0.10), Ni (0.10–43.9), Pb (0.10–54.6) and Zn (0.10–71.0) mg kg^{-1}. Soils with element concentrations above these investigation concentrations are likely to have been contaminated to a significant extent due to the addition of metals in fertilisers, wastes, pesticides, effluents and/or atmospheric sources. These values should be used to trigger further investigation of the reasons/sources for the contamination of the soil and an assessment made of the potential risks to humans or the environment if the contamination continues.

Arsenic, Co, Cr, Cu, Ni, and Pb were highly correlated with soil Al and Fe indicating either that these metals are intrinsically present in the soil matrix, or that contamination has been associated with soils types that are higher in Al and Fe. Soils high in Al and Fe have high fertiliser P requirements (with addition of associated impurities), yet the survey soil P concentrations were not correlated with Al and Fe, implying low fertiliser addition to these soils, and therefore indicating an association of these heavy metals with the background soil matrix mineralogy. Cadmium and Zn were highly correlated with organic matter and soil P, suggesting these metals are added either as intrinsic components of organic matter or contaminants in phosphatic fertilisers, or both.

Heavy metals in soils sampled from different regions of Thailand varied widely in concentration due to differences in soil characteristics resulting from the different characteristics of the soil parent materials. Groundnut, rice and glutinous rice had elevated concentrations of all the metals assessed when compared to the total of the plants sampled.

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ORIGINAL ARTICLE

Effects of rainy season on mobilization of contaminants from tsunami deposits left in a coastal zone of Thailand by the 26 December 2004 tsunami

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Abstract Study on contamination of tsunami sediments deposited on 26 December 2004 conducted shortly after the tsunami in coastal zone of Thailand revealed elevated contents of salts in water-soluble and some heavy metals and arsenic in bioavailable fractions (Szczuciński et al. in Env Geol 49:321–331, 2005). Few months later rainy season started and effected in total rainfall of over 3,300 mm. This paper presents results of survey repeated 1 year after the tsunami. To assess the effects of rainy season on mobilization of previously determined potential contaminants, the same locations were sampled again and analysed with the same methods. The tsunami deposit layer was well preserved but in many locations the sediments were coarser than just after tsunami due to washing out of finer fractions. The water-soluble salts contents were strongly reduced after the rainy season. However, the concentrations of acid leachable heavy metals and metalloids were still elevated in comparison to reference sample from an area not impacted by tsunami. It is possible that the metals and metalloids are successively moved to more bioavailable fraction from forms which were more resistant to mobilization.

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Keywords Tsunami deposits · Contamination · Bioavailable fraction · Coastal hazard · Thailand

Introduction

The large tsunami, which was generated by an earthquake on 26 December 2004, affected most of the countries around the Indian Ocean and was claimed to be one of the world's worst natural disasters in decades. Various aspects of its direct and indirect impacts were reported including medical, sociological, engineering, environmental and geological effects (e.g. Danielsen et al. 2005; Rigg et al. 2005; Ghobarah et al. 2006; Goff et al. 2006; Kench et al. 2006; Morgan et al. 2006; Mruthyunjaya Reddy et al. 2006; Satake et al. 2006; Babu et al. 2007). One of important consequences of the tsunami was deposition of sediment layer on the inundated coastal land areas. These sediments were reported to be rich in salts and other pollutants and buried the former soil horizon (UNEP 2005; Szczuciński et al. 2005, 2006; Boszke et al. 2006; Chaudhary et al. 2006). The tsunami deposits layer may present a long-term threat because accumulated salts and contaminants might be released to ground waters and plants in period of several years.

Thailand belongs to one of the most tsunami-affected countries where about 20,300 ha of land were covered by seawater (UNEP 2005). The tsunami reached in places more that 1.5 km inland (Bell et al. 2005; Siripong 2006; Szczuciński et al. 2006) and its maximum runup was about 15 m (Siripong 2006) but usually it was less than 10 m (Bell et al. 2005; Choi et al. 2006; Siripong 2006; Szczuciński et al. 2006; Thanawood et al. 2006; Tsuji et al. 2006). Most of the inundated area was blanket with a few to several tens of centimetres thick layer of tsunami sediments (Bishop et al. 2005; Szczuciński et al. 2005, 2006) with maximum values of more than 0.5 m. These sediments are composed mainly of silty sand and sand and in distance of 500 m and more from the shoreline they generally do not exceed thickness of 2 cm (Szczuciński et al. 2006). Shortly after the tsunami samples were collected from the tsunami deposits and also from soils not covered by the tsunami (Szczuciński et al. 2005). There was no rainfall between the tsunami and the sampling survey, so the chemical composition was not altered by washing. The analysis revealed that the tsunami deposits have elevated contents of salts (Na^+, K^+, Ca^{+2}, Mg^{+2}, Cl^-, SO_4^{-2}) in water-soluble fraction, heavy metals (Cd, Cu, Pb, Zn) in acid leachable fraction (assumed to be bioavailable), and arsenic in the exchangeable fraction in relation to the reference sample taken from soil of similar grain size composition but not covered by the tsunami (Szczuciński et al. 2005). For the same set of samples also mercury fractionation was performed (Boszke et al. 2006) and it was found that although the difference in the total mercury content are very small, the highly toxic organomercury fraction contribution is higher in the tsunami deposits. Several months after the tsunami rainy season started and total precipitation during that period reached more than 3,300 mm as measured at Phang Nga province meteorological station (Szczuciński et al. 2006). The same sampling locations as studied in 2005 were revisited one year after the tsunami and the tsunami deposits were found to be almost not altered in regard of thickness and spatial distribution (Szczuciński et al. 2006). This study repeats the same analysis as immediately after the tsunami (Szczuciński et al. 2005) to assess the effects of the rainy season on mobilization of contaminants from those deposits. Additionally analysis of arsenic in fractions of varying bioavailability were performed on samples from both: 2005 and 2006 field campaign.

The major objective of our study is to assess long-term impact of tsunami on coastal environment by analysis of effects of rainy season on mobilization of salts and bioavailable (acid leachable and exchangeable fractions) heavy metals and metalloids from tsunami deposits left on land. In the study also usefulness of salt content as a proxy of paleotsunami deposits recognition and preservation potential of the tsunami deposit layers will be discussed.

Material and analytical techniques

Samples were collected from the area flooded on the 26 December 2004 tsunami during field campaign conducted in February 2006. In most cases, the sampling locations (Fig. 1 and Table 1) were identical with those from the previous survey (Szczuciński et al. 2005). Only in the cases where tsunami deposit layer was removed (usually due to cleaning actions) or if it was not possible to approach the former locations, the samples were collected from nearby region (see Table 1) covered with similar tsunami sediments and being in approximately the same distance from the shoreline. The entire tsunami sediments layer was sampled unless it was thicker than 5 cm. Otherwise only the uppermost few centimetres thick layer was collected. One additional sample (16) was taken for reference from an area out of reach of the tsunami wave. Samples were collected using plastic tools and packed into polyethylene bags. Collected samples were affected by UV irradiation (field lamp with antibacterial fluorescent light by Philips) in order to limit biological activity after the sampling. They were transported within 2 weeks to laboratories. They were divided into subsamples for sedimentological and chemical analysis.

To determine grain size distribution, the subsamples were dried and sieved into 13, 0.5-phi interval, grain size fractions ranging from gravel to mud. Salts contained in water-soluble fraction of the samples were determined by standard titration method (Greenberg et al 1992). A water extract was obtained from 1 g of sample treated for 24 h with 100 ml of deionized water. In the prepared extracts: Na, K, Ca, Mg, Cl and SO_4 were measured. The accuracy of measurements was tested by ion balance. Heavy metals (Cd, Cr, Cu, Ni, Pb and Zn) were analysed from extracts obtained by 1-h extraction with 2 mol HCl in 80°C. In this way all the metals, which are potentially bioavailable were separated. The metals were measured with AAS spectrometer in flame mode. The limits of determination were 0.06, 0.22, 0.04, 0.05, 0.5 and 0.14 (mg kg^{-1}) for Cu, Pb, Cd, Zn, Ni and Cr, respectively. Metalloids: As, Se and Sb, were measured in solution extracted by phosphate buffer (concentration of PO_4 about 50 mmol l^{-1} and pH around 6.0) in 80°C for 1 h. Such an extraction is believed to release exchangeable fraction of the metalloids (Orero Iserte et al. 2004). For As determination in the samples analysed in this study and also for those collected in 2005 (the same as presented by Szczuciński et al. 2005) the acid extraction following the procedure of heavy metals bioavailable fraction analysis was additionally performed. Concentrations of metalloids were measured with HG AAS equipment (220FS spectrometer by SpectrAA) with hydride generation unit VGA-77 (Varian). The determination limits were 15 μg kg^{-1}

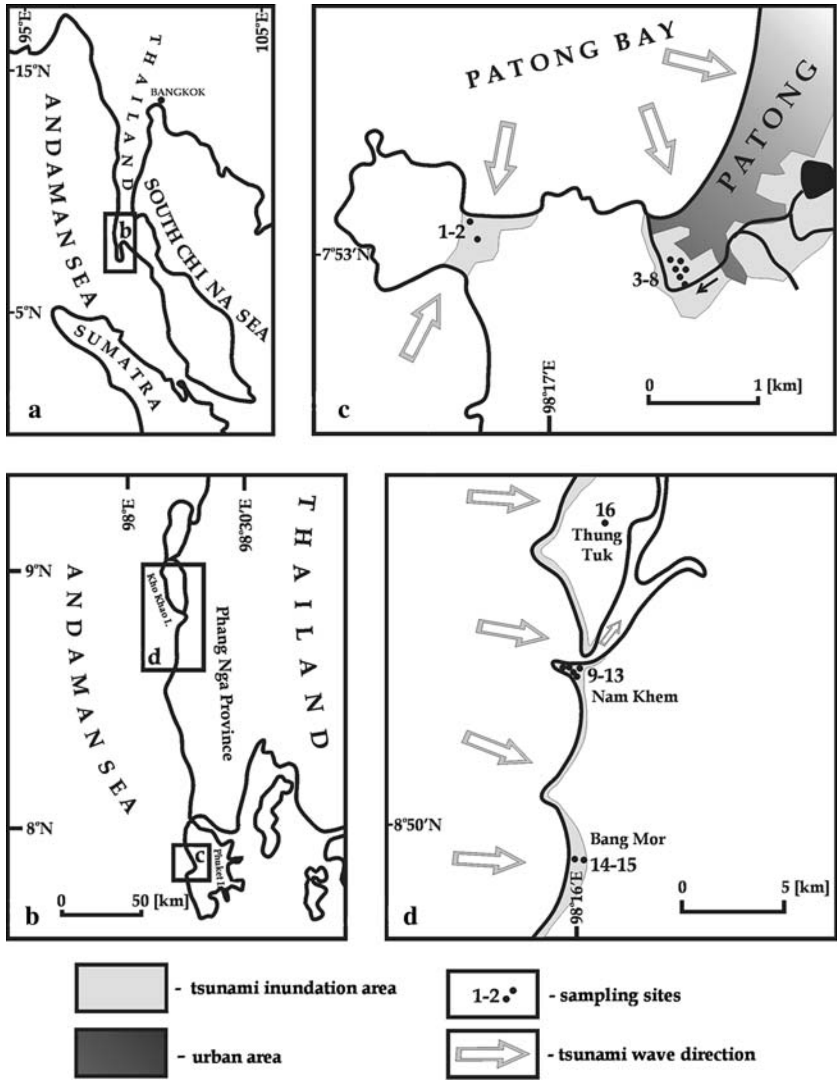

Fig. 1 Study area and sampling sites locations (after Szczuciński et al. 2005)

for all the determined metalloids and the uncertainty below 10%.

Sampling sites

Sampling sites were located in a range of settings representing variable morphology, degree of tsunami damages and pre-tsunami human impact (Fig. 1 and Table 1). Samples 1 and 2 were collected on a narrow isthmus on peninsula, which encompass the southern edge of Patong Bay. Both samples were taken from local small depressions/ponds. The location 2 was subjected to flashing by wastewater. Samples 3–8 were taken from a low-lying terrain, adjacent to a small river in the southern part of Patong city. In a village Nam Khem, which was largely damaged, samples 9–13 were collected. Samples 14 and 15 were collected in tsunami inundated zone in a vicinity of Bang Mor village, and sample 16 was taken as a reference sample from area not inundated by the tsunami in a neighbourhood of Thung Tuk village.

Results

Sediment characteristic

Tsunami deposits at the studied locations are in the form of few centimetres to few tens of centimetres thick, sheet of fine and medium sand. The layer usually resolves upward fining of grain size (in 1–3 sequences). They are generally poorly sorted (Fig. 2) and their mean grain size varies between coarse silt and coarse sand (Table 1). However, most of the samples are in the range of very coarse silt to medium sand. The

Table 1 Sampling locations including distance from the shoreline and calculated distance to the locations of sampling sites from the previous survey in 2005

Sample	Location	Latitude N	Longitude E	Distance from shoreline (m)	Distance to 2005 sampling location (according to GPS coordinates) (m)	Sediment mean grain size (according to method by Folk and Ward 1957)
1	Patong Bay	7°53.088′	98°16.443′	75	13	Medium sand
2	Patong Bay	7°53.014′	98°16.435′	315	17	Very coarse silt
3	Patong	7°52.924′	98°17.309′	430	108	Medium sand
4	Patong	7°52.910′	98°17.320′	480	24	Medium sand
5	Patong	7°52.887′	98°17.328′	520	11	Medium sand
6	Patong	7°52.864′	98°17.349′	545	41	Medium sand
7	Patong	7°52.953′	98°17.328′	390	96	Coarse sand
8	Patong	7°52.938′	98°17.336′	410	13	Fine sand
9	Nam Khem	8°51.470′	98°15.930′	60	19	Very fine sand
10	Nam Khem	8°51.417′	98°15.953′	100	325	Coarse silt
11	Nam Khem	8°51.405′	98°16.310′	570	40	Very coarse silt
12	Nam Khem	8°51.553′	98°15.940′	50	304	Very fine sand
13	Nam Khem	8°51.618′	98°16.527′	1,100	6	Very find sand
14	Bang Mor	8°49.973′	98°16.128′	300	72	Very find sand
15	Bang Mor	8°49.907′	98°16.271′	590	172	Very coarse silt
16	Thung Tuk	8°53.766′	98°16.694′	1,500	0	Medium sand

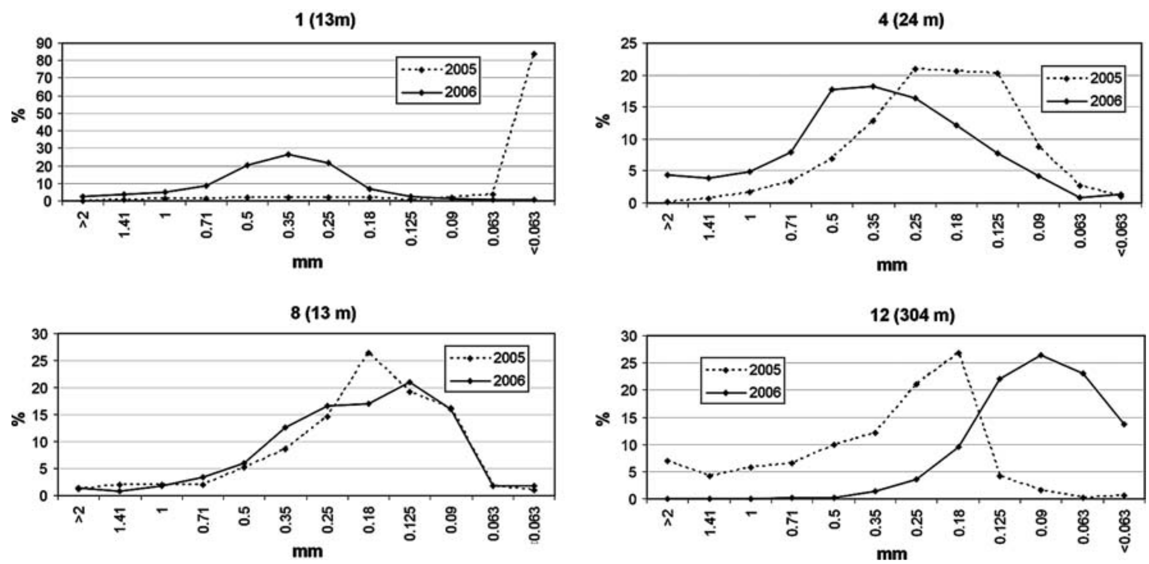

Fig. 2 Examples of grain size distribution for four representative locations sampled in 2005 and in 2006. After the site sampling number, a GPS-based distances between coordinates of the locations in particular years are given (in *brackets*)

samples collected from river valley in Patong town area are generally coarser (medium and coarse sand) than the remaining.

Salts in water-soluble fraction of sediments

Concentrations of major ions determined in water-soluble fraction are reported in Table 2. For all the analyzed samples contents of K and Mg were higher in the tsunami deposits than in the reference sample (16). Except samples 2 (1,300 mg kg^{-1}) and 8 (180 mg kg^{-1}), the K content is in range of 21–85 mg kg^{-1}. Also in regard to concentration of Mg in water-soluble fraction, the samples 2 and 8 are outstanding with values of 2,100 and 450 mg kg^{-1}, respectively. The range of Mg content for the rest of samples is from 5 to 250 mg kg^{-1}. In the case of Ca, only sample 6 (18 mg kg^{-1}) had lower concentrations than the reference one (56 mg kg^{-1}). Most of the samples had Ca content between 130 and 1,600 mg kg^{-1}. Maximum values are again in samples 2 and 8, 1,800 and 6,800 mg kg^{-1}, respectively. Contents of SO_4 were at the lowest level

Table 2 Contents of salts (K, Na, Ca, Mg, Cl, SO_4) leached with deionized water in mg kg^{-1} of dry mass

Sample	K (mg kg^{-1})	Na (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Cl (mg kg^{-1})	SO_4 (mg kg^{-1})
1	85	58	370	92	300	300
2	1,300	26,000	6,800	2,100	34,000	35,000
3	74	147	1,100	78	700	800
4	77	1,200	130	120	2,000	600
5	80	130	210	57	300	200
6	55	85	18	19	300	50
7	61	1,000	340	160	1,700	220
8	180	3,700	1,800	450	8,000	3,400
9	23	95	420	40	200	50
10	35	100	1,300	51	300	50
11	85	1,100	690	200	900	1,300
12	46	98	818	94	1,000	50
13	67	718	793	184	960	820
14	71	260	1,400	250	960	1,100
15	33	110	1,600	75	900	500
16	21	280	56	5	400	50

(50 mg kg^{-1}) in samples 6, 9, 10, 12 and 16 (the reference). Maximum values were measured in samples 2 (350,000) and 8 (3,400), and in the remaining samples they are in range of 200–1,300 mg kg^{-1}. Concentrations of Na and Cl were lower than in the reference samples in samples: 1, 3, 5, 6, 9, 10, 12 and 14 for Na and in 1, 5, 6, 9 and 10 for Cl, respectively. In the remaining samples concentrations of these ions were higher (in the sample 2 significantly higher) than in the reference sample. The ranges of measured values were for Na from 58 to 26,000 and for Cl from 300 to 3,4000 mg kg^{-1}. Among the analysed samples, three are particularly outstanding the sample 2, 8 and 6. The first two are characterized by several times higher values of the studied ions and the last by the lowest values.

Heavy metals in acid leachable fraction of sediments

Following elements were analysed among the heavy metals: Cd, Cr, Cu, Ni, Pb and Zn. The obtained results are listed in Table 3. The concentrations of these metals in acid leachable fraction of tsunami deposits were in almost all cases much higher than in the reference sample (16).

Concentrations of Cd in tsunami deposits is generally several times higher than in the reference sample (0.44 mg kg^{-1}), except sample 4, where very low value of Cd (0.07 mg kg^{-1}) was measured. The remaining samples have concentrations in range of 0.46–2.8 mg kg^{-1}, and only in sample 14 extraordinary high value of 13.3 mg kg^{-1} was measured. Cr had higher concentrations in all the analyzed tsunami deposits samples than in the reference one (0.73 mg kg^{-1}) and are in the range of 0.89 mg kg^{-1} for sample 7 to 8.6 mg kg^{-1} for sample 2. The lowest concentration of Cu was found in sample 4 (0.95 mg kg^{-1}) and in the reference sample (1.2 mg kg^{-1}). The highest concentrations are in samples 2, 7 and 14 (in the range 12–14 mg kg^{-1}). The remaining samples have concentrations between 1.4 and 3.5 mg kg^{-1}). Ni in tsunami deposits revealed higher concentrations than in the reference sample (<0.5 mg kg^{-1}). Its contents were in range of 0.69 (for sample 5) to 3.7 mg kg^{-1} (for sample 8). Also in the case of Pb all the tsunami deposits had 2–13 times higher concentrations. They were in the range of 8.6 (for sample 4) to 62 mg kg^{-1} (sample 2). In the case of Zn the values on tsunami deposits were 2–28 times higher than in the reference sample. They were in range of 3.6–45 mg kg^{-1}, in samples 4 and 13, respectively.

Concerning the spatial changes, the lowest values of the analysed metals were in the reference sample and in tsunami deposits from Patong town (samples 3–7) and in some samples from Nham Khem (9 and 11). The highest concentrations of all the metals were in samples 1, 2 (both from the area south of Patong Bay), 13 (Nham Khem) and 14 (Bang Mor). The differences between the highest and lowest measured concentrations were usually large—at least of an order of magnitude.

Metalloids in exchangeable fraction of sediments

Arsenic in exchangeable fraction is from 329 μg kg^{-1} for the reference sample to 2,009 μg kg^{-1} for sample 2. Values above 1,000 were note also in samples 11, 13 and 15—from Nham Khem and Bang Mor areas. Detected range of Sb concentrations in the studied samples was from 65 to 671 μg kg^{-1}. Maximum value was detected in sample 2. In samples 10,11 and 15 values of Sb were close to that in the reference sample and in

Table 3 Heavy metals in acid leachable sediment fraction

Sample	Cd (mg kg^{-1})	Cr (mg kg^{-1})	Cu (mg kg^{-1})	Ni (mg kg^{-1})	Pb (mg kg^{-1})	Zn (mg kg^{-1})
1	0.93	2.6	3.4	2.9	24	13
2	2.8	8.6	12	1.8	62	42
3	0.46	2.0	2.9	3.0	19	10
4	0.07	1.1	0.95	2.4	8.6	3.6
5	0.54	1.5	1.5	0.69	12	7.4
6	0.53	3.0	3.4	1.1	13	5.4
7	0.90	0.89	14	0.71	21	32
8	0.95	2.6	3.0	3.7	18	7.0
9	0.94	2.5	2.1	0.86	12	8.1
10	1.5	5.1	1.8	1.1	14	6.8
11	2.0	4.9	2.2	0.86	20	6.6
12	1.3	4.7	2.1	0.91	18	6.8
13	2.7	3.2	3.5	0.93	24	45
14	13.3	7.7	13	1.3	49	18
15	1.4	5.9	1.4	1.4	9.7	6.0
16	0.44	0.73	1.2	<0.5	4.8	1.6

samples 12 and 14 were lower. In the case of selenium maximum value was detected again in sample 2 (160 μg kg^{-1}). The remaining samples had concentrations in the range of <15–90 μg kg^{-1}. For ten samples detected, Se contents were lower than in the reference sample (Table 4).

Arsenic in acid leachable fraction of sediments

Arsenic determined in acid leachable fraction was measured for samples collected from the same locations shortly after the tsunami—in February 2005 (details in Szczuciński et al. 2005) and in 2006. The results are presented in Table 5. In both sets, the values for reference sample (16) are much lower (670 and 594 μg kg^{-1}) than for tsunami deposits (690–6,169 μg kg^{-1}). In tsunami deposits samples collected in 2005, arsenic content was in the range of 770–1,680 μg kg^{-1} for locations around Patong Bay (samples 1–8) and between 2,570 and 3,655 μg kg^{-1} for samples from Nham Khem and Bang Mor (9–15). This difference was also evident in samples collected in 2006. However, for most of the locations, the As concentrations increased even fourfold. Only in the case of sampling locations 1, 4 and 7 decrease was observed. The ranges of As concentrations in 2006 were 690–4,316 and 4,154–6,169 μg kg^{-1} for samples from around Patong Bay and from Nham Khem and Bang Mor, respectively.

Table 4 Metalloids in exchangeable fraction

Sample	As (μg kg^{-1})	Sb (μg kg^{-1})	Se (μg kg^{-1})
1	529	106	22
2	2,009	671	160
3	765	158	90
4	646	169	<15
5	487	175	29
6	490	159	23
7	403	121	<15
8	807	323	48
9	730	222	30
10	791	108	<15
11	1,260	203	<15
12	556	65	<15
13	1,859	277	52
14	332	71	70
15	1,205	108	<15
16	329	104	33

Interelement relationships

Table 6 presents the correlation matrix of the analysed elements in the studied sediments. Very high positive correlation (≥0.95) is between major ions in water-soluble fraction (Na, K, Ca, Mg, SO_4, Cl). High cor-

Table 5 Arsenic concentrations in acid leachable fraction in samples collected in the 2005 and 2006 year

Sample	Year of sampling	
	2005 (μg kg^{-1})	2006 (μg kg^{-1})
1	1,680	998
2	935	4,316
3	865	1,815
4	1,645	1,636
5	900	1,285
6	1,035	1,496
7	770	690
8	1,165	1,814
9	3,175	n.a.
10	3,510	5,515
11	3,450	5,764
12	2,730	5,098
13	2,570	4,154
14	3,320	6,169
15	3,655	4,280
16	670	594

n.a. Not analysed

relations (≥0.60) were found also for in relations between them and between metalloids and water-soluble salts. Among the heavy metals statistically significant correlations were for Pb with all the studied elements except Ni and As, for Zn (except Cd, Cr and Ni). Also Cr was well correlated with other elements apart from Se, Sb, Cu, Ni and Zn. Cu revealed high correlation only to Cd and Pb. Ni was not correlated at statistically significant level to any of the studied elements.

Intersite relationships

Correlation indexes were also calculated for similarities in composition of samples from different locations. This analysis was performed for results presented in this paper—1 year after the tsunami, as well as, for results obtained for samples collected shortly after the tsunami and published previously by Szczuciński et al. (2005). The correlation matrices are presented in Table 7—for data from 2005, and in Table 8—based on the results presented in this paper. The correlations between the sampling sites in 2005 were very high (in most cases ≥0.95) and for all the analysed cases were statistically significant. The weakest correlation had sample 16 (the reference), however, it was still above 0.57. For the samples analysed in this paper, the intersite correlations were much weaker, although, still most of the correlation indexes were above 0.5. Statistically significant correlations were obtained for sample 15 in all the cases, and samples 5, 12,13 in only correlation with sample 2 were below 0.5. The latter sample was positively correlated only with 6 other samples. The remaining of the samples had high correlations with 9–13 other sampling sites.

Discussion

Effect of rainy season on tsunami deposits

The tsunami deposits were generally well-preserved 1 year after the tsunami and after the rainy season. The thickness of the layer was the same as shortly after the tsunami, except places where man-made changes were done (cleaning, earth works etc.). Such a situation was documented for a wider area of the coastal zone of Thailand (Szczuciński et al. 2006). Among the studied sites only at the former locations 10 and 12 new constructions were built and the tsunami sediments were removed so the samples were collected from sites located nearby.

Comparison of grain size distributions of the sediments analysed in 2005 and in the present study shows four different scenarios (Fig. 2). Several samples are not altered in regard of grain size distribution (2, 8, 9, 13), in this group is also the reference sample (16). In the case of sample 1, the sediment sampled in present study was much coarser. It is the effect of large spatial changeability at that location, where due to uneven ground the characteristics of tsunami deposits change over short distances. Two samples (12 and 15) were slightly finer. The both locations were, however, sampled in distance of about 100 m from the 2005 locations. The most common situation is that the sediments collected in 2006 are slightly coarser. Such a change was found for a half of the studied the samples (3, 4, 5, 6, 7, 10, 11, 14). Most of them were collected at exactly the same locations as previously or very close to them. The sediment type changed there from fine sand to medium sand (Fig. 2). It was probably caused by

Table 6 Correlation coefficient matrix of the analysed elements and compounds

	Na	K	Ca	Mg	SO_4	Cl	Se	As	Sb	Cd	Cr	Cu	Ni	Pb	Zn
Na	1.00	**1.00**	**0.95**	**0.99**	**1.00**	**1.00**	**0.83**	**0.63**	**0.91**	0.06	**0.54**	0.48	0.16	**0.74**	**0.56**
K		1.00	**0.95**	**0.99**	**1.00**	**0.99**	**0.84**	**0.63**	**0.90**	0.08	**0.55**	0.48	0.17	**0.76**	**0.56**
Ca			1.00	**0.96**	**0.95**	**0.95**	**0.80**	**0.67**	**0.84**	0.21	**0.72**	0.48	0.22	**0.79**	**0.54**
Mg				1.00	**0.99**	**0.99**	**0.81**	**0.64**	**0.91**	0.15	**0.59**	0.53	0.19	**0.80**	**0.59**
SO4					1.00	**0.99**	**0.84**	**0.64**	**0.90**	0.09	**0.57**	0.48	0.15	**0.76**	**0.56**
Cl						1.00	**0.83**	**0.62**	**0.91**	0.06	**0.53**	0.47	0.22	**0.73**	**0.54**
Se							1.00	**0.60**	**0.85**	–0.06	0.29	0.28	0.31	**0.59**	**0.53**
As								1.00	**0.74**	–0.03	**0.50**	0.09	0.07	0.45	**0.64**
Sb									1.00	–0.06	0.38	0.31	0.23	**0.60**	**0.58**
Cd										1.00	**0.62**	**0.58**	–0.10	**0.64**	0.26
Cr											1.00	0.41	–0.04	**0.74**	0.32
Cu												1.00	–0.06	**0.78**	**0.67**
Ni													1.00	0.13	–0.08
Pb														1.00	**0.68**
Zn															1.00

The bold indexes are significant at level of confidence $p < 0.05$. $N = 16$

Table 7 Correlation coefficient matrix of the sampling sites based on their chemical composition from 2005 (data after Szczuciński et al. 2005)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1.00	**0.98**	**0.99**	**0.96**	**0.99**	**0.99**	**0.95**	**0.96**	**0.99**	**1.00**	**0.92**	**0.94**	**0.69**	**0.99**	**0.71**	**0.64**
2		1.00	**0.99**	**0.95**	**0.99**	**1.00**	**0.98**	**0.99**	**0.99**	**0.98**	**0.95**	**0.99**	**0.82**	**0.99**	**0.72**	**0.67**
3			1.00	**0.98**	**1.00**	**0.99**	**0.97**	**0.98**	**1.00**	**1.00**	**0.93**	**0.97**	**0.74**	**1.00**	**0.74**	**0.71**
4				1.00	**0.97**	**0.96**	**0.97**	**0.96**	**0.97**	**0.96**	**0.95**	**0.96**	**0.70**	**0.97**	**0.84**	**0.78**
5					1.00	**0.99**	**0.97**	**0.98**	**1.00**	**1.00**	**0.92**	**0.97**	**0.74**	**1.00**	**0.72**	**0.69**
6						1.00	**0.98**	**0.99**	**1.00**	**0.99**	**0.95**	**0.98**	**0.79**	**0.99**	**0.74**	**0.68**
7							1.00	**1.00**	**0.97**	**0.95**	**0.96**	**1.00**	**0.85**	**0.97**	**0.79**	**0.75**
8								1.00	**0.98**	**0.97**	**0.96**	**1.00**	**0.86**	**0.98**	**0.77**	**0.72**
9									1.00	**1.00**	**0.95**	**0.97**	**0.75**	**1.00**	**0.75**	**0.70**
10										1.00	**0.92**	**0.96**	**0.71**	**0.99**	**0.71**	**0.67**
11											1.00	**0.96**	**0.80**	**0.94**	**0.90**	**0.76**
12												1.00	**0.87**	**0.97**	**0.78**	**0.74**
13													1.00	**0.75**	**0.60**	**0.57**
14														1.00	**0.74**	**0.70**
15															1.00	**0.80**
16																1.00

The bold indexes are significant at level of confidence $p < 0.05$. $N = 15$

Table 8 Correlation coefficient matrix of the sampling sites based on the chemical composition from 2006

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1.00	0.41	**0.92**	0.49	**0.95**	**0.76**	0.45	0.47	**0.88**	**0.79**	**0.80**	**0.76**	**0.93**	**0.73**	**0.92**	**0.63**
2		1.00	**0.53**	**0.84**	0.44	0.27	**0.77**	**0.91**	0.09	0.08	**0.77**	0.44	0.49	**0.66**	0.34	**0.60**
3			1.00	0.47	**0.79**	**0.50**	0.46	**0.56**	**0.76**	**0.83**	**0.77**	**0.80**	**0.80**	**0.93**	**0.95**	**0.50**
4				1.00	**0.62**	**0.61**	**0.97**	**0.95**	0.32	0.19	**0.72**	**0.66**	**0.63**	0.49	0.43	**0.90**
5					1.00	**0.91**	**0.56**	**0.52**	**0.89**	**0.67**	**0.82**	**0.73**	**0.97**	**0.57**	**0.81**	**0.80**
6						1.00	**0.55**	0.43	**0.78**	0.44	**0.63**	**0.61**	**0.85**	0.22	**0.58**	**0.85**
7							1.00	**0.94**	0.34	0.27	**0.63**	**0.74**	**0.57**	**0.51**	0.47	**0.88**
8								1.00	0.23	0.22	**0.68**	**0.70**	**0.53**	**0.66**	0.47	**0.76**
9									1.00	**0.87**	**0.62**	**0.72**	**0.86**	**0.50**	**0.87**	**0.62**
10										1.00	**0.50**	**0.77**	**0.68**	**0.69**	**0.94**	0.38
11											1.00	**0.56**	**0.90**	**0.68**	**0.68**	**0.75**
12												1.00	**0.69**	**0.74**	**0.88**	**0.70**
13													1.00	**0.59**	**0.81**	**0.80**
14														1.00	**0.82**	0.36
15															1.00	**0.54**
16																1.00

The bold indexes are significant at level of confidence $p < 0.05$. $N = 15$

washing of finer particles during heavy rains. The depletion in fine sediment fraction is not observed in finer deposits (silts). The washing in sands, which were poorly sorted (Szczuciński et al. 2005), could be facilitated by removing fine particles—not loaded by overlying grains, from spaces between larger grains forming the framework of the deposits.

Effect of rainy season on content of the contaminants

Water-soluble salts, acid leachable heavy metals and arsenic, and exchangeable metalloids were studied for the same locations shortly after the tsunami (Szczuciński et al. 2005) and 1 year later—after the rainy season (this study—2006). Comparison of the obtained results is presented in Fig. 3.

The major changes are observed in contents of water-soluble salts. Generally their concentrations are much lower in 2006, except of samples 2 and 8. The observed decline in salt content is attributed to dissolution by freshwater during rainy season. Sample 2 is characterized by maximum values of all the studied elements (including heavy metals and metalloids). It was collected at a location impacted by wastewaters from anthropogenic activity, which is probably the reason for outstanding concentrations of contaminants. Although, generally the water-soluble salts are

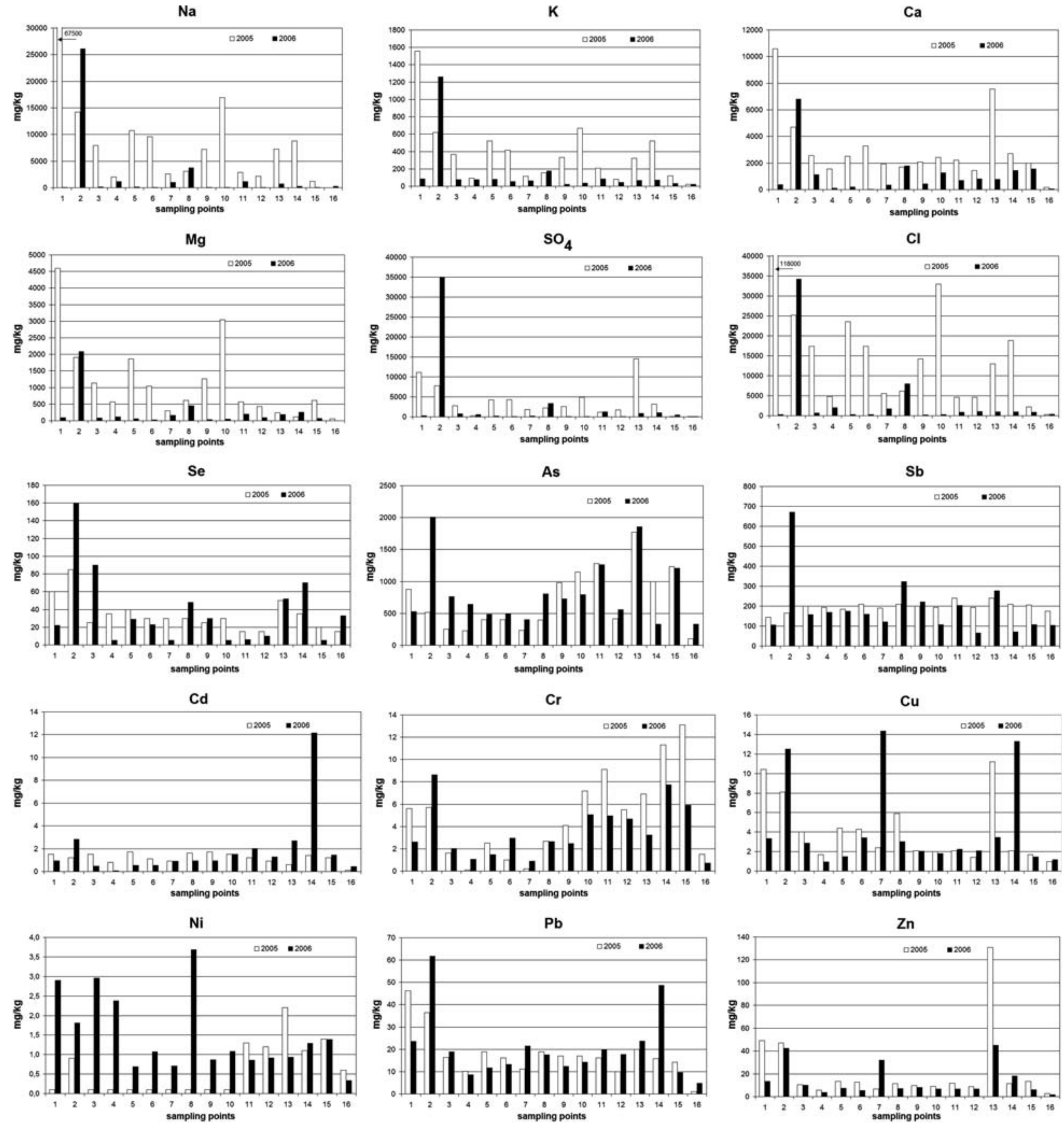

Fig. 3 Comparison of concentrations of the studied elements in water-soluble fraction (for Na, K, Cl, Mg, SO_4, Cl), exchangeable fraction (for Se, As, Sb) and acid leachable fraction (for Cd, Cr, Cu, Ni, Pb and Zn) in tsunami deposits and reference sample shortly after the tsunami (2005) and after the rainy season (2006). The data from the 2005 are after Szczuciński et al. (2005)

removed from the tsunami deposits, it should be noted that after rainy season the concentrations are still higher than in the reference sample.

It is difficult to find general trend of changes when comparing heavy metals in acid leachable sediment fraction. For each element, some samples are enriched and some are depleted after rainy season. For Cd and Pb half of the samples noted decrease and half increase in concentrations. Among the latter particularly elevated were values in sample 14.

Similar situation is in case of Cu, where reduction in its content was found in ten samples, and increased in six—particularly, in samples 7 and 14. Generally reduced concentrations of Cu and were measured for 2006; however, there were also some samples were content of these elements increased. The latter was found in five and two samples for Cr and Zn, respectively. In the case of Ni, after the rainy season its content increased in eleven samples, and in eight of them the increase was significant. In the reference sample, the measured heavy metals contents before and after rainy season varied very little—much less than in most of the samples from tsunami deposits.

Similar trends to that observed in heavy metals were detected also in metalloids. Among them, samples: 12, 9 and 6 were depleted in Sb, Se and As, respectively. For the remaining samples the concentrations of the studied elements increased, particularly in sample 2. Also in the case of As in acid leachable fraction (Table 5) changes after rainy season were not uniform, however, for most of the samples the As content increased.

The presented comparisons of results for heavy metal and metalloids may be surprising, as one would expect decrease in concentrations of these mobile fractions after the rainy season. It is obvious that the mechanisms of mobilization of bioavailable fraction of heavy metal and metalloids are different from simple dilution of water-soluble salts. It is speculated that the removed easily mobilized fractions are recharged by continuously acting chemical weathering processes moving the discussed elements from less to more bioavailable fractions. Probably these processes are active on different stages of decompositions of minerals, as it is shown by a comparison of As in acid leachable (more resistant) and in exchangeable fractions—in both of them increase in concentrations was noted in most of samples. It suggests that both fractions were charged during the study period. In this way, the tsunami deposits may have long-term impact on higher amount of bioavailable potentially toxic elements in the environment. It could be of particular importance in case of elements, which are at elevated background values in this region—e.g. arsenic (Williams et al 1996; Zarcinas et al. 2004; Wattanasen et al. 2006). However, because regional background values are not defined for ‘‘bioavailable’’ fraction, it is not possible to perform more specific assessment. As shown by grain size data, several samples were depleted in finer fractions. However, it is not correlated to acid leachable or exchangeable element concentration changes.

In the 2005 correlation coefficients of analysed elements and compounds were relatively high (Szczuciński et al. 2005) but in the 2006 are even higher (Table 6). One of reasons may be removal of the most mobile water-soluble forms. On the other hand, the comparison of intersite correlations shows much higher values in 2005 (Table 7) than in 2006 (Table 8). It may be related to one major forming process in 2005 and dominance of site-specific conditions during the further alterations as observed 1 year later.

Implications for paleotsunami study

Tsunami deposits preserved in geological record may be useful in assessment of a tsunami hazard of particular regions. For example, they may help to determine recurrence period and potential area of inundation (e.g. Nanayama et al. 2003; Dawson et al. 2004). In some cases, this record may be the only evidence that a region may be at risk from a tsunami. However, identification of paleotsunami deposits is quite complex and is still a subject of discussion (e.g. Nanayama et al. 2000; Pratt 2002; Nott 2003; Goff et al. 2001; Tuttle et al. 2004; Rhodes et al. 2006; Shanmugam 2006). Sediment geochemistry, particularly contents of Na, S, Cl, Ca, Mg, is often used as one of diagnostic features used in identification of paleotsunami and other catastrophic saltwater inundation (e.g. Minoura et al. 1994; Chagué-Goff and Goff 1999; Chagué-Goff et al. 2002; Goff et al. 2004). It is important indicative attribute if sediments deposited in lagoons or lakes are investigated. In the present study, a short assessment of reliability of some of these diagnostic features in the case of tsunami deposits left on land and subjected to washing due to rainfalls was analysed.

One of important features used in paleotsunami studies is grain size distribution, which helps to interpret wave hydrodynamic—for instance current velocity (e.g. Gelfenbaum and Jaffe 2003; Nanayama and Shigeno 2006). As shown by the above presented comparison of grain size distributions of tsunami sediments before and after the first rainy season, it is very likely that overall coarsening of tsunami deposits layer may occur in consequence of washing of finer particles. So it suggest that even material collected shortly after tsunami but not before heavy rains may be not fully representative for the tsunami sedimentary processes.

The next tool used in paleotsunami studies in sediment geochemistry. In particular contents of Na, S, Cl, Ca, Mg, is often used as one of diagnostic features. However, they were used only in the case of lagoon or lake sediments, where salt water may persist after the saltwater inundation event (e.g. tsunami). In some areas, like along large part of coastline in Thailand, such a sediment sinks are missing. Consequently, there is a need to explore sediments left on land. From the above-presented results, it is clear that the water-soluble compounds may be dissolved and probably will be completely removed after several rainy seasons. Some potential may be behind some trace metals (heavy metals and metalloids) as indicators of the marine origin of sediments—at least on local scale, however, this aspect needs to be explored more in future.

Conclusions

The tsunami deposits left in coastal zone of Thailand were still preserved and had the same sediment thickness after rainy season. The most important alterations documented in this study include depletion of fine grain size fraction in poorly sorted tsunami laid sands and significant removal of water-soluble salts. The previously documented (Szczuciński et al. 2005) elevated concentrations of bioavailable heavy metals and arsenic are still sustained after one year. It is possible that this state will be sustain for longer period due to postulated steady recharge of bioavailable fraction from more resistant fractions. After rainy season the intersite correlations were much weaker proving that site specific conditions are important in further chemical changes of the tsunami deposits layer.

The results may have implication for studies of paleotsunami deposits on land. They must take into account post-depositional changes. In particular, washing out of fines and dissolution of salts.

The observed effects may be of significance not only for tsunami impacted coastal zones but also for other saltwater inundations leaving a layer of sediments, e.g. hurricanes (e.g. Turner et al. 2006).

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Research article

Effect of landscape structure on anopheline mosquito density and diversity in northern Thailand: Implications for malaria transmission and control

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Key words: Anopheles; Landscape ecology; Landscape metrics; Landscape management; Malaria mosquitoes

Abstract

The influence of landscape structure on anopheline mosquito density and diversity was studied in a comparison of agricultural and forested landscapes in northern Thailand. Agriculture locations had significantly higher landscape diversity, more patches, smaller mean patch sizes, and more complex patch shapes than forest locations. Mosquito collections were undertaken during both dry and wet seasons from October 1997 to December 1999. The density of two forest-associated species, *Anopheles maculatus* s.s. and *Anopheles minimus* s.l., both primary malaria vectors in Thailand, was significantly higher in forest locations in at least one season. The density of two paddy field-associated species, *Anopheles aconitus* and *Anopheles hyrcanus* group did not differ between locations. *Anopheles aconitus* is a secondary malaria vector and *An. hyrcanus* group is not considered as a vector in Thailand. The density of *An. minimus* s.l. was positively related to forest mean patch size, various water and paddy field landscape metrics and negatively related to landscape diversity. *Anopheles hyrcanus* group was also positively related to water metrics. Anopheline species diversity was negatively related to landscape diversity. Forest fragmentation resulting from human economic activities often increases landscape heterogeneity, which may result in a reduction in anopheline species diversity, as was the case in this study. There are indications that the effect of fruit orchards on anopheline diversity might be different in the dry season compared to the wet season. Fruit orchard landscape metrics affected species diversity negatively in the dry season and positively in the wet season. One reason for this could be that pesticides are typically applied in fruit orchards during the dry season. The conversion of forests to fruit orchards is a major land-use change in northern Thailand. These results show the complexity of vector status in northern Thailand and that vector and agriculture pest control are intricately interrelated. It is therefore important to include both the public health and agricultural sectors in controlling malaria vectors in the country. Our results also indicate that if landscape management should be used for malaria control in northern Thailand large-scale reduction and fragmentation of forest cover would be needed. Such drastic actions do not agree well with current global objectives concerning forest and biodiversity conservation

Introduction

The structure of landscapes may be important for explaining and understanding malaria mosquito ecology (Wood et al. 1992; Rodriguez et al. 1996; Suwonkerd et al. 2002). The location of breeding sites, resting places, blood and nectar sources, as well as landscape heterogeneity may influence mosquito movement and spatial distribution. Landscape structure is the spatial relationship among different land-use types or habitat patches in a landscape (Turner 1989; Dunning et al. 1992). Patches are areas that differ in nature or appearance from the surrounding environment (e.g. differences in land cover or physical structure) and that have biological significance for the organism under consideration (Wiens 1976). Landscape composition (the proportion of different land use and habitat patches in a landscape) and landscape configuration (the spatial arrangement of those patches) are the two features of landscape structure that are required to describe any landscape (Turner 1989; Turner and Gardner 1990; Dunning et al. 1992). Very few studies have investigated the effect of landscapes on malaria vectors and transmission, particularly in Southeast Asia (Wood et al. 1992; Beck et al. 1994; Rodriguez et al. 1996; Suwonkerd et al. 2002).

Malaria transmission in Thailand takes place primarily in rural, forested, and hilly areas in districts that border Myanmar and Cambodia (Ismail et al. 1978; Rosenberg et al. 1990). Malaria mortality in Thailand has decreased drastically during the second half of the last century (Malaria Division 1998). In the border areas, however, 10 to 20% of the population in some villages still become infected every year (H.J.O. pers. observation). Rosenberg et al. (1990) suggested that the reduced malaria risk in Thailand may have been as much an effect of extensive deforestation as of malaria control programs. The forest cover decreased from more than 70% of the country's land area in 1938 to about 23% in 1995 (FAO 1999). The accelerated economic development of Thailand during the last decades has affected human settlement and migration patterns leading to increased pressure on land resources and changes in rural economic structures (Singhanetra-Renard 1993). In agricultural areas in northern Thailand, such changes have been more pronounced and attenuated than in forest areas. Fragmentation of forest areas leading to increased landscape diversity is a common result of human intervention (e.g. Hoover and Parker 1991). Forest fragmentation has been associated with reductions in arthropod species richness (Didham et al. 1996). Such environmental alterations may also affect the distribution patterns and abundance of anopheline mosquitoes (Ismail et al. 1978; Takagi et al. 1995; Suwonkerd et al. 2002).

There are more than 70 different mosquito species of the genus *Anopheles* in Thailand (Harrison et al. 1990), but only a handful are implicated in malaria transmission. In this study we focused on two forest-associated species: the primary vectors *Anopheles minimus* sensu latu Theobald and *Anopheles maculatus* sensu strictu Theobald; and two paddy field-associated species: the secondary vector *Anopheles aconitus* Dönitz and *Anopheles hyrcanus* group, which include species that are generally not considered malaria vectors in Thailand. *Anopheles minimus* s.l. is a species complex of at least two species (Green et al. 1990), but is regarded here as *An. minimus* [s.l.]. It is the most common malaria vector in northern Thailand and is prevalent in forested foothills and forest fringe areas, where it breeds along grassy, shaded banks of slow moving streams (Muirhead Thomson 1940). Such areas are often subject to drastic environmental change, such as deforestation, urbanization, and change in land use (Takagi et al. 1995). The *An. maculatus* group consists of at least eight closely related species (Green et al. 1985). *Anopheles maculatus* s.s. is one of the main malaria vectors in peninsular Malaysia and southern Thailand (Reid 1968; Upatham et al. 1988) and has also been implicated as a vector in northern Thailand (Somboon et al. 1998). It is common in foothill areas, where larvae occur in similar habitats as *An. minimus* (Reid 1968). *Anopheles aconitus* is a secondary vector in Thailand (Malaria Division 1998), but was believed to be responsible for a malaria epidemic in 1989-91 in the central flood plain of Bangladesh (Maheswary et al. 1992). Larvae of *An. aconitus* are found along the grassy edges of rice fields, ponds and swamps (Reid 1968). *An. hyrcanus* group is a large group of very similar species. In Thailand, it consists of at least six species (Baimai et al. 1993), of which three are common; *An. nigerrimus* Giles, *An. peditaeniatus* Leicester, and *An. sinensis* Wiedemann (Suwonkerd, unpublished). These are most prevalent in agricultural locations (Rao 1984) and mainly breed in rice fields, but also in grassy ponds, swamps and ditches exposed to the sun (Reid 1968). *Anopheles sinensis* is an important vector in China (Ho et al. 1962). *Anopheles dirus* sensu latu (Peyton and Harrison), perhaps the most efficient malaria vector in the region (Rosenberg et al. 1990), is not considered here because of its low abundance. *Anopheles minimus* is often considered the principal vector in many areas of northern Thailand, because it is much more common than *An. dirus* (Harbach et al. 1987).

We collected *Anopheles* mosquitoes and data on landscape structure in three agricultural and three forest landscapes in northern Thailand to study if an analysis of landscape structure could be used to explain anopheline density and diversity. Previous observations suggested that malaria transmission is lower in more developed, urbanized locations with a high landscape diversity than in the less developed forest locations with a low landscape diversity (Suwonkerd et al. 2002). As a result of forest fragmentation and high landscape diversity anopheline density and species diversity might also be lower in such locations.

According to Muirhead Thomson (1940) and Ismail et al. (1978), *An. minimus* should be positively associated with forests and water-related landscape parameters, such as stream corridors, paddy fields, and water. Although *An. minimus* almost exclusively breeds in streams, paddy fields and water landscape elements may favor stream-like conditions. According to Upatham et al. (1988), *An. maculatus* should be positively associated with forest landscape elements and use breeding habitats similar to *An. minimus* (Reid 1968). According to Gould et al. (1967), *Anopheles aconitus* should generally be found in areas dominated by paddy field landscape elements. And according to Rao (1984), *An. hyrcanus* group should respond positively to landscape elements of paddy fields and open agriculture. Finally, we suggest that anopheline species diversity and all four species should be negatively associated with fruit orchards because of high pesticide use in fruit orchards.

Methods

Study sites

This study was carried out in six landscapes in five villages in northern Thailand: 1) Pang Mai Daeng village, Mae Taeng district, Chiang Mai province (landscapes PMD1 and PMD2); 2) Mae Mok village, Thoen district, Lampang province (landscape MM); 3) Ban Tae village, Muang district, Lampang province, (landscape BT); 4) Pakkolo village (landscape PK) and 5) Huay Chang Kham village (landscape HCK), both in Muang district, Mae Hong Son province (Figure 1). These sites were selected to include landscapes that were dominated by either agriculture or forest. Thus, landscapes PMD1, PMD2 and MM were defined as agriculture locations and BT, PK and HCK as forest locations. Monthly rainfall data were collected from the closest meteorological stations to the study sites. One meteorological station each represented the Mae Hong Son and Chiang Mai sites, respectively. A third station represented the BT site and a fourth the MM site. There was no difference in the amount of rainfall between these stations during the years 1995-1999 (ANOVA, $F_{3,12} = 0.32$, $P=0.81$; SAS 1996).

Landscape data

The most recent aerial photographs (December 1995) were acquired from the Royal Thai Survey Department, Bangkok. Photographs of a scale of 1:50,000 covering each village were scanned and rectified and used as background for land-use classification and screen digitization. Rectification and digitization were done using ArcView version 3.2. Each digitized polygon (patch) was assigned one of ten land-use classes: agriculture, cultivated land, forest, fruit orchard, paddy field, road, shrub, stream corridor, village, or water (Figure 1). Classification was undertaken by visual inspection of the scanned aerial photograph. The agriculture class represents crops other than paddy rice, such as upland rice, tobacco, and corn. Due to classification difficulties, cultivated land was created as an intermediate class between agriculture and shrub to indicate abandoned agricultural fields or other crops with distinguishable characters from the agriculture class. Agriculture, cultivated land, and shrub were thus classified based on increasing textural roughness on the aerial photograph. The stream corridor, which is usually covered with trees, refers to the riparian zone between the stream and the adjacent land-use class. Village patches also included household gardens. The extent of the analyzed landscapes was fixed by a 2-km radius drawn from a centrally located mosquito collection point in each village. This distance was selected based on the flight ability of *An. minimus* s.l. (Rao 1984; Y. Tsuda, pers. comm.) and the recommended barrier zone surrounding areas targeted by malaria control programs (Bruce-Chwatt 1985). The landscape classification was ground-truthed by visually comparing the classified and actual landscapes. Few if any changes were detected in the land-use patterns between December 1995 (time of aerial photographs) and December 1999 (time of the last mosquito collections).

Landscape and land-use class metrics were calculated using FRAGSTATS*ARC software version 3.0 (McGarigal and Marks 1995). This software quantifies the areal extent and spatial distribution of patches within a landscape as a set of distance- and area-based

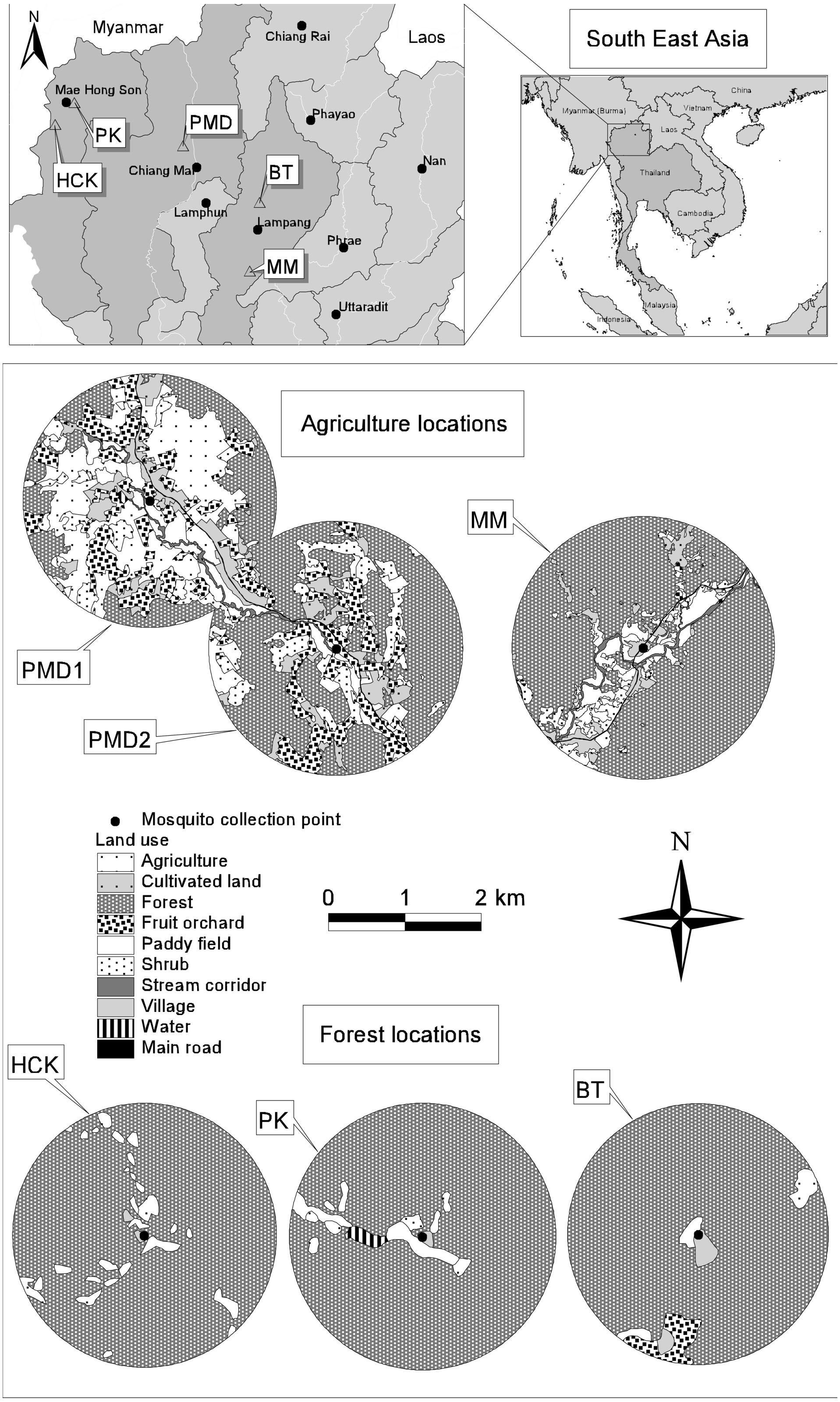

Figure 1. Location of study sites and land use maps of six landscapes in northern Thailand. PMD = Pang Mai Daeng village, MM = Mae Mok village, BT = Ban Tae village, PK = Pakkolo village, and HCK = Huay Chang Kham village.

metrics. These metrics can be divided into two groups: the landscape group, calculated for the whole landscape; and the land-use class group, calculated for each land-use class separately. Out of 23 available metrics from the first group and 15 available metrics for each of the 10 land-use classes (i.e. a total of 173 metrics), we selected a subset of 46 metrics for statistical analysis. The selection of these metrics was based on their presumed ecological significance. Because of strong multicollinearity between many metrics, however, only the following are reported and discussed: modified Simpson's diversity index (MSIDI) from the landscape group; percent cover (COVER), mean patch size (MPS), and mean patch fractal dimension (MPFD) from the land-use class groups. The value of MSIDI indicates the probability that any two patches selected at random will be different land-use classes; the higher the value, the greater the diversity. MSIDI is 0 when the landscape contains only one patch and increases up to the maximum value of ln(number of land-use classes) when the proportional distribution of area among land uses becomes more even. MPFD ranges between 1 and 2 and measures patch shape complexity. An MPFD close to 1 indicates patch shapes with very simple perimeters, such as circles or squares. As MPFD increases, patch shapes become more irregular. A full explanation of metrics and their mathematical formulas can be found in McGarigal and Marks (1995).

Mosquito data

Adult anopheline mosquitoes were collected in all sites during both dry and wet seasons. Dry season is defined here as the period between October and April, when monthly precipitation seldom exceeds 100 mm (Meteorological Department 1999); the wet season extends from May to September. Human bait (2-3 local collectors) sat outdoors and collected mosquitoes landing on their exposed legs with aspirators or vials. Fifty minutes of collection and 10 minutes rest were repeated every hour from sunset to midnight. Generally, mosquitoes were collected on two consecutive nights each collection month. The first collections started in October 1997 and the last ones were finished in December 1999. The collection effort varied among sites. In PMD1 there was a total of 20 collection months and 648 man-hours. The corresponding figures for PMD2 were 21 months and 648 man-hours; for MM 12 months and 752 man-hours; for BT 14 months and 1068 man-hours; for PK 15 months and 1252 man-hours ; and for HCK 14 collection months and 2472 man-hours. Using humans as bait was necessary to obtain data on those species that are actual or potential vectors of human diseases. This collection procedure follows the guidelines of the World Health Organization (WHO 1975) and is the norm for malaria control agencies in Thailand. Local collectors were fully informed of the risk and were under medical supervision of local health authorities. Thus, collectors were not more exposed to mosquito bites or potential disease transmission than in normal circumstances (i.e., when they do not collect mosquitoes).

Mosquitoes were morphologically identified to species using keys of Peyton and Scanlon (1966), Sawadwongporn (1972), Rattanarithikul and Harrison (1973), Harrison and Scanlon (1975), Peyton and Harrison (1979), Harrison (1980), Rattanarithikul and Green (1986) and Rattanarithikul and Panthusiri (1994). Mean mosquito density (number of mosquitoes per bait-hour) and Shannon-Weaver diversity index ($H' = -\Sigma\, p_i \ln p_i$, where p_i is the proportional abundance of species i) were calculated for each site and season and averaged over locations.

Species diversity is a function of the proportional abundance of species and species richness. Estimates of local species richness depend on number of individuals and the area sampled (e.g. Preston 1948). If few individuals are sampled, species richness and diversity may not reflect the true situation, because variation between sites can be a result of differences in sample size. Several non-parametric estimators of species richness have been developed to account for this variation (reviewed by Bunge and Fitzpatrick 1993). Ideally, such estimators should be relatively insensitive to sample size. Continued sampling in sites with low species diversity could result in higher species richness and diversity. To evaluate this uncertainty we calculated an abundance-based estimator of species richness (Chao 1984): $S_{est} = S_{obs} + (F_1^2/2F_2)$, where S_{obs} is the observed number of species, F_1 is the number of singletons (species represented by a single individual) and F_2 is the number of doubletons (species represented by exactly two individuals).

Data analysis

A multivariate analysis was performed to estimate the relative value of the selected landscape metrics in predicting anopheline species diversity (Shannon-Weaver diversity index) and the densities of the four most abundant species: *An. minimus* s.l., *An. maculatus* s.s., *An. aconitus* and *An. hyrcanus* group. Simple correlation and stepwise regression analysis are unsatisfactory when the number of variables is large, because spurious correlations may appear as significant (Martens et al. 1983). Therefore, a type of principal component analysis, Partial Least Squares regression on latent variables (PLS), was used (see Wold 1984). PLS can be successfully applied if variables are strongly intercorrelated and contain significant noise, and if the number of variables is higher than the number of observations (Martens et al. 1983). The first PLS-component is the linear combination of the X variables (landscape variables) that has the largest covariance with the Y variables (mosquito variables). The second PLS-component is the linear combination of the X variables that has maximum covariance with the residuals after the first component has been extracted, given that it is uncorrelated with the first component. The analyses are performed in an iterative manner, such that the component scores of the X matrix are allowed to influence the scores of the Y matrix and vice versa. Cross-validation was used to determine the maximum number of significant PLS components, by computing Q2, which is the fraction of the total variation of the Y's that can be predicted by a component. Q2 is computed as 1-(Prediction Error Sums of Squares/ Residual Sums of Squares of the previous dimension). The results are shown in terms of patterns; thus no causal interpretations can be made. The PLS analysis was run separately for each season on mosquito diversity and densities. The PLS procedure was done using SIMCA-S version 5.1 (Umetri 1994).

Differences in mean landscape metrics between forest and agriculture locations were tested using the Kruskal-Wallis test with chi-square approximation. Differences in anopheline densities between forest and agriculture locations for each season was tested using a nested ANOVA. Type of landscape (agriculture or forest) and location nested within landscapes were the factors included in the model. Kruskal-Wallis and ANOVA analyses were performed using SAS software (SAS 1996).

Results

Landscape data

There were clear differences between agriculture and forest locations (Appendix 1). At the landscape scale, the agriculture locations had more patches, smaller mean patch sizes, more complex patches, and higher landscape diversity than the forest locations. Patch richness (the number of different land-use classes) was higher in the agriculture locations (9-10 land-use classes) than in the forest locations (4-6 land-use classes). Forest cover was significantly lower and more fragmented in the agriculture locations than in the forest locations. Agriculture, cultivated land, and shrub land uses were generally more extensive in the agriculture locations than in the forest locations. The cover and number of fruit orchard patches were generally higher in the agriculture locations. Stream corridors were present in the agriculture locations, but were not detected in the aerial photographs from the forest locations.

Mosquito data and mosquito-landscape relationships

A total of 12,912 mosquitoes of 19 different anopheline species were collected from all sites. Almost 45% of all mosquitoes collected were *An. minimus;* 20% were *An. hyrcanus* group; 9% were *An. aconitus;* 7% were *An. maculatus* s.s. Nineteen percent consisted of other anophelines (Table 1). Eighty percent of all mosquitoes were collected in the forest locations. During the wet season the density of *An. minimus* was significantly higher in the forest locations than in the agriculture locations (Table 1). The pattern was similar during the dry season, although the significance level was higher ($P < 0.1$ instead of $P < 0.05$). The dry season density of *An. maculatus* was significantly higher in the forest locations than in the agriculture locations. No significant difference in *An. maculatus* density was found between locations during the wet season (Table 1). The densities of other species, including *An. aconitus* and *An. hyrcanus* group, were not different between locations for either season.

In the first PLS analysis the densities of the four *Anopheles* species were entered as dependent variables (Y's). The first two components explained comparatively little of the variation in species density during the dry season (11% and 14%, respectively)

Table 1. Seasonal anopheline mean densities (number of mosquitoes per man-hour) (SE in parenthesis) and anopheline species diversity (Shannon-Weaver diversity index , H') in three agriculture landscapes and three forest landscapes in northern Thailand from October 1997 to December 1999. Differences between agriculture and forest locations in each season tested using ANOVA (degrees of freedom for all tests were 1, 4). Dry season = October – April. Wet season = May – September. *Anopheles minimus* s.l. and *An. maculatus* s.s. are primary malaria vectors, *An. aconitus* is a secondary malaria vector, and *An. hyrcanus* group is not a malaria vector in Thailand.

	Dry season				Wet season			
	Agriculture	Forest	F	P	Agriculture	Forest	F	P
Anopheles minimus s.l.	0.236 (0.039)	1.545 (0.323)	4.59	0.099	0.229 (0.044)	1.133 (0.197)	13.71	0.021
Anopheles maculatus s.s.	0.004 (0.002)	0.142 (0.052)	8.21	0.046	0.008 (0.005)	0.446 (0.326)	1.27	0.322
Anopheles aconitus	0.342 (0.218)	0.024 (0.010)	0.60	0.483	0.021 (0.016)	0.029 (0.015)	0.05	0.842
Anopheles hyrcanus group	0.091 (0.043)	0.370 (0.240)	0.98	0.379	0.448 (0.197)	0.791 (0.202)	0.83	0.415
Other anophelines[1]	0.101 (0.024)	0.170 (0.056)	1.70	0.262	0.293 (0.069)	0.871 (0.456)	1.36	0.308
H'	0.610 (0.087)	0.794 (0.059)	0.79	0.425	0.938 (0.010)	1.053 (0.108)	1.07	0.360

[1]In order of decreasing abundance: *An. nivipes, An. splendens, An. pseudowillmori, An. barbirostris, An. vagus, An. willmori, An. tesselatus, An. sawadwongporni, An. kochi, An. dirus, An. jamesi, An. dravidicus, An. annularis, An. culicifacies*, and *An. varuna*.

and nothing of the variation in species density during the wet season. In the first dry season component, *An. minimus* and *An. maculatus* were negatively related to the fractal dimensions of village, stream corridor and cultivated land patches and to landscape diversity (Table 2). A positive relationship was found between these two species and forest mean patch size. In the second dry season component, *An. hyrcanus* and *An. minimus* were negatively related to the mean patch sizes of fruit orchard and village patches and positively related to several water metrics and shrub fractal dimension (Table 2). The third component explained 27% of the variation in species density during the dry season and 51% of the variation in the wet season and is the only component reported here. The third component seems to be related most strongly with *An. aconitus* density in both seasons, but also with *An. maculatus* in the wet season (Table 2). During the dry season, *An. aconitus* density was negatively related to fruit orchard cover, shrub mean patch size, agriculture cover, and landscape diversity, and positively related to forest and paddy field cover. During the wet season, there were negative relationships between both *An. aconitus* and *An. maculatus* densities and shrub mean patch size, water cover, and water mean patch size. The strongest positive relationships were between these two species and fruit orchard mean patch size and fractal dimension. *Anopheles minimus* density showed an opposite and weaker relationship with landscape metrics than *An. aconitus* and *An. maculatus.*

In all landscapes anopheline species diversity (H') was higher during the wet season than during the dry season, but there were no significant differences in species diversity between agriculture and forest locations for either season (Table 1). By including data from both seasons, however, there was a general negative relationship between anopheline species diversity and landscape diversity (Figure 2). Generally, species richness seemed to be higher in forest locations compared to the agriculture locations. The observed number of species (S_{obs}) generally corresponded well with the estimated number of species (S_{est}), except in PMD2 (Appendix 2).

In the second PLS analysis, the anopheline species diversity was entered as dependent variable (Y). The variables contributing most to the description of each component are shown in Table 3. The first component in the dry season showed that anopheline species diversity was negatively associated with fruit orchard cover, agriculture cover, and landscape diversity and positively associated with forest cover (Table 3). In the second component of the dry season anopheline species diversity was positively related to fractal dimensions, particularly those of forest, paddy fields, village, and agriculture land uses (Table 3). This means that as patch complexity increases, species diversity also increases. In the first component of the wet season, shrub mean patch size, shrub fractal dimension, and water cover were negatively related to species diversity and fruit orchard mean patch size was positively related to species diversity (Table 3). The second component of the wet season seems to be related with water-associated metrics, such as water cover, water mean patch size, and paddy field mean patch size. These were all negatively related to species diversity. Fruit orchard fractal dimension was positively related to species diversity (Table 3). The

Table 2. Variables with highest factor loadings from PLS analysis on anopheline species density and landscape variables during dry and wet seasons. MPS=mean patch size. MPFD=mean patch fractal dimension.

	Variable	Factor	Loading
Dry season	Component 1 (Q2=11%)		
	X	*An. minimus*	0.21
	X	*An. maculatus*	0.21
	Y	Village MPFD	− 0.25
	Y	Stream corridor MPFD	− 0.25
	Y	Cultivated land MPFD	− 0.25
	Y	Landscape diversity	− 0.19
	Y	Forest MPS	0.25
	Y	Paddy field MPS	0.23
	Component 2 (Q2=14%)		
	X	*An. hyrcanus*	0.38
	X	*An. minimus*	0.26
	Y	Fruit orchard MPS	− 0.30
	Y	Village MPS	− 0.25
	Y	Water cover	0.38
	Y	Water MPS	0.38
	Y	Water MPFD	0.34
	Y	Shrub MPFD	0.31
	Component 3 (Q2=27%)		
	X	*An. aconitus*	0.37
	Y	Fruit orchard cover	− 0.36
	Y	Shrub MPS	− 0.35
	Y	Agriculture cover	− 0.27
	Y	Landscape diversity	− 0.27
	Y	Forest cover	0.27
	Y	Paddy field cover	0.27
Wet season	Component 3 (Q2=51%)		
	X	*An. aconitus*	0.43
	X	*An. maculatus*	0.33
	X	*An. minimus*	− 0.21
	Y	Shrub MPS	− 0.41
	Y	Water cover	− 0.34
	Y	Water MPS	− 0.32
	Y	Fruit orchard MPS	0.41
	Y	Fruit orchard MPFD	0.40

first two components together explained 88% and 77% of the variation in species diversity during the dry and wet seasons, respectively.

Discussion

This study shows that landscape analysis may be used to explain anopheline species density and diversity in northern Thailand, despite the low number of replications used here. To our knowledge this is the first time

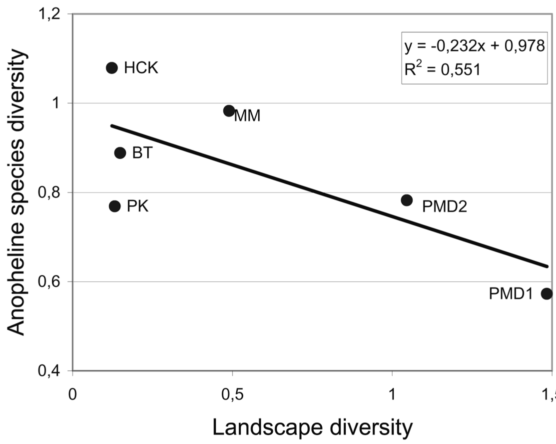

Figure 2. Relationship between anopheline species diversity (H', Shannon-Weaver diversity index) and landscape diversity (Modified Simpson's diversity index) for dry and wet seasons combined. The equation of the regression line and the R^2 is given. See text for landscape site acronyms.

anopheline environmental associations in Southeast Asia have been shown using quantitative landscape analysis. Mapping technology and landscape analysis, could therefore be efficient tools in integrated malaria control strategies in the region and for adapting malaria control planning to local conditions. Such tools have been sought to more efficiently combat malaria (Kitron 1987, Thomson et al. 1996). Furthermore, landscape analysis may be helpful in managing landscapes to create unfavorable environmental conditions for *Anopheles* mosquitoes. Environmental and ecosystem management, involving physical modifications of vector habitats to reduce larval development and human-vector contact, have previously been proposed as options for integrated malaria control strategies (Garcia and Huffaker 1979, Kitron 1987, Ault 1994). Such strategies should focus on environmentally safe management methods.

Anopheline density

Our analysis showed that *An. minimus* and *An. maculatus* were more prevalent in forest locations than in agriculture locations (Table 1). This is no surprise because 80% of all mosquitoes were collected in forest locations. Furthermore, 45% of the total was *An. minimus*. There seem to be seasonal differences in the density of *An. minimus*. During the wet season there were significant differences ($P < 0.05$) between locations, but not during the dry season ($P > 0.05$). This

Table 3. Variables with highest factor loadings from PLS analysis on anopheline species diversity (H') and landscape variables during dry and wet seasons. MPS=mean patch size. MPFD=mean patch fractal dimension.

	Variable	Factor	Loading
Dry season	Component 1 (Q2=42%)		
	X	H'	0.27
	Y	Fruit orchard cover	− 0.33
	Y	Agriculture cover	− 0.33
	Y	Landscape diversity	− 0.31
	Y	Forest cover	0.32
	Component 2 (Q2=46%)		
	X	H'	0.20
	Y	Forest MPFD	0.33
	Y	Paddy field MPFD	0.31
	Y	Village MPFD	0.28
	Y	Agriculture MPFD	0.26
Wet season	Component 1 (Q2=31%)		
	X	H'	0.26
	Y	Shrub MPS	− 0.37
	Y	Shrub MPFD	− 0.35
	Y	Water cover	− 0.26
	Y	Fruit orchard MPS	0.23
	Component 2 (Q2=46%)		
	X	H'	0.22
	Y	Water cover	− 0.38
	Y	Water MPS	− 0.38
	Y	Paddy field MPS	− 0.33
	Y	Fruit orchard MPFD	0.25

is mainly due to a larger variation in density during the dry season in the forest locations (Table 1). We cannot give a plausible explanation for this variation. It would be reasonable to argue that *An. minimus* retreats to the humid forested areas during the dry season and is able to disperse to more populated agricultural areas during the wet season when the climate becomes more favorable. This seems to be the case for *An. dirus* (Wilkinson et al. 1978), but our results do not clearly show a similar pattern for *An. minimus*. Our results, however, support previous research which shows that the highest density peak of *An. minimus* coincides with the wet season (Takagi et al. 1995) and that transmission areas in northern Thailand where *An. minimus* is abundant usually have a high forest cover (Suwonkerd et al. 2002).

The densities of *An. minimus* and *An. maculatus* seem to be negatively related to landscape diversity (Table 2: component 1). This is also evident from the negative relations between these species and the fractal dimensions of village, cultivated land, and stream corridor patches. High fractal dimensions of these land uses seem to indicate high landscape diversity. *Anopheles minimus* density was also related to various water and paddy field metrics, so that when the sizes of these patches increase the density also increases (Table 2). This seemed also to be the case for *An. hyrcanus*.

Abundances of *An. maculatus* and *An. aconitus* were low and they were overrepresented in one landscape each. A larger study including many more landscapes is necessary to reveal more accurate mosquito density-landscape relationships.

Anopheline diversity and richness

We found two apparently contradictory patterns in the effect of landscape heterogeneity on anopheline species diversity. The first pattern shows that anopheline species diversity is negatively associated with landscape diversity (Table 3: component 1 and Figure 2). This indicates that anopheline species diversity in northern Thailand may be low in locations with many land-use classes and little forest cover and that species diversity may decrease as forest cover is reduced and converted into other land uses, such as agriculture and fruit orchards. This is also illustrated in the first PLS component of the dry season, where landscape diversity and land-use covers were dominating factors (Table 3: component 1). The landscape diversity index used here (MSIDI) is a rough index of landscape diversity and simply relates to the number and proportion of different land-use classes. It does not indicate the importance of separate land-use classes or give information about the shapes of land-use patches. Anopheline species diversity was particularly low in PMD1, which was the most developed and urbanized of the six sites (Figure 1). Human activities such as logging, farming, fruit growing, as well as increased rural socioeconomic development, may all affect anopheline species diversity negatively. Easton (1994), for example, reported that urbanization in Macao resulted in a decline to zero of several anopheline species. Evidence suggests that fragmentation of large forest tracts generally reduces arthropod species diversity (Klein 1989; Gibbs and Stanton 2001). The second pattern, on the other hand, indicates that anopheline species diversity in northern Thailand may be positively associated with the fractal dimensions of patches, particularly forest, paddy field, village and agriculture patches (Table 3: component 2). Fractal dimensions increase as patch shapes become more irregular. More irregularly-shaped patches could be a result of habitat fragmentation and land-use intensification. This pattern seems contradictory to the first pattern. Our interpretation of these results is that the two seemingly opposite processes – which actually refer to either landscape composition or landscape configuration – might be at work at the same time. As the number of land-use classes increases at the expense of forest cover (change in landscape composition), anopheline species diversity may decline. In some landscapes, patch shapes may simultaneously become more complex (change in landscape configuration), and as a result of this, anopheline species diversity may increase. Alternatively, the two processes may be separated in time; in already developed locations with a high landscape heterogeneity, species diversity may increase as patch shapes become more complex, because the newly formed habitat edges may function as refuges for many species. Increased species diversity with increasing landscape heterogeneity has been shown in temperate cultivated areas, typically in generalist arthropod communities (Jonsen and Fahrig 1997, Thies and Tscharntke 1999, Weibull et al. 2000). The responses to landscape heterogeneity certainly depend on the behavior and ecology of species, as exemplified by the following two situations (Hoover and Parker 1991). First, high landscape complexity caused by a network of corridors and linear elements may promote dispersal and survivorship of many insect species. Alternatively, high landscape complexity caused by fragmentation and insularity may interrupt species colonization and exchange of genetic material, thus increasing the chances of extinction.

The negative relationship between anopheline species diversity and landscape diversity seems mainly to be driven by agricultural landscapes (Figure 2), although the variation in species diversity in agricultural landscapes (H' ranging from 0.57-0.98 $\approx$ 0.4) was similar to that in forest landscapes (H' ranging from 0.77-1.08 $\approx$ 0.3). The reason for the variation in anopheline species diversity in the forest locations could be related to landscape mean patch sizes, since they also display large variation (Appendix 1). In the forest landscapes, anopheline species diversity seemed to be higher where there were relatively many patches, the mean patch size was small, and the patch shapes were more complex (data not reported here).

The estimated species richness in PMD2 was higher than the observed (Appendix 2). This could mean that further sampling might have resulted in a higher species richness and diversity in this site. The reason for the observed low species richness in PMD2 is not obvious, but could reflect the fact that this site has not undergone such large environmental change as in the neighboring PMD1 site, where species richness was lowest. This result also indicates that areas situated close to each other can display large variation in species richness and diversity and probably also in density. Small-scale spatial variation in anopheline densities was found, for instance, in Papua New Guinea (Smith et al. 1995; Hii et al. 1997). Such small-scale variation can have important consequences for disease transmission (Smith et al. 1995).

Implications for malaria transmission and control

The close relationship between malaria, malaria mosquitoes and forests in Southeast Asia has been discussed in many studies (e.g. Ismail et al. 1978; Myo et al. 1988; Rosenberg et al. 1990; Lwin and Htut 1991). The ecological function of forests for forest-associated anophelines, such as *An. minimus* and *An. maculatus*, is not clearly known. Are forests essential habitats in the life cycle of the mosquito? Or does forest cover act as a socio-bioindicator of undeveloped, natural areas with little human intervention, in which mosquitoes have the best chance to survive and where transmission of malaria can be easily maintained? It is possible that these mosquitoes use forests as resting places or for feeding on forest-dwelling animals as has been shown for *An. dirus* (Eyles et al. 1964, Prakash et al. 1997). *An. dirus* is very strongly associated with forest areas (Ismail et al. 1975) and also uses forests as a refuge during the dry season (Wilkinson et al. 1978). The relationship between malaria and forests could, as mentioned, also be explained from socioeconomic perspectives (Butraporn et al. 1986). Forest villages are usually situated further away from urban centers, the economy is based on agriculture and collecting and hunting in the forest. In general, people are poor and their houses are simple and give insufficient protection from mosquitoes. People in the forest areas are therefore more exposed to infective mosquito bites and have fewer resources available for anti-mosquito measures than people in developed areas. Nevertheless, there seems to be a long evolutionary history indicating the relationships between malaria, anophelines and forests. It has even been suggested that human malarial parasites originated from zoonotic simian plasmodiids in the Southeast Asian tropical forests during prehistoric times (Poolsuwan 1995).

Landscape management for malaria control in these environments, based on our results, would involve large-scale reduction and fragmentation of the forest cover. Such drastic actions would negatively affect forest anophelines by reducing canopy cover, resulting in high sun exposure, low humidity, and fewer breeding sites and day resting places. Removing forest areas does not, of course, agree well with current global objectives concerning forest and biodiversity conservation. Careful considerations of the potential benefits and disadvantages are necessary if landscape management is used to control these species. Following our results, control of *An. minimus* might also be achieved by reducing the sizes of paddy field patches and water bodies (Table 2). More dams and paddy fields may increase the number of potential breeding habitats for this mosquito, such as in the channels leading water from dams or streams to the paddies. These channels are common in many rural areas and although there is usually no overstory shade as in the typical stream habitats, grasses growing at the edges of such channels may give enough shade and reduce the water current velocity enough to provide good breeding habitats. Overgaard et al. (2002) showed that water velocity was the most important factor explaining the density of *An. minimus* larvae and larval control could be achieved by increasing the water velocity by, for example, straightening the water channels or removing edge vegetation.

It is interesting to note that various fruit orchard metrics were negatively correlated with anopheline diversity and with the density of some anophelines (Table 2, Table 3). The reason for this could be that the intense use of pesticides in fruit orchards (Wehner 2000) might negatively affect the abundance and distribution of all anophelines. Gingrich et al. (1990) partially explained the absence of *An. dirus* at their study site in southeastern Thailand to the intensive use of pesticides during the fruit growing season. Our results also indicate that the response to fruit orchards could be different in the dry and wet seasons, however. Generally, fruit orchard indices were negatively related to species diversity in the dry season, but not in the wet season (Table 3). This could be a result of the fact that pesticides in fruit orchards are more often used in the dry season (Wehner 2000). Fruit orchards could therefore function as a semi-natural habitat for mosquitoes and a surrogate for forests during the wet season. Differences in fruit type and orchard management probably influence this pattern, however. Rosenberg et al. (1990) suggested that fruit tree plantations may act as favorable vector habitats, but they did not distinguish between seasons. Singhasivanon et al. (1999) found that up to 35% of the malaria cases in one district in western Thailand were acquired from commercial plantations, of which a majority were fruit orchards. The conversion of forests to fruit orchards is a major land-use change in northern Thailand (C. Walton, University of Leeds, personal communication) and should be viewed with great concern. New research should focus on determining the function of fruit orchards in the transmission of malaria and detecting seasonal differences. Furthermore, emphasis should be put on joint action between health and agricultural institutions in controlling malaria. Possibilities for implementing integrated vector and fruit pest control should also be investigated.

In general, it seems that landscape analysis, such as that undertaken here, may give an indication as to whether or not a landscape is of good quality for anopheline presence. Such analyses may allow us to make predictions about how anopheline fauna will change as a result of landscape changes and it may give us clues as to how landscapes can be managed to suppress populations of disease vectors.

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Appendix 1

App 1. Mean and standard deviation (SD) of landscape structure metrics for landscapes in agricultural and forest locations in northern Thailand in December 1995 (n = 3 for each location). Differences of means between agriculture and forest locations tested using Kruskal-Wallis test (χ^2 = Chi-Square approximation test statistic, P=probability). See McGarigal and Marks (1995) for a full explanation of metrics and their mathematical formulas.

	Agriculture		Forest			
Metrics[1]	Mean	SD	Mean	SD	χ^2	P
Whole landscape						
NP	143.7	18.5	17.3	12.3	3.86	0.049
MPS	8.9	1.1	103.3	70.5	3.86	0.049
MPFD	1.369	0.03	1.3	0.03	3.86	0.049
MSIDI	1.007	0.5	0.135	0.01	3.86	0.049
Agriculture						
COVER	14.5	17.6	1.8	0.4	3.86	0.049
NP	27.7	8.0	4.7	3.2	3.86	0.049
MPS	8.5	11.6	7.9	7.0	0.43	0.513
PSSD	20.2	29.1	1.1	1.3	2.33	0.127
MPFD	1.364	0.02	1.267	0.02	3.86	0.0495
Cultivated land						
COVER	4.9	2.1	0	0	4.35	0.037
NP	23.0	4.6	0	0	4.35	0.037
MPS	2.7	1.2	0	0	4.35	0.037
PSSD	3.8	1.4	0	0	4.35	0.037
MPFD	1.351	0.01	0	0	4.35	0.037
Forest						
COVER	52.5	26.5	93.4	0.6	3.86	0.049
NP	13.0	3.6	1.0	0	4.35	0.037
MPS	49.4	18.1	1173.7	7.5	3.86	0.049
PSSD	98.2	66.1	0	0	4.35	0.037
MPFD	1.350	0.07	1.237	0.03	3.86	0.049
Fruit orchard						
COVER	11.4	9.6	1.0	1.8	2.40	0.121
NP	23.3	18.0	0.3	0.6	3.97	0.046
MPS	5.1	4.1	12.9	22.3	0.44	0.507
PSSD	6.2	5.3	0	0	4.35	0.037
MPFD	1.331	0.001	0.4	0.8	3.97	0.046
Paddy field						
COVER	4.8	2.4	2.6	1.2	1.19	0.275
NP	14.7	9.9	9.0	11.3	1.19	0.275
MPS	4.5	1.4	7.4	5.1	0.43	0.513
PSSD	4.0	0.9	4.6	4.8	0.43	0.513
MPFD	1.359	0.02	1.305	0.02	3.86	0.049
Stream corridor						
COVER	1.1	0.4	0	0	4.35	0.037
NP	2.0	1.0	0	0	4.35	0.037
MPS	7.2	1.1	0	0	4.35	0.037
PSSD	3.5	3.0	0	0	2.40	0.121
MPFD	1.528	0.01	0	0	4.50	0.034
Road						

App 1. Continued.

Metrics[1]	Agriculture		Forest			
	Mean	SD	Mean	SD	χ^2	P
COVER	0.3	0.04	0	0	4.35	0.037
NP	1.3	0.6	0	0	4.50	0.034
MPS	2.7	0.7	0	0	4.35	0.037
PSSD	0.8	1.4	0	0	1.00	0.317
MPFD	1.723	0.05	0	0	4.35	0.037
Shrub						
COVER	7.5	3.8	0.1	0.2	3.97	0.046
NP	28.7	8.7	0.3	0.6	3.97	0.046
MPS	3.5	1.6	1.8	3.0	0.44	0.507
PSSD	4.3	2.2	0	0	4.35	0.037
MPFD	1.391	0.06	0.420	0.7	3.97	0.046
Village						
COVER	3.0	2.6	0.8	0.8	2.33	0.127
NP	9.0	6.2	1.7	0.6	2.63	0.105
MPS	5.0	2.8	5.6	4.4	0.05	0.827
PSSD	3.9	1.9	1.8	2.9	1.19	0.275
MPFD	1.373	0.03	1.258	0.02	3.86	0.049
Water						
COVER	0.1	0.08	0.3	0.5	0.05	0.817
NP	1.0	1.0	0.3	0.6	0.89	0.346
MPS	0.5	0.5	3.6	6.3	0.05	0.817
PSSD	0.4	0.7	0	0	1.00	0.317
MPFD	0.922	0.798	0.423	0.733	1.34	0.246

[1]Landscape metrics acronyms: COVER = percent area, NP = number of patches, MPS = mean patch size (ha), PSSD = patch size standard deviation, MPFD = mean patch fractal dimension, MSIDI = modified Simpson's diversity index

Appendix 2

App 2. Mean density of anopheline mosquitoes in no. per man-hour (± 95% confidence interval), species diversity (H') and species richness (S). Data collected in six landscapes in northern Thailand during dry and wet seasons. See text for landscape acronyms. S_{est} calculated according to Chao (1984); see text for details. *Anopheles minimus* s.l. and *An. maculatus* s.s. are primary malaria vectors, *An. aconitus* is a secondary malaria vector, and *An. hyrcanus* group is not a malaria vector in Thailand.

	Agriculture locations			Forest locations		
	PMD1	PMD2	MM	BT	PK	HCK
Anopheles minimus s.l.	0.169 (± 0.062)	0.236 (± 0.096)	0.333 (± 0.141)	0.882 (± 0.527)	2.104 (± 0.802)	1.050 (± 0.491)
Anopheles maculatus s.s.	0.002 (± 0.003)	0	0.023 (± 0.016)	0.653 (± 0.859)	0.055 (± 0.032)	0.136 (± 0.134)
Anopheles aconitus	0	0	0.871 (± 0.981)	0.026 (± 0.037)	0.004 (± 0.006)	0.050 (± 0.035)
Anopheles hyrcanus group	0.181 (± 0.141)	0.103 (± 0.079)	0.634 (± 0.755)	0.265 (± 0.407)	0.962 (± 0.737)	0.412 (± 0.358)
Species diversity (H')	0.572 (± 0.238)	0.782 (± 0.199)	0.983 (± 0.260)	0.888 (± 0.221)	0.768 (± 0.166)	1.079 (± 0.211)
Observed S (S_{obs})	11	12	14	12	16	15
Estimated S (S_{est})	11	16.5	14.5	12	18.25	15.5

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Original Contributions

Impact of Land-use Change on Dengue and Malaria in Northern Thailand

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Abstract: Land-use change, a major constituent of global environmental change, potentially has significant consequences for human health in relation to mosquito-borne diseases. Land-use change can influence mosquito habitat, and therefore the distribution and abundance of vectors, and land use mediates human–mosquito interactions, including biting rate. Based on a conceptual model linking the landscape, people, and mosquitoes, this interdisciplinary study focused on the impacts of changes in land use on dengue and malaria vectors and dengue transmission in northern Thailand. Extensive data on mosquito presence and abundance, land-use change, and infection risk determinants were collected over 3 years. The results of the different components of the study were then integrated through a set of equations linking land use to disease via mosquito abundance. The impacts of a number of plausible scenarios for future land-use changes in the region, and of concomitant behavioral change were assessed. Results indicated that land-use changes have a detectable impact on mosquito populations and on infection. This impact varies according to the local environment but can be counteracted by adoption of preventive measures.

Keywords: integrated model, land-use change, mosquito-borne diseases, dengue, malaria, Thailand

Introduction

Large areas of the earth's surface are being modified by human activities, constituting an important component of global environmental change. The associated land-use changes have been related to emerging and reemerging diseases (Patz et al., 2004), among multiple, complex factors operating at a range of temporal and spatial scales (Wilcox and Colwell, 2005). Environmental factors are of prime importance to the transmission of vector-borne diseases and include those associated with the host or the vector. The objective of this interdisciplinary study was to investigate empirically the impact of land-use change on

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populations of mosquito vectors of dengue and malaria, and on transmission of dengue in northern Thailand. A conceptual model linking landscape, people, and mosquitoes was first elaborated. Results of a series of empirical studies based on extensive data collection were integrated by a set of equations. Scenarios were then developed based on possible future changes in land use and/or human behavior, and quantified using the integrated model.

The complexity of vector-borne disease transmission has long been recognized and, with it, the need for integrating various factors in models to improve understanding of the system. The most widely known models of disease transmission by mosquitoes to humans are based on the Basic Reproductive Rate (R_0) and the Entomological Inoculation Rate (Rogers, 1988; Anderson and May, 1991; Snow and Gilles, 2002). A key variable in these models is the density of vectors (all vector species included) in relation to humans. Abundance and diversity of vector habitats, as provided by the local environment, and particularly for the immature stages, will promote high vector densities. The behavior and spatial and temporal distributions of human and vector populations are heterogeneous. Even though remote sensing allows describing landscape heterogeneity at a scale that is relevant for insect vectors (Tran and Raffy, 2006), many models do not represent the effects of land cover on vectors, nor do they represent land use as an indicator of human activities and hence of human presence near vector habitats. Most environmental factors currently included in models relate to meteorological or climatic conditions (Focks et al., 1993, 1995).

Conceptual Model

We first developed a conceptual model representing interactions between people (as agents of land-use change and disease hosts), the landscape (as being used by people for their livelihood as well as providing habitats for mosquitoes), and mosquitoes (as disease vectors) (Fig. 1).

People and Landscape

The natural, cultural, and economic environments combine to create conditions to which people in general, and land users in particular, respond and adapt by modifying their land use, e.g., their farming practice (Lambin et al., 2001, 2003). Land use also determines the location and movements of people in the landscape at certain times of the day and of the year. The location of certain activities such as farming may be close to areas with high densities of mosquito breeding sites, at times of day or during seasons that could correspond with mosquito biting peaks.

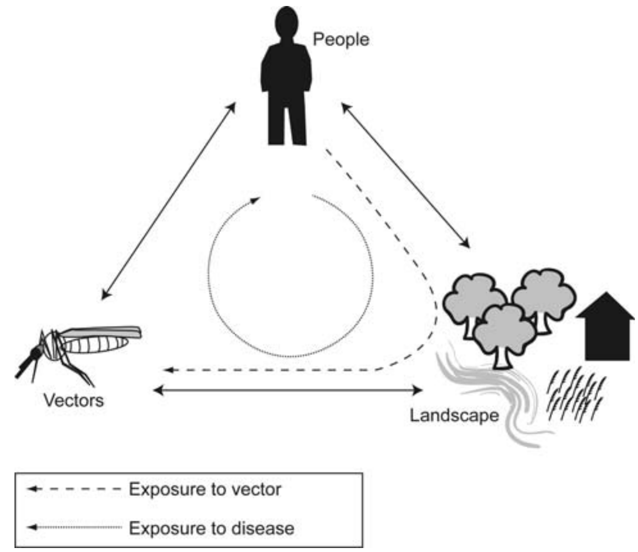

Figure 1. Conceptual model linking people, mosquitoes, and the landscape.

Landscape and Mosquitoes

The spatial distribution of vector-borne diseases is restricted typically by the geographical range of the vector or reservoir host and by their habitat preferences (Kitron, 1998). The immature stages of mosquitoes depend on freestanding water habitats for their survival and development (Service and Townson, 2002). These habitats include a variety of natural and artificial containers and bodies of surface water. Land-use change could allow the colonization of new habitats or the extension or reduction of a vector's range, but could also modify the composition of the mosquito vector community, because vector species differ in their habitat preferences for the immature stages (Patz and Norris, 2004).

Mosquitoes and People

The exposure to mosquito-borne diseases depends on the prevalence of infection and on the exposure of people to biting mosquitoes. Any factor contributing to increased mosquito populations, mosquito longevity, and closer contact between humans and mosquito vectors can influence transmission dynamics. Conversely, most preventive and control measures related to the vector aim to reduce the

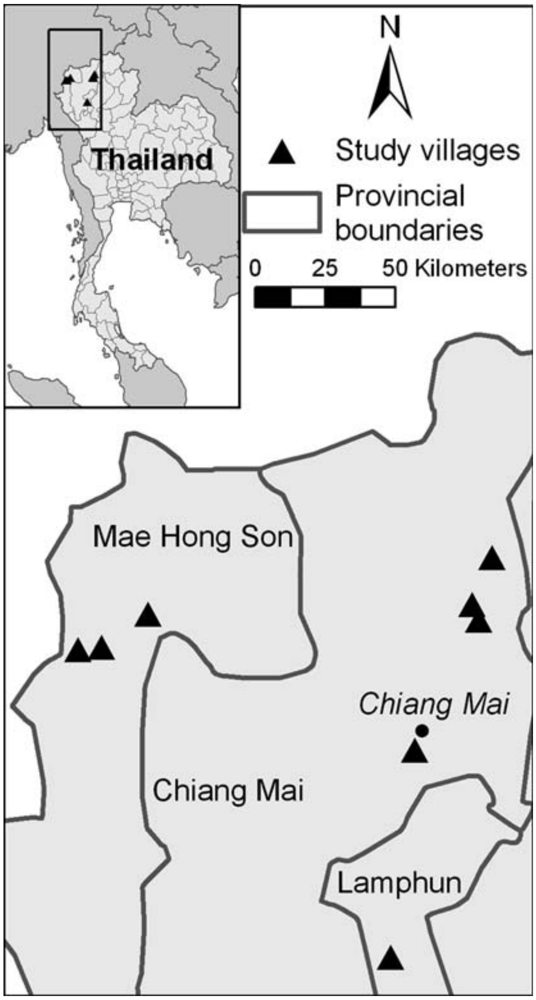

Figure 2. Location of study sites.

mosquito population, the number of contacts between mosquitoes and humans, or the period when humans are infective, for example by rapid detection and treatment of disease. Social and behavioral patterns of humans have thus a significant impact on the epidemiology of mosquito-borne diseases (Fungladda and Butraporn, 1992; WHO, 1985).

Study Area

People–mosquito–landscape interactions were analyzed through extensive data collection over 3 years in seven villages.

In northern Thailand, natural forests are dominated by dry dipterocarp forests and, on moister sites, mixed deciduous forests (Schmidt-Vogt, 1999). Montane forests are found at high altitudes. Lowland farmers usually cultivate irrigated plots in the fertile valley bottoms (from one to three crops a year, including a dry-season crop other than rice) and upland plots of field or tree crops. Upland swidden (slash-and-burn) farmers grow upland rice as well as a variety of vegetables. Three study villages were located in Mae Hong Son province (Fig. 2): Ban Nong Khao Klang, a highland village with rotational swiddening; Ban Huai Pong Kha Nai, and Ban Huai Chang Kham, with irrigated farming and some upland fields. Three villages were included in Chiang Mai province: Ban Pa Nai, located in a wide irrigated valley with intensive irrigated farming supplemented by orchards; Ban Hueng Ngu, located in a narrower irrigated valley surrounded by large areas of fruit orchards; and Pong Bua Baan, a recently created village on the hill slope near Ban Hueng Ngu. Ban Pang, in Lamphun province, is in a narrow lowland valley surrounded by hill slopes where large areas were cleared for longan orchards. A peri-urban village near Chiang Mai, where agriculture is disappearing due to urban development, was also included in the entomological and epidemiological surveys.

The landscape is varied and heterogeneous but landscape units (human settlements, fields, orchards, forests) are larger than the Landsat pixel or are spatially clustered (Fig. 3). Landsat data, in combination with field observations, are thus appropriate to describe the relationship between landscape attributes, the presence of larval habitats, and human exposure to infection.

Materials and Methods

Data Collection

Land cover and land-cover change maps were derived from two Landsat images (Path 131, Row 047: 3 February 1989, TM5, 30 m resolution; and 5 March 2000, ETM+, 30 m; Eros Data Center, Sioux Falls). The images were coregistred, and radiometrically corrected using the invariant features method (Schott et al., 1988; Séguis and Puech, 1997). Image subsets corresponding to the study villages were georeferenced using the 1:50,000 topographic map of Thailand (Royal Thai Survey Department, 1992). Except for one subset where ground control points were scarce, all image subsets had root mean square errors lower than one pixel. Land cover and land-cover change were analyzed using, respectively, supervised maximum likelihood classification and change detection techniques. The accuracy assessment used aerial photographs from 1995 and field observations. Estimated Kappa classification accuracy statistics (KHAT) (Congalton, 1991) ranged between 0.75 and 0.86 for all subsets for both years. The villages were selected

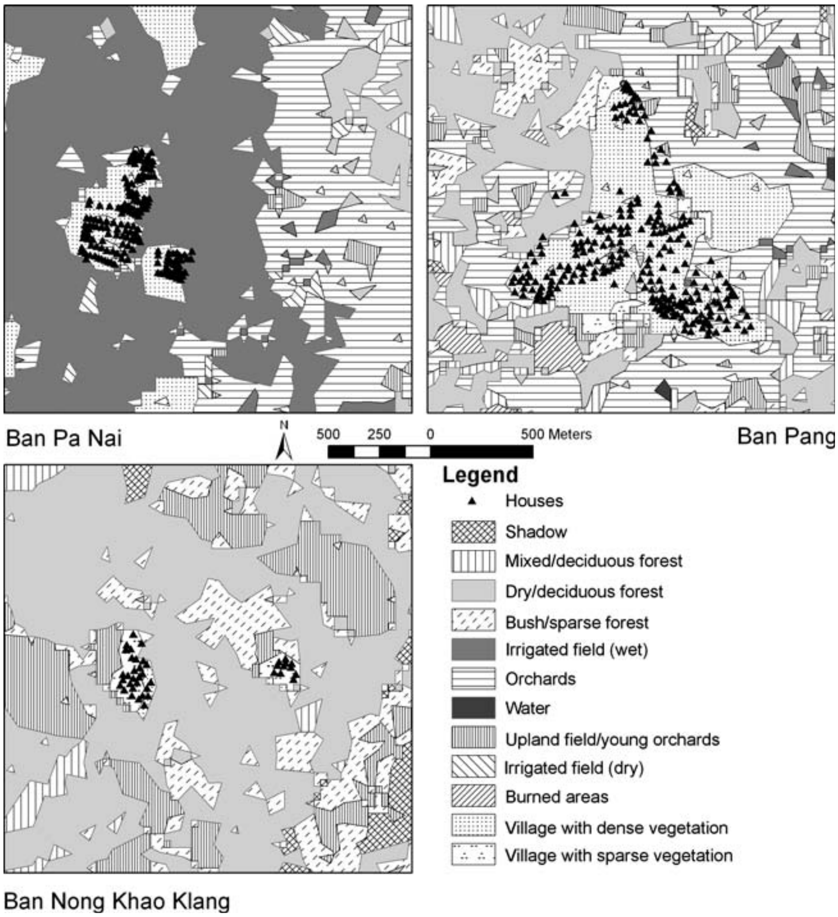

Figure 3. Land cover in three sites.

based on preliminary land-cover change analysis to cover a range of typical northern Thailand landscapes, and on epidemiological records obtained from local or provincial governmental agencies.

A survey of 223 farming households in seven villages allowed the identification of the most important changes in farming systems (Vanwambeke et al., 2006a). A close-ended questionnaire collected household information (occupations, composition, migrant status), agricultural inputs, cultivated areas and creation of new fields, crops grown and production sold, land tenure, forest products gathered, fishing, and fuel consumption. The questionnaire asked detailed information for 2001 and comparative information was collected for two preceding periods.

Mosquito larvae were collected in and around the study villages, up to 5 km from the village center, on eight occasions between May 2003 and April 2004, including the dry season (November–April) and wet season (May–October). A 5 km distance allows covering areas used by the villagers daily (based on village administrative boundaries and as confirmed by interviews) and potential sources of mosquitoes, considering maximum flight distance. Each of the 790 collections was associated with a description of larval habitat, date, and geographic coordinates collected with a Global Positioning System (GPS) with an average positional accuracy smaller than 10 m. Larval habitats were sampled by walking transects (over 900) that were on average 144-m long. Transects were located in each land-cover type detected by remote sensing around each village, well within the land-cover type (at more than 30 m from the edge). All larval habitats were surveyed except in land-cover types where they were very abundant, such as irrigated fields. In this case, a representative random sample was selected independently of the presence or absence of mosquito larvae. Habitats were searched for larvae by emptying the water from containers or by dipping with an enamel pan in larger water bodies. Measures of larvae numbers were recorded in categories of numbers. A sample of mosquito larvae was preserved in ethanol for identification. Morphological identification to species for *Aedes* or to species group for *Anopheles* was conducted by Ralph E. Harbach (National History Museum, London). Outdoor evening landing collections of adult females were conducted at 5–11 stations in each village, 11 times (two evenings each) between May 2001 and February 2003. In the analyses presented here, *Aedes albopictus* and *Ae. aegypti*, (= *Stegomyia albopicta* and *St. aegypti*, respectively, of Reinert et al. [2004]), and the *An. minimus* and *An. maculatus* groups were included. *Anopheles dirus* s.l., a complex of primary malaria vector species, was excluded from the study since very few were found in the study area. Adult data for species groups of *Anopheles* will be presented elsewhere.

Epidemiological data were collected in each village for either malaria or dengue, in a prospective survey over 3 years. The Medical Ethical Committee of Chiang Mai University approved the study, and local permission and collaboration were obtained. Villagers were asked to participate voluntarily in the study. After explaining the purpose of the study, written informed consent was obtained. Potential individual risk determinants were asked by formal questionnaire and included: sex, age, profession, place of birth, knowledge of dengue, daytime location, evening location, housing condition, and use of preventive measures. The dengue survey included the collection of blood samples to test for dengue antibodies (IgM). At the start of the survey, it included 1928 participants, of more than 4 years old in three villages, who were followed-up four times over 3 years (van Benthem et al., 2005; Vanwambeke et al., 2006b). The follow-up rate after 3 years was 81% (fifth survey). Surveys took place in September 2001, 2002, and 2003 (end of the rainy season) and in March 2002 and 2003 (end of the dry season). The participation rate varied from 25% in the peri-urban village to 78%–99% in the rural villages. The malaria survey followed a similar protocol, but, due to a very low incidence in the study villages, risk determinants could not be identified and are thus not reported here.

Methods

A multilevel logistic regression identified the characteristics of households and villages favoring the adoption of farming strategies. Epidemiological and entomological data were integrated with the land-cover maps in a geographic information system (GIS), which was then used to characterize each collection point (larval habitat or house) in terms of landscape structure and land use. Spatial and temporal risk determinants for recent dengue infection were analyzed using multiple logistic regression (van Benthem et al., 2005) and multilevel logistic regression (year, individual, and household) (Vanwambeke et al., 2006b). This method allows consideration of nested data, such as households in villages, or people within households, which violate the assumption of data independence (Kreft and De Leeuw, 1998). Multilevel methods combine within-group and between-group relationships (Snijders and Boskers, 1999), and integrate variables at several levels, e.g., village/household.

Integrated Model

The number of new infections for a disease d in a village v caused by a mosquito taxon c (i.e., incidence per mosquito species/species group) in a year y can be expressed as:

$$\begin{aligned} Disease_{cdvy} = {} & Potential\ Biting\ Rate_{cy} \\ & * Actual\ Biting\ Probability_{v} \\ & * Infective\ Bite\ Probability_{dc} \end{aligned} \quad (1)$$

where $Potential\ Biting\ Rate_{cy}$ is the number of bites for mosquito taxon c and year y, $Actual\ Biting\ Probability_{v}$ is the probability for a potential bite to reach a person in village v, and $Infective\ Bite\ Probability_{dc}$ is the probability for a bite to be infective for disease d for mosquito taxon c. This served as the general framework for constructing the set of equations forming the model. Estimates of mosquito populations based on landscape data were used. In the case of dengue infection, transmission risk was then estimated taking human risk behaviors and preventive measures into account. The model thus included three steps: (i) production of larvae according to the availability of habitat for the immature stages (for malaria and dengue vectors), (ii) development of larvae and infection of adult mosquitoes (for malaria and dengue vectors), and (iii) for dengue only, the number of infective bites received by people according to risk behavior and use of preventive measures. The model functioned at the village level and infections (for dengue) were assumed to take place in or around houses (van Benthem et al., 2005). The detailed formulation of each step and their parameterization was based on the results of the statistical analyses of the data collected in the field and by remote sensing.

Statistical Results

Land-use Change

The main land-use changes observed between 1989 and 2000 in the rural study sites in northern Thailand were the clearing of forest for swidden farming or for permanent

Table 1. Percentage of Land Cover Change between 1989 and 2000 in Village Territories

	NKK	PKN	HCK	BPN	BHG	PBB	BP
Intensification		0.3	0.3	7.7	0.5	0.2	0.0
Clearings		0.1	0.1	0.7	6.9	14.9	6.9
Growth of orchards				0.7	0.1	1.4	1.00
Swidden farming	1.6	0.4	1.6				
Other changes[a]	0.7	0.4	1.7	0.3	4.6	3.4	1.7

NKK, Ban Nong Khao Klang; PKN, Ban Huai Pong Kha Nai; HCK, Ban Huai Chang Kham; BPN, Ban Pa Nai; BHG, Ban Hueng Ngu; PBB, Pong Bua Baan; BP, Ban Pang.

[a]Other changes include forest thinning, forest regrowth, other field conversions, change in water bodies and land cover modification (without change of land cover class).

Table 2. Summary of Multilevel Models of Adoption of New Land Use Strategies

Dependent variable	Intra-class correlation	Significant explanatory variables	Snijders and Bosker's R^2
Intensification of irrigated areas	0.77	Household area of upland field, partial market orientation, social network	0.80
Expansion of orchards	0.44	Household area of upland field, collection of forest food products, household area of orchard, migrant status, village-level average area of orchard	0.46

fields (mostly orchards), and the intensified use of irrigated fields. Clearings for permanent fields represented between 5% and 61% of the change observed in rural villages; these changes occupy up to 15% of a village's territory (Table 1). Many clearings were related to orchard expansion, a strategy adopted by 15% of the interviewed households. The adoption of orchard expansion was related to the average orchard area per household in the village (adjusted Odds Ratio (aOR) = 3.77, 95% confidence interval (95%CI) = 0.98–14.60); traditional farming units, as proxied by the area of upland field, were less likely to expand the orchard area (aOR = 0.40, 95%CI = 0.21–1.03), as were those with a large area of orchard already under use by the household (aOR = 0.19, 95%CI = 0.07–0.52). The model had a Snijders and Bosker's R^2 of 0.46. Intensification of irrigated land (Snijders and Bosker's R^2 = 0.80) is related to the adoption of dry-season, drought-tolerant crops, but was mostly explained by village-level factors (intra-class correlation, i.e., proportion of observed variance at village level, 0.70). It was also related to the existence of a social network, measured by the number of other adopters in the village (aOR = 1.14, 95%CI = 1.01–1.28) (Vanwambeke et al., 2006a). Model results are summarized in Table 2.

Habitat of the Immature Stages of Mosquitoes

Data for presence/absence of larvae were collected at the level of habitats and were then related to landscape variables. The use of transects allowed the identification of larval habitats in various land-cover types, in the dry and wet seasons. The species and species groups were associated with habitat types, from which we derived a proportion of habitats used in the wet and dry season. Density and proportion of use were thus always associated with specific land-cover types (Tables 3, 4). *Aedes aegypti* was found exclusively in artificial containers in settled areas. *Aedes albopictus* was mostly found in artificial containers in villages but also in orchards, and in natural containers in both land covers. *Aedes albopictus* occupies a larger proportion of artificial containers in villages than *Ae. aegypti*. Except for artificial containers in orchards, all types of *Aedes* larval habitats had a higher density during

Table 3. Density and Proportion of Use of *Aedes* Larval Habitat: Mean Value (SE)

	Density in dry season, n ha^{-1}	Density in wet season, n ha^{-1}	Use by *Ae. aegypti*	Use by *Ae. albopictus*
Artificial containers in villages	21.62 (71.56)	139.39 (244.68)	0.16 (0.04)	0.66 (0.05)
Artificial containers in orchards	7.25 (34.75)	6.23 (49.6)	NA	0.37 (0.17)
Natural containers in villages	1.35 (9.16)	20.64 (70.65)	NA	0.5 (0.11)
Natural containers in orchards	0 (0)	7.81 (42.30)	NA	0.5 (0.14)

NA, not applicable.

the wet season. Members of the *An. minimus* and *An. maculatus* groups were found both in forest and villages, in stream habitats and ground pools. The density of stream margins is higher in villages. Stream pools are found more often in forests. Both species groups use a larger fraction of most of the larval habitats in the dry season, when some of them are denser. *Anopheles minimus* tends to use a larger fraction of the available larval habitats than *An. maculatus*. *Anopheles minimus* was found in the majority of stream margin habitats in villages and in a large fraction of those in forests. Members of both species groups were found most frequently in the dry season (Vanwambeke et al., 2007). A more detailed analysis of the influence of weather was not possible as we lacked localized meteorological data. Larvae collection rounds were however spread throughout the year and cover the intra-seasonal variability.

Risk Determinants of Dengue Seropositivity and Recent Dengue Infection

Six percent of the human study population showed recent infection in 2001, but rates of dengue infection varied between surveys and between sites, from less than 1% to over 25%, with a peak in 2002. Although spatial and temporal variation in significant risk determinants was observed, some risk determinants were recurrent. Factors associated with increased risk of infection were the use of abate (a larvicide) (aOR = 1.42, 95%CI = 0.99–2.02) and people spending evenings outside (aOR = 1.52, 95%CI = 1.01–2.29). Factors decreasing risk were the absence of water around the house (aOR = 0.63, 95%CI = 0.46–0.86) and the use of bednets (aOR= 0.43, 95%CI = 0.24–0.80) (van Benthem et al., 2005; Vanwambeke et al., 2006b).

Parameterization of Integrated Model

The section below provides the detailed formulation of each step of the integrated model and describes its parameterization based on the results of the above statistical analyses.

Larval Population As a Function of Landscape Structure

The first step of the model estimates the larval density likely to be found around a village. The land area considered was species/species group specific. It was defined by a circular buffer around the village corresponding to the average flight distance of the species/species group considered, avoiding overlap with neighboring villages by allocating each part of possible overlaps to the nearest village. No feedback between the adult and the larval population was included. The larval population for a given season was estimated from landscape data as:

$$L_x = \sum_{i=C}^{i} \sum_{j=H}^{j} \left[S_{x(c)} * D_{(h-c)} (dry/wet) * U_{x(h-c)} * Avn_x \right] \quad (2)$$

where L_x, the number of larvae of species x, is the sum of the average number of larvae present in habitats found in each land-cover type. There were H types of habitats and C types of land cover. All types of habitats were not found in each type of land cover. In one land-cover type c, for one habitat of type h, the number of larvae was the product of the area of the land cover $S_{x(c)}$ and the density of habitat type in that land cover $D_{(h-c)}$, by the proportion of use of that habitat type in that land cover by species x $U_{x(h-c)}$, and by the average number of larvae in each habitat used Avn_x.

Densities of habitats varied according to season (dry or wet). This product was then summed over all habitat and land-cover types. Initial values of $S_{x(c)}$ were calculated using the land-cover map of 2000. The variables $D_{(h\text{-}c)}$ and $U_{x(h\text{-}c)}$ were estimated from larval collection data based on transects (Tables 3, 4).

Adult Mosquito Development and Infection

The second step of the model estimates the number of larvae likely to become infective adult mosquitoes and the number of meals the females will take on humans. Attempts to link statistically larval habitats to adult mosquito abundance were unsuccessful, as the data sets were not matched temporally, and spatially explicit meteorological data were not available to produce a model with a satisfactory predictive power. This step was therefore based on parameters retrieved from the literature and on classic transmission modeling (Rogers, 1988; Smith and McKenzie, 2004).

The number of adults of species/species group x, A_x, generated from the pool of larvae L_x, depends on the survival rate of larvae to adulthood and the development time, which is a function of temperature. This was calculated for a model time-step of 1 month:

$$A_x = L_x * s * P/d(t) \quad (3)$$

where s is the survival rate, P is the length of the time step in days and $d(t)$ is development time in days as a function of temperature. This formulation is a simplification that ignores the age structure among larvae in the estimation of L_x. A new pool of larvae L_x is produced $P/d(t)$ times in each time step of the model. Since land-use change is the focus of the model, average climatic conditions were used in the model. Monthly mean temperatures over a 12-year period in Chiang Mai were used.

B_x, the number of potential bites given to humans by the emerged adults, depends on their longevity, length of gonotrophic cycle, and anthropophily:

$$B_x = A_x * \frac{Lon * An * F}{2G} \quad (4)$$

where Lon is the mean longevity in days, An is the proportion of bites to humans, and G is the length of gonotrophic cycle in days. A factor of two restricts bites to females, which are assumed to represent half of the emerging adults. One bite is assumed to take place per gonotrophic cycle, except in the case of *Aedes* mosquitoes, for which a factor F accounting for multiple feeding behavior was included ($F = 1$ for *Anopheles*). A fixed rate of anthropophily was used. Lon and G are temperature-dependent, but the range of temperatures in the area is small enough for these to be considered fixed in the model.

The number of potential infective bites I_x depends on the proportion of infective mosquitoes:

$$I_x = B_x * R_x(I) \quad (5)$$

where $R_x(I)$ is the proportion of infective mosquitoes in the mosquito population.

The combination of Equations (3), (4), and (5) gives:

$$I_x = \left[L_x * s * P/d(t) * \frac{Lon * An * F}{2G}\right] * R_x(I) \quad (6)$$

Literature sources for the parameters included here can be found in Appendix. Cross-referencing between several sources was often necessary. Final values were based on an expert judgment based on these sources. Equation (6) combines the *Potential Biting Rate* and the *Infective Bite probability* of the general Equation (1).

Infective Bites Received by People

The third step of the model was only developed for dengue since risk determinants for malaria infection could not be studied due to a very low incidence. It estimates, from the number of potential infective bites I_x, the number of bites actually reaching susceptible people, based on data from the epidemiological survey. First, the number of potential infective bites from each species/species group was summed over a genus to the total number of potential infective bites for a disease:

$$I_{tot} = \sum_{i=X}^{i} I_x \quad (7)$$

This total was then used in the calculation of actual infective bites. The number of actual bites cannot be larger than I_{tot}. Preventive measures reduce the ratio of actual to potential bites, and risk behaviors increase that ratio to a theoretical maximum value of one. In the model, the non-adoption of risk behavior was represented in the same way as the adoption of preventive measures. The efficacy of these measures was represented by the attributable risk fraction (Bruzzi et al., 1985; Rothman, 1998) estimated from the statistical analysis of dengue risk determinants.

Table 4. Density and Proportion of Use of *Anopheles* Larval Habitat: Mean Value (SE)

	Density in dry season, n ha^{-1}	Density in wet season, n ha^{-1}	Use by *An. minimus*—dry season	Use by *An. minimus*—wet season	Use by *An. maculatus*—dry season	Use by *An. maculatus*—wet season
Stream margins in villages	45.91 (92.02)	8.88 (35.08	0.9 (0.07)	0.9 (0.13)	0.14 (0.09)	0 (0.15)
Stream margins in forest	1.14 (19.18)	1.93 (18.69)	0.68 (0.06)	0 (0)	0.05 (0.03)	0 (0)
Stream pools in villages	0 (0)	0 (0)	0.5 (0)	0.5 (0.15)	0 (0)	0.25 (0)
Stream pools in forest	46.92 (205.56)	0 (0)	0.09 (0.05)	0.04 (0.09)	0.44 (0.08)	0.04 (0.09)
Small pool in forest	2.32 (30.89)	10.48 (71.97)	NA	NA	0.36 (0.14)	0.07 (0.06)

NA, not applicable.

$$AB_{tot} = \left[I_{tot} - \left[\sum_{i=P}^{i} (I_{tot} * M_p * E_p) + \sum_{j=R}^{j} (I_{tot} * M_r * E_r) \right] \right] * SR \quad (8)$$

where AB_{tot} is the total number of infective bites received by people, M_p is the rate of use of a preventive measure in the village population, E_p is the efficacy of the preventive measure in protecting people from bites, M_r is the rate of non-use of a risk behavior in the village population, E_r is the efficacy of the non-risk behavior in protecting people from bites, and SR is the rate of susceptible people in the population. M_p, E_p, M_r, and E_r were calculated from data collected during the study. Only the most important risk determinants for dengue infection related to human behavior and use of preventive measures were retained. AB_{tot} is equivalent to infection, but not to symptomatic dengue fever cases, since most infections are asymptomatic (Vanwambeke et al., 2006b). The sum of preventive measures and risk behavior used in Equation (8) corresponds to the *Actual Biting Probability* of the general Equation (1).

Error Estimation and Model Verification

Standard errors were calculated for each model parameter based on field-collected data ($D_{(h\text{-}c)}$, $U_{x(h\text{-}c)}$, and M_p, E_p, M_r and E_r). Propagated errors were calculated following Mulligan and Wainwright (2004). In the calculation of the number of larvae, most parameters had a small standard error (Tables 3, 4); the largest errors were found for natural container habitats and habitats located in the forest. In those areas, habitats are not homogeneously distributed over space, and their density was therefore more difficult to estimate. In the case of human behavior, the largest errors were found for the variables related to mosquito development and habitat (water around houses and use of abate). The calculation of a standard error assumes a normal distribution, whereas $U_{x(h\text{-}c)}$, M_p, and M_r are proportions and follow a binomial distribution. Approximations of standard errors were used but may have resulted in inflated errors.

Accurate prediction of disease incidence cannot be expected from this model, given the abbreviated structure of the model component on disease transmission. However, as no independent data were available to validate the other components of the model, a crude verification compared the model result for a baseline scenario, corresponding to the observed situation, with the observed number of recent dengue infections. Note that only passive surveillance of dengue fever cases is carried out by public health authorities in the study area, whereas the model predicts infection, and 65%–99.7% of infections were asymptomatic. We compared the number of dengue infections calculated by the model for three villages and the recent infections measured in the study population, for the dry and wet seasons (Table 5). The model predicted well the observations of September 2001 for all three sites. The match was less precise for September 2003, especially in the valley site with orchards close by. In May 2003, the model predicted correctly the observations for the dry season in one site but not in the other two. Errors could be related to risk determinants that were not included, such as protective housing characteristics in the peri-urban site. The year 2002 was a peak for dengue transmission in Thailand, and the model results did not predict the number of infections observed. Cyclical peak incidence in dengue cases has been observed in the form of waves emanating from Bangkok (Cummings et al., 2004). The explanation for these cycles is still uncertain, but recent hypotheses emphasize the role of interserotypic cross-immunity and immune selection of strains (Adams et al., 2006; Wearing and Rohani, 2006).These processes are not represented in the model. Aside from this peak year, the model produced a reasonable estimate of the number of new infections at the village level, especially in the wet season.

Table 5. Verification of Model Output: Numbers of New Dengue Infections

Infection data	Valley site (orchards distant)	Valley site (orchards near)	Peri-urban site
Observed September 2001	6	24	25
Observed May 2002	39	163	44
Observed September 2002	59	131	160
Observed May 2003	23	28	8
Observed September 2003	3	5	15
Model output September	6	23	21
Model output May	8	29	26

Scenarios

Scenarios provide plausible alternative images of how the future might unfold. Scenario results are not predictions. They are particularly useful when predictions cannot be made, e.g., to test the possible impact of events outside the domain of observations. Scenarios were generated at the village level to account for the diversity in environmental and social contexts. Scenarios included land-cover change (Scenarios 1 and 2), also combined with human behavioral change (Scenario 3), and changes in the density of mosquito habitats (Scenarios 4 and 5). Model outputs were compared to baseline conditions corresponding to the observed situation in the study villages. Villages were selected for scenario testing according to the importance of the vectors or disease considered. For example, low numbers of dengue vectors were found in upland villages, and transmission is currently unlikely in those areas.

Scenario 1: Forest-cover Decrease

A decrease in forest cover around villages was observed in several study sites, for example, related to agricultural expansion of orchards. As *Anopheles* mosquitoes partly occupy habitats in forest, this is expected to lead to a decline in their population. The scenario considers a 50% decrease in forest cover in the area within flight distance from the village. Significant impacts were noted for members of the *An. minimus* and *An. maculatus* groups, two important malaria vector taxa in Southeast Asia that inhabit both forests and village areas in the dry season. We selected two villages where large numbers of *Anopheles* are found and where malaria transmission had been recorded in the past few years. Forest closely surrounded the first village but was located further away from the other one, located in a valley. The decrease in forest cover resulted in a change in the population of both mosquito species group in the forested site and for the valley site. In the forested site, the difference in the *An. minimus* group was predicted to be slightly smaller than the decrease of *An. maculatus* group, and was proportional to the decrease in forest cover. In the valley site, the population of the *An. minimus* group was predicted to decrease much less than the population of the *An. maculatus* group (Table 6). This difference was due to the distinct distribution of habitats in the two villages: in the forested site, the village area provides approximately 4% of the *An. minimus* group, whereas in the less forested site, the village area provides approximately 27% of the population.

Scenario 2: Orchard Increase

Orchard expansion either takes place at the expense of forest, at a certain distance from villages, or by conversion of existing fields near villages. This was tested for two valley sites with high levels of dengue infection but different landscape patterns and varying importance of orchards in the farming system. Orchards increase in area in both villages, as they do in much of northern Thailand. An increase in the *Ae. albopictus* population is likely to result, leading to a significant effect on dengue transmission. Doubling the orchard area ($S_{x(c)}$) within the flight-distance of the mosquito had a large impact on *Ae. albopictus* populations (Table 7). In a site where orchards are on the valley slopes surrounding the irrigated valley floor (orchards are further than 500 m away from the village), orchards contributed 17% of the *Ae. albopictus* larvae in the dry season and 4% in the wet season. In another site where orchards are located in close proximity to the village (<100 m), they contributed

Table 6. Model Predicted Number of Larvae and Percentage Change in the Number of Larvae of *Anopheles* Species Groups

	An. minimus group			*An. maculatus* group		
	Baseline larvae no.	Result larvae no.	% Change	Baseline larvae no.	Result larvae no.	% Change
Scenario 1—forested site	361,885	188,681	−46	1,753,876	877,880	−50
Scenario 1—valley site	225,136	143,349	−36	1,191,236	599,658	−50
Scenario 4—valley site	225,136	241,315	+7	1,191,236	1,304,339	+9

30% of *Ae. albopictus* larvae in the dry season and 8% in the wet season. The increase in number of *Ae. albopictus* larvae was therefore larger in this site, as orchards contribute a larger part of the population. In that site, the number of larvae was over 30% larger in the dry season.

Scenario 3: Orchard Increase and Increased Use of Preventive Measures

Orchard cultivation and the commercialization of fruit crops is generally associated with an increase in household income and with social changes related to engagement in a market economy. These changes could result in better knowledge about disease risk factors and more investment in protective measures against mosquito bites, or more generally in housing and sanitation improvements. Such effects have been observed for protection against malaria in Africa (see Ijumba and Lindsay, 2001, for examples). To what extent does better prevention compensate for the increase in potential bites caused by an increase in mosquito population in and around orchards? Actually, the rate of use of preventive measures being already very high in the valley villages studied, marginal improvements more than compensated for the increase in potential bites. Combining a 100% increase in orchard area (as in Scenario 2) with the use of preventive measures (M_p) led to a complete suppression of all *Aedes* bites.

Scenario 4: Dam Construction

Numerous dams have been erected in northern Thailand in the past, and various projects are currently under planning. Downstream of dams, streams create favorable habitats for mosquitoes, often under tree cover. This would favor *Anopheles* species that inhabit forests. This scenario simulated a change in the density of permanent stream margin and stream pool habitats. With a year-round 10% increase in stream habitats in forest areas, both *An. minimus* and *An. maculatus* populations increased by a proportion smaller than 10%, with a minor seasonal effect (Table 6). This effect is related to the respective contributions of forest and village areas in the total mosquito populations in the dry and wet seasons.

Scenario 5: Artificial Container Elimination

Dengue prevention campaigns in Thailand and elsewhere emphasize the elimination or covering of artificial containers by citizens, as they provide the main larval habitat for dengue vectors and are often found around houses on private properties. A 50% decrease in the density of artificial containers in villages during the wet season, when water-filled artificial containers are most frequently found, was simulated. *Aedes aegypti*, which only lay eggs in artificial containers in villages, was decreased proportionally, as expected. *Aedes albopictus* also breeds in artificial containers in orchards where larval habitats were not eliminated and therefore its population decreased by a smaller percentage (Table 7). Still, artificial container elimination was predicted to lead to a significant decrease in the number of infective bites received by people.

Discussion and Conclusions

The impact of land-use/land-cover change on the risk of two of the most serious mosquito-borne diseases, malaria and dengue was investigated. Extensive data collection and statistical analyses were conducted by entomologists, epidemiologists, and land-use scientists, who then combined their efforts in building an integrated understanding of the relationships between mosquito populations, disease transmission, and land use. This interdisciplinary work led to a model including explicit causal relationships based on empirical observations. This permits the examination of the effects of changes in specific aspects of the system studied, mostly land-use changes frequently encountered in northern Thailand. The integrated model explicitly includes the link between landscape attributes and larval vector ecology.

Table 7. Model Predicted Number of Larvae and Percentage Change in the Number of Larvae of *Aedes* Species Groups

	Ae. aegypti			*Ae. albopictus*		
	Baseline larvae no.	Result larvae no.	% Change	Baseline larvae no.	Result larvae no.	% Change
Scenario 2—orchards far	1113–7177[a]	1113–7177[a]	0	5890–35,387[a]	6994–37,323[a]	+19–4[a]
Scenario 2—orchards close	3919–25,269[a]	3919–25,269[a]	0	25,933–138,349[a]	34,144–149,404[a]	+32–8[a]
Scenario 5—orchards far	7177	3589	−50	35,387	20,392	−43
Scenario 5—orchards close	25,269	12,635	−50	138,349	81,103	−41

[a]Dry–wet season.

It combined empirical statistical relationships with a simplified representation of the biology of vector development and vector-borne disease transmission. It details causal relationships linking changes in land cover, vector abundance, and risk of infection better than would be the case with purely empirical relationships. It integrates land use and landscape heterogeneity into approaches in epidemiology that have often assumed the environment to be a homogenous space. The model also accounted for a variety of human risk and preventive behaviors.

The data and scenario analyses suggested that land-use changes that are currently widespread across northern Thailand have a detectable impact on mosquito populations, leading to a population increase of some species or species groups, and a decrease of others. Forest decrease, associated in our scenarios with a decrease in malaria vectors, is often related to the expansion of orchards, which hosts *Ae. albopictus*, a dengue vector. Mosquitoes laying eggs in more than one land-cover type and/or more than one larval habitat type have more complex—and thus less easily predictable—responses to land-use/land-cover change, as was illustrated by Scenario 2 and *Aedes* mosquitoes. Beyond the relationship between land-use change and mosquito population, the impact on infection and disease of these changes is further complicated by human behavior. The location of human residences and activities in relation to sources of mosquitoes is a crucial element. Changes in orchard area led to an increase in *Ae. albopictus* population but this could be counteracted by adaptive and preventive measures. Deforestation is associated with a decrease in *An. minimus* populations but, as this species group also breeds in villages where it is in closer contact with humans, changes in housing infrastructure could potentially increase biting rate. Policy intervention, education campaigns, and adoption of preventive measures can counteract (or enhance) effects caused by land-use change, as indicated by Scenario 3.

The unexpected effect of the use of abate (that increases the risk of dengue infection) suggests that the adequate use of preventive measures should be monitored. Delayed or incorrect application could explain this relationship. Use of preventive measures such as abate may also reflect a high mosquito density, as found elsewhere (Thomson et al., 1996). Interactions between land-use change, use of preventive measures, and control policies often lead to non-linear effects on the presence of different mosquito species (Ijumba and Lindsay, 2001). Agricultural intensification and orchard expansion can result in greater integration of households into a market economy, more contacts with urban centers, better awareness about disease risk, and higher income to invest in preventive measures, e.g., window screens and bednets. These changes can influence disease transmission at least as strongly as effects on mosquito populations, and can act towards an increase or a decrease of the risk.

Changes in land use, preventive measures, and control policies will not necessarily have the same effects in different villages. Their impact depends on many factors, including landscape structure, type of housing, level of education, and immigration of infected individuals. Policy intervention for disease control therefore needs to be fine-tuned to local ecological and social settings. Land-use change does have an influence on mosquito populations and disease transmission risk, but its exact effect cannot be easily predicted without this local-scale contextual information.

These results cannot be balanced easily against potential effects of climate change. The relative importance of changes in climate and in land cover would likely vary between places and occur at different spatial and temporal scales. Combining the region-wide effects of climate and the landscape-level effects of land cover and land use on disease transmission is an important challenge.

The value of intact ecosystems, such as forests, in regulating pathogens and disease has been suggested by a number of authors (e.g., Costanza et al., 1997; Foley et al., 2005). The results of this study, which shows that some vectors may increase while others decrease as a result of natural forest conversion, suggests that, at least on the local landscape scale, the presence of forest ecosystems may contribute to, and not diminish, disease. Thus, it could be argued, ecosystems provide "disservices" as well as services. The potential ecosystem "disservice" of supporting vectors should be considered in land-use planning and ecosystem management. The complexity of vector-borne disease transmission calls for an integrated approach considering ecological, biological, and human aspects (Spiegel et al., 2005). Scenario formulation combined with an integrated model calibrated on a large data set allowed assessing of the implications for potential transmission of likely changes in land use, human behavior, control policies, or any combination of these. Interactions between the various changes call for further efforts in developing an interdisciplinary, integrated approach to the multiple factors that influence the intensity of disease transmission. The practice of disease control has already recognized the need for such an integrated approach (Carter et al., 2000; Reiter, 2001), but still suffers from institutional barriers to its implementation.

Feedback from a high risk of disease transmission to land management should exist in cases where the disease risk is high enough to influence land-use decisions. Land conversion that would significantly increase disease risk beyond any capacity to apply preventive measures should be avoided or regulated through policies. In the case of malaria and dengue in Thailand, such a feedback was not observed given available preventive measures that are effective and can be applied at a socially acceptable cost.

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Appendix

Table 1. Literature Sources for Biological Parameters

	Aedes	*Anopheles* typical	*An. minimus*	*An. Maculates*
S	30	19[a]	ND	ND
d(t)	ND	4, 16	8	ND
Lon	30, 1	16	14	27
An	23		8, 9, 10, 14, 22, 24, 26[b]	8, 9, 16, 21, 26, 27[b]
G	ND	4, 16	14	ND
Rx(I)	23	4	3, 5, 6, 7, 8, 10, 12, 14, 17, 18, 20, 24, 25, 26	3, 6, 8, 10, 11, 12, 13, 15, 16, 17, 20, 27, 28, 29
F	2	—	—	—

ND, no data.

[a]Data were available from a restricted number of sources, of which none considered the species included in the present study. Data and references are summarized in 19.

[b]A range of values were obtained from the following references, and a final informed estimate was made.

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QUATERNARY COASTAL MORPHOLOGY AND DEPOSITION IN THAILAND

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Thailand is part of the Asian continent that is generally considered to be tectonically stable compared to adjacent regions in southeastern Asia. However, studies of Quaternary stratigraphic sequences, depositional processes and coastal morphology of the Thailand coast, have provided evidence of continuing Cenozoic epeirogenic movement influencing coastal evolution. These movements have affected coastal and river depositional responses to climate and eustatic sea level change. The Quaternary marine formations are extensive along the coastal zone for a distance of about 1850 km in the Gulf of Thailand and occur sporadically along the 865 km west coast of the Thai Peninsula.

On the Thai Peninsula, the emergence of the west coast has resulted in the formation of numerous islands, drowned valleys, short and narrow beaches and truncated headlands, in the high energy coastal erosion regime of the Andaman Sea. Steep-gradient, short rivers form floodplains of comparatively thin deposits of Quaternary sediments, and narrow bays backed by crescent shape sand ridges. This contrasts with the east coast where thick sequences of Quaternary fluvial and deltaic aggradational deposits, and Holocene progradational beaches, sand spits, tidal flats and lagoons, are indicative of tectonic subsidence with a coastal current transporting sediment into the region.

Along the coastal Central Plain, the Chao Phraya delta is underlain by a thick Plio-Pleistocene deltaic and coastal marine sedimentary sequence. This has accumulated in a basin where the Quaternary tectonic environment is affected by epeirogenic uplift of the western highlands and tilting of the Central Plain. At the western Central Plains margin, rivers have formed distinct alluvial fans while the rest of the coastal plain has landscape features formed in the river delta–prograding coast environment that preceded the postglacial marine transgression.

INTRODUCTION

For this review of Quaternary coastal processes the Thailand coast is grouped into three regions: the west coast Thai Peninsula, east coast Thai Peninsula, and the coastal Lower Central Plain (Fig. 1). Quaternary depositional processes within each region have been classified according to paleoenvironments into fluvial, coastal, laterite, volcanic and lacustrine deposits. The stratigraphic sequences have been broadly grouped into two chronostratigraphic units — Pleistocene and Holocene formations (Dheeradilok, 1992). The Holocene–Pleistocene boundary can be clearly recognized at the coast by an abrupt change in consistency from a soft marine clay to a stiff fluvial sand and clay. In upland areas a laterite formation can also be used as a key marker of the Pleistocene–Holocene boundary (Mekong Secretariat, 1980). A laterite with embedded tektites is also an important horizon for recognizing laterites of Pleistocene age.

Extensive deposits of Quaternary non-marine sediments form the Central Plain area and are overlain with thick marine Holocene clay in the Lower Central Plain. Regional correlations have been made using lithostratigraphic units (Fig. 2). Within the various sequences, the ages of some of the key horizons have been determined mainly by radiocarbon dating.

GEOMORPHIC FEATURES

The landscape of the west coast of the Thai Peninsula is characterized by numerous islands, drowned valleys, steep cliffed and truncated headlands, and small coves or embayments. Embayments are backed by short and narrow beaches, distinctive crescent shape beach ridges, and steep narrow floodplains with thin deposits of Quaternary sediments formed by the short, steep-gradient swift rivers that flow into the Andaman Sea (Fig. 3). Headlands between the bays have steep cliffs and truncated rock spurs as a result of exposure to wave action along a high energy coast. Coastal wave action is predominate during the SW monsoon from April to September (CCOP Secretariat, 1989). In Phang Nga Bay the distinct straight channels running subparallel to N–S direction demonstrate the domination of tidal currents on coastal processes along much of the west coast.

In contrast, the east coast is characterized by a broad coastal plain with sand bars, beach ridges and cheniers occurring in Nakhon Sri Thammarat, Songkhla, Pattani and Narathiwat provinces (Fig. 3). Tidal flats with large lagoons and sand spits are also common along the east coast as well as prodelta deposition at the mouth of the Tapir River in the Surat Thani province. These geomorphic features are a result of Holocene coastal progradation with rivers depositing sediment derived from erosion in the western upland area, and sand carried into the area by first southerly and later northerly-directed longshore current.

Further north in the Gulf of Thailand, the coastal floodplain (Lower Central Plain) landscape, has been formed by fluvial and deltaic deposition by the Chao Phraya, Mae Klong, Mae Nam Thachin and Bang Pakong rivers, and coastal progradation deposition with sediment transported into the area by first southerly and later northerly-directed longshore current. Landscape features include tidal flats and beaches.

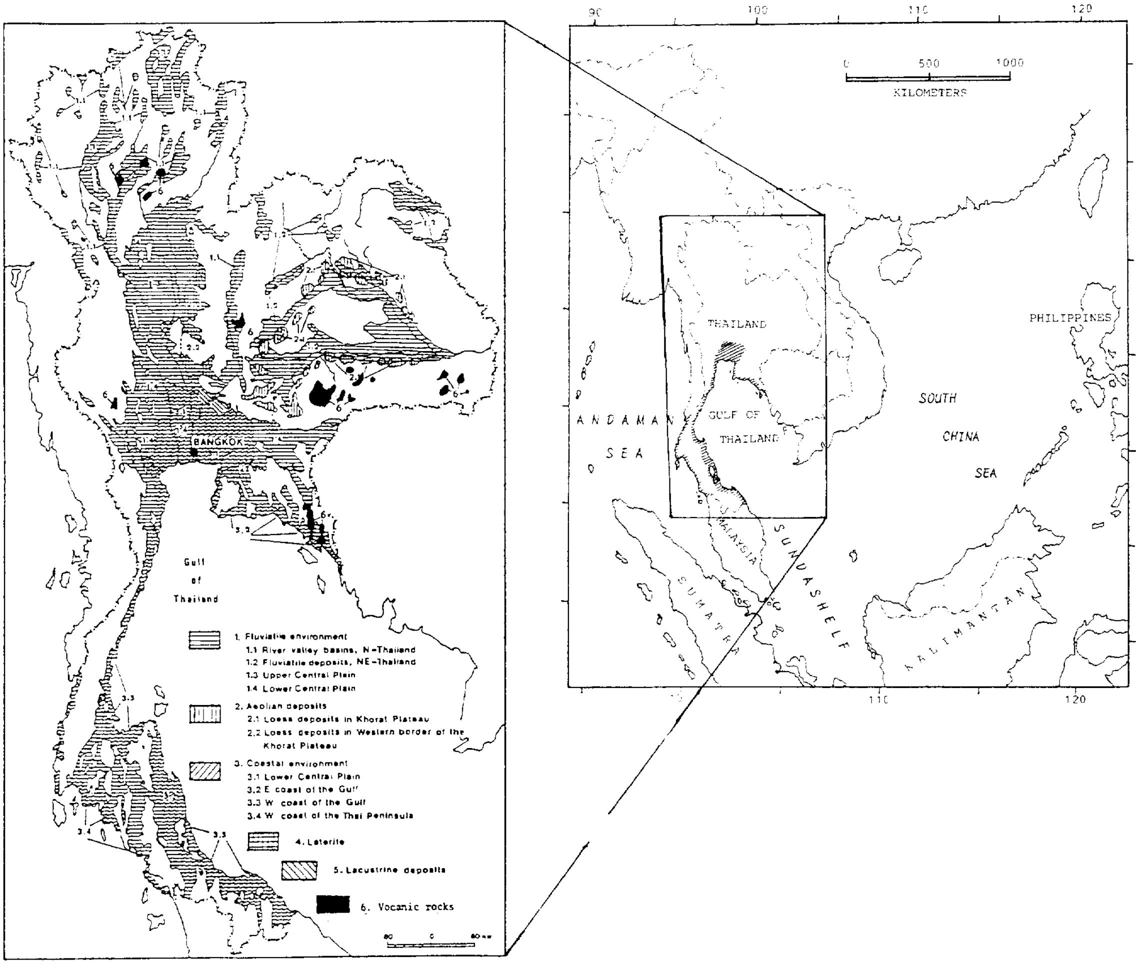

FIG. 1. Map showing the distribution of Quaternary of Thailand.

STRATIGRAPHIC SEQUENCES

Eastern Coast

Quaternary sedimentary sequences are over 200 m thick at the eastern coast of the Thai Peninsula (Sawata *et al.*, 1982). The deposits are mainly sand, clay and gravel layers of Pleistocene colluvial and fluvial origin. Several lateritic layers can be found in this sequence. Tin placer deposits occur at about 40 m below ground surface, immediately below gravel beds in the Hat Yai area (Suthakorn, 1971).

Along the coast a soft, marine Holocene clay overlies a stiff Pleistocene clay formation. This abrupt change marks the boundary between late Pleistocene and early Holocene. It is related to rivers downcutting into their floodplains in response to shortening of their courses imposed by rising sea level. This rapid reduction in total channel length occurred prior to the Holocene marine transgression and subsequent regression and coastal progradation. An erosional unconformity (disconformity) marks the Holocene–Pleistocene boundary.

The lateritic layers within the colluvium and fluvial sediment are believed to be a result of Pleistocene climate changes. The weathering which took place during the late Pleistocene to produce the laterite or oxidized zone on the surface of stiff clay, occurred during a long period of relatively warm climate. It is generally accepted that after 18,000 BP world climate became relatively warmer, ice caps and glaciers receded and sea level rose. During the 18,000–9000 BP period regional fluctuations of climate have affected depositional rates at many Pacific Ocean rim countries and the laterite zones would have been formed during periods of relatively warm climate. Radiocarbon dates of peat deposits from the top of the stiff Pleistocene clay show that the uppermost laterite formation formed before 9000–12,000 BP (Chaimanee, 1987).

Western Coast

The thickness of Quaternary sequences at the west coast is about 20 m and consists of Pleistocene sediments that are mainly residual fluvial deposits which overlie Tertiary or

	Northern Intermontain basin (Lampang basin)	Northeastern Thailand: Khorat Plateau Area (Udomchoke, 1989)	Northeastern Thailand: Low-land Area (Tung Kula Ronghai, TKR)	Central Plain: Upper Central	Central Plain: Lower Central	Southern Thai Peninsula (Songkhla Lake Basin)
HOLOCENE	Meander belts Flood plain PHASE V Alluvium	Alluvium Flood deposits with shells and sherds Wind blown sand Red and yellow loess	Sand of meander belt Clay Non-organic sand	Meander belt Flood plain Terrace I (Sawankalok earthenware)	Bangkok Clay Fm (marine): Top soil alluvivial Subtidal shell & peat (5,000-4,000 -yrs) Soft Clay mem Intertidal	Fluvial/Recent beach dep. Channel/Lacustrine Old beach ridge/Tidalflat peat (4,300-6600 yrs) Flood plain
PLEISTOCENE – UPPER	Laterite Fluviatile deposits PHASE IV Laterite Basaltic flow PHASE III Nam Mae Jang Fm. (0.65-0.95 mys) deep erosion	Organic Sand (34,000-20,000 yrsBP) Ferricrete Young Gravel beds with *tektite* (0.7 my)	Organic sand Lower non-organic sand	Alluvial fan Fm | Kam Phaeng Phet Fm. ---?---	Chao Phaya Fm (non-marine): Estuarine Deltaic sand/silt Stiff Clay mem Lacustrine marl Fm ---?---	Fluviatile dep Redsoil Fm Laterite
PLEISTOCENE – MIDDLE / LOWER	Laterite PHASE II Gravel bed PHASE I Mae Taeng Fm --- Unconf ---	Older Gravel beds (Phu Khao Thong Fm) Bedded iron oxides and Geothite	Alluvial sediments of unknown composition Erosion	Fluviatile coarse sand and gravel with remains of (Terrace III) *Hippopotamus, Stegodon and Bubalus* | Ping Fm.	Phra Pradaeng mem Phra Nakhon mem Somut Prakan mem ---?---	Pediments/Gravel bed. (Terraces) Laterite ---?---
PLIOCENE	Claystone, Siltstone Sandstone	Basalt Weathered Khorat Group	Weathered Mahasarakham Fm.	Upper Miocene	Plio-Miocene	Weathered Older rocks

FIG. 2. Correlation of Quaternary deposits of Thailand.

older rocks. The Pleistocene sediments are capped by intertidal Holocene silt sediments with occasional interbeds of beach sand.

The Quaternary stratigraphic sequences of the west coast are exposed at the Satun area. A Pleistocene laterite layer overlies weathered Carboniferous rocks and is capped by Holocene intertidal deposits. The profile of the Pleistocene fluvial sediments overlying the Tertiary beds can best be observed near the town of Krabi (Chaimanee *et al.*, 1991). Uplifted Tertiary deposits containing coal beds are exposed near the coast of Krabi, as are remnants of coastal landforms including limestone stacks and limestone sea caves containing cemented Holocene shells. These shells are 5 to 10 m above mean sea level and have been radiocarbon dated with ages ranging from 5740 to 3530 BP (Chaimanee *et al.*, 1991). This provides evidence of Holocene eustatic sea level fluctuations (Tjia, 1989) possibly accentuated by a component of tectonic uplift along the west coast during the last 6000 years.

Lower Central Plain

In the Lower Central Plain at the Chao Phraya delta a 650 m thick fluvial, deltaic and almost horizontal Plio-Pleistocene–Holocene sedimentary sequence has accumulated (Piancharoen *et al.*, 1976). The upper part of this sequence contains two formations — the Chao Phraya and the Bangkok Clay formations (Dheeradilok, 1992). In the late Pleistocene, after the deposition of the Plio-Pleistocene deltaic sequences, the sea transgressed over the Lower Central Plain beyond Uthai Thani (Fig. 4), then subsequently receded during the last glacial period 70,000 to 14,000 BP. Pre-14,000 BP sediments are grouped in the Chao Phraya Formation. The postglacial marine transgression occurred over the Central Plain inland as far as Ayutthaya (Fig. 4) 11,000 to 3000 BP (Nutalaya and Rau, 1981) as sea level rose in response to warmer climates. The marine Holocene Bangkok Clay Formation was deposited during the marine transgression and subsequent stable sea level.

QUATERNARY TECTONIC MOVEMENT

Thailand is located on what was considered to be a stable land area when compared to adjacent regions in southeast Asia. To the west of Thailand the Indian and Eurasian continental plates are colliding resulting in Cenozoic tectonic deformation features in Thailand and elsewhere in southeast Asia. In Thailand, two different fault systems can be distinguished; north–south normal transform faults and conjugate northwest–southeast and northnortheast–south southwest strike–slip faults. The Mae Ping and the Three Pagodas faults trend in a northwest–southeast direction while the direction of the Uttaradit, Ranong, and the Klong Marui fault zone is northnortheast–southsouthwest. Strike–slip motions have also created northeast–southwest extensional tectonic regimes at the terminations of these faults and the associated initial extrusion has resulted in a clockwise rotation of continental blocks in southeast Asia (Barr and McDonald, 1978, 1991; Bunopas and Vella, 1989).

In southern Thailand the Ranong and Klong Marui faults

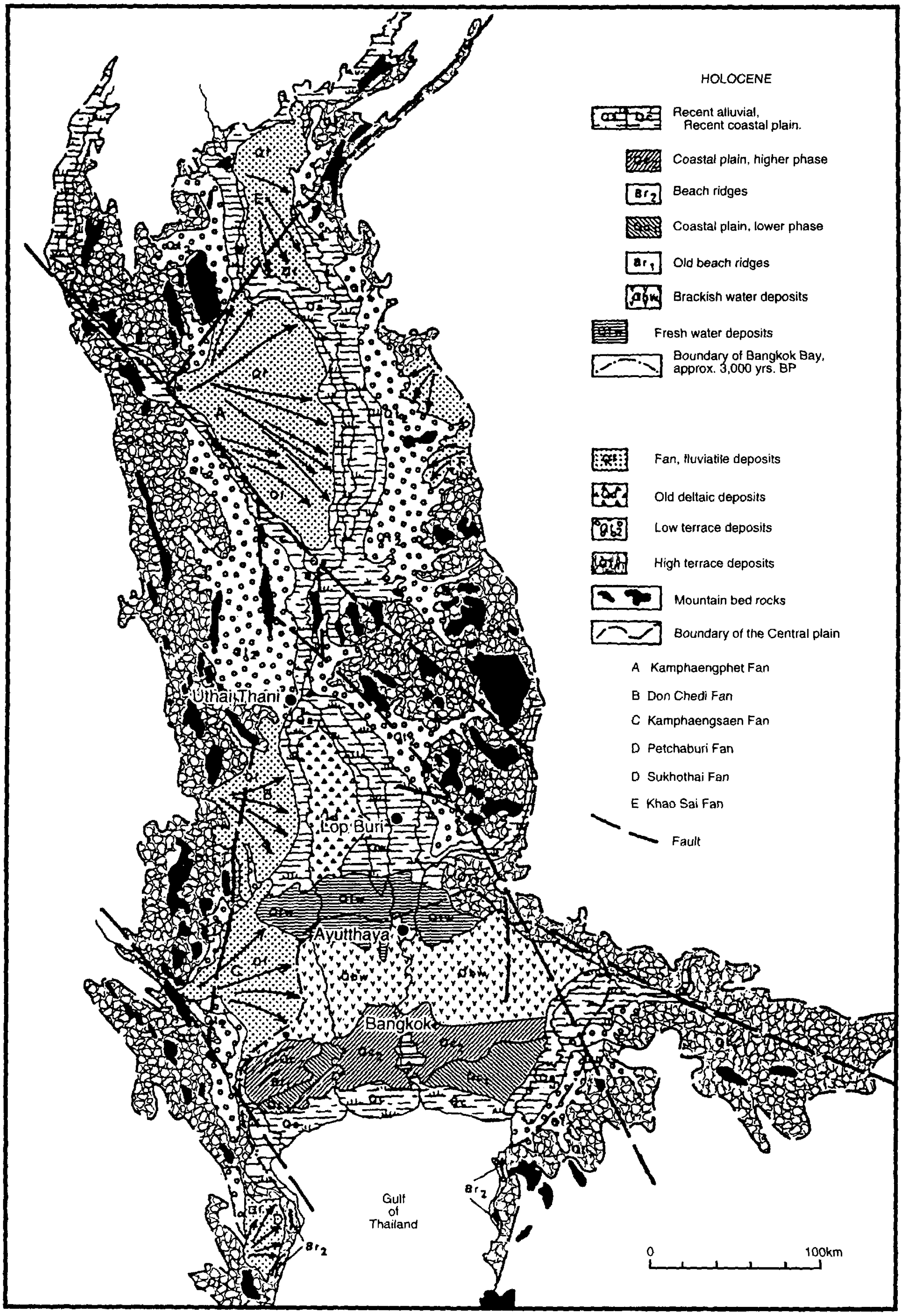

FIG. 3. Thai Peninsula showing geomorphic features, prograding beach ridges on east coast and numerous islands and narrow beaches separated by truncated headlands on the west coast of Thai Peninsula.

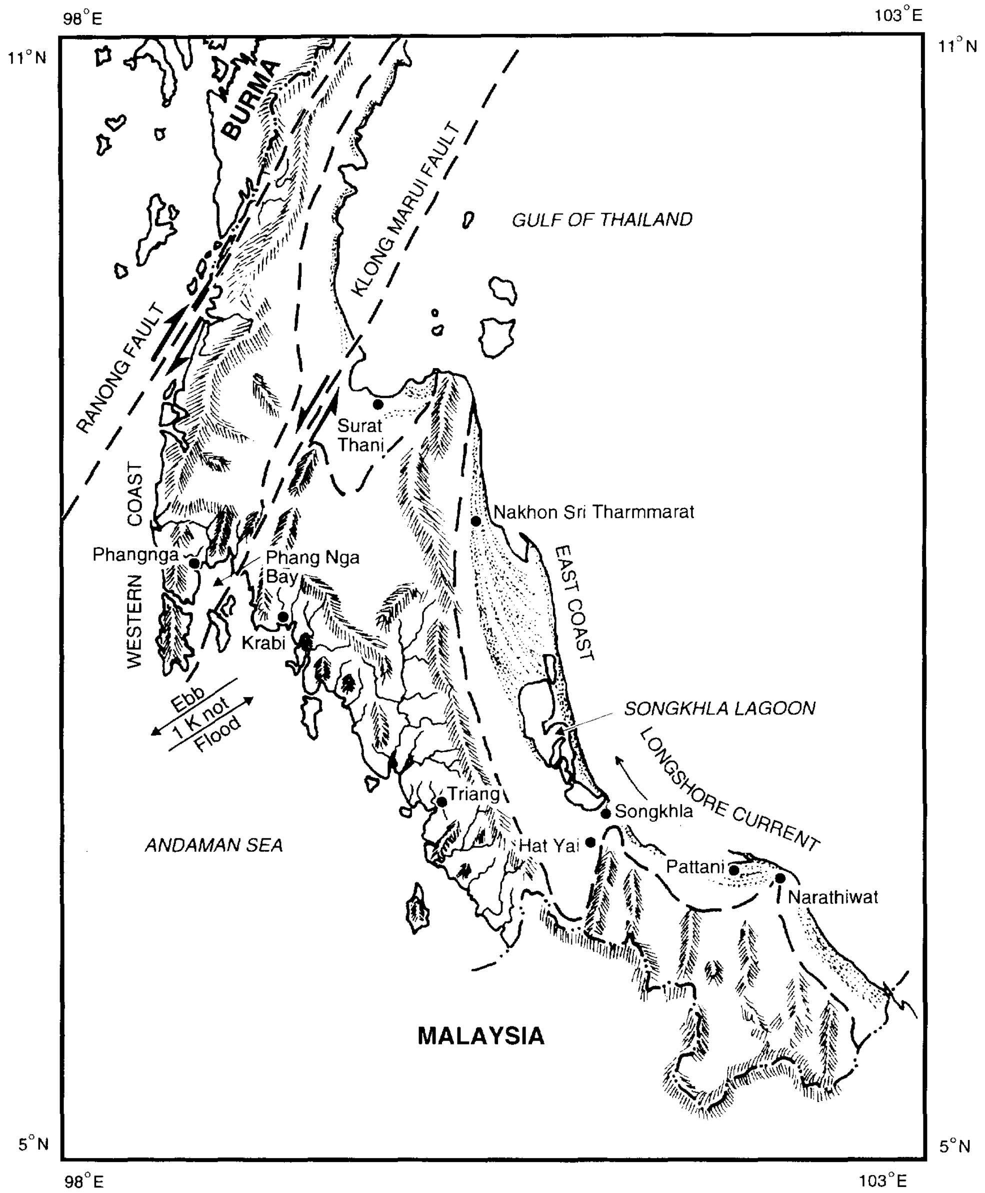

FIG. 4. Generalized surficial geology of the Central Plain of Thailand (complied by Dheeradilok, 1987).

are related to the crustal movements as is the occurrence of shallow intrusive rocks including geyserite at the western coast (Raksaskulwong *et al.*, 1989). In northern and northeastern Thailand near the Cambodia–Laos border crustal disturbances are inferred from the occurrence of Quaternary basaltic effusive rocks.

The western coast of the Thai Peninsula has been affected by Quaternary crustal movements. The Quaternary coastal deposits are mainly thin accumulations at the head of bays. The distinctive coastal landform with steep cliffs, short but steep-gradient river courses, and narrow crescent-shaped beach ridges, suggests river and coastal processes adjusting to epeirogenic uplift. The uplift of the western coast resulted in the emergence of thick Tertiary age coal beds and associated terrestrial fossil shells.

The thick Plio-Pleistocene sedimentary sequences in the Chao Phraya basin indicate the influence on deposition of regional subsidence related to tectonism both within the basin and in the adjacent western highlands. The dominant trends of faulting are northwest and northeast. North–south faults also exist. The direction of river alignments within the Central Plain and strike ridges along the margin of the plain are controlled by faults of Tertiary and Quaternary age (ESCAP Secretariat, 1989; Knox and Wakefield, 1983).

At the eastern rim of the Lower Central Plain, thick deposits of lacustrine marl in the Lop Buri and Saraburi areas are indicative of crustal stability for most of the Pleistocene (Nutalaya *et al.*, 1984). This contrasts with the occurrence of alluvial fans formed by rivers emerging from the uplifted high terrace deposits of the western margin of the plain (Fig. 4) related to crustal movement of a half-graben structure.

CONCLUSION

Throughout the Cenozoic Era the collision of the Indian and Eurasian continental plates has resulted in tectonic deformation of Thailand with faulting and crustal uplift and subsidence. Quaternary basalt effusive rocks in northern and northeastern Thailand and the emplacement of shallow intrusive rocks including geyserites at the west coast provides further evidence for continuing crustal strain. The effects of tectonism have been imposed on the climatic-controlled Quaternary fluvial and coastal processes and Holocene eustatic sea level fluctuations.

The landscape of the coastal Lower Central Plain of Thailand, developed during the Holocene marine transgression and subsequent coastal progradation at about 11,000 to 3000 BP, as fluvial and coastal processes adjusted to the rising and subsequent relatively stable sea level. The Holocene marine Bangkok Clay Formation which covers most of the Lower Central Plain accumulated at this time. The 650 m thick Plio-Pleistocene, fluvial and deltaic sedimentary deposits that underlie the Holocene deposits are a result of Cenozoic tectonic subsidence within the basin and erosion and depositional processes adjusting to tectonic uplift of the adjacent western highlands.

On the Thai Peninsula, there are contrasting coastal processes operating on the east and west coasts. In the west, truncated headlands with steep cliffs separate narrow bays backed by beaches with crescent shape sand ridges, short but steep-gradient river courses and thin Quaternary deposits. On the east coast a broad Holocene progradational plain with a series of long beach ridges or cheniers, sand spits and lagoons has formed in response to the postglacial marine transgression and subsequent coastal progradation. Sand derived from erosional processes at the western upland area and transported by rivers and the east coast longshore current provides sediment for coastal progradation.

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Quaternary geology and sapphire deposits from the BO PHLOI gem field, Kanchanaburi Province, Western Thailand

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Abstract

One of the most famous blue sapphire deposits in Thailand and SE Asia is from the Bo Phloi District, Kanchanaburi Province, Western Thailand. This paper presents the results of our gemstone investigation as well as establishing the Bo Phloi depositional sequence as one of the Quaternary Type Sections in the region. Relationships among the sedimentology, depositional sequences and geomorphology were investigated in order to understand the gemstone depositional features. Sedimentary structures and textures of the sequences show that the deposition of gemstones is related genetically to fluvial processes. Gemstones are recognized in floodplain and low terrace deposits where gemstone paystreaks concentrate mostly inside layers of gravel beds and foreset-bedded gravels lithofacies. C-14 dating of wood and peat within gemstone-bearing layers indicated that the deposit formed during the middle to late Pleistocene. The gemstone-bearing gravel bed defines a north–south trend along the incised palaeo-channel of an ancient braided river system in the middle part of the basin.

Keywords: Bo Phloi; Pleistocene; Sedimentology; Foreset-bedded; Banka

1. Introduction

Studies of ruby and sapphire deposits in Thailand have been carried out for more than two decades. However, it is uncertain when gemstones were first discovered in the Bo Phloi Basin. The detailed sedimentology and geomorphology have not yet been undertaken and the distribution of the gemstone depositional area has not been systematically mapped. Mafic volcanic rocks, alkaline basalt in particular, are believed to be the major carrier of ruby and sapphire in Thailand and adjacent countries in SE Asia based upon the petrology and geochemistry of these deposits (Arunyakanon, 1988; Barr and Macdonald, 1978; Vichit, 1987; Yaemniyom, 1982; Sutthirat et al., 1994).

The Bo Phloi District occupies the centre of the gem field and is located 30 km north of the town of Kanchanaburi. This work was performed mainly in the central part of the area where gemstone mining occurs in order to define and describe the sedimentological features. The first part of the paper will provide a general description and classification of landforms. Afterwards, description of the sedimentology will lead to the evaluation of gemstone reserves in order to construct an evolutional model for the basin. The ultimate results are expected to provide precise information on the palaeo-environment and the distribution of gemstone-bearing gravel strata. Organic material consisting of wood and peat from layers overlying gemstone-bearing gravel beds is presumed to indicate the age of geological events in the basin.

2. Methodology

A careful study of sedimentology in relation to the classification of landforms provides a better understanding of basin evolution. The work began with the interpretation of vertical aerial photographs, accompanied by mapping, before conducting pitting and coring operations. A one-by-one-square-metre test pit was constructed to study stratigraphic sequences. The depth of test pits depends on various factors such as rock basement and the depth of gemstone paystreak. In places where a gemstone placer occurs at a depth too deep for pitting, percussion drilling (so-called "Banka") is a more suitable tool designed to sample the deeper stratigraphic sequences. Banka drilling was also applicable for evaluating gemstone reserves. In the laboratory, morphometrical gravel analysis was carried out to

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evaluate the shape and type of gravels while sieve analysis was conducted to determine the size distribution of unconsolidated sediment.

3. Regional geology

The study area includes a north–south basin, the Bo Phloi Basin, which is sandwiched on both sides by north–south trending mountain ranges. Rocks in the area range from Precambrian to Recent excluding the Cretaceous and early Tertiary (Bunopas and Bunjitradulya, 1975). The Precambrian Thabsila gneiss represents the oldest metamorphic unit in the area. Exposures of Cambro-Ordovician U-Thong Marble, Ordovician Thung Song Group, Silurian–Devonian Bo Phloi Formation and Quaternary deposits were also reported. Intrusions of Triassic granites are scattered in the western mountain ranges. The prominent basaltic eruption at Khao Lan Tom is believed to be the source of blue sapphire and associated minerals found in the basin. The so-called Khao Chong Insi Fault represents a dominant thrust fault that exposed the Thabsila Precambrian gneiss in the northeastern portion of the study area.

4. Geomorphology

Mapping from aerial photographs reveals a variety of geomorphological landforms. Landforms have been classified into three categories consisting of those related to denudation, those of fluvial-colluvial origin and those of fluvial origin (Choowong, 1996). Seven different types of landforms, related to a denudational origin have been further distinguished consisting of mountains of Precambrian gneiss, a karst area of Cambro-Ordovician limestone and marble, mountains of Silurian–Devonian quartzite, hills of metamorphic and sedimentary rocks, mountains of Triassic granite, hills of Tertiary basalt and a peneplain. The peneplain originated from fluvial–colluvial processes and is dominated by two different features; the first is a layer of laterite about 3 m thick and the second is calcareous travertine on lime rich rocks (calcrete) with the thickness ranging from 0.3 to 4 m. Both features display undulating surfaces. Laterite with honeycomb structure is also common. In areas where the combination of landforms cannot be distinguished by air-photos, the term piedmont plain is used to represent the unit of fluvial–colluvial origin.

Landforms of fluvial origin are those genetically related to erosional features along the denuded mountain ranges. The dominant features are river terraces and floodplains, which formed extensively on both sides of the Lam Ta Phoen stream (the major intermittent stream in the central part of the area). High terraces comprise the marginal plain along the eastern part of the basin. Laterite more than 2 m thick marks the high terrace. Middle terraces are apparent along the eastern and western margins of the basin. Tektite has been found inside lateritic gravel beds and gemstone bearing gravel beds of the middle terraces. Low terraces are covered by overbank deposits and therefore are only exposed in the open mines. Wood fragments are also found, particularly in the low terrace deposits. Floodplains with 2.5 km wide deposits were recognized along both sides of Lam Ta Phoen and are much wider to the south in the Khao Chon Kai area. Floodplain deposits consist of gravel beds at the base and layers of stratified sand and silty clay on top. Floodplains also cover parts of the ancient point bar deposit. Small natural levees can be seen along both sides of the Lam Ta Phoen stream.

5. Analyses of Quaternary sediments

Quaternary fluvial successions have been described from the palaeo-channel in the central part of the basin where exposed by open pit mining (Fig. 1). In places, primary sedimentary structures and river terraces along both sides of the main palaeo-channel indicate that an incised-braided river is being developed in the alluvial plain of the basin.

5.1. Elementary facies description

The classification of lithofacies is based on Miall (1984). Here lithofacies of the incised channel deposits are divided into eight sub-facies. Two gravelly facies are composed of massive gravels (Gm) and foreset-bedded gravels (Gp). The sandy lithofacies are subdivided into trough and wedge-shaped cross-bedded sands (St), cross lamination sand (Sc), foreset laminated sands (Sp) and planar stratified sand (Ss). The silty clay lithofacies consists of horizontal laminated silt (Sl) and a combination of silt and mud (Sm).

5.2. Facies a: massive gravels (Gm)

Gravels consist of subangular to subrounded quartzite pebbles, cobbles and boulders up to 20 cm in diameter but an average around 10 cm in diameter. They are matrix supported by sand grains and locally show imbrication. Massive gravels form laterally planar and continuous beds. Horizontal strata consisting of fine particles within massive layers of gravel are uncommon. Weathered basaltic gravel was also recognised.

5.3. Facies b: foreset-bedded gravels (Gp)

Gravels of quartzite, chert and quartz with subangular to subrounded textures have a mean diameter of 7 cm and form a large scale foreset-bed, mixed with layers of medium- to coarse-grained sands. Gravel imbrication is also present. The megastratification dips up to 25° and measures 2–3 m long and 60 cm in height. Cross-stratified sand is common on top of the megastratification.

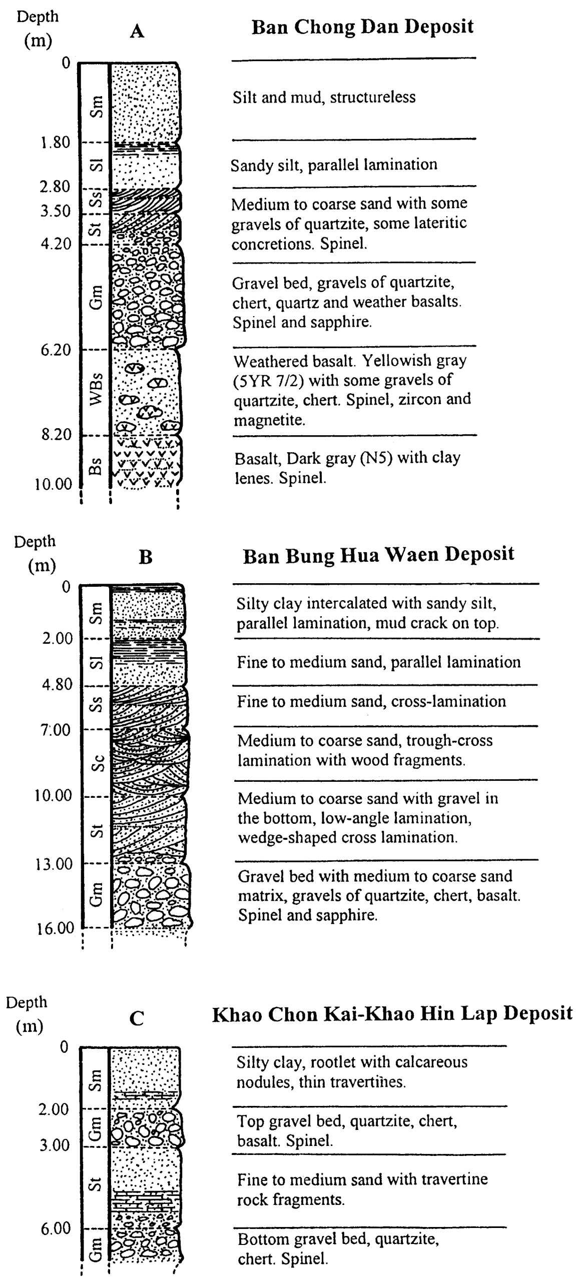

Fig. 1. Quaternary stratigraphic sequences showing different lithofacies at 3 depositional locations. (A) Bang Chong Dan Deposit, (B) Ban Bung Hua Waen Deposit and (C) Khao Chon Kai-Khao Hin Lap Deposit (see Fig. 3 for each location of these deposits).

5.4. Facies c: trough and wedge-shaped cross-bedded sand (St)

An extensive medium- to coarse-grained sand deposit measuring up to 10 m long and 4 m high with a concave shape overlies the foreset-bedded gravel. The major internal structures consist of trough cross-bedding and wedge-shaped cross-bedding, which are abundant and display a fining upward of grain size.

5.5. Facies d: cross lamination sands (Sc)

Normally, extensive medium to coarse-grained sand occurs that typically measure 30 cm wide (sometimes up to 50 cm) and averages around 20 cm thick (sometimes up to 30 cm). Significant sedimentary structures such as cross lamination and low angle lamination were observed. Cobbles and pebbles are not present in the sequence. Wood fragments are also recorded. The average dip angles of cross lamination range from 25 to 30° with a general trend in an east–west direction. Clearly they indicate the major flow direction of north–south braided rivers.

5.6. Facies e: foreset laminated sands (Sp)

Medium and coarse-grained sands display dip angles of 10–20°. Locally, the foreset-laminated sand indicates oxidizing conditions based on the colors of strata. The east–west dipping direction of laminated sands is used to indicate the point bar and flow direction of the palaeochannel.

5.7. Facies f: planar stratified sand (Ss)

This facies consists of fine- to medium-grained sand displaying planar and horizontal stratification. It originated as overbank sediments. The thicknesses of the facies range from 1 to 5 m. Fine sand with a planar stratified layer overlying layers of massive gravel was occasionally observed. Thin parallel lamination indicates the latest flash-flood event within a low flow regime.

5.8. Facies g: horizontal laminated silt (Sl)

Three layers of silt are recognized (1) thin horizontal laminated silt, (2) a thick layer of silt, and (3) a layer of thin laminated silt with low angle lamination. These layers are situated at the top of a fining upward sequence formed by suspended channel deposits. The massive layer of silts contains rootlets and some plant remains. The horizontally laminated silt has been attributed to an upper flow-regime and was deposited mainly on top of point bar sequences.

5.9. Facies h: silt and muds (Sm)

This extensive facies consists of structureless clayey silt ranging in color from yellowish brown to grayish brown. The facies commonly occurs as laminated strata. The upper surface of each unit is partly eroded and commonly shows mud cracks. The fine- to very fine-grained particles indicate quiet water conditions of point bar deposits.

6. Morphometrical gravel analysis

Judging from the morphometrical gravel analysis, fluvial deposits displaying subangular to subrounded grains indicate a short transport distance from the original source rock (Fig. 2A). The stones are mainly quartzite and chert but

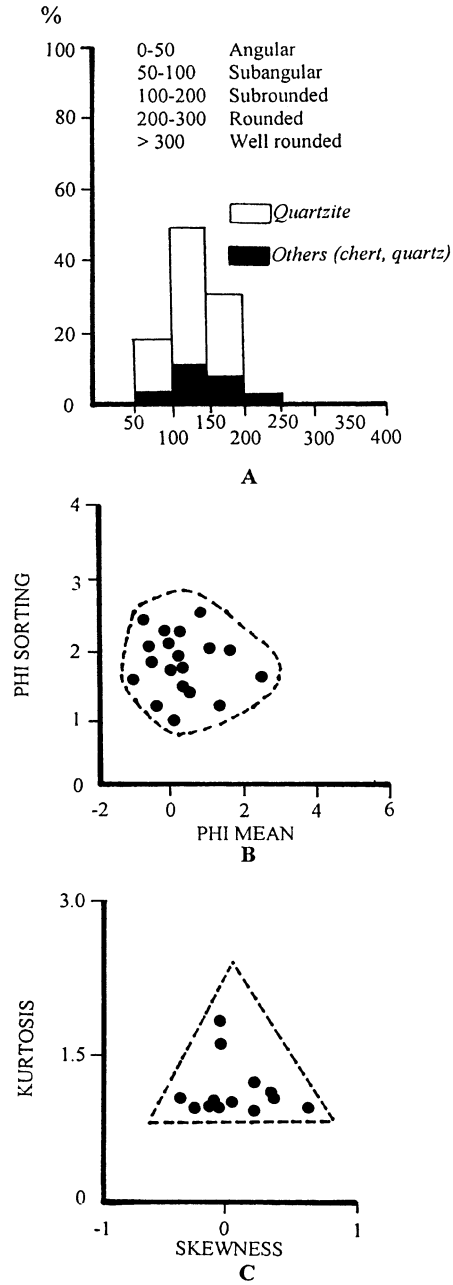

Fig. 2. Sedimentary analyses of gravels and sand deposited in a gem-bearing gravel bed showing (A) histogram of morphometrical analysis of gravel indicating degree of roundness, (B) and (C) scattergram plots of statistic values of sand matrix, Bo Phloi Type Section.

gravels of weathered basalt are also observed indicating that they were either transported from upstream source rocks or represent deeply weathered bedrocks.

7. Particle size analysis

Samples for particle size analysis were collected from the Gm, Gp, St, Sc, Sp and Ss facies and analyzed by sieving. The results are illustrated in histograms, various kinds of graphs and scattered statistical parameters (Fig. 2B and C). Within the area, river sand came from granite outcrops to the west that supplied a large amount of quartz sand and also some mica flakes to the intermontane basin. Sand sizes from various localities are generally fine to very coarse-grained (−0.9–2.33 in phi scale).

8. Radiocarbon dating

The sedimentary profile represents fining upward sequences formed by fluvial action. Wood fragments were typically found at depths between 3 and 5 m, whereas peat was recorded in the deeper layer near the base of the sequences. The meandering of a braided channel was generally recognized. The depth, types of specimens and C-14 age of each organic sample collected from different layers are summarized in Table 1. It was apparent that the wood materials were reworked. Therefore, the dates determined for the wood and peat may not represent the original age of deposition.

9. The episodic evolution of the Basin

Geographically, the Bo Phloi Basin is situated along the southeastern portion of the Three Pagodas Fault in western Thailand. Bunopas and Vella (1983) suggested that the Mae Ping and Three Pagodas Faults (both trending NW–SE) had been active since the late Cretaceous or early Tertiary. The sinistral strike-slip faults caused many Tertiary basins in Thailand to form in the north–south direction, as for example the Mae Moh Basin in northern Thailand. The Bo Phloi Basin is a small intermontane basin trending north–south and apparently developed along north–south faults. This north–south faulting presumably was active

Table 1
Dating of wood and peat samples by radiocarbon

Sample no. and OAEP no.	Grid references	Depth from surface (m)	Types of samples	C-14 age (yrs in BP)
BP 21 and 1468	532855	4.50	Wood	440 ± 160
BP 23o and 1470	528848	14.00	Wood	24,600 ± 3500
BP 23A and 1469	528845	15.00	Peat	26,200 ± 3200
BP 59/3 and 1471	529837	9.00	Wood	27,700 ± 3500
BP 60/3 and 1472	529841	15.60	Wood	32,600 ± 4100
BP 60/5 and 1473	529841	15.80	Peat	35,600 ± 4200
BP 60/6 and 1474	529841	15.80	Peat	33,450 ± 4200

Table 2
Evolution of the Bo Phloi Basin related to its geomorphological landforms

Phase	Events	Relative age
1	Development of peneplain and alluvium by fluvial braided channel, followed by extrusion of the late Tertiary basalt along fracture zones at Khao Lan Tom and Huai Nam Pu. Then, the basalt flowed westward into the basin.	Pliocene
2	The upper strata of alluvium accumulated and accompanied by the formation of high terrace, middle terrace and low terrace.	Late Pliocene to early Pleistocene, middle Pleistocene and late Pleistocene
3	Flooding formed thick uppermost sediments and recent Lam Ta Phoen developed later on.	Holocene

during the late Tertiary and influenced the development of various landforms and the formation of laterite in the peneplain on both sides of the main channel.

Apparently, the evolution of the basin was related to its geomorphological landforms. The episodic evolution of the Quaternary stratigraphy can be divided into three phases as follows.

Phase I: After the erosional and depositional landforms had developed during the late Tertiary, small tectonic adjustments resulted in extrusion of corundum-bearing basalts along the fracture zones of Silurian–Devonian basement rocks in the eastern part of the basin (at Khao Lan Tom and as seen at Khao Chong Insi Fluorite Mine). The basalt may have then flowed westward into the middle portion of the low-lying basin plain and covered an older alluvial substrate. Unfortunately, there has not been enough field evidence to determine how many basaltic flows occur in the area.

Phase II: A narrow sinusoidal river, which later became braided, had developed on the upper alluvial sediments. The river formed terraces at three different levels, namely high terraces (early Pleistocene), middle terraces (middle Pleistocene) and low terraces (late Pleistocene). During this phase, corundum and other associated heavy minerals may have been released from the weathered corundum-bearing basalt and were deposited during formation of the middle terraces.

Phase III: From the late Pleistocene until the Holocene, many tributaries of the Lam Ta Phoen stream developed and drained into the basin. Wood materials dated by C-14 indicate that the sinusoidal braided channel reworked and deposited them within layers of sediment overlying the gem-bearing layers (Table 2).

10. Gemstone Placer deposit

Local prospectors have long searched for sapphires in this

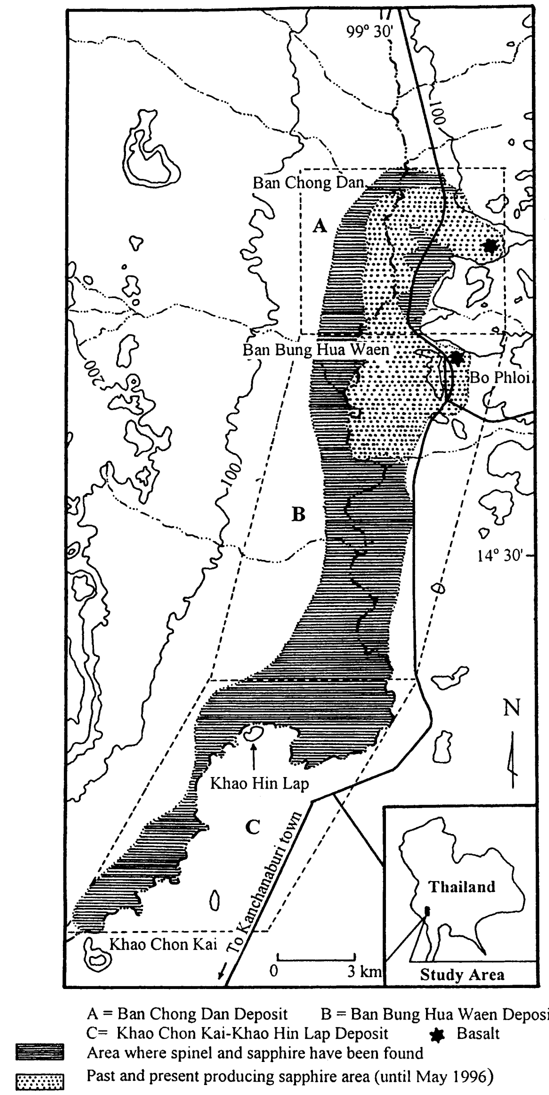

Fig. 3. Gemstone distribution in the Bo Phloi district, Kanchanaburi province with 3 depositional locations (see 3 typical sections in Fig. 1).

area by pitting into gravel layers about 1 and 2 m deep. Until the last decade, mechanized sapphire mining has been performed by many companies in deeper layers to the west and in the centre of the basin. Judging from the test pits, Banka bore-holes and sections along mining-faces, the gemstone deposits in the basin can be divided into three main locations as follows (Fig. 3).

10.1. Ban Chong Dan deposit

Here gemstones are found within the gravel bed overlying layers of weathered basalt. Gemstone paystreaks range from 1 to 4 m thick and are found at an average depth of 14 m from the surface. Basalt recognized east of Khao Skylab is believed to be the source of the gemstone. (Arunyakanon, 1988; Choowong, 1996).

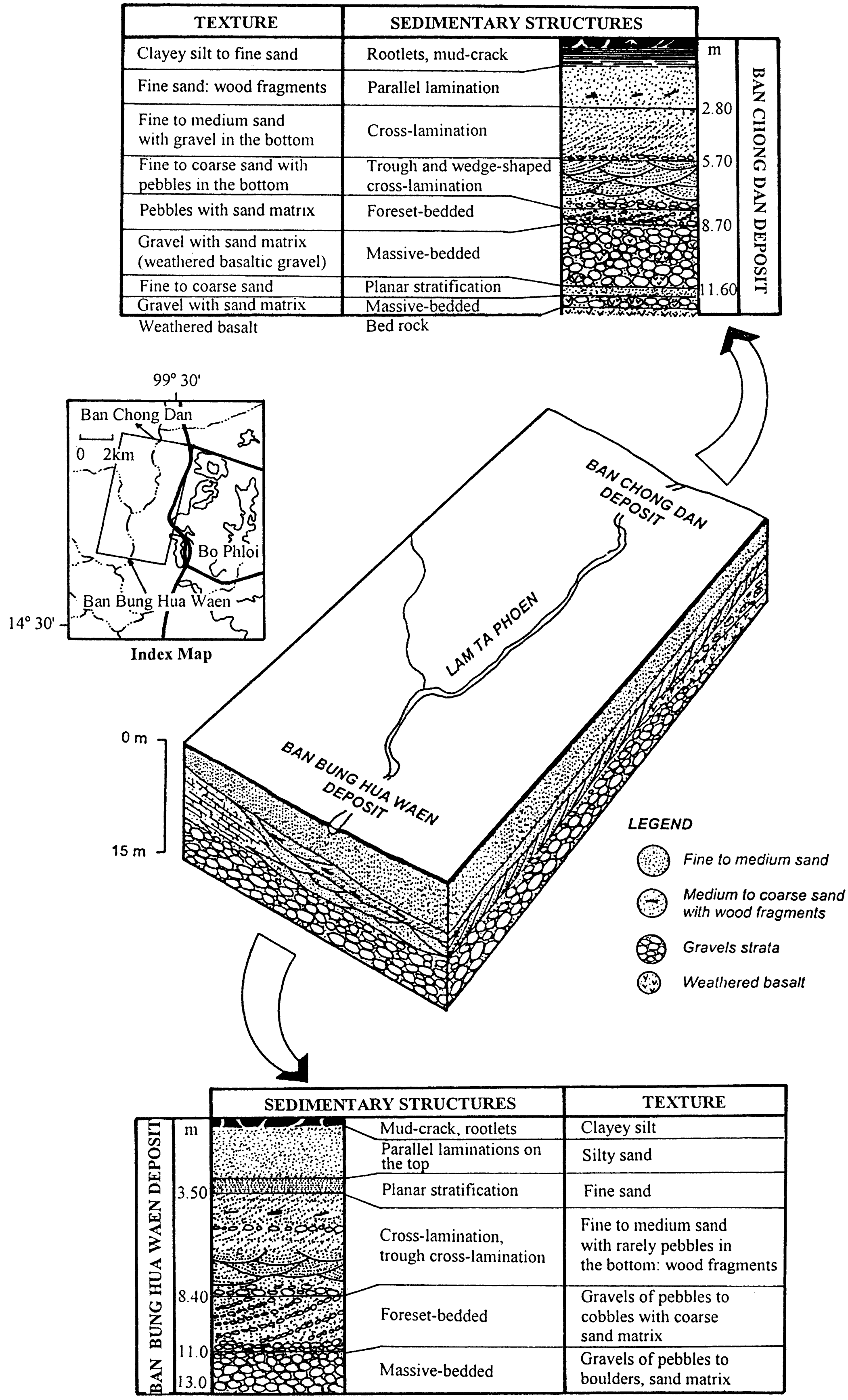

Fig. 4. Schematic block diagram and sedimentary facies illustrate the correlation of two typical depositional sections of the Bo Phloi Type section.

10.2. Ban Bung Hua Waen deposit

Surrounding this area is a gem-bearing gravel bed with a maximum thickness of 5 m. The gravel layer contains unweathered basaltic gravels mixed with abundant quartzite and chert. The depth of gemstone paystreak ranges from 8 to 17 m from the surface. Gemstones in this locality are similar in size but less abundant than in the Ban Chong Dan Deposit. The important source of gemstones around the Ban Bung Hua Waen Deposit is likely the basaltic flows at Khao Lan Tom and some may also have been transported from Bang Chong Dan.

10.3. Khao Hin Lap and Khao Chon Kai deposits

There are two different gemstone depositional layers in this area. Gemstone paystreak has been found at the surface down to a depth of 2 m and also below 6 m depth. The lower layer can presumably correspond to a layer of gem-bearing gravel at the Ban Bung Hua Waen Deposit. However, it is likely that the basalt was exposed somewhere near this locality based on the following evidence, (1) the long transport distance of high specific gravity minerals from Ban Chong Dan and Ban Bung Hua Waen to this location is unlikely, (2) the existence of numerous euhedral and subhedral black spinel that are still preserved, (3) the gemstone depositional layer here is shallower than both localities indicated above, and (4) some loose basaltic blocks have been recognised in nearby test pits (Arunyakanon, 1988; Choowong, 1996).

11. Discussion and conclusion

Studies of the geomorphology and sedimentology are undertaken in order to aquire a better understanding of gemstone deposition. A schematic model showing the relationship between the occurrence of gems and their host-sediments was constructed (Fig. 4). Although the area where gemstone has been deposited is well recognized, the precise extent of the gemstone deposit is still uncertain. Unfortunately, basaltic flows, which reportedly occur beneath the gem-bearing gravel beds, cannot be dated due to a lack of samples. In addition, the results of C-14 dating of wood materials found in the strata overlying the gem-bearing layer seems complicated in terms of stratigraphic continuity. However, dating indicates that the sinousity of the main channel reworked some of the wood materials which were then redeposited on top of the sequence. Even the occurrence of tektite was linked to the middle Pleistocene (around 700 ka, Udomchoke, 1988). Perhaps the tektite in layers of gem-bearing gravel may have also been reworked from sediments somewhere upstream. However, it is suggested that these gem-bearing gravel beds were deposited following the age of the tektite, sometime after the middle Pleistocene. In conclusion, the sedimentology of the incised channel-filled sediment and its structures and textures indicate that the layers containing gem-bearing gravels within the Bo Phloi Basin were deposited by a braided river within a closed intermontane basin during the Quaternary Period.

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Review article

Soil erosion and its impacts on water treatment in the northeastern provinces of Thailand

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Abstract

The economy of Northeast Thailand is mainly based on agriculture. The transformation of forestlands to agricultural areas and the encroachment of riverbanks within the Phong watershed have caused severe soil erosion. Strong storms in rainy season exacerbate the problem of soil erosion. Difficulty in getting water drives people in the upstream region to live on riverbanks. Soil erosion affects water utility by increasing the turbidity in the Phong River and also by decreasing the water storage capacity of small reservoirs for the upstream residents, as well as that of the Ubolratana Dam. The rate of siltation in the Ubolratana Dam was estimated to be 1.5 million tons/year during 1965–1990. The main source of water supply is surface water in the Phong watershed, and fluctuating turbidity makes water treatment difficult. The maximum turbidity in the upstream Phong River exceeds 5000 NTU, whereas it is reduced to be about 300 NTU at the intake point of Khon Kaen Municipal Water Treatment Plant because the Ubolratana Dam works as a huge clarifier. Khon Kaen Municipal Waterworks has a daily water supply of 72,960 m^3/day. The average amounts of alum used in the wet (May–October) and dry (November–April) periods are 42.33 g/m^3 and 28.46 g/m^3, respectively. The average costs of the amounts of alum used are 0.213 and 0.143 Bahts/m^3 during the wet and dry periods, respectively. Fluctuation of turbidity in raw water makes it difficult to adjust alum dose, resulting in treated water quality unstable, and handling of sludge disposal difficult.

Keywords: Land uses; Soil erosion; Turbidity; Water treatment; Phong watershed

Contents

1. Introduction

The northeastern region of Thailand covers 170,000 km^2 and is bounded on the north and the east by the Mekong River,

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which is the border with Laos; on the west by the Phetchabun Mountain Range and on the south by the Dangrek Mountain Range, where there is a border with Cambodia. According to the Bank of Thailand (2004), the area and population in the northeast account for one third of the whole country's area and population, whereas their income is only about one tenth (11.2%) of the national income. Most of the population in the northeast Thailand lives on farming. The 1995 per-capita income was only 24,311 Bahts/year, which was the lowest in the country. The average income was only one ninth of the average annual per capita-income of the Bangkok residents (238,894 Bahts).

The Phong watershed (Fig. 1) is the most important watershed in the upper northeast region of Thailand. The Phong River is a tributary of the Chi River system, which flows into the Mekong River. Its catchment covers 1,518,900 ha, extending to five provinces of Chaiyaphum, Khon Kaen, Loei, Nong Bua Lumphu, and Petchaboon. The upstream watershed area is divided by the four main rivers namely the Phrom, the Choen, the Phaneng, and the upstream Phong. These rivers run into the Ubolratana Dam, which is located in the middle region of the Phong watershed. The downstream Phong River is divided into two river sections, namely sections from the Ubonratana Dam to Nong Wai irrigation weir and from the weir to Mahasarakam dam. The upper Phong watershed shares 79.59% of the total watershed area, and its land is comprised of 27.33% forest, 64.05% agriculture (mainly rain-fed paddy fields and plantations producing crops such as cassava, corn and sugarcane), and 8.62% other uses. The majority of the agricultural land has been transformed from forestland in the last few decades. This land transformation, together with farming practices without soil conservation, causes soil erosion and increased suspended solids in rivers, which silt up reservoirs, raise the riverbeds and affect water quality and water uses due to elevated turbidity levels in the rainy season.

There are two main state organizations responsible for water supply in Thailand. The Metropolitan Waterworks Authority (MWA) supplies water to three central provinces of Bangkok, Nonthaburi and Samut Prakan. The Provincial Waterworks Authority (PWA) provides services of water supply to the

Table 1
Slope length and steepness in the Phong watershed classified by different types of land use

Rivers	Slope length and steepness		
	Forest	Crop	Paddy
Choen	0.03–1.32	0.03–0.19	0.03–0.19
Phaneng	0.03–1.32	0.03–0.06	0.03–0.52
Phrom	0.03–1.32	0.03–0.52	0.03–1.32
Upstream Phong	0.03–1.32	0.03–0.52	0.03–1.32
Ubonratana Dam	0.03–0.60	0.03–0.06	0.03–0.19
Downstream Phong	0.03–0.60	0.03–0.52	0.03–0.06

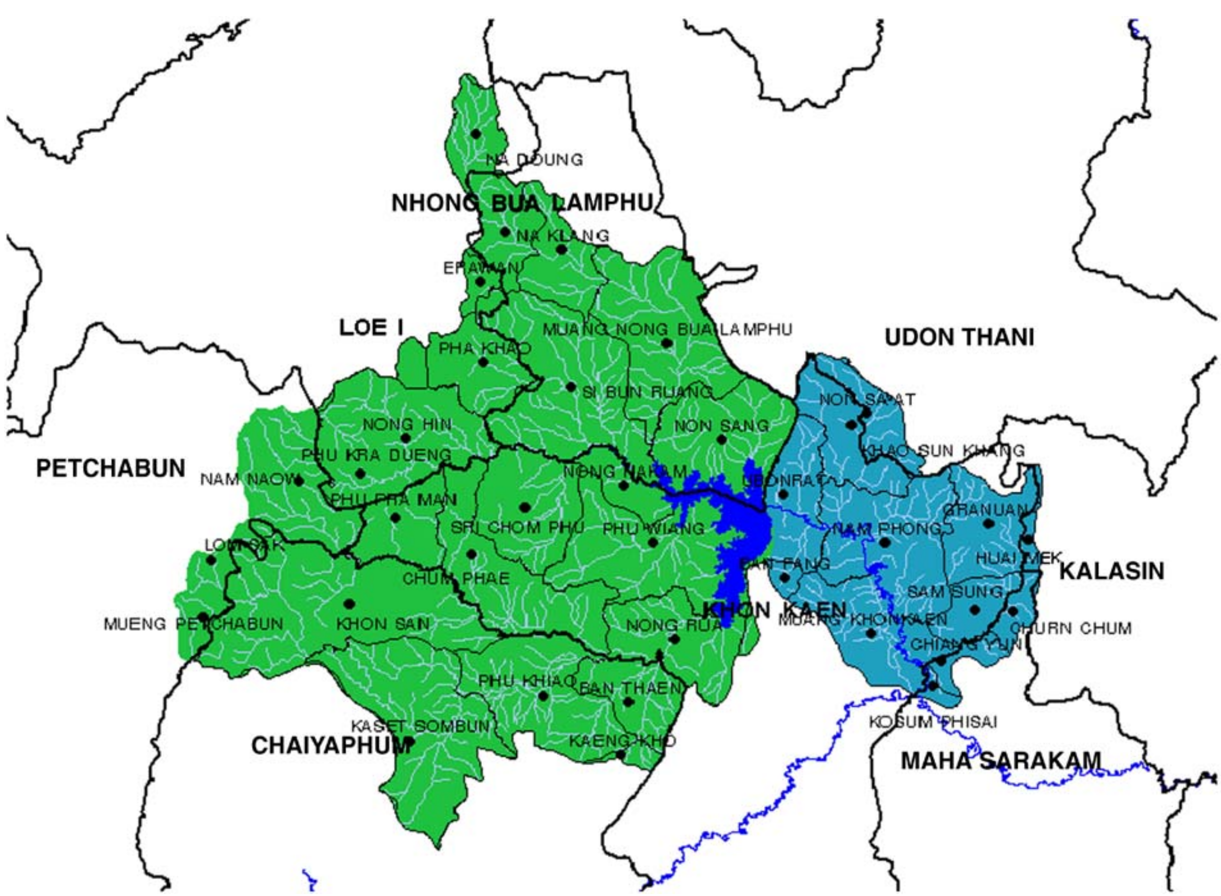

Fig. 1. The Phong Watershed Map (KKU, 1995).

Table 2
Land use in the upper Phong watershed

Land use	Area (ha)	Upstream watershed area accounted for (%)	Remarks
1. Reservoir	30,830.08	2.55	–
2. Agriculture	774,295.04	64.05	Rice, cassava, sugar cane, corn
3. Forest	330,392.32	27.33	Evergreen and non-evergreen forests
4. Community and household industry	40,020.00	3.31	Rice noodle production and brick manufacture
5. Industry	–	–	Two sugar mills
6. Others	33,365.60	2.76	Grasslands and abandoned areas

remaining 73 provinces. According to the PWA (2004), 80.66% of provincial water treatment plants use surface water as raw water, whereas the rest of water treatment plants (19.34%) use groundwater.

This paper focuses on the problem of soil erosion and its effect on water supply in the Phong watershed. The main objectives are to describe the situation of soil erosion in the upper Phong watershed based on data collected from several local and national organizations and to evaluate the impacts of soil erosion on municipal water supply in Khon Kaen City, which uses the Phong River as a source of raw water.

2. Current situations

2.1. Phong watershed characteristics

The highest average rainfall is in September. The southern part of the watershed has quite low average annual rainfall (800 mm) compared to the northern part of the watershed (1300 mm). The lowest average rainfall in the Phong watershed is in January (3.86 mm), a dry season, compared to the highest one found in September (227.35 mm), a wet season. The highest amount of runoff is in September and October in the range of annual runoff from 46.7 to 68.5%. The range of annual specific rainfall yield per area is in between 4.24 and 10.09 l/s km^2

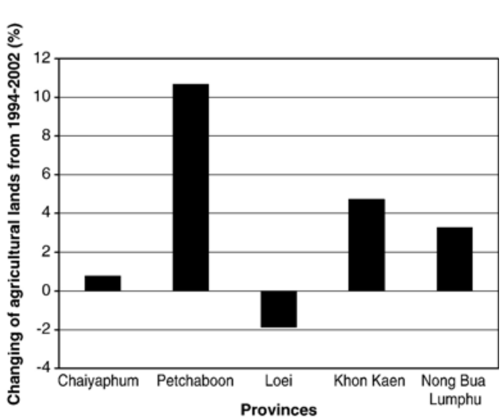

Fig. 2. The mean annual rates of increase of agricultural land between 1994 and 2002. (% per year).

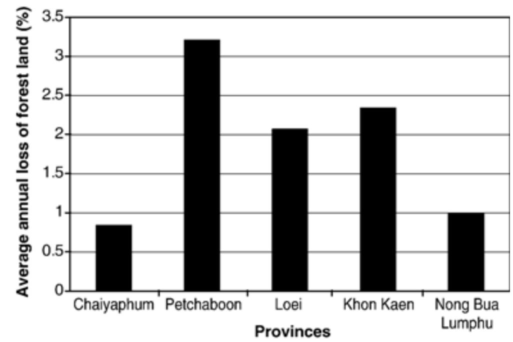

Fig. 3. The mean annual losses of forestland between 1988 and 1999. (% per year).

(KKU, 2003). According to the water samplings data in January (a dry season) and July (a wet season) 2006, the flow rate is very low in a dry season (average 0.45 Mm^3/day) and very high in a wet season (average 1.25 Mm^3/day).

Regarding the slope length and steepness, Table 1 summarizes its values classified based on different land use types in the Phong watershed. Table 1 clearly indicates that crop plantations and paddy fields can be found even in the high slope length and steepness of forest areas, especially in the Prom and upstream and downstream Phong Rivers.

The water samples collected in the years 2004 and 2005 in the upper Phong watershed show that averages turbidity, suspended solids, and total coliform were clearly much higher in the wet season compared to the dry season at 316 NTU (wet): 8.87 NTU (dry), 175.88 mg/l (wet): 13.73 mg/l (dry) and 815 MPN/100 ml (wet): 451.66 MPN/100 ml (dry), respectively. However, averages of TDS, NO_3^-, PO_4^{3-}, alkalinity and conductivity were lower in a wet season than a dry season as following; 149.88 mg/l (wet): 161.62 mg/l (dry), 0.47 mg/l (wet): 0.99 mg/l (dry), 0.09 mg/l (wet): 1.50 mg/l (dry), 83.73 mg/l as $CaCO_3$ (wet): 118.72 mg/l as $CaCO_3$ (dry), and 181.90 mS/cm (wet): 260.28 mS/cm (dry), respectively. When comparing the upper Phong water quality with the surface water standard of Thailand, we found that concentrations of NO_3^- and total coliform in both wet and dry seasons were lower than the class 2 surface water standard set for both values at 5.0 mg/l and 5000 MPN/100 ml, respectively.

2.2. Land use in the upper Phong watershed

A total of 1,208,900 ha of upstream Phong watershed can be divided into different land use types such as agriculture, forestry, community and industry. The breakdown of land uses as of 1995 is shown in Table 2.

Table 3
The percentages of forest and agricultural lands in the upper Phong watershed

Rivers	Agricultural land* (%)	Forest land (%)
Choen	67.75	32.25
Phaneng	58.64	41.36
Phrom	47.45	52.55
Upper Phong	96.02	3.98

*Including paddy, crops and grass and empty lands.

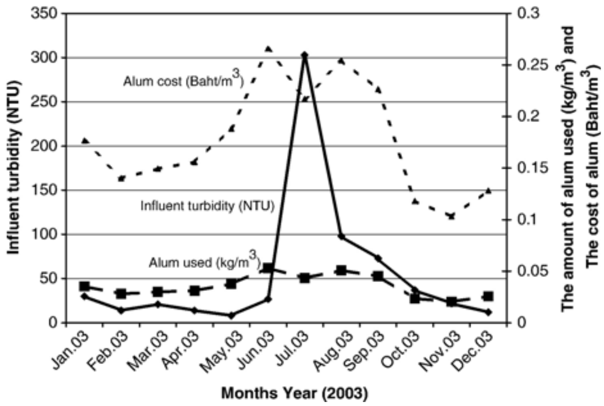

Fig. 4. Influent turbidity-alum used-alum cost at a water treatment plant.

The agricultural lands increased between 1994 and 2002 in the provinces of Chaiyaphum, Nong Bua Lumphu, Khon Kaen and Petchaboon at average annual rates of 0.77, 3.28, 4.71, and 10.66%, respectively. Between 1988 and 1999 all of forest areas in all the provinces of Chaiyaphum, Nong Bua Lumphu, Khon Kaen, Petchaboon and Loei had been decreased at the average annual rate of 0.84, 1.00, 2.34, 3.21, and 2.07%, respectively (Office of Agricultural Economics, 2004) (Figs. 2 and 3).

According to the Khon Kaen University (KKU) report (2003), a study conducted by the Office of Environmental Planning and Policy in 1994 reported that 93.54% of the upper Choen was covered with forest in 1983. Later in 1993, the forestland was considerably reduced to only 68.31%. During the same period, the deforestation rate increased from 184.00 ha in 1983 to 704.00 and 3268.96 ha in 1989 and 1993, respectively.

In addition, the Bank of Thailand (2004) states that use of natural resources during the economic development in the northeast Thailand was extravagant. Soil, water, and forest resources are depleting at staggering rates. More than 1.6 million ha of forests was destroyed during the past 20 years, from approximately 4 million ha in 1975 to only 2.24 million ha in 1995. 0.32 million ha was encroached and turned to paddy and 0.64 million ha was turned into crop fields. Transformation of land use from the forest area into agricultural area in the past 30 years within the Phong watershed resulting in the remaining of only 10–15% of the total watershed area have caused many problems such as flooding, soil erosion and sedimentation, soil salinity, and water quality (KKU, 2003).

2.3. Impacts of soil erosion on water quality and water quantity

The suspended solids in the main rivers of the upper Phong watershed was monitored by Khon Kaen University (2003). The results show that the amounts of transported suspended solids in the rivers of Phrom, Choen, upper Phong, Phaneng were 0.06, 0.32, 1.04, 0.19 tons/ha/year, respectively. According to KKU (2003), the highest amount of suspended solids transportation was found in the upper Phong River (1.04 tons/ha/year) because of the less forest coverage compared to the higher forest coverages in other rivers (Table 3).

The Electricity Generation Authority of Thailand (EGAT) reported that the average annual amount of siltation in the Ubolratana dam was 1.50 million tons/year during 1965–1990. It has decreased the water storage capacity by 32.90 million m^3, which is about 1.4% of its maximum storage capacity of 2263 million m^3 (KKU, 2003).

People living in the upper Phong watershed are dependent on rainfall and rivers, which provide them with agricultural products, fish and other aquatic products, and water itself. Fish is especially an important source of nutrients including proteins for the local population, and it brings also small amounts of income to them. Nett et al. (2004) identified soil erosion and high suspended solids in rivers as the pollutant most limiting to fishery health in oxbow lakes in the Mississippi Delta; when suspended sediment loads exceeded 80 to 100 ppm, fish growth rates were dramatically reduced. Those living in the upper Phong watershed always face difficulty in getting water in dry season, and difficulty in removing suspended solids in the rainy season. This is due to highly fluctuating flows (ranging from the lowest at 0.003 Mm^3/day to the highest at 13.98 Mm^3/day) in those rivers and also soil erosion due to stormy rainfall. Farming in the dry season further exacerbates the conflicts over water use. Furthermore, as the people way of life in the upper Phong region and rivers become inseparable, the access to rivers is considered as a first priority whenever they plan for their settlements. As the result of this, during a rainy season, they usually face a problem of riverbanks eroded caused by the huge volume and speedy rivers. Sometimes their houses and agricultural lands located along riverbanks are washed away by turbulent rivers.

2.4. Impacts of soil erosion on the Khon Kaen Municipal Water Treatment Plant

The Khon Kaen Municipal Water Treatment Plant is located in the downstream of the Ubolratana Dam near the Phong River. The service population is 51,712 persons and daily supply of water is 72,960 m^3. The water treatment plant has a treatment train composed of coagulation, rapid sand filtration and

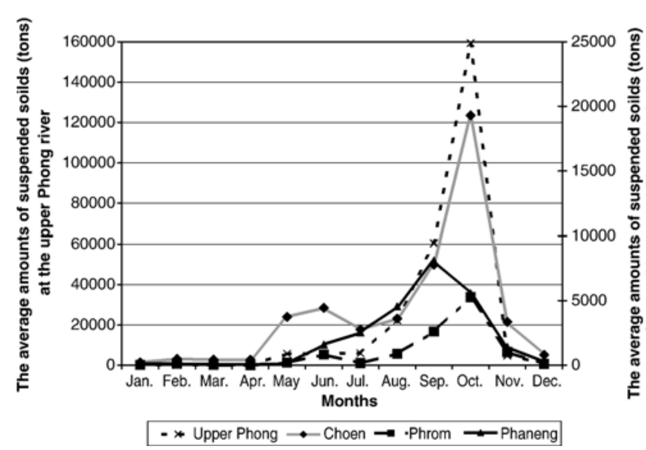

Fig. 5. The monthly mean amounts of suspended solids in the upper Phong watershed. (Tons/month).

chlorination. In the coagulation process, alum and lime are added to remove suspended solids. The sludge was stored in open ponds, and the supernatant is discharged into a canal.

According to the operational data obtained from the plant in 2003, the highest and the lowest concentrations of the turbidity in the Phong River during a rainy period (May–October) and during a dry period (November–April) were 303 NTU in July and 12 NTU in December, respectively (Fig. 4). The maximum turbidity at the point of water intake for the Khon Kaen Water Treatment Plant was significantly lower than those of upper Phong Rivers, which sometimes exceeds 5000 NTU. This is because the Ubolratana Dam works as a huge sedimentation tank for the Phong River. Fig. 5 shows the monthly mean amounts of suspended solids that are carried down in the upper Phong water system. It is interesting to note that the amount of suspended soils increases in the beginning of the rainy season (May–June), once decreases in July, and then goes up to the maxima in October. The increase of the amount of suspended solids in the beginning of the rainy season might be resulting from the flushing of topsoil from uncultivated bare lands during a dry season by heavy rainfall into a river. This amount of suspended solids would increase to the maxima in October because of the increasing of both rainfall intensity and frequency towards the month of October.

As a result of the higher concentration of turbidity during a rainy period, the amount of alum used is considerably increased to 23.60–53.17 g/m^3 (average of 42.33 g/m^3) from 20.61 to 35.34 g/m^3 (average of 28.46 g/m^3) in dry period. This is also in correspondence to the jar test results that require higher alum dosages in the ranges of 27.50–60.00 ppm and 20.00–35.00 ppm during wet and dry periods, respectively. The costs of alum ranged 0.12–0.27 Bahts/m^3 (average of 0.213 Bahts/m^3) and 0.10–0.18 Bahts/m^3 (average of 0.143 Bahts/m^3) during wet and dry periods, respectively (Fig. 4). At present, a household pays a water tariff at a rate of 7.75 Bahts/m^3, the higher cost of alum used during a wet period is accounted for 2.75% of the water tariff compared to 1.85% during a dry period.

The annual sludge generation at the Khon Kaen Municipal Water Treatment is calculated using the data of alum used (kg/m^3), the concentration of total solids (kg/m^3) and water production (m^3). The result reveals that the total annual sludge generation at the water treatment plant in 2003 was 4865 tons. Assuming that a cost of sludge disposal is 300 Bahts/ton, it would annually cost the Khon Kaen Municipal Water Treatment 1.46 million Bahts.

3. Discussion

As surface water is the main source of water supply (80.66%) for the Provincial Waterworks Authority (PWA), soil erosion and turbidity increase in surface waters are the most serious problem for PWA. The Phong watershed, wherein the Khon Kaen City is located, is one of such examples. The transformation from forestry land to agricultural land has caused a severe problem of soil erosion. According to the KKU report (2003), the erosion rate within the Phong watershed (12,000 km^2) is at 0.12 mm/year. This has caused the accumulation of sediment in the Ubolratana dam (until the year 1990) at the total amount of 37.50 million tons or about 1.5 million tons/year since 1965. This consequently results in the decrease of water storage capacity in the dam itself. In addition, this also affects the river water quality by increasing the average amount of suspended solids up to its peak of 159,373 tons in the upper Phong River (Fig. 5). According to Sthiannopkao et al. (2006), soil erosion in the upper Phong River was estimated to increase the suspended solids in a river by the annual concentration of 72 mg/l during 30 year simulation period of the effects of soil erosion on river water quality and on agricultural production in the upper Phong River.

As rainfalls in tropical countries like Thailand are heavy (the average amounts ranging from 139.26 to 227.35 mm/month) soil erosion rates go up in the rainy season, whereas people suffer from occasional water shortage. Soil erosion is especially serious in the transformed land area. This finally causes much higher amount of suspended solids in all rivers of the upper Phong region ranging from 133 to 159,373 tons/month during a wet period (May–October) and from 4 to 4910 tons/month during a dry period (November–April) (Fig. 5). Furthermore, during a rainy period, a river is very turbulent, causing difficulty for eroded soil and particles to be settled down. As the result of this, river water quality worsens during dry period with much less amounts of rainfall at the average between 3.86 and 34.03 mm/month. It is clear to state that the increase in river suspended solids caused by soil erosion affects the water treatment plant in Khon Kaen City by increasing the operational costs. When comparing the costs of alum used between wet and dry periods using their average values mentioned in the section of current situations, it is found that based on the data of daily water production at 72,960 m^3/day on February, 2004, the amounts of alum used in the wet (average 42.33 g/m^3) and dry (28.46 g/m^3) periods are 3088.40 kg/day and 2076.44 kg/day, respectively. The costs of the amount of alum used are 15,442 Bahts (1 kg alum is 5 Bahts) and 10,382.2 Bahts in wet and dry seasons, respectively (Fig. 4). Based on this calculation, it clearly indicates that the higher turbidity obtained during a wet period costs the higher expenditure on the amount of alum used at 5059.80 Bahts compared to the same payment during a dry period.

Considering the amount of sludge generated, it is calculated at the annual amount of 4863 tons. This would cost the Khon Kaen Municipal Water Treatment Plant 1.46 million Bahts/year. In addition, according to the data obtained from the Khon Kaen University Water Treatment Plant, located at the lower Phong region and uses of the Phong River, it is found that the average amounts of backwash water in 2002–2003 were at 3205.50 and 2429.18 m^3 during wet and dry periods, respectively. This indicates the impact of river turbidity on its treatment plant. However, the cost of higher amount of chlorine used is not yet included. According to MWA (2004) studying on the effect of turbidity on disinfection in water treatment, reports that when the concentration of turbidity is decreased resulting in also decreasing the amount of chlorine used. The amount of chlorine used is increased following the increasing amount of turbidity at the beginning of a treatment process, a pre-chlorination. However, the amount of chlorine used in the contact tank (after water goes through a rapid sand filtration) is not dependent on the amount of water turbidity.

4. Conclusions

The Phong River is an important source of water supply in the upper northeastern provinces, especially in Khon Kaen City. The land transformation from forest to agricultural lands, especially in the upper regions has caused a problem of soil erosion, resulting in increasing of the amounts of suspended solids in a river in particular in a rainy season. As the result of this phenomenon, the operation costs at the Khon Kaen Municipal Water Treatment plant are substantially increased during a wet period compared to a dry one. The average amounts of alum used are 42.33 g/m^3 in the wet period compared to 28.46 g/m^3 in the dry period. In addition, according to the data obtained from Khon Kaen University Water Treatment Plant, it indicates that the average amounts of backwash water are higher in the wet compared to the dry periods at 3205.50 and 2429.18 m^3, respectively. Because of this, it is worth noting that integrated land use management in the upper Phong watershed must be implemented in order to maintain good surface water quality and also its quantity for sustainable use as a source of water supply within the Phong watershed. As a result of this implementation, the costs of water treatment as a whole would be significantly reduced, especially during a wet period.

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Soil erosion and participatory remediation strategy for bench terraces in northern Thailand

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Abstract

This study was carried out in Pang Prarachatan village, which is located in Chiang Rai province of northern Thailand. The farmers in this village construct bench terraces to reduce soil erosion and increase plant productivity. However, severe soil erosion occurs frequently on the bare bench terraces. This study investigates the impact of bench terracing on soil erosion. The use of weeds and plant residues to control soil and nutrient losses were also investigated using model slope plots and an artificial rainfall system. Finally, the knowledge gained from this study was transferred to the farmers through a workshop in the village, and their acceptance of the results was evaluated by means of a questionnaire. The severity of soil erosion is thought to vary according to the structure of the bench terrace and the ground cover conditions. Rills are the primary form of erosion on bare bench terraces. In addition, some rills develop into gullies that can run from the upper terrace down to the lower terrace. Nevertheless, rills and gullies are rarely found on weed-covered terraces. Moreover, the results of an erosion experiment using model slope plots and artificial rainfall systems showed that plots covered with weeds and plant residues had much less surface runoff and soil and nutrient losses than bare soil. The amounts of nitrogen and phosphorus absorbed by weeds were 4.7 and 2.3 times smaller than the nitrogen and phosphorus losses due to soil erosion, respectively. The results of the field surveys and model slope experiment were announced to the farmers through participatory workshop in August 2003. The first questionnaire, conducted just after the workshop, clearly showed that around 90% of the farmers agreed to cover their slopes with weeds and plant residues so long as it did not affect soil fertility and plant growth. However, the second questionnaire, conducted in January 2004, showed that only 29% of farmers were covering the bench terraces or non-terraced slopes in their farmlands with weeds and plant residues. Therefore, participatory activities should continue to be held regularly in order to ensure greater acceptance and practice of soil conservation on the part of the farmers.

Keywords: Soil conservation; Bench terrace; Rill erosion; Weed cover; Thailand

1. Introduction

Thailand is located in Southeast Asia, where monsoons are common. Soil erosion is a serious problem affecting crop productivity and the incomes of farmers in mountainous areas. Soil erosion is severer on steep slopes, where government agents seldom go, especially along the border of Thailand and Myanmar. Most of the people in the mountainous areas of Thailand belong to ethnic minority groups that differ from those in the lowlands of Thailand. Legally, people are not allowed to cultivate slopes with grades greater than 35%. However, many ethnic groups have settled here and have been cultivating the land for hundreds of years. Recent population increases have forced them to practice deforestation and intensive cultivation to survive. These practices have resulted in soils of low fertility and insufficient food to feed the population. Thai governmental officers from the Department of Land Development and the Royal Forestry Department have promoted several conservation techniques

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for reducing soil erosion. However, severe soil erosion still occurs in the mountainous areas.

The Department of Land Development, which deals with agricultural land development, recommends that farmers living on slopes with grades between 12% and 35% construct bench terraces or hillside ditches combined with buffer strips of vegetation such as vetiver (*Vetiveria zizanioides*) or napier grass (*Pennisetum purpureum*) (Attaviroj, 1996) to control erosion. While terrace paddy cultivation is traditional for some ethnic groups in Thailand, using such techniques for upland crops is new, and most farmers are not familiar with soil and water conservation practices for terraces for upland crops.

Moreover, in traditional slash-and-burn farming, farmers prefer to keep the slopes bare with no ground cover or buffer strips, which exposes the soils to storm rainfall and surface runoff. Rill and gully erosion predominate on the slopes between the bench terraces, but not in conventional fields. Therefore, many farmers still hesitate to construct bench terraces as a conservation measure.

The objectives of this study are: to survey the structure and erosion characteristics of bench terraces in farmlands in northern Thailand, to investigate effects of weed cover on reducing soil erosion, and to observe how participatory methods can improve the farmers' acceptance and implementation of the remediation strategies.

2. Research area and methods

2.1. Research area

This study was carried out in Pang Prarachatan village, which is located in Mae Fah Luang sub-district (Fig. 1). The government established this village for a hill tribe that was to resettle and reforest the woods. In this village, the total number of households was 72. The populations are minority groups of Thai Yai, Lua, Lue, and Akha, and 44.8% of respondent farmers migrated from Myanmar. Fifty-four percent of respondent farmers did not get official education, and they are communicating with their native language. The main crops are fruits such as litchi (*Litchi chinensis*), santol (*Sandoricum koetjape* Merr.), and longan (*Dimocarpus longan* Lour.). Bare bench terraces are common in this village (Mihara et al., 2004).

2.2. Field survey

The structure and erosion characteristics of bench terraces in Pang Prarachatan village were surveyed in August 2001 and 2003. August is the middle month of the heavy rainfall season in Thailand, so this makes it easier to observe soil erosion. The structure of the bench terraces, the grade of the slope between the bench terraces, the bed width, and the ground cover of terraces were all investigated. The erosion characteristics, such as sheetwash, rilling, and gullying, were evaluated by observation of the terraces. Fifty-four samples of surface soil (0.01–0.06 m deep) were taken from the terraces and the physical properties such as particle size distribution, dry density, and saturated permeability, and the chemical properties such as nitrogen, phosphorus, and organic matter content were analysed. Management practices relating to maintaining the bench terraces were also investigated.

2.3. Slope model experiment

An experiment was conducted using a slope model to confirm the effectiveness of a weed cover in reducing soil and nutrient losses. Dimension of the slope model was

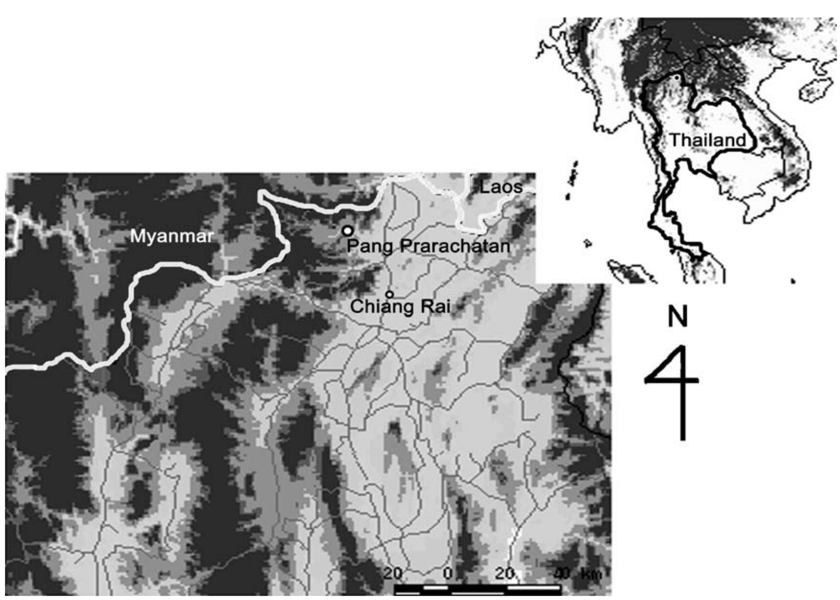

Fig. 1. Research area in Chiang Rai, northern Thailand.

0.50 m wide, 0.20 m deep, and 2.00 m long, and it was set at 8°. According the soil particle size distribution as shown in Table 1, the soil texture was light clay, as is the soil in Pang Prarachatan village. The nitrogen and phosphorus concentrations were 3327 and 376 mg·kg^{-1}, respectively, which are higher than their concentrations in the soils in Pang Prarachatan village. The soil was compacted, and then weeds were allowed to grow naturally. The dry density of the soil is shown in Table 2. *Setaria viridis* (L.) Beauv. was the dominant weed in the model slope plot, as shown in Table 3. The weeds were cut and left on the surface.

Before the erosion experiment, to achieve uniform soil water condition among plots, the simulated pre-rainfall at very low intensity was supplied to soil surface covered with cloth until draining the percolating water, then the plots were left for 24 h. For the erosion experiment, the simulated rainfall intensity at 58–62 mm h^{-1} was continuously supplied for 2 h to enhance severe erosion in slope model plots. Falling height of raindrop was 1.19 to 1.49 m, and raindrop size was 3.12 mm in diameter. Amount of surface runoff, the losses of soil, nitrogen and phosphorus were subsequently observed.

2.4. Chemical analysis

The residues of weeds were collected after the experiment, and the mass was measured after being oven dried at 70 °C for 72 h. Total nitrogen in soil and weeds was analysed by micro-Kjeldahl method (Dewis and Freitas, 1984). Total phosphorus in soil and weeds was analysed by means of absorption spectrophotometry after decomposition with potassium peroxodisulphate (Central Kagaku Corporation, 2001).

The amount of soil in surface runoff was analysed by oven dry method. Total nitrogen and phosphorus of the water samples were analysed by means of absorption spectrophotometry after decomposition with potassium peroxodisulphate ($K_2S_2O_8$) (Central Kagaku Corporation, 2001).

Table 1
Physical and chemical properties of compacted soil in model slope plots

Soil properties	Unit	Measured value
Specific gravity	g cm^{-3}	2.63
Particle size distribution	International Soil Science Society Classification	
Gravel	%	0.6
Coarse sand	%	8.3
Fine sand	%	30.4
Loam	%	29.4
Clay	%	31.3
Soil texture	International Soil Science Society Classification	Light clay
Dispersion ratio	%	32.7
Organic matter	g kg^{-1}	153
Total nitrogen	mg kg^{-1}	3327
Total phosphorus	mg kg^{-1}	376
Number of soil samples		6

Table 2
Dry density of soils before and after rainfall experiment

Plot	Dry density (g cm^{-3})			
	Before rainfall experiment^{A}		After rainfall experiment^{B}	
	Surface ~0.10 m deep	0.10~0.20 m deep	Surface ~0.10 m deep	0.10~0.20 m deep
Bare plot^{A}	0.98^{a,*}	0.98^{a}	0.99^{a}	0.96^{a}
Weed- and residue-covered plot^{B}	0.99^{a}	0.97^{a}	0.90^{b}	0.92^{ab}

Capital letters indicated significantly different at 95% confidence base on two-way ANOVA.
Small letters indicated significantly different at 95% confidence base on one-way ANOVA applying LSD for post hoc tests.
*Each mean obtained from 3 soil samples.

2.5. Participatory remediation

The results of field surveys and slope model experiment were announced to the farmers through a workshop that employed a participatory method. The workshop was held in August 2003. The pattern of soil erosion on sloping farms and mechanism of weed cover on reducing soil erosion were demonstrated to farmers. Farmers were free to attend the workshop, and they could independently discuss and raise their ideas with researchers. Additionally, a model terrace was constructed without removal of weed cover in sloping land. There was no incentive offering to farmers who wished to apply weed cover for soil conservation in this village. Questionnaires were given just after the workshop and in January 2004. The farmers' acceptance and adoption of the practice of using weed covers to reduce soil erosion was evaluated.

3. Results and discussion

3.1. Structure of bench terraces and soil erosion

The farmers in Pang Prarachatan village constructed various types of bench terraces by hoe on steep slopes as

Table 3
Species and density of weeds in model slope plot

Scientific name	Common name	Density (stem m^{-2})
Setaria viridis (L.) Beauv.	Green bristle grass	18
Oxalis Corymbosa DC.	Violet wood sorrel	9
Erigeron philadelphicus L.	Philadelphia fleabane	8
Stenactis annuus Cass.	–	8
Cyperus microiria Steud.	–	6
Commelina communis L.	Asiatic dayflower	5
Others		22
	Total	76

Table 4
Structure of bench terraces in Pang Prarachatan village

Type	A	B	C	D
Slope features of terrace bed	Level	Outward slope	Level with shoulder bank	Outward slope with weed cover
Number of surveys	3	3	3	3
Slope (s, %)	90	78	49	45
Vertical interval between bench terraces (V.I., m)	0.010*s* (0.90)	0.014*s* (1.09)	0.012*s* (0.59)	0.009*s* (0.39)
Horizontal interval between bench terraces (H.I., m)	100(V.I.)/s+(0.25) (1.25)	100(V.I.)/s+(0.65) (2.05)	100(V.I.)/s+(0.07) (1.27)	100(V.I.)/s+(0.53) (1.40)
Bed width in cultivated area (m)	0.37	0.73	0.28	0.86
Cross sectional view of terrace				
Dominant erosion	Rill and gully	Rill	None dominant	None dominant
Erosion severity	Severe	Severe	Slight	Slight

a conservation practice (Table 4). The bench terraces were classified into 4 groups according to the features of the terrace bed slope. Type A terraces were level, Type B were outward sloping, Type C were level with the shoulder bank, and Type D had an outward slope and a weed cover.

There was a tendency for the vertical interval between bench terraces to become higher as the slope increased. Slopes varied from 45% to 90% in all types, and the vertical interval between terraces ranged from 0.39 to 1.09 m. The vertical interval between terraces could be expressed as 0.009s to 0.014s, where s is the slope as a percentage. However, the horizontal intervals between bench terraces ranged from 1.25 to 2.05 m, as indicated by the equations in Table 4.

There was a tendency for the bed width to become narrower as the slope increased. Narrow terrace beds may increase the velocity of surface runoff and promote soil erosion, but they can also prevent slope failures from excessive water seepage. Therefore, surface erosion tended to worsen as the slope increased.

Severe erosion caused by rills and gullies was observed in Type A bench terraces. Some rills developed into gullies that ran from the upper terrace down to the lower terrace. Type B bench terraces had no gully erosion but severe rills, and the density of rill erosion in Type B terraces was higher than in Type A terraces. Farmers in Pang Prarachatan village tended to plant tea and fruit trees on the terrace beds and keep the land bare in order to avoid weed–crop competition for nutrients. However, rill or gully erosion became prevalent on the bare bench terraces of Type A and B. Fig. 2 shows the density of rill erosion in a Type B terrace in August 2001. This terrace has been unused since 2002 due to the soil's low productivity. Soil erosion may have promoted the loss of nutrients in this terrace.

However, soil erosion was not prevalent in Type C and D terraces, indicating that the banks and weed covers in these terraces were effective in reducing soil erosion. According to observations of bench terraces in Pang Prarachatan village, rills and gullies were severe on bare bench terraces but slight on terraces with erosion

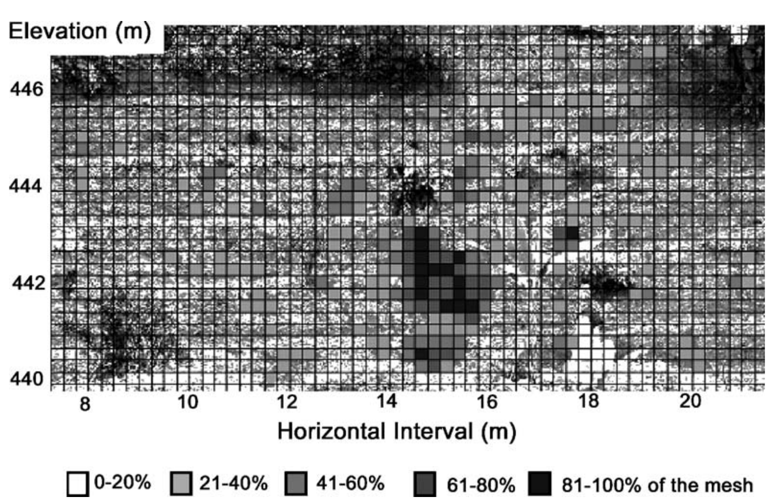

Fig. 2. Rill erosion density in bare Type B (outward sloping) bench terraces in Pang Prarachatan village.

Table 5
Physical properties of terrace soils in Pang Prarachatan village

Type	Specific gravity	Particle size distribution (%)*					Soil texture	Dispersion ratio (%)
		Gravel	Coarse sand	Fine sand	Silt	Clay		
A: level	2.69^{b}	1.0^{a}	18.7^{a}	27.0^{a}	15.8^{b}	37.4^{a}	LiC	27.3^{a}
B: outward slope	2.68^{c}	1.3^{a}	19.3^{a}	20.2^{c}	20.5^{a}	38.6^{a}	LiC	28.6^{a}
D: outward with weed cover	2.70^{a}	4.0^{a}	16.9^{a}	23.3^{b}	17.4^{ab}	38.2^{a}	LiC	21.7^{a}

Each mean obtained from 6 soil samples.
Small letters, in a column, indicated significantly different at 95% confidence base on LSD analysis for one-way ANOVA.
*International Soil Science Society Classification; LiC: light clay.

controlling measures such as shoulder banks or weed covers. Weed covers appeared to be particularly effective for conserving soil erosion.

3.2. Soil properties of bench terraces

Reddish colored soils covered the ground in Pang Prarachatan village. The soil properties of the bench terraces are summarized in Table 5. The soil samples taken from the terraces were light clay (LiC) according to the International Soil Science Society Classification (Hillel, 1971). The dispersion ratio ranged from 21% to 29%, indicating that the soils were erosive (Middleton, 1930).

A comparison of the soil properties of the beds and slopes of bench terraces in Pang Prarachatan village is summarized in Table 6. There was a tendency for the dry density to be higher in the weed-covered terrace than in the others, while the saturated permeability was lower in the weed-covered terrace than in the others. There were no significant differences in organic matter, nitrogen and phosphorus concentrations in the soils between the terrace beds and the slope, but slightly different among the terrace types.

3.3. Effectiveness of weed covers in reducing soil erosion

Many factors affect soil nutrients, including the time when fertilizing is done and the amount and type of fertilizer used. This makes it difficult to compare the nutrient concentrations in the soils of the terraces under farmers' practice. Therefore, in order to confirm the effectiveness of weed covers in reducing soil and nutrient losses, an experiment was conducted using a slope model with an artificial rainfall system. *S. viridis* (L.) Beauv. was the dominant weed in the slope model plot, as shown in Table 3.

The results of the experiment are summarized in Fig. 3. The cumulative surface runoff from the bare plot was 3.7 times higher than that from the weed- and residue-covered plot, indicating that percolation in the weed- and residue-covered soil was much higher than in the bare soil. Moreover, the cumulative soil loss and total nitrogen and phosphorus losses from the bare plot were 182.8, 159.0, and 72.6 times higher, respectively, than those from the weed- and residue-covered plot.

The nitrogen concentrations in the weeds ranged from 10,200 to 12,300 mg kg^{-1}, and the phosphorus concentration was 3200 to 4000 mg kg^{-1}. As the total mass of dry weeds was 0.27 kg m^{-2}, the total amounts of nitrogen and phosphorus absorbed by the weeds were 2.99 and 0.96 g m^{-2}, respectively. The amounts of nitrogen and phosphorus that were absorbed by weeds were 4.7 and 2.3 times smaller than the nitrogen and phosphorus losses of 13.99 and 2.20 g m^{-2} due to soil erosion, respectively. Moreover, many scientists have reported that ground cover is an important factor in conserving the soil and nutrients (e.g, Lal, 1997; Gaskin and Gardner, 2001; Hazarika and Honda, 2001).

Although farmers in Pang Prarachatan village tended to keep the terraces bare to avoid weed–crop competition for

Table 6
Comparison of soil properties in beds and slopes of bench terraces in Pang Prarachatan village

Type	Dry density (g cm^{-3})	Saturated permeability (cm s^{-1})	Organic matter (g kg^{-1})	Nitrogen (mg kg^{-1})	Phosphorus (mg kg^{-1})
Type A: level					
Bed	1.10^{ab}	0.029^{b}	82.3^{b}	1219^{b}	113^{ab}
Slope range	1.05^{ab}	0.17^{a}	83.3^{b}	1395^{ab}	125^{a}
Type B: outward slope					
Bed	1.13^{ab}	0.011^{bc}	94.5^{a}	1510^{ab}	67.1^{bc}
Slope range	0.99^{b}	0.14^{ab}	97.3^{a}	1351^{ab}	63.4^{c}
Type D: outward with weed cover					
Bed	1.21^{a}	0.011^{bc}	83.5^{b}	1338^{ab}	81.5^{abc}
Slope range	1.18^{a}	0.023^{b}	91.4^{ab}	1630^{a}	92.7^{abc}

The survey was carried out with no control over the farmers' practices.
Each mean obtained from 3 soil samples.
Small letters, in a column, indicated significantly different at 95% confidence base on LSD analysis for one-way ANOVA.

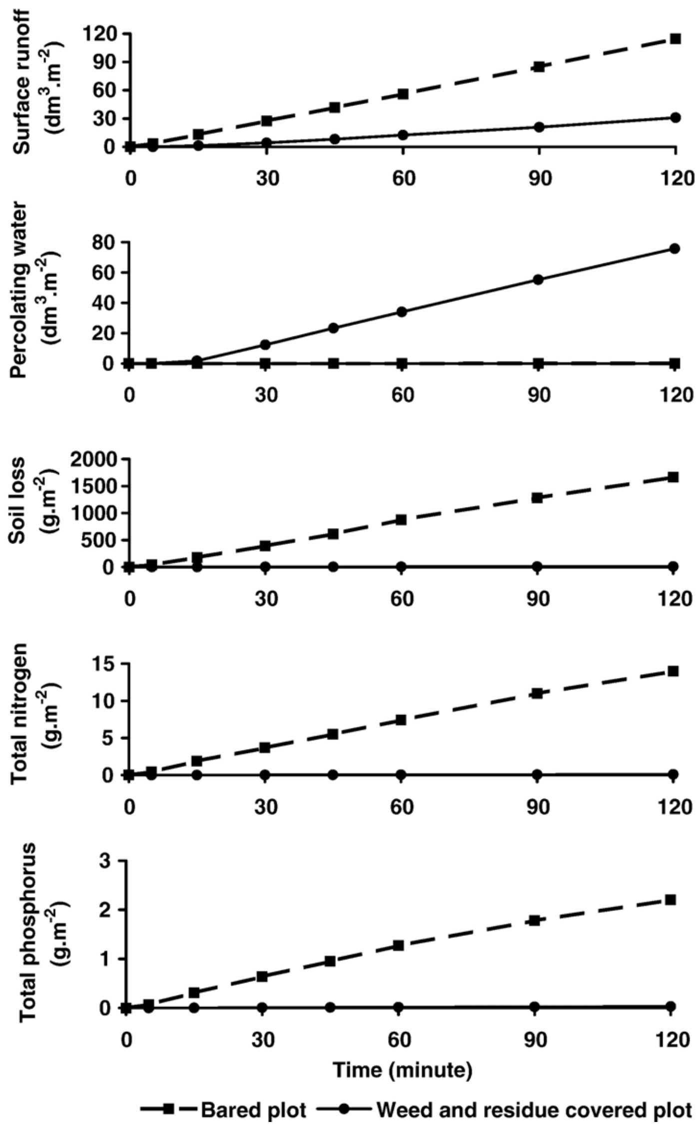

Fig. 3. Comparison of cumulative discharge and soil and nutrient losses between bare plot and weed- and residue-covered plot.

Fig. 4. Use of weed cover on bench terrace to minimize soil erosion in Pang Prarachatan village.

Fig. 5. Bare bench terraces are common in Pang Prarachatan village.

nutrients, nutrient losses from soil erosion may be remarkably higher than the amount of nutrients absorbed by weeds. Weed cover may be the cheapest and most effective way to preserve bench terraces.

3.4. Participatory remediation of using weed cover for soil conservation in farmlands

Forty-two questionnaires from the first survey, which was conducted just after the workshop, were available for data analysis. The results showed that around 90% of the farmers had agreed to cover the slopes with weeds and residues so long as it did not affect soil fertility and plant growth. However, the second questionnaire, conducted in January 2004, showed that only 29% of the 31 respondent farmers were covering the bench terraces or non-terracing slopes in their farmlands with weeds and plant residues.

Fig. 4 shows the terraces of one farmer who was very aggressive in conserving soil. He kept weeds on the slopes of his terraces. Comparing to the common bare terraces in Pang Prarachatan village, as shown in Fig. 5, his terrace had only slight erosion. Therefore, participatory activities should continue to be held regularly in order to ensure greater acceptance and practice of soil conservation on the part of the farmers.

4. Conclusion

The results of the field survey showed that the severity of soil erosion is thought to vary according to the structure of the bench terrace and the ground cover condition. Rills were the primary form of erosion on bare bench terraces. In addition, some rills developed into gullies that ran from the upper terrace down to the lower terrace. Nevertheless, rills and gullies were rarely found when weeds covered the bench terraces.

The results of an erosion experiment using model slope plots equipped with artificial rainfall systems showed that plots covered with weeds and residues had much less surface runoff and soil and nutrient losses than bare soil. The amounts of nitrogen and phosphorus absorbed by weeds were 4.7 and 2.3 times smaller than the nitrogen and phosphorus losses, respectively, indicating that weed covers can effectively conserve bench terraces. Therefore, participatory activities should continue to be held regularly in order to ensure greater acceptance and practice of soil conservation on the part of the farmers.

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Assessment of tillage erosion rates on steep slopes in northern Thailand

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Abstract

The switch from shifting cultivation to more permanent highland cropping systems in northern Thailand led to an increase in soil tillage intensity. In order to quantify soil losses by tillage erosion, a tillage experiment was set up and an on-farm survey was conducted. Soil fluxes due to manual tillage on five slopes (32–82%) were measured by monitoring tracers, by measuring tillage step characteristics and by collecting soil material in a trench. The trench method yielded soil flux values that were significantly smaller than those obtained by the tracer or the step method. Soil fluxes resulting from one manual tillage pass ranged between 39 and 87 kg/m on the tested slopes. On slopes up to 60%, there were no significant differences in soil fluxes. However, on slopes steeper than 70%, soil fluxes increased significantly because the angle of repose for soil clods was exceeded. The soil fluxes are used to construct a nomogram for estimating soil loss rates resulting from manual tillage erosion as a function of slope and plot length. Rates on a typical upland field (slope 30%–50%, slope length 30–50 m) range from 8 to 18 t/ha · tillage pass, so tillage erosion is a significant contributor to the total soil loss. It dominates on short fields and fields with buffer-strips, whereas water erosion is the more important form of soil loss on middle size and long fields. Increasing land pressure will result in

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increasing tillage erosion rates, and these need to be considered when assessing soil degradation rates or when studying hillslope evolution.

Keywords: manual tillage; tillage erosion; land pressure; weed pressure; steep slopes; northern Thailand

1. Introduction

The hills of northern Thailand are a rugged area with steep slopes and soils with medium to poor fertility, which are exposed to an erosive monsoon climate seven months per year. The farmers of this area have developed a land-use system to cope with these fragile resources. In the traditional shifting cultivation system, new clearings were planted with upland rice or maize for subsistence purposes, and some tribes planted poppy for cash income. When soil fertility declined and weed pressure increased, the fields were left fallow for a period of at least 7 to 12 times the cropping period (Kunstadter et al., 1978). This is probably the best way to use the local resources when no external inputs are available (Beets, 1990; Driessen and Dudal, 1991; Rerkasem et al., 1994). The traditional shifting agriculture can still be observed in remote areas, such as the western part of northern Thailand (Rerkasem et al., 1994).

During the 1980's, the highland environment has been changing rapidly. Land pressure is increasing steadily because of:

1. natural growth of the hilltribe population,
2. immigration from lowland and neighbouring countries,
3. government initiated land-use planning and massive reforestation schemes.

This has resulted in a decline of the available fallow area and a more intensive use of the agricultural land. Several agricultural problems that were inherent parts of highland agriculture become now more articulated. These are accelerated water erosion, nutrient depletion, increasing weed pressure and the accumulation of soil borne diseases. At the same time, recently constructed, permanently accessible roads are playing a major role in the spread of new cash crops.

The steep slopes (those with angles of 20%–80%) combined with intense rainfall make the agricultural fields prone to erosion. According to data collected from experimental runoff plots and caesium-137 measurements, the erosion rates of open fields vary widely between 5 and 90 t/ha · yr (based on Tangtham, 1991; Soil Fertility Conservation Project, 1992; Forsyth, 1994). In a traditional shifting cultivation system, soil loss in new clearings is generally very small, as the roots of the fallow vegetation create stable aggregates (e.g. Ryan, 1995) which enable an efficient infiltration (field observations). The average annual erosion rate is negligible, especially when the long fallow periods are taken into account. However, as the fallow period shortens, the mean annual erosion rate increases. It is enhanced by the breakdown of stable aggregates on fields that are used for longer than one year, and by the inflow of run-off water from neighbouring fields and from the denser network of footpaths.

An often overlooked process contributing to soil loss is manual tillage. Traditionally, hilltribe farmers did not till their fields, because fallow periods and subsequent burning guaranteed weed free soils with a good structure (Hinton, 1970; Grandstaff, 1980;

Fig. 1. The major purpose of manual tillage in northern Thailand is to control weeds.

Collins et al., 1991). Tillage is still uncommon in areas where fallow land is still abundant, such as in the western part of northern Thailand and Laos (W. Roder, pers. commun., 1995), but farmers started to till the land as a response to increasing weed pressure (Grandstaff, 1980). In our case study village, Pakha, tillage became widespread around 1989 (Fig. 1). Deep tillage (rough tillage; mean clod size equals 10–20 cm) during the dry season is an effective way to control perennial grasses and retards the emergence of annual broadleaved weeds (Van Keer et al., 1995). Additional reasons to till the land are to break a sealed top layer, enhance fertility or to prepare a seedbed (mainly for upland rice). To kill re-emerging weeds, the fields are tilled superficially (fine tillage; mean clod size equals 2–5 cm) once or twice more before planting (stale seedbed method), depending on the crop and the weed pressure. Other disturbances of the topsoil take place during planting and weeding. Table 1 shows the usual cultivation practices for the four most important field crops at Pakha, but these can be varied, depending on labour availability, previous crop and present weed pressure. Sometimes, herbicides are used as an alternative, especially when there is a labour shortage. However, the local farmers consider deep tillage a more efficient weed control measure than herbicides.

Soil tillage can influence the soil's sensitivity to water erosion. It breaks up the (crusted) soil surface and dramatically increases macroporosity and soil surface roughness, thereby increasing the surface depression storage as well as the infiltration capacity of the soil. However, tillage also decreases the soil's resistance to detachment by raindrop impact or flowing water (Govers et al., 1994). Tillage also has a direct effect on soil movement, but this process is poorly documented. The only studies to date have concentrated on tractor-plough tillage on gentle slopes (Mech and Free, 1942; Bollinne, 1971; Papendick and Miller, 1977; Lindstrom et al., 1992; Revel et al., 1993; Govers et

Table 1
Cultivation practices which disturb the topsoil for the five most important annual crops at Pakha during the cropping season of 1994 and 1995

	Upland Rice	Maize	Soy Beans	Cabbage	Ginger
Cultivation Period	6 months	3 months	3 months	3 months	5 or 10 months
Land Preparation					
- Deep tillage (hoe)	X	[X]	[X]	X	X
- Breaking of clods / fine tillage (hoe)	X			X	[X]
- Cleaning (hoe or rake)	X			X	
- Pre-weeding (hoe)	X				
- Construction of beds (hoe)				X	
Planting	bamboo stick	hoe	bamboo stick/ little hoe	little hoe	hoe
Weeding					
- 1st weeding	little hoe	hoe or knife	[(little) hoe]	little hoe	little hoe
- 2nd weeding	hand + knife	[hoe]			[hand + knife]
- 3rd weeding	[hand + knife]				

- The fields are normally slashed and burned before deep tillage.
- [ ]: Indicates that this activity does not always take place.

[shaded] = Activities during which soil movement can take place.

al., 1994). Little quantitative information is presently available on soil losses caused by manual tillage (Roose, 1994), which is a widespread method of land preparation in many tropical countries. A small step at the top of a field is a clear indicator of soil movement due to manual tillage.

The purpose of this study is to assess the effect of manual tillage on soil movement under conditions prevailing in northern Thailand. We focus on the deep tillage operation (rough tillage) which is the first step in land preparation (Table 1), as it has the greatest impact on topsoil movement. Soil flux by tillage erosion is quantified as a function of slope angle and slope length. A comparison with soil losses due to water erosion is made, and finally the implications for agricultural sustainability are briefly discussed.

2. Materials and methods

2.1. Site selection

A survey of cultivation practices and an on-farm experiment were initiated in 1994 in an Akha tribe village named Pakha, which is located in Chiang Rai Province (20°N and

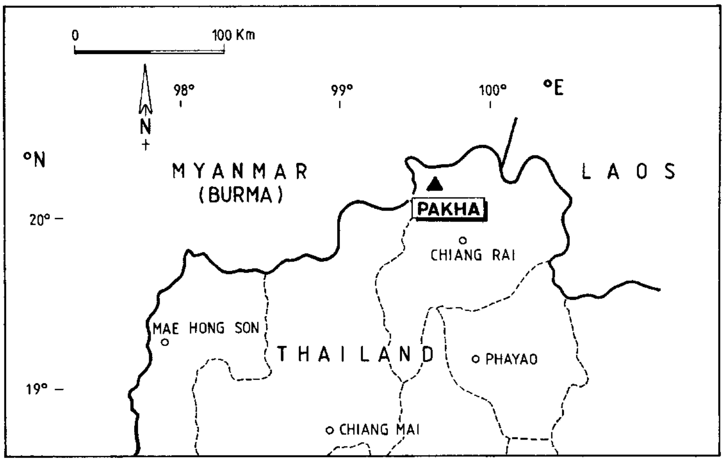

Fig. 2. Location of the on-farm experiments.

100°E) (Fig. 2), in an area which is representative of the northern Thai highlands (Turkelboom, 1993). This village was selected because it has a more progressive farming system. The land-use is in full transition because of: (1) relatively high land pressure, (2) decline of soil productivity, (3) construction of a permanent road nearby (which gives reasonable access to urban markets), and (4) reforestation activities by the Forestry Department. Because of these current changes, the effects of land pressure could be studied before they take place in other areas.

2.2. Tillage experiment

Soil movement by manual tillage was measured in farmers' fields during the dry season of 1994/95. On 5 slopes (32%, 41%, 51%, 60% and 82%), small plots, 4 m wide and 4.5–8 m long, were demarcated with bamboo sticks (Fig. 3). The parent material is phyllite, and the soil has a clay content of 30–40%; it is classified as Humic Cambisol (FAO-classification). After removing all the weeds from the plots, they were tilled by local farmers in a traditional way, i.e. starting from the bottom of the field and moving up the slope. Farmers used a hoe with a steel blade about 16 cm long and 16 cm wide, and a wooden handle about 80 cm long (Fig. 4). A new blade is 21.5 cm long, but the farmers regularly sharpen the cutting edge, so that in use the hoe blades were between 10 and 20 cm long.

In order to measure the soil flux three complementary methods were used: the tracer method, the trench method and the step method.

2.2.1. Tracer method

Since it is very difficult to mark soil clods themselves, 180 white painted stones, taken from a nearby river, were used as tracers. The longest axis of the stones ranged between 2.7 and 13.3 cm. These tracers were placed randomly in a narrow furrow below a reference line (marked by a string) at the top of the plot, and the furrow was refilled with soil (Fig. 3). The farmers then tilled the plot moving up the slope until they passed

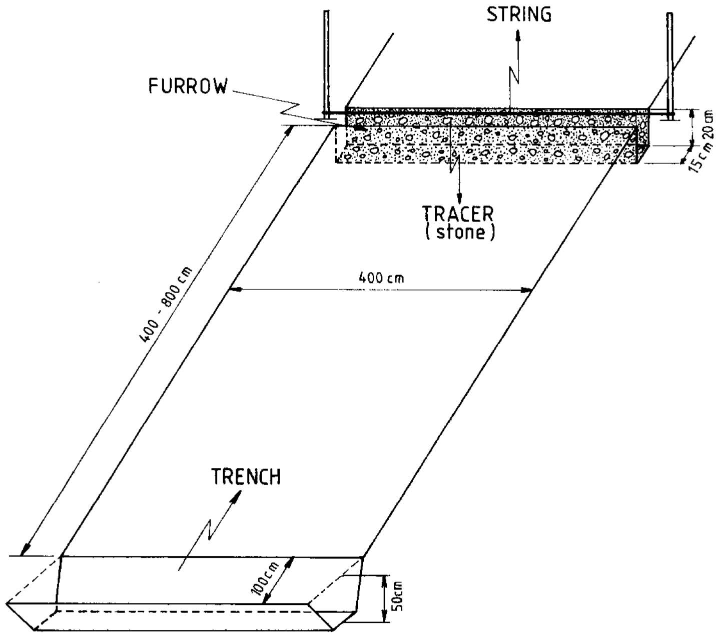

Fig. 3. Lay-out and dimensions of the observation plots.

the furrow. It was hypothesised that the stones moved in a similar way to the clods, and are representative indicators of downslope soil movement. Afterwards, the original soil surface above the narrow trench was marked with a string, to measure the average tillage depth and the displacement distance of the tracers that were moved. Hence, tracers that were installed in the furrow below the plough depth were not taken into account. The tillage depth was measured vertically in the field, and transformed to tillage depth perpendicular to the soil surface by multiplying by the cosine of the slope angle.

The mass of soil that passes a unit contour length for one tillage pass is called the ''soil flux''. This flux can be calculated using Eq. (1):

$$\text{Soil flux (kg/m} \cdot \text{tillage pass)} = \text{DD} \cdot D \cdot \text{BD} \tag{1}$$

where DD = mean downslope displacement distance of the tracers (m), parallel to the soil surface, D = mean tillage depth (m, measured perpendicular to the soil surface), BD = dry bulk density of the soil (= 1100 kg/m^3).

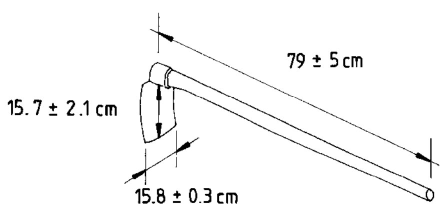

Fig. 4. Dimensions of a typical hoe used by Pakha farmers.

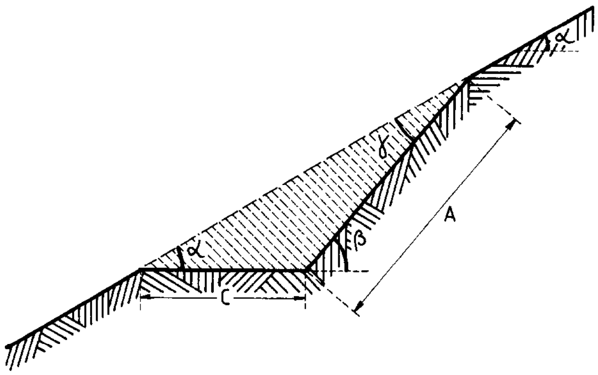

Fig. 5. Cross-section through a tillage step, and the parameters needed to calculate the soil flux by the step method. A, α and β are measured in the field. The shaded area represents soil lost by manual tillage and equals $C \cdot A \cdot \sin\beta/2$, with $C = A \cdot \sin\gamma/\sin\alpha$ and $\gamma = \beta - \alpha$.

2.2.2. Trench method

To collect displaced topsoil, a trench 4 meters long was dug at the bottom of each plot and lined with a plastic sheet. The soil flux was measured directly by this method and calculated using Eq. (2):

$$\text{Soil flux}\,(\text{kg/m}\cdot\text{tillage pass}) = \frac{M\cdot\text{DM}}{W} \qquad (2)$$

where M = mass of moist soil collected in the trench (kg), DM = oven dry soil as percentage of M (range DM = 87–90%), and W = observation width (4 m).

2.2.3. Step method

A small step at the top of the plot is the most obvious indicator of soil movement by manual tillage. Here soil is moved downwards but not replaced by any soil from further upslope. The volume of this scar should correspond with the amount of soil moved into the trench at the bottom of the plot. Tillage steps degrade easily and need to be measured soon after tillage. The dimensions of the step were measured three times at each site. The soil flux was then calculated using Eq. (3) (Fig. 5):

$$\text{Soil flux}\,(\text{kg/m}\cdot\text{tillage pass}) = \frac{\sin(\beta-\alpha)\cdot\sin\beta\cdot A^2\cdot\text{BD}}{\sin\alpha\cdot 2} \qquad (3)$$

where α = slope angle of original soil surface, β = slope angle of step, A = length of the step slope (m, measured down the angle β), BD = dry bulk density of soil (= 1100 kg/m^3).

2.3. Field survey

In addition, an on-farm survey was conducted while farmers were tilling their land in February 1996. On eight fields, vertical tillage depth and hoe dimensions were measured. Farmers' perception and knowledge of cultivation practices and the tillage operations were investigated by informal discussions both in the field and at their home. Further field observations gave an additional understanding of the farmers' field management and its consequences. The angle of repose of soil aggregates in field conditions was identified at 15 sites by measuring the slope angle of the soil surface where clods had started to slide down as a result of tillage.

3. Results and discussion

3.1. The nature of the tillage operation

Tillage depth depends on a large number of factors. The length of the hoe blade and the slope of the field were expected to be important factors controlling tillage depth, but field measurements showed that many other factors are interfering (Figs. 6 and 7). Farmers adjusted tillage depth according to the local weed pressure. Fields or areas with much grass (e.g. *Imperata cylindrica*) were tilled deeper in order to kill the roots and rhizomes effectively by drying them on the soil surface. Old fallows that contain few grasses were therefore tilled superficially, whereas older fields infested with grasses were tilled deeper. Another factor was the presence of stones at the soil surface, which limited the tillage operation, and hence decreased its depth. An average of 8.2 cm (s.d. 1.9 cm, $n = 21$) perpendicular to the soil surface was calculated for use in Eq. (1).

The mean displacement distance measured by the tracer method ranged from 0.5 m to 1.1 m, depending on the slope angle (Table 2). Size of stones was not correlated with the displacement distance ($r < 0.20$), which suggests that the stones are a suitable tracer.

On the steepest plot (82%), the angle of repose was exceeded and clods started to roll or slide down by gravity. On-farm measurements indicated that the angle of repose of

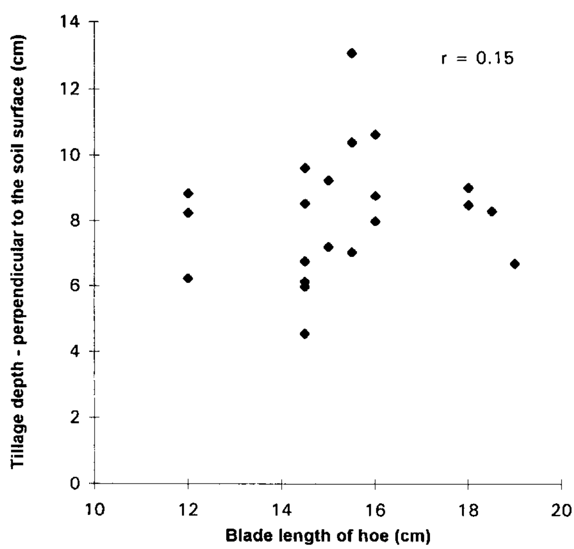

Fig. 6. Relationship between blade length of hoe and tillage depth (field survey).

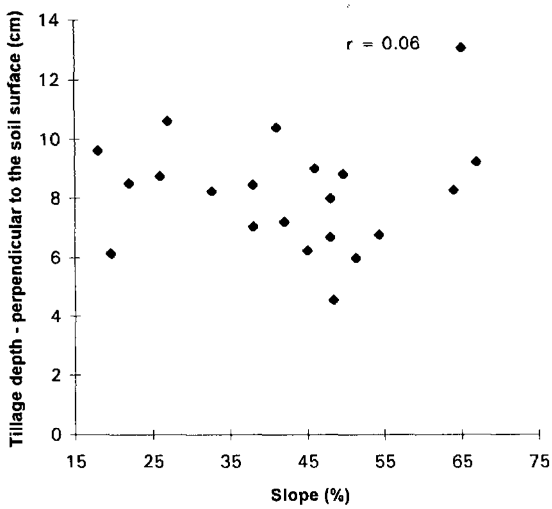

Fig. 7. Relationship between slope and tillage depth (field survey).

soil clods is about 74–78% for clearings of established bamboo and grass fallows, and 68–74% for cultivated fields older than one year. Tillage of older fallows leads to larger and stable clods, because of the root reinforcement of the soil aggregates (see introduction). Texture and stoniness affected the angle of repose as well, but they seem to be less important than the root content. The method of tillage was another variable; fine tillage (superficial tillage) resulted in a lower angle of repose than rough tillage (deep tillage).

3.2. Comparison of methods to measure soil flux by tillage erosion

Fig. 8 shows soil fluxes obtained by the three methods after one manual tillage pass. The results of the tracer and step methods are very similar. The difference between them is the shape of the curve: the step method shows a linear trend, whereas the tracer shows a slightly exponential curve. This can be attributed to clods rolling down on the steepest plot; these influence the shape of the tracer curve but not that of the step method.

The trench method also shows a slightly increasing soil flux with increasing slope, but at much smaller soil flux values. This is the only method that collects the transported soil directly, so it was expected to give more accurate measurements. However, it

Table 2
Mean displacement distance of soil due to manual tillage (assessed by tracer method)

slope angle (%)	mean displacement distance (m)	standard deviation (m)	observations (No.)
32	0.50	0.19	170
41	0.48	0.26	169
51	0.53	0.20	175
60	0.56	0.28	171
82	1.09	0.44	178

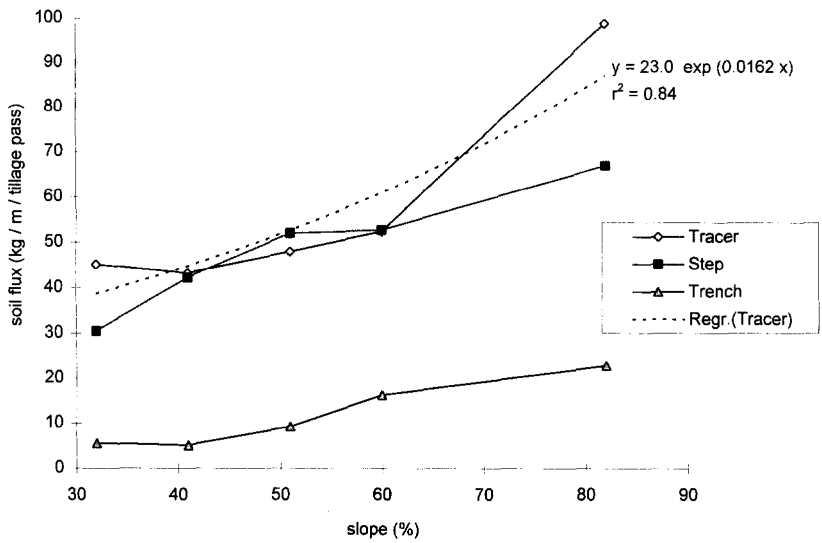

Fig. 8. Relationships between slope and soil flux after one manual tillage pass, assessed by three different methods.

under-estimates soil fluxes because of the plastic lined trenches, which formed a physical barrier hampering free tillage just upslope of the trench. The farmers probably did not use the same force when they were tilling the soil near the trench and did not lift clods into the trench, resulting in an unrepresentative mass of soil collected in the trenches.

The step method seems quite accurate and is clearly the fastest. It is recommended for quick assessments, although a correction factor is needed for slopes steeper than 70%. The tracer-method is probably slightly more accurate, but it is more time consuming. It is useful when verification is needed. The trench method could be potentially useful, although great care should be taken because of the border effects. One improvement could be to use compacted trenches (without a plastic cover) which allow free tillage.

Further calculations are based on the tracer method, as it was shown to be the most reliable. The "tracer-curve" can be described by an exponential function, as shown in Eq. (4).

$$\text{Soil flux}\,(\text{kg/m} \cdot \text{tillage pass}) = 23.0 \cdot \exp(0.0162 \cdot \alpha) \quad (r^2 = 0.84) \qquad (4)$$

with α = slope angle expressed as a percentage.

3.3. Quantification of tillage erosion rates

The soil fluxes for one tillage pass ranged from 39 to 87 kg/m depending on the slope (Eq. (4) and Fig. 8). For slopes less than 60%, soil fluxes did not change substantially with slope. An increase in soil flux was observed for slope angles between 60 and 82%, as the soil clods start to roll down-hill once the angle of repose has been exceeded.

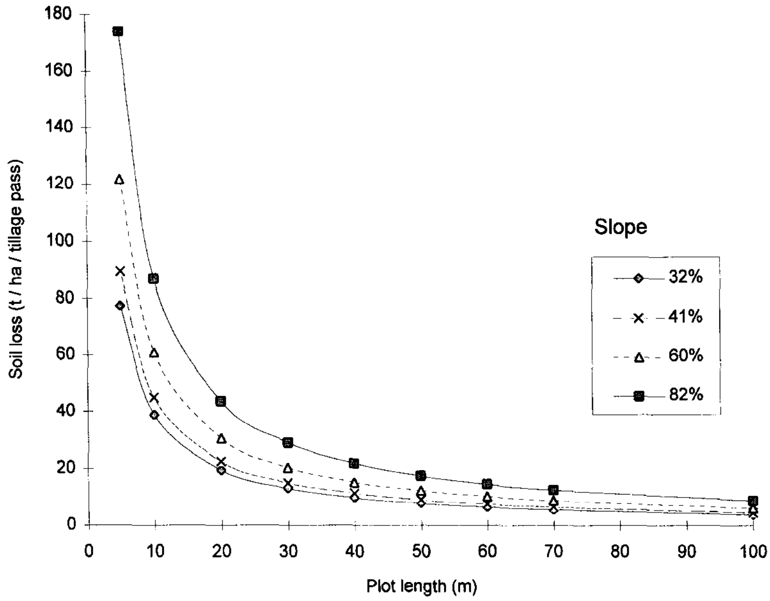

Fig. 9. Calculated mean soil loss after one tillage pass as a function of plot length and slope, based on Eqs. (4) and (5).

Soil losses per hectare for one tillage pass as a function of plot length and slope are shown in a nomogram (Fig. 9). Soil losses are calculated using Eqs. (4) and (5):

$$\text{Soil loss}\,(\text{kg}/\text{ha}\cdot\text{tillage pass}) = \frac{\text{flux}\,(\text{kg}/\text{m})\cdot 10\,000\text{m}^2}{\text{parcel length}\,(\text{m})\cdot\text{ha}} \tag{5}$$

The nomogram (Fig. 9) shows that the soil losses can be very large, especially on short plots located on steep slopes. For a typical hilltribe field plot with a length of 30–50 meters and a slope angle of 30–50%, 8–18 t/ha would be moved by one deep tillage operation. This indicates that tillage erosion can contribute significantly to soil degradation, hillslope evolution and soil profile truncation.

4. Consequences of tillage erosion

4.1. Land pressure and tillage erosion

An increase of land pressure affects the rate of tillage erosion in various ways:

- Increasing land pressure results in more frequent cropping, which leads to a greater tillage frequency on the same plot.
- Semi-permanent land utilisation for annual crops leads to increasing weed pressure, which requires more frequent tillage and weeding. Besides the first deep tillage pass, also the subsequent seedbed preparation, planting and weedings are expected to contribute small, but significant amounts to the total tillage erosion (see Table 1).

However, the increasing use of herbicides reduces the need for tillage and weeding, and will therefore decrease the amount of tillage erosion.

- With the gradual disappearance of older fallows, the angle of repose of soil clods declines. Fields steeper than 65% become therefore more prone to tillage erosion.

In general, it can be concluded that tillage erosion becomes more significant when land pressure increases.

4.2. Alley cropping and tillage erosion

Some soil conservation measures aim to minimise water erosion by reducing the slope length. For example, in the much promoted alley cropping system, the slope length

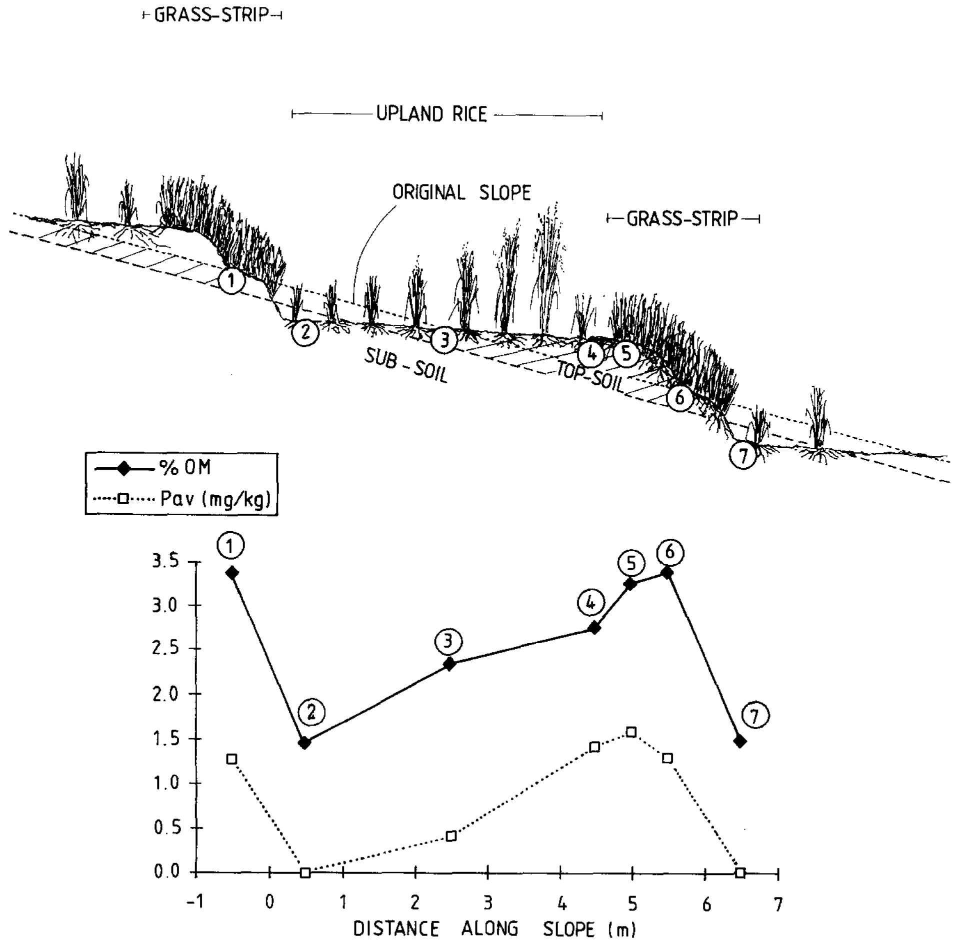

Fig. 10. Cross-section through a six year old alley cropping field with grass buffer-strips, showing the fertility redistribution of topsoil (0–20 cm) affected by tillage erosion (after Turkelboom et al., 1996). %OM = organic matter content (Walkley and Black). Pav. = available phosphorus content (Bray II).

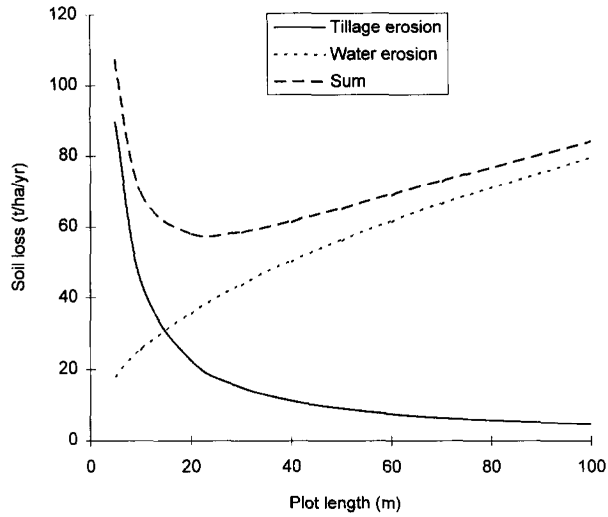

Fig. 11. Comparison of tillage erosion (after one tillage pass), and water erosion in function of slope length. For inter-rill and rill erosion, a mean annual soil loss of 50 t/ha·yr was assumed for a plot on a 40% slope with a length of 40 m and cultivated with annual crops. This rate was extrapolated for shorter and longer plots using the L-factor of the U.S.L.E.:

$$\mathrm{L-factor} = \sqrt{\frac{\mathrm{plot\,length\,(m)}}{22.13\,\mathrm{m}}}$$

(Wischmeier and Smith, 1978). Mean soil loss figures for tillage erosion were deduced from Fig. 9.

is reduced to about 5 m by buffer-strips. Water erosion can be effectively controlled if the buffer-strips are well established (Soil Fertility Conservation Project, 1992). On the other hand, tillage erosion can reach values up to 170 t/ha/tillage pass (Fig. 9). This leads to an accumulation of tilled soil towards the buffer-strips and a gradual formation of a terrace. However, a disadvantageous side-effect is that tillage erosion affects the spatial variability of the soil fertility, as fertile topsoil accumulates near the buffer-strips (Fig. 10). This can create a severe gradient of yield decline in the upper zone of the alley (Turkelboom et al., 1996). A similar process takes place in larger fields, but at a slower pace and with a less pronounced fertility gradient.

4.3. Water erosion versus tillage erosion

For a typical upland field 40 m long with annual crops and a slope angle of 40%, an average soil loss by interrill and rill erosion of 50 t/ha · yr can be assumed in northern Thailand (based on Tangtham, 1991; Soil Fertility Conservation Project, 1992; Forsyth, 1994). One deep tillage operation on such a field creates a soil loss equal to 20% of the soil lost by water erosion (Fig. 11). Plot length has two opposing effects on mean soil loss: water erosion is positively correlated with plot length, but tillage erosion is negatively correlated with it. As a rule of thumb, on cultivated fields shorter than 15 m, tillage erosion is the dominant process causing soil loss whereas water erosion is more important on longer fields (Fig. 11).

However, comparing tillage erosion with water erosion has limitations. First, it should be kept in mind that both water erosion and tillage erosion can vary considerably depending on the local conditions. Second, the transport distance by the two processes is quite different. Runoff water is able to transport soil over longer distances, and is more likely to reach a stream. Soil moved by tillage erosion has more chance to accumulate at the bottom of the field, especially when the field is concave or when there is a vegetative border at the bottom of the field. Third, the effect of the two erosion processes on nutrient transport is also different. Rill and inter-rill erosion often selectively remove the finer (mostly more fertile) particles. Tillage erosion moves a part of the fertile top-soil downslope in an indiscriminate way. The impact on soil fertility therefore depends on the nutrient distribution over the profile.

Hence, the impact of tillage erosion is influenced by the shape of the slope, the presence of border-vegetation, the location of the field with respect to the surface water bodies and the nutrient distribution over the profile.

5. Conclusions

The transformation of shifting cultivation to more permanent highland cropping systems in the highlands of northern Thailand has led to a more pronounced effect of tillage erosion. The easiest method to assess tillage erosion consists of measuring the tillage-step characteristics. The tracer method could possibly serve as a confirmatory method.

Soil transport by manual tillage on steep slopes contributes significantly to the total volume of soil lost (average between 8 and 18 t/ha · tillage pass, maximum of up to 170 ton/ha · tillage pass) and is an important landscape-forming process.

The impact of tillage erosion depends on a number of factors:

- In short fields and in fields with effective soil conservation barriers (e.g. alley cropping) tillage erosion is the most important form of soil erosion. This can rapidly lead to terrace formation and substantial fertility gradients. In longer fields, water erosion is the dominant erosion process.
- Steepness of the slope seems to have little effect on soil fluxes, until the slope exceeds the angle of repose (about 70%). Cultivation of annual crops should be avoided on these very steep fields, as the complete topsoil could slide down.
- Tillage-demanding crops such as upland rice and cabbage lead to greater tillage erosion rates than maize or beans.
- As the first purpose of tillage is to control weeds, the pressure and type of weed will influence tillage erosion rates.
- Tillage erosion produces a net loss of soil when soil is deposited outside the field, because of slope convexity, the absence of barrier vegetation or the proximity of streams.

In conclusion, although not at all apparent, tillage erosion is an important process, which has to be considered when assessing soil degradation rates or when studying landscape changes.

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Socio-ecological Determinants of Land Degradation and Rural Poverty in Northeast Thailand

by

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INTRODUCTION

'A majority of the population in the rural areas of Southeast Asia is living in absolute poverty; although the economies of these countries have achieved high growth-rates in the 'modern sector', the numbers of the rural poor are not decreasing' (Suthasupa, 1987).

In 1978, Thailand ranked forty-fourth in the world in terms of Gross National Product (GNP), thirty-first in annual growth-rate of *per caput* GNP, and had a GNP annual growth-rate of 7% (Kurian, 1982). In the last decade, Thailand has continued to show impressive economic growth — in 1986, for example, ranking thirty-third in terms of GNP, twenty-fifth in terms of annual growth-rate of *per caput* GNP, and had a GNP annual growth-rate of 9.2% (Kurian, 1991). Moreover, despite the world-wide economic slowdown of recent years, growth-rates in Thailand remain high, with an average annual GDP growth-rate of 7.6% from 1980–90 — up from 7.3% for the 1965–80 period (IBRD, 1992).

While these statistics may be impressive, particularly when compared with those of other Third World countries, we find that in the early 1990s approximately 24% of the country's population remains below the poverty line. Moreover, in spite of these impressive growth-figures, in the northeastern region of Thailand about 38% of the population falls below the poverty line, which represents an actual increase from the 1980 level of 36% (Suganya, 1990). Similarly, the environmental degradation of this region has continued to cause alarm.

These and other indicators — to be discussed below — point to the fact that in the Northeast the poverty and the environmental situation are worsening, despite the impressive growth-rates for the country as a whole. How can we explain this phenomenon of growing poverty and environmental degradation in a period of rapid economic growth?

This paper will explore and analyse several of the underlying social and economic factors contributing to the problem of rural poverty and land degradation in Northeast Thailand. The analysis will include a discussion of the interplay of important economic and ecological factors that are contributing to this problem. In particular, this study will focus on the impact of changing economic policies on rural ecological stability, and the implications of these policies for poverty and its alleviation in the rural community.

We will first discuss the movement from a system of local production geared to meeting subsistence needs, towards one that begins to promote 'expanded production' and private accumulation of wealth in Northeast Thailand. Following this, we will discuss some of the problems that have accompanied this transition. We will then turn to the analysis of the failure of several of the approaches to 'development' that have been tried in the Northeast, and the ways in which development projects have either failed to alleviate, or in fact have contributed to, rural poverty and environmental degradation in the region. Finally, we will indicate some of the possible policy implications that can be derived from this study.

SOCIO-ECOLOGICAL CONDITIONS OF THE NORTHEAST

The semi-arid Northeast accounts for about one-third of Thailand's land-area and population. In 1987 the region's population was 18.67 million people (it is now estimated at around 19.5 millions), which represents approximately 34% of the country's population (Seri & Hewison, 1990). More than 80% of the population in the Northeast is rural, consisting primarily of farm families living at the subsistence level. The region is the poorest in Thailand: GNP *per caput* in the Northeast was 8,124 baht*, compared with an estimated 20,236 baht* for the nation as a whole (National Statistical Office, 1990; IBRD, 1992). The agricultural production potential of the region is limited by infertile soils and a bi-modal rainfall pattern with long dry intervals.

The people of the Northeast belong primarily to the Thai–Lao ethnic group. In the past they had made appropriate adjustments to the prevailing environmental constraints of poor soils and irregular and uncertain rainfall patterns, as their habitations were established on raised grounds to escape the frequent flooding during monsoons. Moreover, their land-use and land-cultivation practices were adjusted to meet the requirements of the local environment. As Dixon has described, 'The unreliable environmental conditions of the north-east result in few farmers willingly holding one plot of homogeneous paddy land. In wet years, low-lying land is either inundated and unplantable or subject to extensive crop loss. Similarly, in

* US $1 = 26 baht at 1991 exchange rate.

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dry years high land may be too dry to plant or the crop may be seriously damaged by drought. Farmers attempt to spread the risk by holding land in a variety of situations' (Dixon, 1990).

Prior to the early twentieth century, the majority of the people in the region supplemented their subsistence-oriented agricultural production with the raising and selling of cattle (primarily buffalo). This was also a reasonable response to the local environmental constraints. The sale of cattle generated enough income to act as insurance against the risk of crop failure, which was not an uncommon occurrence, given the frequent inadequacy of monsoons. In years of drought, cattle would be bartered for rice from other regions of the country. In normal rainfall years, upland rice-crops would meet the local food demand.

However, over time this economic activity was hurt by the loss of traditional markets for buffalo which had extended throughout the Central region and as far as the Thai–Burmese border. This was due to the change in agricultural techniques away from a dependence on buffalo and other animals, and the loss of grazing land to increased rice cultivation, among other contributing factors. The potential of cattle-raising as an effective source of cash income to the rural poor was further reduced by the passage of laws which required licences for the sale of cattle in the markets in Bangkok and the other urban centres. This gave virtual monopoly to the licenced merchants, and resulted in much lower returns to Northeasterners, who now had to sell through the licenced merchants (Keyes, 1982).

In the absence of direct access to urban markets, the people were left with two options: either switch to some other economic activity, or increase their herd's size in order to make up for the low returns per animal which they could get as a result of the merchants' monopolistic control of the cattle market. Wherever carried out, the increase in herd size has led to increased pressure on the carrying capacity of the regional pastures and grazing lands.

The shift away from a reliance on cattle-raising was also affected by the policies adopted during the 1960s — aimed at developing the country's economy through rice and other cash-crop exports. Although the promotion of rice exports affected the Central region above all, these policies encouraged a shift towards cash-crop production and the monetization of the rural economies in other parts of Thailand as well. In the face of new limitations to the raising and selling of cattle, many northeasterners had to find new cash-generating farming activities. These included (i) increasing the total area under rice cultivation (both of the local glutinous as well as the export-oriented non-glutinous variety), and (ii) initiating the cultivation of such cash-crops as Cassava (*Manihot utilissima*) and Kenaf (*Hibiscus cannabinus*) for export markets.

Regarding the first possibility — *i.e.* increasing the local area under cultivation — food insecurity has led the local people to put as much area under Rice (*Oryza sativa*) cultivation as they possibly can. One of the strategies that has evolved is to grow as much Rice as possible in the good-rainfall years in order to be able to store enough for the bad agricultural years; another strategy is to grow as much surplus Rice as possible, and sell it immediately in order to generate cash that will be used to buy Rice for household consumption as and when needed (Medhi & Chamratrithirang, 1984). The alternative to increasing production — namely of undertaking the cultivation of new cash-crops — leads directly to a total dependence on the market, and therefore on market prices. Both of these possibilities require the clearing of large tracts of new land for purposes of cultivation.

In part because of this need to bring new land under cultivation in a region with limited arable land (19% of the total), the natural forest area has dwindled from the former 42% of the total land-area of the region to only 15% in 1960 (Seri & Hewison, 1990). This forest land has served as an important source for grazing, fodder, and fuel. The depletion of this resource has not only further reduced the possibility for productive livestock-based economic activities, but has also created a significant domestic energy shortage, as the main source of cooking energy for the rural population is fuel-wood and charcoal. In addition, the dwindling forest resource is adversely affecting the third-best non-farm source of household income, namely the additional income generated by the manufacture and sale of charcoal for local markets and large urban centres.

Moreover, despite the fact that large expanses of forest land have been placed under cultivation in the Northeast, we find that 10% of the households in the region still do not have access to their own land but have had to cultivate rented land. In addition, a large percentage of the households that have access to their own land do not have formal titles of ownership, and as a consequence of this land-tenure insecurity and other important contributing factors, now face severe problems of land degradation, as will be explained below. These conditions result in increasing land hunger in a region that is arid and ecologically unsuitable for the growing population and increasing demands that are being placed on the land.

Ecological Disequilibrium

The interplay of many socio-economic forces has led to the practice of a modified form of swidden agriculture in the region. This traditional method involves the clearing of forest land and the burning of trees and other vegetation for the cultivation of food-crops. Traditionally, the land has been left fallow for ten to fifteen years, to regain a vegetative cover and rebuild the nutritive base. However, under current practices, to support the ever-increasing human and domestic-animal populations, each parcel of land is left fallow for only three or four years.

Resource-poor Northeastern farmers have taken the logical choice of making use of this method of cultivation to meet their growing needs for food and cash. First, given the land scarcity that has developed in recent decades, the forest land is the only land available to a substantial section of the rural population. Second, for the resource-poor farmer who lacks the means to undertake intensive agriculture, this is the 'best' available technique of cultivation. In the absence of fertilizers, the clearing of new forest lands provides fertile and productive sites in a short period of time. This is due to the fact that the burning of trees and other vegetation releases important plant nutrients which ensure a reasonable yield, at least in the short run.

This method is also the most labour-efficient means of site preparation for agriculture. Although it is usually assumed that labour is not an important consideration for the northeasterner, this is not always true; given the poverty of the northeastern farm family, a growing number of individuals — primarily male members — leave the Northeast for farm or non-farm labour in other regions, including Bangkok. This type of migration, referred to as 'circulation' (Goldstein, 1987), is on the increase. This has resulted in many families being headed by female members for long periods of time. The absence of young and able-bodied male labour for agricultural activities makes swidden agriculture very attractive to the farm household because, with swidden agriculture, fire is the main tool of site and soil preparation, and this reduces the need for a high manual labour input; this also reduces the time needed for land-clearing.

Land hunger, resource poverty, and migration, are thus three of the most important reasons for the extensive conversion of forest land to agriculture through swidden cultivation. In addition to these factors, the cash needs of recent decades have encouraged the clearing and burning of forested areas for the specific purpose of growing cash-crops such as Kenaf (a substitute for jute) and Cassava — the latter for export to Europe as animal feed. The area under Cassava cultivation in the Northeast has shown a gradual increase from 3.2 million rai (1 rai = 0.16 ha) in 1975–76 to 7.5 million rai in 1990–91, thereby more than doubling the area used for the cultivation of this crop (Traub, 1989; Center for Agricultural Statistics, 1991). It is worth noting that cultivation of Cassava was promoted for a time when Thailand was facing a balance-of-trade problem due to the 'oil crisis' and increasing costs of oil imports; ironically, the Northeast has the least energy consumption in the country, particularly of fossil-fuel energy. (It is also somewhat ironic that livestock production in the region has decreased as grazing lands are converted to grow Cassava, which will be shipped to Europe in pellet form to feed subsidized European livestock production.)

The important point about Cassava-growing in these areas is that it is agronomically unsound, as Cassava is a very nutrient-demanding crop. This results in the quick depletion of the soil fertility of the newly-opened areas, and thereby necessitates the clearing of more land. Therefore, the true costs of planting Cassava should include the loss of potential future agricultural and wood production from lands that have become infertile, and are thus abandoned. Moreover, although farmers have been encouraged to produce crops such as Cassava and Kenaf as a way to secure a cash income readily, the long-term benefits are also called into question by the fluctuating prices of the crops. (Even when the export prices for these commodities are high, the compensation received by the farmer for his or her labour is usually very small; when prices are low, the compensation is all the more problematic.) For these reasons, benefits from this type cultivation may not be sustainable, and the long-term costs may very well include the impoverishment of a great deal of land-area — particularly that under Cassava production.

It may be argued that the impoverishment of the soil in this way could be avoided through a greater awareness among farmers of the long-term effects of current practices. However, we should note that the lack of security with regard to land ownership reduces the possibility for private or official institution-building that could lead to sound rural development programmes despite these problems. The lack of land-tenure security stems in part from the lack of ability to formalize the titles of ownership. Although the Comprehensive Land Code of 1954 defines the procedures for the issuance and registration of privately-owned land, the process had been completed for only 31% of the rural households throughout the country. In addition, 42% of the Northeast has been classified as 'forest area'. In some of these areas the land has been under the occupation of squatters for more than 15 years, and some lands were declared as forest areas even after they were settled and cleared! This has resulted in reduced farm investment and land improvement (Feder & Onchan, 1987).

The study conducted by Feder & Onchan shows that security of ownership, where it exists, has resulted in higher investments in site and farm improvements. However, more than 50% of the farmers in the Northeast were found to be prevented from carrying out farm improvement activities by resource constraints, and ownership was found to be a very important factor in securing institutional credit. The credit worthiness of the borrowers with land collateral was 150% higher than that of the group with no land collateral. This inability to receive formal titles of ownership, and therefore have access to institutional financing, was found to result in farm households being forced to borrow from local money-lenders. The problems associated with this arrangement are well known in the development field.

These socio-economic factors have resulted not only in a lack of farm investment and land improvement, but also in the shortening of the fallow from a traditional ten to fifteen years' period to a period of only three or four years as indicated above. This is not enough time to replenish the nutrient levels of the land to the point that is necessary to sustain agriculture. The falling yields lead to a vicious cycle of reduced fallow and further degradation of the farm lands, with the ultimate result that many of these formerly cultivated areas may have to be abandoned altogether.

In this way, the resilience of these inherently fragile lands is slowly dying out and resulting in uncultivable barren lands. Therefore, the policies and trends discussed here have resulted not only in an increasingly impoverished rural population, but also in a situation that is threatening the very resource on which the people depend for their sustenance and survival.

Development Attempts

In the past, the main focus of government development policy in Northeast Thailand was aimed at the construction of roads, railways, and irrigation systems. However, the models on which these projects were based were not always appropriate for the conditions prevailing in the Northeast.

The fourth Five-Year National Economic and Social Development Plan (1971–75), for example, focused on large-scale infrastructural investments, including irrigation and water-supply systems which were designed to increase the agricultural potential of the rural areas. The irrigation models and technology used were the ones developed for the capital-intensive agriculture of the Central region, where the farming communities had traditionally established themselves near the main rivers and streams. This pattern was reasonably suited (at least in a technical sense) to the irrigation model originally developed for capital-intensive agriculture in the US and Europe. However, as described earlier, in the Northeast the habitations have been traditionally established on elevated and more scattered areas, with farmers cultivating dispersed sites as a response to the periodic flooding of low-lying areas and the periodic drying-up of higher-level sites. Therefore, the terrain and traditional layout of habitations and cultivated sites made the application of the Western models of capital-intensive centralized irrigation systems extremely problematic.

These water-resource development schemes carried out by the Royal Irrigation Department were of limited effectiveness, due to the lack of understanding of the local biophysical factors and traditional socio-ecological patterns. An entirely different scheme that took into consideration the different characteristics of the terrain and the periodic forces to which it is subjected, might have worked; however, the majority of the irrigation projects undertaken during this period ultimately showed poor results. Bruns (1991) points out that these schemes had high rates of failure, and Vanpen (1986) comments that an evaluation of these schemes showed less than a 10% increase in family incomes. Mayson (1984) estimates the failure rates for weirs which were established as part of the Job Creation Program to be as high as eighty to ninety per cent. Moreover, the promise of a stable source of irrigation water encouraged households to concentrate their productive activities closer to the newly-developed water and irrigation sources than they might otherwise have done. Then, with the failure of these projects, and in the absence of adequate irrigation and yet high fertilizer inputs on an ongoing basis, the increasing density of the population simply could not be sustained.

Threatened by rising poverty in the Northeast and an increasing potential for large-scale migration to Bangkok, the government responded by initiating new micro-level projects as part of the overall development plan. These projects included cooperative village projects and land-settlement projects, among others.

The efficacy of this approach was limited by the inherent inefficiencies associated with such projects. For example, under one land settlement project, landless people were to be settled on abandoned or newly-opened forest lands. However, this required a great deal of coordination between the Land Development Department, financial institutions, the Forest Department, and other local administrative agencies. The full coordination of these departments was found to be difficult to achieve.

Policies Often Conflicting

Second, the village cooperative scheme involved establishing food- and wood-based economies in the vicinity of the forest areas. However, the settlers were given only usufruct rights and not ownership rights. This was a result of a contradictory land and forest protection and development policy. According to the settlement plans, landless people were to be settled on public land, which was mostly forest land. However, at the same time the forest policy aimed at maintaining at least 40% of the land in the Northeast as forest areas (and this despite the fact that the actual forested area is now down to 15% of the total land-area).

Although this forest policy is often defended on the basis of ecological principles, these principles have no clear scientific basis. The idea that a minimum of about 33% of total land-area should be kept under forest is one that originated in the forest policies of the US and other developed Western countries, and is not necessarily appropriate for regions such as Northeast Thailand. This is all the more true when the classification simply refers to the legal status of the area, rather than the actual tree-cover.

Of course, one reason for the desire to maintain at least 33% or even 40% of the land under the classification of 'forest area', and not open it up to settlement, is certainly due to ecological concerns as well as the significant socio-economic concerns tied to deforestation problems, as discussed above. However, other reasons for this classification may, in reality, include such considerations as the benefits that some officials, charcoal-kiln owners, and timber smugglers, derive from this way of classifying the land. Moreover, opponents to reforestation projects (such as the one launched in the Northeast) often see these projects as 'camouflage plans to turn the evacuated areas into corporate pulp plantations' (Handley, 1991). (It has also been suggested by an anonymous referee that one of the most significant problems involves the Royal Thai Forest Department, as this RFD is 'notorious for being extremely conservative and highly unwilling to allow any of "its" land to be allocated to other departments. The RFD is a very old institution, and in fact is one of the government institutions that has played the strongest role in extending the control of central government into most remote areas. Prior to the advent of the RFD, local people themselves had at least usufruct, if not formal ownership, of the forest land they occupied.')

No matter what the reasons may be behind the specific forest policy that was developed for Northeast Thailand, we know that the effect has been to close off a significant area for settlements, put more pressure on the areas that are open to cultivation, and in so doing put forest policy in direct conflict with the land settlement projects. (For more on these and related issues, *see* Hafner [1987, 1990].)

Plot Sizes and Permanence Important

The micro-level projects also suffered from unrealistic assumptions regarding the plot sizes that were made available to the settlers. In the absence of irrigation facilities and inputs such as fertilizers, the sustainable farm size for an average family is at least 15 rai (2.4 ha). However, the plot size made available to these settlers was on the average only 5 to 10 rai. In order to make this latter farm size into a sustainable entity, the cost of land improvement and material inputs would be about $1,000 per family in the establishment stage. In addition, the maintenance of the productivity on a sustained basis would require regular material and labour inputs of a substantial amount. The absence of any institutional support for meeting these needs resulted in the settlers' lack of involvement in the project, and ultimately in the abandonment of these lands.

Another contributing factor to the failure was the lack of permanence of most of these project communities. The projects were encouraging a kind of multiple-cropping system in which trees, food-crops, and cattle, are raised simultaneously. This meant that the farmers ultimately would have to move to different sites when the old sites became unavailable, as the tree-shade increasingly worked against, and ultimately prevented, the production of food-crops. The primary purpose of these projects was actually the reforestation of the denuded forest lands, rather than the production of subsistence crops for the stated beneficiaries. Thus, the lack of enthusiasm on the part of the project 'beneficiaries' is understandable, as the project was in fact perpetuating the insecurity from which the farmers sought relief.

Finally, the effects of insecurity of land ownership took their toll on the participants in these projects as well. The cooperatives that survived the project period crumbled soon after the project period was over.

The Equity Model

The failure of the large-scale infrastructural as well as micro-level policies of rural development has resulted in a revaluation of rural development strategies. A relatively new approach — called the 'equity model' — has been proposed as an appropriate rural development model in Thailand, including the Northeast. The salient features of the 'Poverty Stricken Area Development Plan', effective since 1982, were as follows (from Suthasupa, 1987):

a) Poverty-stricken areas are considered as the target areas.
b) Subsistence level is the primary goal of rural development in order to provide basic minimum services to rural people in the poverty-stricken areas.
c) Emplasis is placed on helping rural people to help themselves eventually.
d) Simple techniques and low investment should be employed.
e) Let rural people solve their own problems to the best of their ability.

This development plan involved an investment of 8.6 million baht (US $1 = 26 baht, 1991 exchange rate), with the Thai government contributing 7.2 million baht and the rest coming from foreign loans (Suthasupa, 1987). The plan's targets included raising the average rate of agricultural production from the prevailing annual rate of 1% to 2% in the project period. Project activities took the form of a 'village basic service programme', which included the development of village fisheries, water resources, buffalo banks, and livestock development, as well as primary health-care, nutrition reinforcement, and hospital services. Village production activities had as their goal the development of agricultural credit facilities, upland rice seed production, and soil and land improvement. The execution of these programmes and activities involved the National Rural Development Committee (NRDC); the Ministries of Interior, Education, Public Health, Agriculture, and Cooperatives; the Office of National Social and Economic Development (NSED); the Provincial Rural Development Committee (PRDC); the District Rural Development Committee (DRDC); and the Tambon Council (TC).

This approach, which is intended to be 'participatory' and 'bottom-up' in nature, would appear to be both more appropriate to the conditions of the Northeast and better conceived than the earlier programmes. However, we find that this approach as well has been beset with problems which would appear to stem from causes other than the lack of sufficient funding, as will be discussed below. Some of the problems that emerged as this programme was implemented are summarized below (from Suthasupa, 1987):

1. There was a lack of public participation in the policy-making process.
2. The target areas were often changed to suit the budget allocation to different provinces and regions.
3. The ambiguous selection procedure and definition of poverty-stricken areas led to the selection of a high percentage of non-poverty-stricken areas for the programme.
4. There was a lack of coordination among different parts of the project.
5. The lack of qualified people to help with administration was an additional constraint.

A few comments regarding these points may help to clarify the difficulties involved in this type of approach. The first and last points indicate that, despite the participatory intent of the project, it appears that most of the policy decisions are taken at the central (national) level, and that the participation of local individuals and institutions may have been practically absent. Moreover, although the lack of qualified personnel could certainly pose problems, we need to recognize that, particularly in the field of agroforestry, the local people themselves may prove to be an important source of knowledge and expertise that has often been overlooked.

A programme that is truly 'participatory' needs to build on the potential contributions of the cultivators, who may already possess a great deal of experience and knowledge that is appropriate to the local socio-ecological conditions. However, any attempt to change development and administrative institutions and individual practices that are thoroughly 'top-down' in orientation (as reflected in the attitudes and behaviour of scientists, administrators, and other 'experts'), and convince them to value the ideas and knowledge of the local population, is a difficult and often impossible task under present conditions.

The second, third, and fourth, points — regarding frequent changes in target areas in view of budget allocations, difficulties involved in selecting truly poverty-stricken areas, and the lack of coordination among different parts of the project — indicate problems that result in a lack of consistency which may make appropriate institution-building and planning very difficult. For example, in this case the plans called for the simultaneous development of health centres, nutrition improvement, and water-resource improvement, in the project areas. However, it seems that different segments were implemented in different locations, and this disjointed implementation may have rendered the whole effort ineffective.

We need to understand exactly why this lack of consistency arose. Is it something that can be changed, or does it reflect more fundamental problems with the way the decision-making and implementing organizations function?

The point regarding the selection of non-poverty-stricken areas underlines our conviction that the real problem is not simply a lack of coordination among, or a lack of understanding on the part of, implementing agencies. Contrary to what might be inferred from Suthasupa's discussion — that these are technical difficulties which might be tackled and overcome — the point regarding the selection of non-poverty-stricken areas gives further evidence that the real problem lies with target-oriented planning in general, and the ways in which decision-making and implementing organizations work in particular. The key issue here appears not to be lack of coordination or information or understanding, but rather the realities surrounding the setting of targets.

Let us look at this point in more detail. In the absence of advanced project planning, and due to the uncertainty of the budget, we know that the achievement of targets in the real poverty-stricken areas is difficult, as these areas lack most of the infrastructure that is necessary for the desired development activities. Under such conditions, the logical option for the project-implementing officers and workers is to look for secure areas where the infrastructure will ensure the achievement of the targets. This strategy is tied to the fact that the evaluation standard for efficiency and services is invariably fixed according to the achievement of physical and financial targets, rather than according to more qualitative indicators of the people's welfare. Given the focus on quantitative indicators, non-poverty-stricken areas provide a surer way to achieve the proposed targets.

This also indicates that the real problem lies in the realities of the decision-making and implementation process, and not in the lack of coordination among, or information available to, these agencies, or in any lack of sufficient funding for the programmes or projects. Only a fundamental reorientation in the thinking and evaluation procedures of decision-making and implementing agencies would allow for more participatory approaches to succeed, rather than fail to meet their intended goals. Such a fundamental reorientation — one that challenges established hierarchies of power and expertise — may only begin to emerge if there is strong internal and external pressure for such a change.

For now, we need to analyse clearly the ecological problems from the perspective of the powerful socio-economic forces that govern their trends over time, and analyse development programmes and projects not from the perspective of their ideals, but rather in terms of the socio-economic forces which they represent and the realities that they face on the ground. Then, as political and economic necessities ultimately drive institutions to change, and as new possibilities arise, we may have a better understanding of the forces that determine these changes. We may then be able to address more effectively the underlying causes of soil and land degradation, and the resulting impoverishment of the people of the rural areas. However, until political and economic necessities — and strong internal and external pressures — begin to force institutions to change in such fundamental ways, we need to recognize clearly why these agencies act in the manner that they do, and recognize why development projects — even well-meaning ones — are likely to fail to meet the actual needs of the local people in the region.

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Summary

The discussion above illustrates the inadequacy of many of the development strategies that have been pursued in Northeast Thailand. The prevailing social, political, and economic, policies and trends have resulted in the transformation of the people of the Northeast from a relatively self-sustaining population to an increasingly impoverished one. In the course of the movement away from relatively self-sufficient subsistence-oriented production, they have been exposed to both the 'rigours of the market' and changing policies regarding access to markets, cash-crops, and land tenure — with all of their destabilizing, and in this case impoverishing, effects. This transformation has resulted in increased land degradation and rural poverty in the Northeast.

Threatened by the potential political and social repercussions of these changes, development authorities have tried to respond by exploring different institutional and implementation strategies. These included infrastructure investments based on models derived from other regions, as well as land settlement, village cooperatives, and other micro-level projects.

The failure of these approaches to alleviate rural poverty in the Northeast prompted more 'participatory' and 'bottom-up' development strategies (*e.g.* in the form of the 'equity model'). However, these attempts as well have run into difficulties, with explanations centring around the lack of coordination among different development agencies, lack of training, and related problems. Such explanations focus on technical issues that presumably could be overcome with more coordination, information, and technically-skilled people. The question is: can an improvement in the method of implementation of these projects, actually alleviate the problems of poverty and land-degradation in the rural Northeast?

This study indicates that the real problem lies more in the failure to confront the reasons why these policies have been designed and implemented in the ways that they have been to date — including problems associated with the development 'paradigm' which is being used — as well as the failure to confront the actual circumstances and requirements of the local people involved. It is critically important to recognize the underlying forces that have resulted in resource poverty, migration, land hunger, and land insecurity, and to recognize and castigate the policies that themselves result in land degradation. Until

the underlying causes are recognized, and pressure is exerted to bring about change, rural development projects, no matter how well-meaning, are likely to differ primarily in the degree to which they fail to alleviate, or in fact even contribute to, rural poverty and environmental degradation in the region.

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