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MSEC special issue No. 17, September 2008

Management of Soil Erosion and Water Resources in the Uplands of Lao P.D.R.

IRD Institut de recherche pour le développement

International Water Management Institute

MSEC

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ອອກແບບ ແລະ ຈັດໜ້າ ໂດຍ: ຂັນຄຳ ອ້ວນອຸດົມ, ສູນຂໍ້ມູນຂ່າວສານ, ສຄກປ

Foreword

This special issue of the Lao Journal of Agriculture and Forestry aims to highlight some of the recent activities undertaken by the partnership established between the International Water Management Institute (IWMI), an organization funded by the Consultative Group on International Agricultural Research (CGIAR), the Institut de Recherche pour le Developpement (IRD), a French public science and technology research institute under the joint authority of the French ministries in charge of research and overseas development and the Lao National Agriculture and Forestry Research Institute (NAFRI). The partnership was initiated in 2003 when IRD and IWMI took over IBSRAM and the ADB to support the activities of the Management of Soil Erosion Consortium (MSEC) in Lao PDR.

In order to alleviate poverty, government agencies in Lao PDR have grouped and resettled upland villagers next to upgraded roads in an effort to provide better access to education, health and markets. To protect biodiversity and preserve some of the last remaining pristine forest environments of Southeast Asia, governmental policy has also reduced the overall area of cultivated land throughout the country. Such land use policies together with the growing market demand have resulted in very rapid land use changes in the uplands of northern Lao PDR. The ensuing need to adequately keep rapid land use changes under control has, in turn, induced a pressing demand for research on the interactions between policy makings, social and biophysical processes and their dynamics in the uplands.

In this context, the IWMI-IRD-NAFRI partnership has embarked, through the MSEC, on an ambitious programme of long-term biophysical studies at the catchment scale which resulted in the collection of a unique dataset about soil erosion processes in South-East Asia, which will be publicly accessible at the end of 2008. This effort has also been a unique occasion to assess the impact of land use changes on soil erosion and water quality, and to test alternative farming practices that minimize the negative impacts of these land use changes.

Agriculture remains the backbone of Lao PDR's economy: it generates more than 50 per cent of the national GDP and provides jobs to 84 per cent of the population. However, agricultural diversification in Lao PDR remains extremely low to world standards. From a policy making standpoint, it is both tempting and convenient to assume that the adoption of modern farming techniques and knowledge, applicable to a vast array of situations with no or minor alterations, is the way to deal successfully with major environmental challenges posed by rapid land use change. However, such a view does not take into account the diversity of physical and human environments which make up the basement of Lao agriculture.

In a renewed effort to address such burning issues, the IWMI-IRD-NAFRI partnership has recently expanded its activities towards the management of a wider array of environmental services in the context of the uplands of Lao P.D.R. The research reported in this special issue indicates that (i) the combination of biophysical measurements together with socio-economic information represents a promising option to assist policy making processes and (ii) optimizing land use management in the Lao PDR will likely depend as much on recognizing local specificities, limits and potentials as on modernizing farming techniques and practices.

Sincerely,

ດຣ. ມົນທາທິບ ຈັນເພັງໄຊ

Dr. Monthathip Chanphengxay
General Director, NAFRI

September 2008

ບົດນຳ

ວາລະສານກະສິກຳ ແລະ ປ່າໄມ້ ສະບັບພິເສດນີ້ ໄດ້ສັງລວມຜົນຂອງການຄົ້ນຄວ້າທົດລອງຮ່ວມກັນລະຫວ່າງ ສະຖາບັນ ຄົ້ນຄວ້າ ວິທະຍາສາດ ເຕັກນິກ ກະສິກຳ ແລະ ປ່າໄມ້ (NAFRI), ສະຖາບັນຄຸ້ມຄອງນ້ຳສາກົນ (IWMI) ແລະ ສະຖາບັນ ຄົ້ນຄວ້າ ເພື່ອການພັດທະນາ ປະເທດຝຣັ່ງເສດ (IRD). ການສຶກສາຄົ້ນຄວ້າຮ່ວມກັນ ໄດ້ເລີ່ມແຕ່ປີ 2003, ຫຼັງຈາກຄະນະກຳມະການຄົ້ນຄວ້າ ແລະ ຄຸ້ມຄອງດິນສາກົນ (IBSRAM) ໄດ້ມອບວຽກງານ ການຄົ້ນຄວ້າທົດລອງ ກ່ຽວກັບ ການຄຸ້ມຄອງທີ່ດິນ ແລະ ນ້ຳ ໃຫ້ແກ່ສະຖາບັນ ຄຸ້ມຄອງນ້ຳສາກົນ (IWMI) ແລະ ສະຖາບັນຄົ້ນຄວ້າ ເພື່ອການພັດທະນາ ປະເທດຝຣັ່ງເສດ ເປັນຜູ້ຮັບຜິດຊອບແທນ.

ເພື່ອຫຼຸດຜ່ອນຄວາມທຸກຈົນຂອງປະຊາຊົນໃນເຂດພູດອຍ ແລະ ປົກປັກຮັກສາ ຊັບພະຍາກອນທຳມະຊາດ ໄວ້ໃຫ້ຍືນນານ. ລັດຖະບານ ສປປ ລາວ ໄດ້ມີນະໂຍບາຍມອບດິນມອບປ່າ ແລະ ເຕົ້າໂຮມບ້ານເຂດຫ່າງໄກສອກຫຼີກ ເພື່ອສາມາດເຂົ້າເຖິງການບໍລິການຂອງລັດ ດ້ານຄົມມະນາຄົມ, ສຶກສາ, ສາທາ ແລະ ການຕະຫຼາດ. ຍ້ອນການເພີ່ມຂຶ້ນຂອງປະຊາກອນ ບວກໃສ່ຄວາມຕ້ອງການຜົນຜະລິດກະສິກຳຂອງຕະຫຼາດພາຍໃນ ແລະ ພາຍນອກ ເປັນສາເຫດເຮັດໃຫ້ການນຳໃຊ້ທີ່ດິນ ໃນເຂດພາກເໜືອ ມີການປ່ຽນແປງຢ່າງວ່ອງໄວ.

ສະນັ້ນ, ສະຖາບັນ ຄົ້ນຄວ້າ ວິທະຍາສາດ ເຕັກນິກ ກະສິກຳ ແລະ ປ່າໄມ້ (NAFRI), ສະຖາບັນ ຄຸ້ມຄອງນ້ຳສາກົນ (IWMI) ແລະ ສະຖາບັນຄົ້ນຄວ້າ ເພື່ອການພັດທະນາ ປະເທດຝຣັ່ງເສດ (IRD) ຈຶ່ງໄດ້ຮ່ວມມືກັນຄົ້ນຄວ້າ ການຄຸ້ມຄອງຊັບພະຍາກອນທຳມະຊາດ ໂດຍສະເພາະແມ່ນ ດິນ ແລະ ນ້ຳໃນເຂດອ່າງໂຕ່ງ ໂດຍໄດ້ເກັບກຳຂໍ້ມູນການເຊາະເຈື່ອນຂອງດິນ ເພື່ອປະເມີນຜົນກະທົບຂອງການນຳໃຊ້ທີ່ດິນ ຕໍ່ການເຊາະເຈື່ອນຂອງດິນ ແລະ ຄຸນນະພາບນ້ຳ ແລະ ໄດ້ທົດສອບເຕັກນິກການປູກຝັງທີ່ສາມາດຫຼຸດຜ່ອນຜົນກະທົບທາງລົບ ຕໍ່ການປ່ຽນແປງການນຳໃຊ້ທີ່ດິນ.

ພວກເຮົາຫວັງວ່າ ຂໍ້ມູນດັ່ງກ່າວນີ້ ຈະເປັນປະໂຫຍດບໍ່ຫຼາຍກໍ່ໜ້ອຍ ໃຫ້ແກ່ຜູ້ອ່ານ, ນັກຄົ້ນຄວ້າ, ນັກພັດທະນາ, ຕະຫຼອດຮອດນັກຮຽນ ນັກສຶກສາ ໄດ້ນຳໄປໝູນໃຊ້ເຂົ້າໃນວຽກງານຂອງຕົນ. ພວກເຮົາພ້ອມແລ້ວທີ່ຈະຮັບເອົາຄຳຄິດຄຳເຫັນ ເພື່ອປັບປຸງໃນອະນາຄົດ.

ດຣ. ມີນທາທິບ ຈັນເພັງໄຊ

ດຣ. ມີນທາທິບ ຈັນເພັງໄຊ
ຫົວໜ້າ ສະຖາບັນ ຄົ້ນຄວ້າ
ວິທະຍາສາດ ເຕັກນິກ ກະສິກຳ ແລະ ປ່າໄມ້

ກັນຍາ 2008

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The authors

ສາລະບານ
Table of Contents

ໂຄງການຄຸ້ມຄອງການເຊາະເຈື່ອນຂອງດິນ ໃນ ສ.ປ.ປ ລາວ: ຜົນສຳເລັດ, ກິດຈະກຳທີ່ກຳລັງປະຕິບັດ ແລະ ວຽກງານຄົ້ນຄວ້າສະເພາະໜ້າ ສຳລັບ ເຕັກນິກກະສິກຳ ເຂດພູດອຍ

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ອາແລງ ປີແອເຣ, ໂອນກາ ວິຊຽກ

ບົດຄັດຫຍໍ້

ບົດແນະນຳສະບັບນີ້ ໄດ້ເວົ້າເຖິງສິ່ງທ້າທາຍ ທີ່ພົວພັນເຖິງກະສິກຳເຂດພູດອຍ ແລະ ການອະນຸລັກດິນ ໃນເຂດອາຊີຕາເວັນອອກສຽງໃຕ້. ຈຸດປະສົງຫຼັກ ຂອງໂຄງການຄຸ້ມຄອງການເຊາະເຈື່ອນຂອງດິນ ແມ່ນເພື່ອພັດທະນາເຕັກນິກທາງເລືອກສຳລັບກະສິກຳເຂດພູດອຍ ຊຶ່ງສາມາດປ້ອງກັນການເຊື່ອມໂຊມຂອງດິນ ແລະ ປັບປຸງຊີວິດການເປັນຢູ່. ໂຄງການດັ່ງກ່າວ ໄດ້ເລີ່ມແຕ່ປີ 1998 ເປັນຕົ້ນມາ ໂດຍການປະສານງານກັບ ສະຖາບັນຄຸ້ມຄອງນ້ຳສາກົນ (IWMI). ຜົນຂອງການຄົ້ນຄວ້າເຫັນວ່າການປ່ຽນແປງຂອງການນຳໃຊ້ທີ່ດິນ ເນື່ອງມາຈາກການເພີ້ມຂຶ້ນຂອງປະຊາກອນ, ນະໂຍບາຍການນຳໃຊ້ທີ່ດິນ ແລະ ຄວາມຮຽກຮ້ອງຕ້ອງການຂອງຕະຫຼາດ ມີຜົນກະທົບແຮງຕໍ່ການອານຸລັກທີ່ດິນ ໃນເຂດພູດອຍ. ການນຳໃຊ້ທີ່ດິນຢ່າງຕໍ່ເນື່ອງ, ລະບົບຮອບວຽນ 2-3 ປີ ເກີດມີຫຍ້າຫຼາຍ, ຄວາມອຸດົມສົມບູນຂອງດິນຫຼຸດລົງ, ຜົນຜະລິດເຂົ້າໄຮ່ຕົກຕ່ຳ ສຸດທ້າຍ ຊາວກະສິກອນທີ່ເຄີຍປູກເຂົ້າໄຮ່ໃນເມື່ອກ່ອນ ໄດ້ຫັນມາປູກໝາກເດືອຍແທນ. ການປູກພືດໄລຍະສັ້ນ ເຮັດໃຫ້ມີການເຊາະເຈື່ອນຂອງດິນສູງສົ່ງຜົນກະທົບຕໍ່ຄວາມອຸດົມສົມບູນຂອງດິນ ແລະ ຄຸນນະພາບນ້ຳ. ການປັບປຸງປ່າເຫຼົ່າ ໂດຍການນຳໃຊ້ພືດອາຫານສັດ, ພືດຕະກຸນຖົ່ວ, ໄມ້ອຸດສາຫະກຳ ອາດຈະເປັນທາງເລືອກທີ່ດີສຳລັບແກ້ໄຂບັນຫາດັ່ງກ່າວ. ນອກຈາກນີ້ແລ້ວ ໂຄງການຄຸ້ມຄອງການເຊາະເຈື່ອນຂອງດິນ ໄດ້ຮັບເອົານັກສຶກສາມາຝຶກງານໃນສາຂາວິຊາຕ່າງໆ ທັງໝົດ 79 ຄົນ ໃນນັ້ນ ນັກສຶກສາພາຍໃນ ມີ 43 ຄົນ ແລະ 36 ຄົນ ມາຈາກຕ່າງປະເທດ. ສະນັ້ນ ພື້ນທີ່ອ່າງໂຕ່ງຫ້ວຍປ່ານໍ່ ບ້ານຫຼັກສິບ ສາມາດເປັນບ່ອນສຶກສາກ່ຽວກັບການເຊາະເຈື່ອນຂອງດິນ ໃນເງື່ອນໄຂການປູກໄມ້ສັກ, ໝາກເຍົາ ແລະ ປໍສາ. ບົດຮຽນ ແລະ ປະສົບການຈາກພື້ນທີ່ດັ່ງກ່າວ ຍັງສາມາດນຳໄປປັບປຸງໃຊ້ໃນເຂດອ່າງໂຕ່ງອື່ນໆ ເຊັ່ນ: ນ້ຳຄານ/ນ້ຳງື່ມ. ໃນບົດນີ້ ໄດ້ສັງລວມຂໍ້ແນະນຳ ແລະ ຫົວຂໍ້ການຄົ້ນຄວ້າທີ່ໄດ້ຈັດພິມ ແລະ ຈັດຕັ້ງປະຕິບັດ ຢູ່ໂຄງການດັ່ງກ່າວ.

The MSEC project in the Lao PDR: Achievements, ongoing activities and perspectives on sustainable alternative farming practices for the uplands

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Abstract

This introductory paper presents the overall challenges associated with upland agriculture and soil conservation in Southeast Asia and the main objectives of the Management of Soil Erosion Consortium (MSEC) to develop alternative farming practices that combat land degradation and improve household livelihoods. This international project, coordinated by the International Water Management Institute (IWMI), was launched in Laos in late 1998. One of the projects major findings is that land use changes due to increasing populations, government policies and market demand, are significantly affecting soil conservation in the uplands of the Lao PDR. Increased pressure on cultivated land has led to increased weed invasion, which has caused soil and labour productivity to decrease. When a threshold of productivity decline was reached, farmers abandoned the traditional system based on upland rice and replaced it by Job's tear and maize and short (2-3 year) fallow periods. These annual crops are clearly associated with soil losses at the catchment scale with negative impacts on soil fertility at the field scale (on site effects) and stream water quality which can affect downslope land users (off-site impacts). Improved fallow systems appear to be interesting alternatives to regular fallow. When a dense understorey is maintained, fodder crops for livestock and tree plantations can also be considered as possible improvements on the current systems with short fallow. The MSEC project in Laos has trained scientists from the National Agriculture and Forestry Research Institute (NAFRI) in catchment hydrology and management, 43 Laotian and 36 International students have also been provided with field experience in various disciplines during three to seven month long projects. In the coming years, the Houay Pano catchment could serve as a platform for pilot studies on teak, biofuel production (Jatropha) and paper mulberry. In parallel, the MSEC collective expertise could be used at a larger scale in a similar environment (Nam Khan and/or Nam Ngum watersheds). This paper lists the main recommendations and publications which have stemmed from this extensive research project.

Key words: *Land use changes; Slash and burn systems; Soil conservation; Capacity building; Lao P.D.R*

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Introduction

In order to address endemic poverty in the uplands, the Lao PDR government has been resettling upland communities in order to ensure improved access to services such as roads, education, healthcare and markets. In addition, a specific objective of the policy is to reduce shifting cultivation in order to protect biodiversity and preserve some of the last remaining pristine forests in Southeast Asia. These land use policies together with growing market demand have resulted in rapid land use changes in the uplands over the past few years.

To study the impact of these changes on the environment and crop yields, a catchment in northern Laos was selected in late 1998 as a benchmark site for the Managing Soil Erosion Consortium (MSEC). The MSEC network, which was initially supported by the International Board For Soil Research And Management (IBSRAM) and the Asian Development Bank (ADB) and is currently funded by International Water Management Institute (IWMI) and Institut de Recherche pour le Développement (IRD), operates in five Southeast Asian countries, namely, Indonesia, the Lao P.D.R., the Philippines, Thailand and Vietnam. This consortium supports the ultimate goal of sustainable watershed development through an approach that seeks to establish an enabling environment for sustainable use of natural resources to address the twin objectives of resource conservation and food security. An organisational model that engages scientists and research institutions to tackle a common goal was employed. The model allows the participation of those who are willing to contribute, exploits synergies, and is mutually beneficial. Research planning was undertaken through consultation among concerned National Research Institutions, International Research Centres and farmers. The whole idea of the programme is to take a bottom-up approach in research planning with iterative discussions between stakeholders to define and implement the research undertaking.

In the Lao PDR, the main objectives of the study were to: (1) Train national scientists and students in catchment hydrology, soil science, agronomy and weed science; (2) Collect and interpret scientific data on the impact of land use changes on weed invasion, crop yields, soil erosion and water quality; (3) Test alternative farming practices that would address some of the land degradation issues associated with land use change, whilst enhancing household livelihoods.

Experimental design

As part of this study to assess the impact of land use changes on the hydrological attributes of the catchment, four hydrological gauging stations and sediment traps (weirs) were installed along the main stream of the Houay Pano catchment (60 ha), near Ban Lak Sip village, in Luang Prabang province.

Experimental instruments were also set up in four smaller sub-catchments (0.6 ha) to compare traditional slash and burn agriculture with alternative cropping systems such as rotations with fallow improved with legumes; with or without pineapple; and the "no-till plus mulch" system developed by Centre International de Recherche Agronomique pour le Développement (CIRAD). The experiments and intensive monitoring started in 2001 and are ongoing. The main biophysical and socio-economic features of this experimental site are presented in detail by Valentin et al (this issue).

Main scientific results

Some important scientific insights have emerged from this ongoing project (see list of papers below). In the Lao uplands, until the end of the 1990s, 1 year cropping periods were followed by a long fallow break of approximately 8 years; this was viewed as a sufficiently long period to restore a medium-sized secondary forest between two cropping cycles so that soil fertility and weed control could be maintained at reasonable levels. The MSEC program established that such cultivation practices generated 5.8 tons ha^{-1} yr^{-1} of sediment, due to various erosion processes such as rill and gully erosion (Figure 1), during cultivation and 0.3 ton ha^{-1} yr^{-1} during the fallow period. The average total annual sediment yield was therefore 0.9 ton ha^{-1} yr^{-1} under this "traditional" shifting cultivation system (Figure 2). In recent years, because of the increased population density resulting from both natural growth and relocation policies, the land area available for cultivation has dropped from 1.7 to only 0.27 ha per capita. This population pressure drastically altered traditional shifting cultivation systems, so that cropping is now often conducted for two consecutive years while fallow periods have been shortened to 1 to 4 years.

Concomitantly, a rapid and significant reduction in the fraction of cultivated catchments covered by secondary forest occurred. In the Houay Pano catchment, this proportion decreased from 18 to 6% between 2001 and 2006. Until 1998, upland rice was the dominant crop cultivated in the Houay Pano catchment. Since then, because of ever increasing weed pressure, farmers have attempted to diversify their production systems by growing cash crops such as Job's tear and more recently maize. This change in cropping pattern and associated shorter fallow period has led to a dramatic increase in sediment delivery, which is now approximately double (11.3 tons ha^{-1} yr^{-1}) that of previously observed cropping phases. Overall, this more intensive system with 2-year cultivation followed by 2-year fallow periods associated with the substitution of upland rice by Job's tear, maize and cassava (Figure 3a and 3b), has led to a significant increase in average annual sediment yields, which now amount to 5.9 tons ha^{-1} yr^{-1} or an increase of 600% compared to the traditional system.

Studies undertaken in the project to investigate improved fallow systems have demonstrated than annual sediment yields can be reduced to a mere 0.1 ton ha^{-1} yr^{-1}, which is three times less than the traditional fallow. Continuous direct sowing and mulch-based conservation agriculture produced 0.7 ton ha^{-1} yr^{-1} (Figure 2c and 2d). Economic and technical constraints, such as the need for herbicide to suppress weeds, are currently limiting the adoption of the direct sowing system in Houay Pano. It seems more likely that farmers may adopt the improved fallow system, especially those who grow paper mulberry (Broussonetia papyrifera) from which sustainable incomes can be derived (Figure 4).

Other soil conservation management strategies were also examined by the team. Although MSEC has not carried out long-term monitoring in teak plantations in the catchment, preliminary measurements show that this popular tree crop does not provide sufficient soil protection to prevent degradation and sediment generation due to a lack of understorey development (Figure 3c). In the Houay Pano catchment, sediment trapping by vegetation growing along the stream is rather limited because within the riparian zone subsurface water from the hillslope exfiltrates. Alternating the pattern of cultivated and fallow plots within the catchment so as to create a non-stationary vegetation mosaic along the hillslopes was not found to be an efficient way to control soil erosion: this is mostly because of gully formation along steep cultivated slopes, which rapidly connects the fields where soil erosion occurs to the main stream, without interruption by sediment trapping areas. This would explain why there is a high correlation between the percentage area of cultivated land in the catchment and soil erosion.

Another significant result highlighted by the project is the importance of tillage erosion on steep slopes. Tillage erosion is the process of downhill soil translocation caused by the force applied by agricultural tools and gravity (Figure 3d). In northern Laos, weed pressure is rapidly increasing due to the shortening of the fallow period; hence increasing the number of soil tillage operations. Soil losses due to tillage increase with slope and are of the same order as those due to water erosion processes (Figure 5).

Capacity Building and knowledge dissemination

The MSEC project in Laos has trained NAFRI scientists in catchment hydrology and management. To date, 43 Lao students mainly from the Faculty of Agriculture (Annex 1) of Nabong and 36 international students (Annex 2) have been given research experience in the field under this programme (Figure 6). Two international symposiums on sustainable sloping lands management were organised in 2004 and 2006 (http://www.nafri.org.la/). Information and training workshop are also regularly organised. Our scientific reports are frequently published in local and international journals (See list below). This programme has also generated technical innovations (see pictures) which are suitable for use in developing countries and/or difficult field conditions.

Recommendations

Some practical recommendations and research priorities for the coming years have emerged from these initial findings. In terms of land use policy, it seems clear that more land area should be allocated to farmers to enable them to implement the improved fallow system which has proved a promising land management tool. Cash crops such as cassava, Job's tears and maize, which, in the current short fallow systems, are associated with the highest erosion rates, should not be encouraged. Upland rice, which is the country's staple crop and is of foremost cultural importance, can be tolerated as long as it does not lead to uncontrolled use of herbicides. Weeding operations are not only extremely time-consuming but they induce land degradation through tillage erosion. Ideally, steep land should not be cropped at all but left either under fodder or tree cover. With the foreseeable development of livestock, fodder crops should be encouraged provided that cattle are not allowed to roam freely along steep hillslopes, as trampling and cattle tracks are known to lead to severe gully erosion. Tree plantations can be considered as a relevant alternative provided that they mimic the structure of native forest with a dense understorey. In this respect, teak, as currently managed, does not appear to be the best candidate.

Perspectives

Many researchers have advocated the need for long-term studies at the catchment scale, not only to monitor the impact of current land use changes on water and erosion regimes but also to capture the impact of rare climatic events and test alternative farming systems. In this respect, the team trained by the MSEC programme and the equipment installed in the Houay Pano form an invaluable observation platform worth maintaining for the foreseeable future. On the basis of a simple set of routine measurements, this observatory field site could serve as a platform for pilot studies on teak, biofuel production (Jatropha curcas) and paper mulberry. In parallel, the MSEC collective expertise could be used at a larger scale in a similar environment (Nam Khan and/or Nam Ngum watersheds). In addition, the growing expertise of the present team on alternative perennial cover crops (teak, rubber tree, jatropha) could also be useful for studies in other environments (Vientiane plain, central and southern Laos).

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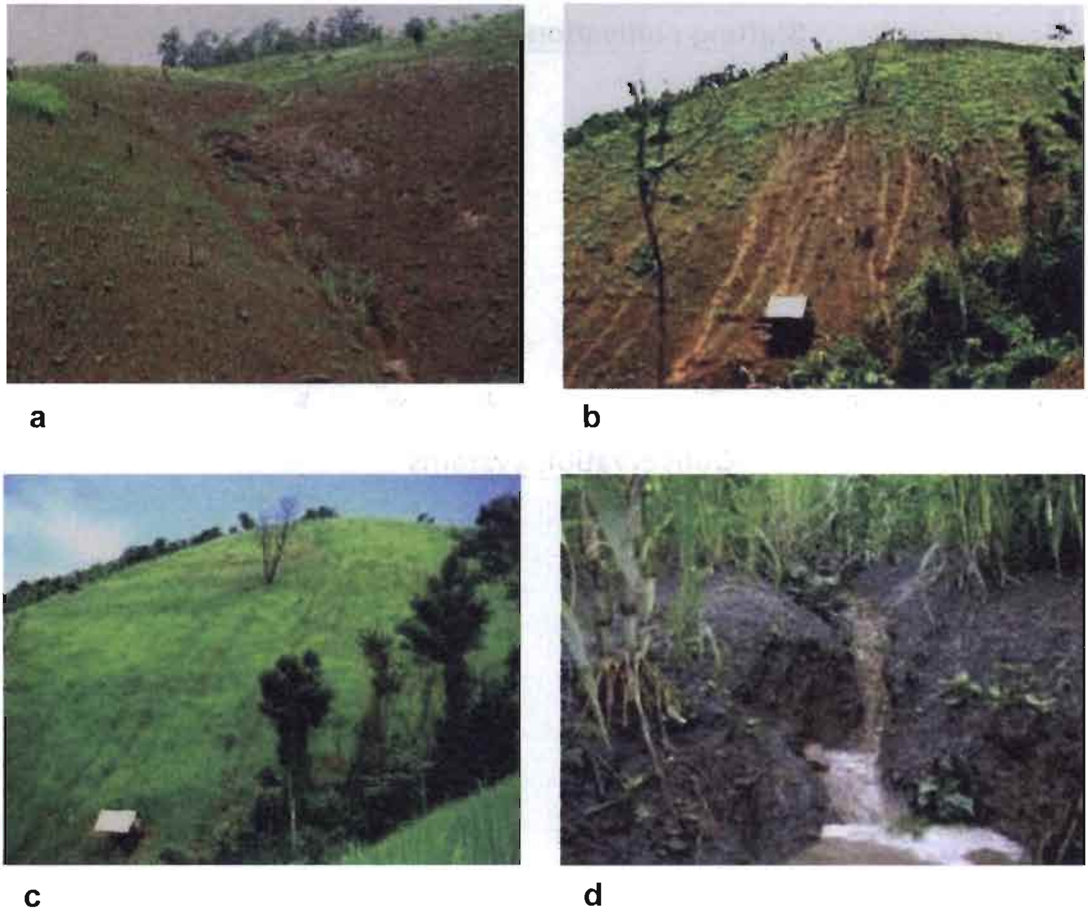


***Figure 1** – Due to inappropriate cropping practices on steep land, the soil top layer is removed by runoff, which exposes underlying rocks and causes the development of gullies **(a)**. Rills that developed at the onset of the rainy season **(b)**. are still active even when the crop has been established **(c)**. Sediments removed from the fields have therefore little chance to be deposited and are easily transported into the main stream down slope **(d)**. Finer particles, which contain nutrients and organic matter, can thus be exported from the catchment and transported over long distances.*

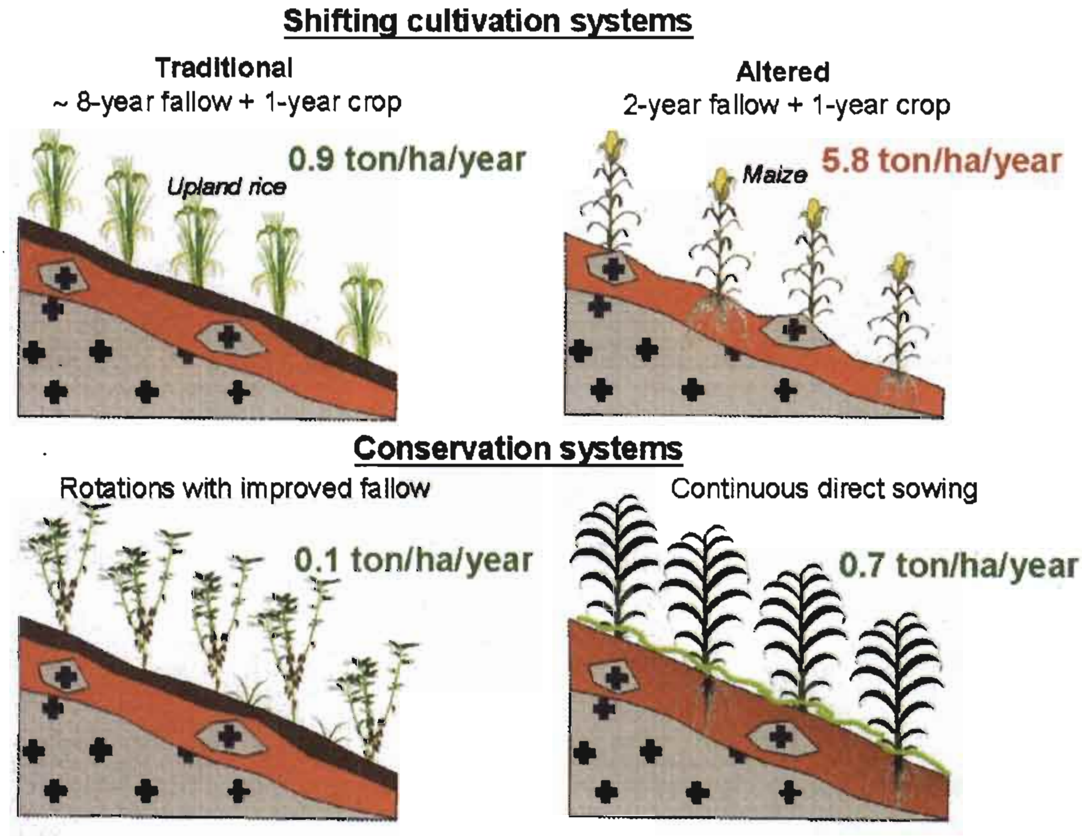
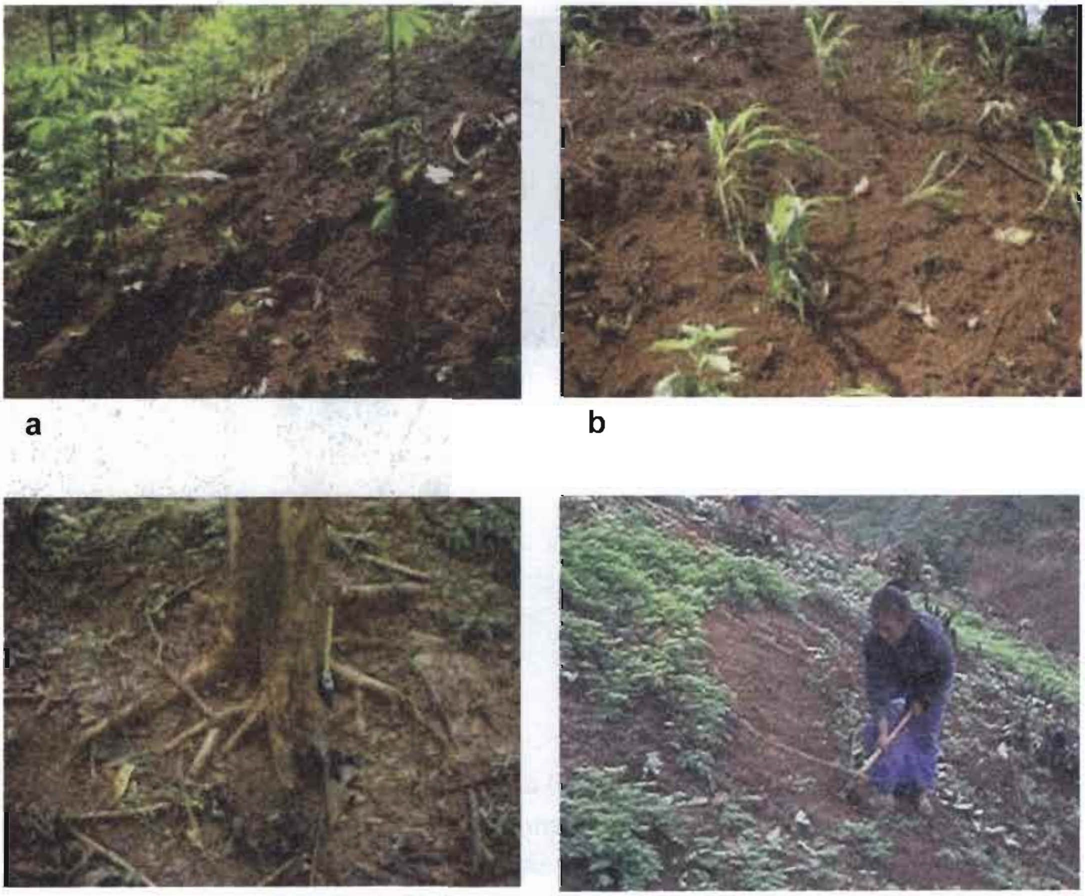


***Figure 2** – Mean annual soil erosion when land is managed by a full cycle of traditional **(a)** and altered shifting cultivation systems **(b)**, and two conservation systems, i.e. rotations with improved fallow **(c)** and continuous direct sowing **(d)**.*



a b c d

***Figure 3** – Cassava **(a)**, maize **(b)** and teak **(c)** are not the best candidates to replace upland rice from a soil conservation perspective. Tillage erosion associated with weeding can be as serious as water erosion on steep slopes **(d)**.*

a

b

***Figure 4** – Sufficiently long fallows (3 – 5 yrs) are effective in reducing soil erosion because they offer good soil cover. Fodder crops (here ruzi grass, Brachiaria ruziziensis) maintain soil cover even at the beginning of the rainy season and thus protect the soil from erosion efficiently **(a)**. Paper mulberry makes these fallows economically productive due to the growing market demand **(b)**.*

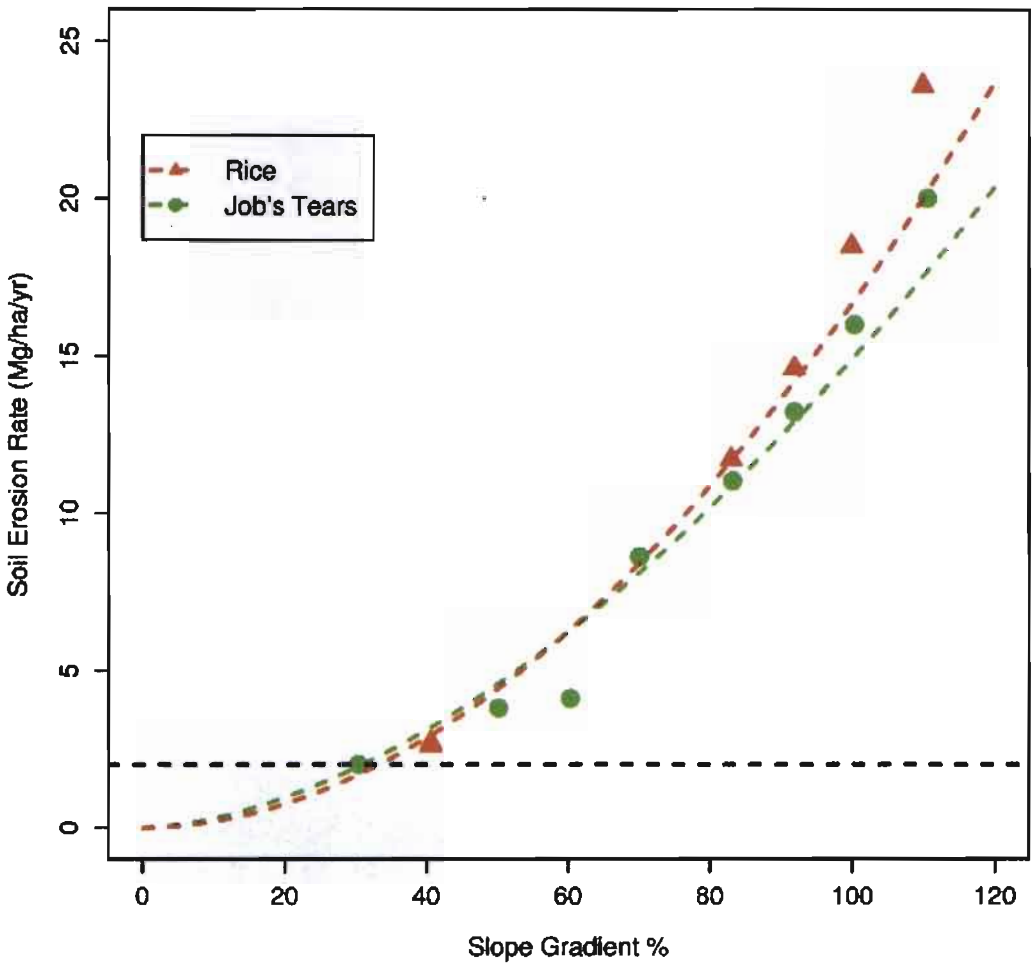


Figure 5 *– Tillage erosion as influenced by slope gradient for Job's tear and upland rice.*

Figure 6 – *The Houay Pano catchment and its sub-catchments are invaluable experimental field sites for training scientists and students, monitoring the impact of land use changes on hydrology and sediment yields, and testing innovative farming practices.*

***Annex 1a** – List of Lao students that contributed to MSEC-Laos from 2001 to 2007.*

Name & surname	Year	Sexe	Diploma	Nationality	MSEC's supervisor	School/University	Shortened title
Bounsamay SOULILEUTH	2001	man	B.Sc.	Lao	Anneke DE ROUW	FOA Vientiane	Productivity of slash and burn cultivation…
Khambai PHANTHAVONG	2001	man	B.Sc.	Lao	Christian VALENTIN	FOA Vientiane	Assessment of soil loss …
Bi MOA	2001	man	B.Sc.	Lao	Anneke DE ROUW	FOA Vientiane	Study of soil erosion …
Khampaseth XAYYATHIP	2002	man	B.Sc.	Lao	Vincent CHAPLOT	FOA Vientiane	Spatial and temporal variations of runoff…
KeoOudone LADSACHACK	2002	man	B.Sc.	Lao	Anneke DE ROUW	FOA Vientiane	Weeds Population in the Croping Systems…
Vanhthieng PHOMMASOULINH	2002	man	B.Sc.	Lao	Anneke DE ROUW	FOA Vientiane	Yield Factor and Component of Job's Tear…
Sengsavanh MIXAY	2002	man	B.Sc.	Lao	Vincent CHAPLOT	FOA Vientiane	Controlling Factors of Organic Carbon …
Bounmy KEOHAVONG	2002	man	H.D.	Lao	Christian VALENTIN	FOA Vientiane	Gully Erosion…
Thanongkham VENETHONGKHAM	2003	man	B.Sc.	Lao	Vincent CHAPLOT	FOA Vientiane	Evaluation of Soil Erosion…
Kongmany THAMMAVONGSAY	2003	man	B.Sc.	Lao	Anneke DE ROUW	FOA Vientiane	Impact of soil erosion…
Kolakhanh CHANTAVONG	2003	man	B.Sc.	Lao	Anneke DE ROUW	FOA Vientiane	Jobs'tear Cultivation, Improved fallow …
Pheng Hey XAY CHOU	2003	man	B.Sc.	Lao	Vincent CHAPLOT	FOA Vientiane	Rill Erosion in a 60 ha Catchment…
Sengkeo TASAKET	2003	man	B.Sc.	Lao	Christian VALENTIN	FOA Vientiane	The Assessment of Water Erosion…
Khosada VONGSANA	2004	man	Engineer	Lao	Anneke DE ROUW	ESA d'Angers	Suivi Agronomique d'une jachere…
KeoUdom PHAYAXAY	2004	man	B.Sc.	Lao	Anneke DE ROUW	FOA Vientiane	Study and compare number of weeds …
Kethsadong SILYTHONE	2004	man	B.Sc.	Lao	Christian VALENTIN	FOA Vientiane	Study the Teak effect in Steep with Soil…
Khamko THAMMAVONG	2004	man	B.Sc.	Lao	Christian VALENTIN	FOA Vientiane	Assessment tillage erosion by Hmong…
Phoutasene DUANGKEO	2004	man	B.Sc.	Lao	Christian VALENTIN	FOA Vientiane	Assessment of Rill Erosion in Houay Pano…
Hatsadong CHANTHANOUSONE	2005	man	H.D.	Lao	Anneke DE ROUW	FOA Vientiane	Weed seed Dispersal during Rainstorms…
Linh SOUKKHAMTAT	2005	man	B.Sc.	Lao	Anneke DE ROUW	FOA Vientiane	Weed-crop Competiton in Smallholders…
Inpaeng DOUANGVONGSA	2005	man	B.Sc.	Lao	Olga VIGIAK	FOA Vientiane	Characterisation of Vegetations…
Saiphone INTALA	2005	man	B.Sc.	Lao	Christian VALENTIN	FOA Vientiane	Comparison of the Impacts of…
Phouthone CHANTHAVONGSA	2005	man	B.Sc.	Lao	Alain PIERRET	FOA Vientiane	Monitoring of fine root dynamics…

***Annex 1b** – List of Lao students that contributed to MSEC-Laos from 2001 to 2007.*

Name & surname	Year	Sexe	Diploma	Nationality	MSEC's supervisor	School/ University	Shortened title
Sayyavong VANTHALATH	2005	man	H.D.	Lao	Christian VALENTIN	FOA Vientiane	Runoff generation and soil…
Sisomphone SOUTHTAVONG	2005	man	B.Sc.	Lao	Olivier RIBOLZI	FOA Vientiane	Study on Groundwater-Surface…
Sith PHALY	2005	man	H.D.	Lao	Anneke De Rouw	FOA Vientiane	Improved fallows in the Nam Ou…
Bounthom PHALI	2006	man	B.Sc.	Lao	Olivier RIBOLZI	FOA Vientiane	Investigating mechanisms of storm…
Khankham APHAIVONG	2006	man	B.Sc.	Lao	Olga VIGIAK	FOA Vientiane	Sediment trapping efficiency…
Khonesavanh BOUNYAVONG	2006	man	B.Sc.	Lao	Alain PIERRET	FOA Vientiane	Monitoring of root growth dynamics…
Ounlam LUANGKONGKHAM	2006	man	B.Sc.	Lao	Olivier RIBOLZI	FOA Vientiane	Subsurface features of soils…
Nou YANG	2006	man	B.Sc.	Lao	Christian VALENTIN	FOA Vientiane	Runoff generation and soil…
Bouanguene SIPHONESAY	2006	man	H.D.	Lao	Jean-Pierre THIEBAUX	FOA Vientiane	Erosion process and soil losses..
Bounyadeth THEBPHALACK	2006	man	B.Sc.	Lao	Olivier RIBOLZI	FOA Vientiane	Hydrology and floods generation…
Touan VONGVIHAN	2006	man	H.D.	Lao	Olivier RIBOLZI	FOA Vientiane	Monitoring sediment concentration…
Alounsavath CHANPHENGSAY	2006	man	B.Sc.	Lao	Anneke De Rouw	FOA Vientiane	Survey on land use changes…
Anan BOUATHONG	2007	man	H.D.	Lao	Christian VALENTIN	FOA Vientiane	Runoff Generation and Soil…
Phouthong PHOTHISAT	2007	man	B.Sc.	Lao	Jean-Pierre THIEBAUX	FOA Vientiane	Study of Soil Erosion…
Bee Xiong CHIAKOUA	2007	man	B.Sc.	Lao	Yann LE TROQUER	FOA Vientiane	Assessment of soil water content…
Axue XONGYERMOUS	2007	man	B.Sc.	Lao	Olivier RIBOLZI	FOA Vientiane	Comparison of Productivity of Two…
Vue Xiong Lee VUE HER	2007	man	B.Sc.	Lao	Emmanuel BOURDON	FOA Vientiane	Assessment of Allelopathic Effects…
Phonesay SENGSOULYCHANH	2007	man	H.D.	Lao	Olivier RIBOLZI	FOA Vientiane	Effect of Land Uses on Surface Water…
Chanthanousone THAMMAHAKSA	2007	man	H.D.	Lao	Alain PIERRET	FOA Vientiane	Soil Indicators of Mainstream Groundwater…

Annex 2a *– List of European students that contributed to MSEC-Laos from 2000 to 2007.*

Name & surname	Year	Sexe	Diploma	Nationality	MSEC's supervisor	School/University	Shortened title
ılia CORONEL	2000	female	Engineer	French	Catherine AUBERTIN	INA Paris Grignon	Etude d'un système agraire…
ɔrence CAILLENS	2000	female	Engineer	French	Catherine AUBERTIN	INA Paris Grignon	Etude d'un système agraire…
ice DUPIN	2001	man	Engineer	French	Christian VALENTIN	ISTOM	Estimation des pertes en terre…
ədéric JULLIEN	2001	man	Engineer	French	Anneke DE ROUW	ISTOM	Impact de la baisse du temps…
ıranger PHILIPPE	2001	man	Engineer	French	Anneke DE ROUW	INA Paris Grignon	Study of weeds …
venael GIBOIRE	2001	man	Engineer	French	Vincent CHAPLOT	WAGENINGEN University	GIS-based dynamic integrated…
ıbelle GAY	2002	female	Engineer	French	Anneke DE ROUW	ISTOM	Dynamique des populations…
wan COADOU LE BROZEC	2002	man	Engineer	French	Vincent CHAPLOT	ISTOM	A case study with Houay Pano…
an-Philippe VENOT	2002	man	Engineer	French	Anneke DE ROUW	INA Paris Grignon	L'abattis/brulis: un système…
lien TESSIER	2002	man	Engineer	French	Vincent CHAPLOT	ISTOM	L'abattis/brulis: un système…
ırs JONSSON	2002	man	B.Sc.	Swedish	Vincent CHAPLOT	UAS Sweden	Erosion and land use…
ıniel MELIN	2002	man	B.Sc.	Swedish	Vincent CHAPLOT	UAS Sweden	Erosion and land use…
ıdreas NILSSON	2002	man	B.Sc.	Swedish	Vincent CHAPLOT	UAS Sweden	Erosion and land use…
ıarlotte DUMAS DE RAULY	2003	female	Engineer	French	Anneke DE ROUW	INA Paris Grignon	Etude de l'impact de l'érosion…
arie ALEXIS	2003	female	M.Sc.	French	Sylvain HUON	UPMC Paris	Influence du mode de culture…
ılie BERNADOU	2003	female	Engineer	French	Vincent CHAPLOT	ENSA Rennes	Runoff, soil and soil organic…
uillaume LESTRELIN	2003	man	Ph. D.	French	Christian VALENTIN	Universit of Durham	Changing life, changing nature(s)…
ırélie PELLETREAU	2004	female	M.Sc.	French	Christian VALENTIN	University of Paris	Pricing soil degradation…
arole THEVENET	2004	female	Engineer	French	Anneke DE ROUW	INA Paris Grignon	Suivi de l'implantation d'une…

Annex 2b – List of European students that contributed to MSEC-Laos from 2000 to 2007.

ne & surname	Year	Sexe	Diploma	Nationality	MSEC's supervisor	School/University	Shortened title
rion CASAGRANDE	2004	female	Engineer	French	Anneke DE ROUW	INA Paris Grignon	The seedbank in slash and burn…
n-Guillaume ROBIN	2004	man	Engineer	French	Vincent CHAPLOT	Agrocampus Rennes	Evaluation de la sédimentation…
ɔtiste FRERE	2004	man	M.Sc.	French	Christian VALENTIN	ULP Strasbourg	Etat de surface et paramètres physiques…
thilde DOUILLET	2005	female	Engineer	French	Anneke DE ROUW	INA Paris Grignon	Weed seed dispersal during rainstroms…
ıel SAINTE CLUQUE	2005	man	Engineer	French	Norbert SILVERA	Groupe Esiee Pairs	Conception de pluviographs…
ni NEGRE	2005	man	Engineer	French	Anneke DE ROUW	INA Paris Grignon	Compétition riz pluvial/adventices…
ment DUVERT	2005	man	B.Sc.	French	Olivier RIBOLZI	Université d'Avignon	Study of groundwarter/surface water…
h-Duc HUA	2005	man	Engineer	French	Christian VALENTIN	Institut Polytechnique, Paris	Stage de "contact humain"…
a VIGIAK	2005	female	Post-Doc	Italian	Christian VALENTIN	Sponsored by IWMI	Trapping efficiencies of cultivated…
a VAN BREUSEGEM	2006	female	M.Sc.	Belgian	Olga VIGIAK	WAGENINGEN University	Sediment trapping capacity…
jolaine PUDDU	2006	female	M.Sc.	French	Olivier RIBOLZI	Hydrogéologie Neuchatel	Interactions hydrologiques nappe-ruisseau…
té LAIR	2006	female	M.Sc.	French	Alain PIERRET	ENSA Montpellier	Comparaison des propriétés structurales…
nain MARTIN	2006	man	Engineer	French	Olivier RIBOLZI	ENSG Nancy	Modélisation du transport de soluté…
ɜntin ROUVEIROLLES	2006	man	Engineer	French	Anneke DE ROUW	ENSA Montpellier	Ecology and productivity of paper mulberry…
ie LEBRETON	2007	female	Engineer	French	Olivier RIBOLZI	INSA Rennes	Rôles de l'occupation des sols…
re MOUSQUES	2007	female	Engineer	French	Alain PIERRET	ENITA Bordeaux	Etude de faisabilité pour la mise en place…
ɜtte CUNY	2007	female	Engineer	French	Olivier RIBOLZI	ENSG Nancy	Etude de la qualité de l'eau d'un ruisseau…
lolf B. VAN DER HELM	2007	man	M.Sc.	Dutch	Olga VIGIAK	WAGENINGEN University	Evaluating alternative land use scenarios…
thieu GALVEZ	2007	man	M.Sc.	French	Olivier RIBOLZI	ENS Paris	Experiment and modelling of nitrate transfers…

ໂຄງການຄຸ້ມຄອງການເຊາະເຈື່ອນຂອງດິນ ໃນ ສ.ປ.ປ ລາວ: ສະພາບທາງດ້ານກາຍະພາບ - ເສດຖະກິດສັງຄົມ ແລະ ການວາງແຜນຄົ້ນຄວ້າທົດລອງ

ຄຣິສຕຽນ ວາເລນຕິນ, ກີໂຍມ ເລສເຕີລິນ, ກອງແກ້ວ ພະຈອມພິນ, ອານາເກ ເດີຣູ, ອາລຸນສະຫວັດ ຈັນເພັງໄຊ, ວັງຊັງ ຊັບໂປລດ, ເອມານູເອນ ບວກດົງ, ຊັງປີແອ ບຣິກເກ, ປີແອ ມາກຊັງ, ອາແລງ ປີເອເຣ, ໂອລີວີເອ, ຣິໂບນຊີ, ຊັງປີແອ ທີໂບ

ບົດຄັດຫຍໍ້

ນະໂຍບາຍການນຳໃຊ້ທີ່ດິນ ບວກກັບຄວາມຕ້ອງການຂອງຕະຫຼາດ ເຮັດໃຫ້ການນຳໃຊ້ທີ່ດິນໃນເຂດພູດອຍ ມີການປ່ຽນແປງຢ່າງໄວວາ ໃນຊຸມປີທີ່ຜ່ານມາ. ການຫັນປ່ຽນດັ່ງກ່າວ ໄດ້ເກີດມີເຫດການ ການພົວພັນລະຫວ່າງ ການຜະລິດກະສິກຳ ແລະ ຜົນກະທົບທາງອ້ອມຕໍ່ສິ່ງແວດລ້ອມ. ເພື່ອແກ້ໄຂບັນຫາດັ່ງກ່າວ ໂຄງການເຊາະເຈື່ອນຂອງດິນ ໄດ້ສຶກສາການເຊາະເຈື່ອນດິນ ໃນເຂດອ່າງໂຕ່ງຫ້ວຍປ່ານົ່, ບ້ານຫຼັກສິບ ເມືອງ ແລະ ແຂວງຫຼວງພະບາງ. ບົດນີ້ ໄດ້ສັງລວມຂໍ້ມູນທາງດ້ານກາຍະພາບ ແລະ ເສດຖະກິດສັງຄົມ, ວິທີການຕິດຕາມການປ່ຽນແປງການນຳໃຊ້ທີ່ດິນ ແລະ ຜົນກະທົບຂອງດິນຕົກຕະກອນ ແລະ ຄຸນນະພາບນ້ຳ.

The MSEC project in the Lao P.D.R. at a glance: biophysical and socio-economic background and project experimental set up

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Abstract

Land use policies together with growing market demand have resulted in rapid land use changes in the uplands of the Lao PDR over the past few years. These changes have led to questions concerning the link between agricultural activities and off-site impacts. To tackle this issue the Management of Soil Erosion Consortium has equipped a catchment in northern Laos, ten kilometres from Luang Prabang. This paper summarises the main biophysical and socio-economic characteristics of this catchment and the associated village community. It also presents the main methods used to monitor the land use changes and their impacts upon catchment hydrology and sediment yield.

Key words: *Upland agriculture; Soil erosion monitoring; Runoff monitoring; Benchmark site; Lao P.D.R*

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Introduction

As part of its poverty eradication programme, the government of the Lao PDR has resettled upland communities so that they can access services and commodities such as roads, education, health care and markets. A specific objective of this resettlement policy is to eradicate shifting cultivation which is considered a threat to the unique biodiversity of some of Southeast Asia's last remaining pristine tropical forests. These land use policies together with growing market demand have resulted in rapid land use changes in the uplands of the Lao PDR over the past few years.

Land degradation results from a complex combination of spatially and temporally dependent processes (Scherr, 1999; 2000). Recent work highlighted that for effective management strategies for Southeast Asian uplands to be designed, knowledge about the interactions between environmental and anthropic dynamics must first be gained through long-term catchment studies (Tomich et al, 2004; Sidle et al, 2006ab). A key element in achieving this goal is to integrate biophysical and land-use characteristics in a holistic approach. For example, several scientists have questioned the impact of deforestation on large-scale flooding, suggesting that these effects have been overestimated (Kiersch and Tognetti, 2002; Bruijnzeel et al, 2004) and that major sources of sediments can be roads, poorly constructed and maintained terraces, coffee plantations or bank erosion (Sidle et al, 2006b). In developing countries in particular, investment priorities should be switched from disaster recovery to the assessment of catchment vulnerability and resilience to change (Mirza, 2003). Questions that are central to the design of suitable environmental policies include: establishing firm evidence for causal links between agricultural activities and off-site impacts; examining the relevance of incentives-based management systems for the maintenance of watershed services; determining relationships between prolonged population growth and improved access to markets and adaptive responses for sustainable land management.

In an attempt to address these issues and provide sound data on the extent of accelerated soil erosion resulting from rapid land-use change, a regional network called 'the Management of Soil Erosion Consortium' (MSEC) was established in the late 1990s. The MSEC network, which was initially supported by IBSRAM and the ADB and is currently funded by IWMI and IRD, operates in five Southeast Asian countries, namely, Indonesia, the Lao P.D.R., the Philippines, Thailand and Vietnam. In the Lao P.D.R., the MSEC programme selected the Houay Pano catchment to implement long-term monitoring of changes in farming practices and the resulting runoff and sediment yields, at the whole catchment scale (Valentin et al., this issue). This consortium also aims to: 1) Train national scientists and students in catchment hydrology, soil science, agronomy and weed science; 2) Collect and interpret scientific data on the impact of land use changes on weed invasion, crop yields, soil erosion and water quality; and 3) assess various innovative land-use practices to reduce soil losses and enhance the livelihood of affected communities (Maglinao et al, 2004).

The objectives of this paper are to summarise the main biophysical and socio-economic settings of the Houay Pano catchment and the Ban Lak Sip community as well as the main methods used to monitor the land use changes and their impacts upon catchment hydrology and sediment yield.

Biophysical environment

The Houay Pano catchment was selected as the benchmark catchment of the MSEC project in the Lao PDR in 1998. The Houay Pano Catchment was selected because it is representative of a shifting cultivation area and has accessibility to roads and transport facilities. It is located near the Ban Lak Sip village (102° 10' 2" E; 19° 50' 54" N), 10 km South of the UNESCO world heritage city of Luang Prabang (Luang Prabang Province, northern Lao PDR) (Figure 1). The catchment covers an area of 0.62 km^2 and encompasses 9 sub-catchments (Table 1) with different land uses. It was first cleared of primary climax Dipterocarp forest in the late 1960s and has since been cropped using shifting cultivation practices, with no inputs. The duration of the fallow period has declined from an average of 8.6 years in 1970 to 3.2 years in 2003 (Lestrelin et al., 2005; Lestrelin and Giordano, 2007). The initial biophysical and socio-economic inventory was conducted in November and December 1998. Approximately two months were devoted to laboratory activities and map preparation.

The catchment elevation ranges from 400 to more than 800 m a.s.l. (Figure 2). Parts of the village land rise above 700 metres. The terrain is steep with a mean slope gradient of 30%, ranging from 0% to more than 100%. The climate is a wet-dry monsoon tropical climate, with an average annual rainfall of ~1300 mm/year (Figure 3). The rainfall pattern is highly seasonal, with 77% of the rainfall occurring during the rainy season from mid-May to mid-October, while the November to March period is cool and mostly dry. The drainage system comprises a 1200 m long second-order perennial stream of irregular topography that receives water from several ephemeral streams. The stream within the Houay Pano catchment is a tributary of the Xon stream (see Ribolzi et al, this issue) which is a sub-tributary of the Num Dong River before its confluence with the Mekong River in Luang Prabang. The water in Houay Pano originates from the upper part (mountain) of the catchment and runs down to the Houay Xon.

The catchment's geological substrate is composed of Permian to Upper Carbonifer argillites and siltstones. Soil distribution (Figures 4 and 5) along the catena typically comprises: shallow Inceptisols along the crests; deep, clayey Ultisols and Alfisols (which cover 30 and 50% of the catchment area, respectively) along the slopes; and clayey Dystrochrepts with fluvic and redoximorphic features at the footslopes and along the stream banks (Soil Survey Staff, 1998). The Inceptisols are thought to have derived from Alfisols from which the sub-surface argillic horizon has been eroded (Chaplot et al., 2005a,b). As a general trend, soil thickness decreases from a few meters (up to 4m) to a few tens of centimetres in the uphill direction. Likewise, the thickness of organic topsoil horizons decreases dramatically from the base to the top of slopes.

Approximately 80% of the land use within the catchment is rotating land, under the no-input shifting cultivation system typical of Southeast Asia (Figure 6). In most years, less than 15% of the area within the Houay Pano catchment is farmed. Upland rice and job's tear production accounts for 80%. As mentioned above, the Houay Pano catchment started to be cleared for slash-and-burn agriculture in the late 1960's and by the mid-1990's the original vegetation had almost been entirely removed (Figure 7). In 1994, the Land and Forest allocation scheme assigned land use allocation in the Houay Pano catchment, considering both protection and production. At present, the Houay Pano catchment is composed of residual mixed deciduous and dry Dipterocarp forests, regenerated secondary forest mixed with grass (bush fallow), teak and banana plantation, orchard, and annual upland crops such as rice, maize, corn, job's tear and groundnut. One year cultivation of annual crops, mainly upland rice (Oryza sativa), maize (Zea mays), or Job's tears (Coix lacrima Jobi), is followed by a fallow period, which is currently 4 years long on average (Ribolzi et al, this issue), during which secondary vegetation covers the fields. Teak and banana plantations extend over 14% of the catchment, while vegetable cropping is concentrated in small patches along the stream. Riparian areas are mainly of convex or convex-concave shape, steep, and narrow. Most of the riparian land is covered either with a grass/shrub native vegetation dominated by Microstegium ciliatum, bamboos, or banana plantations.

In these systems, weed invasion is one of the most important constraints to upland rice cropping. Because of this weed pressure, which tends to increase with increased cropping intensity and shortened fallow periods, a larger number of weeding operations per cropping cycles is required. These weeding operations are responsible for tillage erosion, i.e. the process of downhill soil movement caused by the combined action of hand tools used for weed removal and gravity. Tillage erosion is an important form of erosion in the Houay Pano catchment, leading to soil losses equivalent to water erosion on 70% slope gradients (Dupin et al., 2002). Overall, because of more intense cropping, reduced fallow duration, increased weed pressure and the loss of soil fertility that ensued, yields have reportedly declined to about half the 3-4 t ha-1 which was achieved under long fallow shifting cultivation 20 years ago.

Socioeconomic environment

Settlement in Ban Lak Sip started in the 1960s with the arrival of families originating from northern provinces. The village was officially founded after the 1975 revolution. Five neighbouring communities were resettled in Ban Lak Sip in 1976, 1982 and 1996. By 2003, the village population totalled 503 inhabitants, of which more than 80% were members of the Khamu ethnic group. In terms of livelihood, Ban Lak Sip residents are currently involved in a variety of on-farm activities, though annual cropping – mainly upland rice for subsistence and Job's tears sold to export companies based in Luang Prabang – is the most important activity for almost all village households. Annual cropping is practised according to the rotational shifting cultivation system: plots are commonly cultivated for one or two successive years followed by a three year fallow period. In addition to annual cropping, vegetable production (e.g. chilli, beans, coriander and several grasses) based on a continuous cultivation system, forest product gathering (e.g. fuel wood, bamboo shoots, and grasses), hunting (mainly small rodents and birds), livestock farming (e.g. poultry, pig, cattle) and perennial tree production (mainly teak and banana) also form important land-based livelihood activities.

These activities take place in different parts of the landscape, depending on slope and elevation. In general, annual cropping as well as gathering and hunting activities occur in the high elevation areas while livestock production is almost exclusively conducted in and nearby the village and on lower slopes. Vegetable cropping and tree plantations are found throughout the landscape. It is noteworthy that almost one third of the activities from which households derive their livelihood take place in the high elevations and steep slope zones.

In general, since 1990 the village households have changed from relatively specialised production to diversification. While in 1990, an average household was engaged in two or three livelihood activities (usually annual cultivation of glutinous rice, collecting-hunting and poultry farming), in 2003, with a strong development of tree plantation (essentially teak and banana), vegetable cultivation (mainly cash crops sold at the Luang Prabang markets) and non-farm employment (e.g. small trading by the roadside, construction or factory worker, etc.), the same household had four or five different sources of income. As they diversified their activities, farmers also increased the area they cultivated and the amount of time spent on livelihood activities.

The land use that underwent the most conspicuous expansion is tree plantations, which nearly quadrupled in extent and now occupy nearly as much area as annual crops. Vegetable cropping has also shown a very significant expansion. The largest increase in labour input corresponds to vegetable cropping, non-farm activities and livestock farming (with the recent development of pig, goat and fish farming). As mentioned above, workloads associated with annual cropping activities also increased during the period both in terms of the number of workers and average workload. In fact, the average household workload increased sharply over the entire survey period, from 156 to 244 days of activity per year. Finally, there has also been a relative reorientation in the location of livelihood activities. Annual cropping and vegetable cropping have expanded mainly in the flattest parts of the landscape, while plantation agriculture has expanded across all elevations.

The gradual opening of the country to a more liberal economy together with the national land reform have played major roles in shaping the development trajectory of Ban Lak Sip (Lestrelin and Giordano, 2007). However, land degradation has also played a significant role. To some extent, many of the strategies adopted by the villagers have contributed to avoid soil erosion being a major constraint on their livelihood. By devoting additional labour to annual cultivation and cultivating larger areas, some farmers have simply attempted to stabilise agricultural yields and maintain agricultural production at an acceptable level. Yet, soil erosion is a persistent issue for these villagers. Engaging more radical changes, others have adopted full-time non-farm occupations and successfully untied their livelihoods from land-related constraints. Generally, by diversifying their activities, adopting non-farm occupations and spending more time on alternatives to annual cropping such as livestock farming, tree plantation or vegetable cultivation, a majority of villagers have indirectly reduced the limiting effects of soil erosion on local livelihoods.

At the same time some farmers have started to cultivate annual and vegetable crops in flatter parts of the landscape which, as observed by Forsyth (1996) in northern Thailand, can be seen as an adaptive change related to local perceptions of higher erosion risk on steep slopes. Unfortunately these flatter zones are very limited in extent. By cultivating on the few flat areas of the village land, farmers take advantage of the sediment eroded from the slopes. Finally, the major expansion of teak plantations may also be seen as a combined effort for both developing alternatives to annual cultivation and controlling soil erosion by maintaining land cover on the slopes. However, while many farmers confirmed the first explanation, teak plantation was never described as a way to control erosion. Actually, and this illustrates villager local knowledge, some scientists argue that soil erosion may be increased under teak plantation due to the absence of undergrowth, the concentration of raindrops on the large leaves and their amplified 'splash effect' when they reach the soil (e.g. Bruijnzeel, 2004). In fact, the plantation of teak in upland fields is often the main option chosen by the farmers when the land is too degraded and annual cropping has become unprofitable.

Environmental and land use monitoring

As the benchmark site of the MSEC programme in the Lao PDR, the Houay Pano catchment has been extensively instrumented for hydrological and sediment load monitoring. Four V-notch sediment traps (weirs) were installed along the perennial stream and in each of the 4 sub-catchments which act as drainage area for the ephemeral streams that feed the main stream during storms (Figure 8). In each weir, water level is measured at a constant distance upstream of the flume using an automatic water level recorder. Hand-held gauges are also used in association with this automatic set up. The relation between water level and discharge (rating curve) was determined for each stream-gauging station, using a current-meter along a section across the stream to measure simultaneously flow velocity and water level. Water level data collected at the weirs are downloaded weekly.

During flow events, water samples are collected using automatic samplers (operational since 2002). These samplers collect water with a time-step which varies from 5 to 10 min. depending on flow stages (rise, peak, rapid and slow decrease). In the laboratory each sample is flocculated using alumina sulphate, filtrated, oven-dried at 60°C and weighed to assess the sediment concentration (g l^{-1}). Bedloads, i.e. sediments trapped at the bottom of weirs, are also collected after every main rainfall event. Five to ten samples are collected, starting from the upper part of the weirs, weighed, oven-dried and weighed again to assess their water content, and thus the total dry mass of sediments. The total sediment yield at the catchment level is derived by adding the suspended load to the bedload.

A rain gauge network consisting of six manual totalizers and one automatic weather station was installed to account for the spatial and temporal rain distribution and the environmental variability. The automatic weather station's rainfall recorder is used to calculate rainfall intensity at a 6 min. time-step. Weather data thus collected are downloaded weekly.

Annual land use maps were prepared every year from detailed field surveys. Observed land use included fallow (Fw), degraded secondary forest (Forest), teak plantation, bananas, upland rice, Job's tear (Coix lacryma-jobi L.), sesame, maize. Experimental equipment was set up in four sub-catchments to compare four farming systems: (i) the current rotational slash and burn system as the control, and three innovative systems (ii) improved fallow with Cajanus cajan and Crotalaria micans, (iii) improved fallow with contour planting and (iv) mulch planting without tillage (de Rouw et al., 2003).

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***Table 1** - Main environmental characteristics of the 9 study sub-catchments: the total surface area (area), the minimum (Min), maximum (Max) and mean altitude (Z); the mean slope gradient (S); the sub-catchment perimeter (Perim), the index of compactness of Gravelius (Rc) which is the ratio of the perimeter P of the sub-catchment to the perimeter of a circle which have the same surface area (after Chaplot et al., 2005a).*

Catchment number	Area	MinZ	MaxZ	MeanZ	S	Perim	Rc
	(ha)	(m)	(m)	(m)	(%)	(m)	(m^{-1})
1	19.6	558	718	623	61	1745	0.1
2	13.6	515	669	571	53	1576	0.11
3	16.7	488	621	544	51	2163	0.13
4	8.2	430	592	513	48	1637	0.14
5	2	415	518	429	56	1254	0.22
6	0.64	530	585	562	52	358	0.11
7	0.6	514	588	553	62	392	0.13
8	0.57	477	580	534	54	452	0.15
9	0.73	423	505	459	54	421	0.12
Whole	62.4	415	718	567	54	4196	0.15

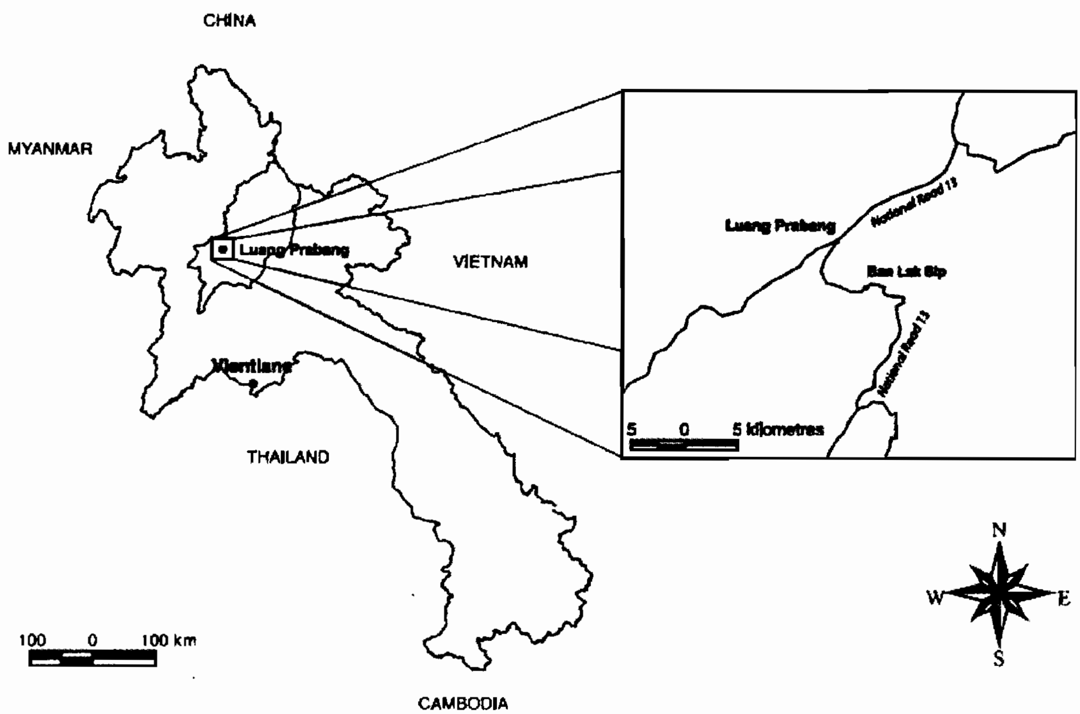

__Figure 1 –__ Location of the MSEC experimental site (Houay Pano) in Laos.

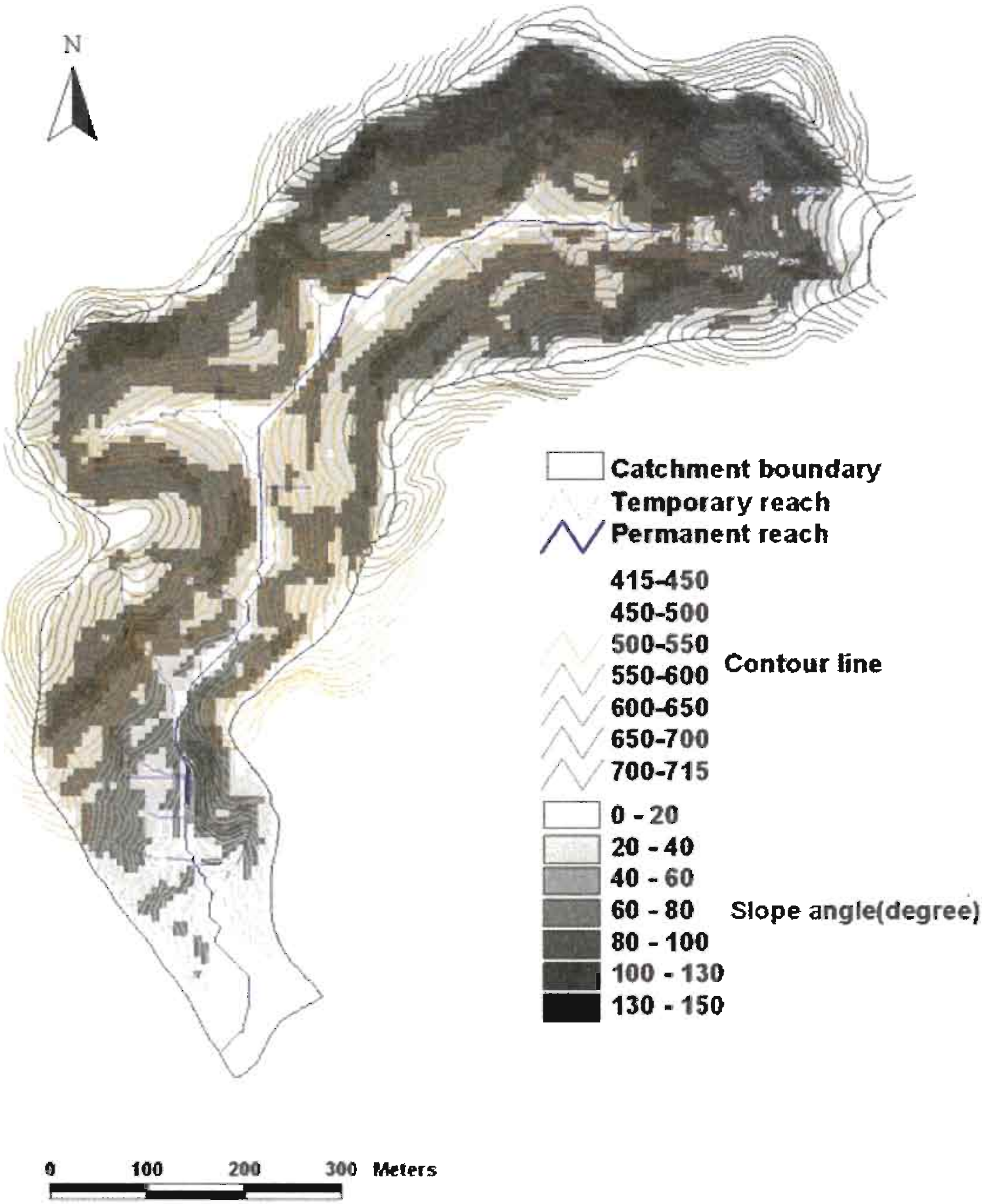

Figure 2 – *Topography and main morpho-hydrological features of the Houay Pano catchment.*

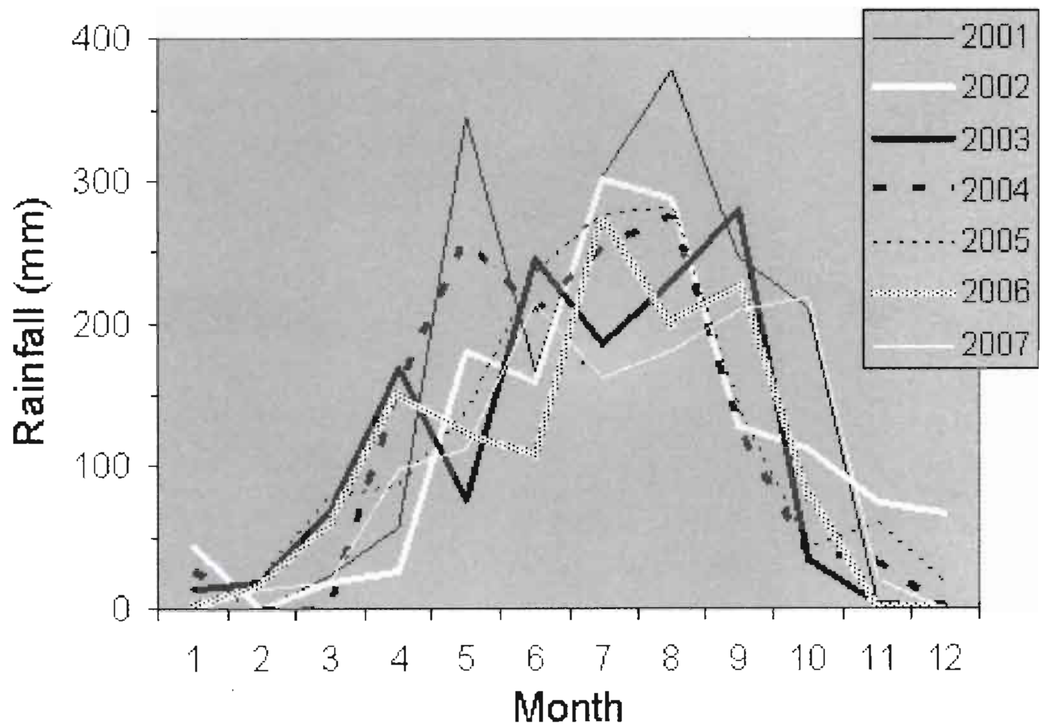

Figure 3 *– Annual rainfall distribution within the Houay Pano catchment.*

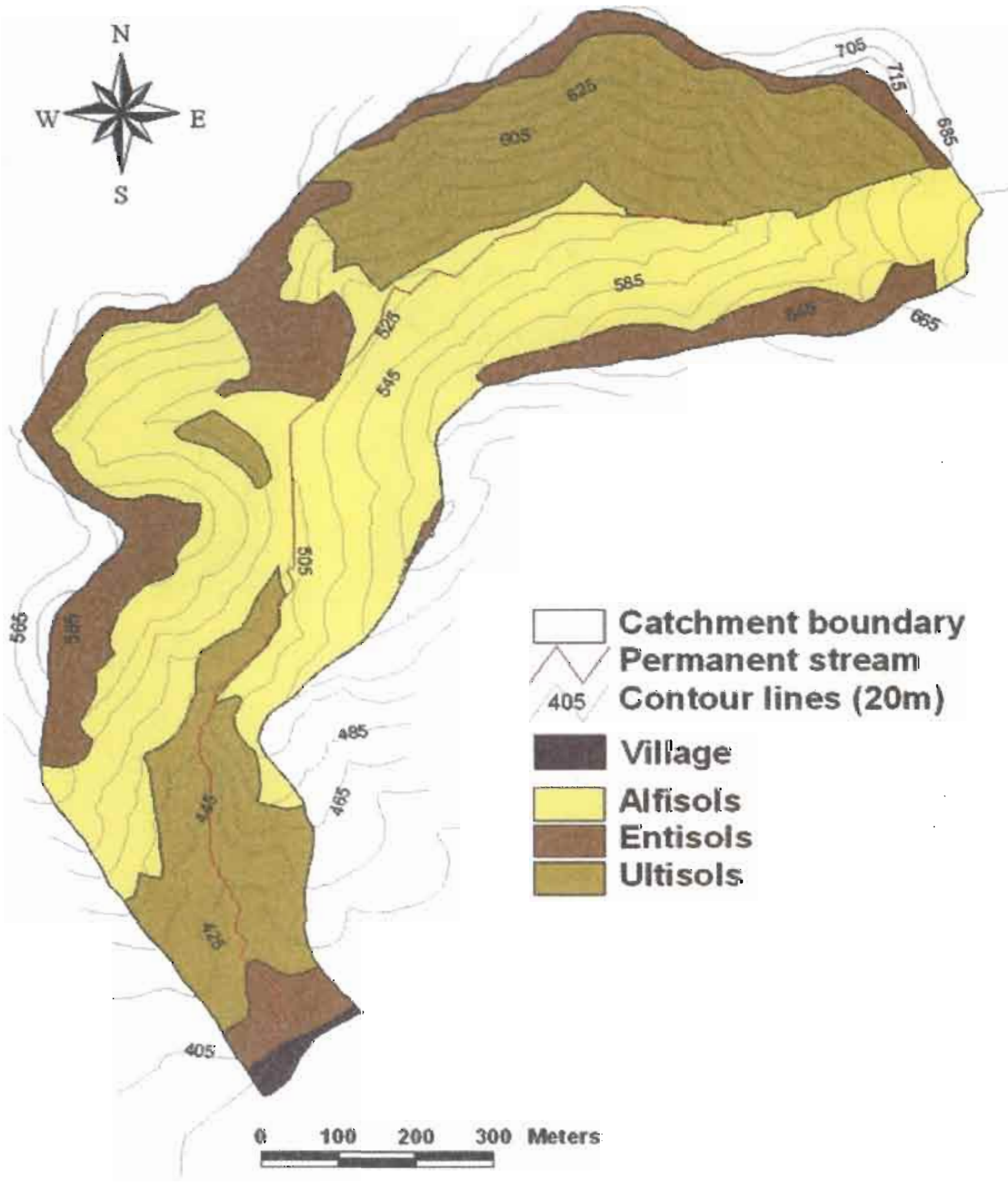

Figure 4 *– Soil map of the Houay Pano catchment.*

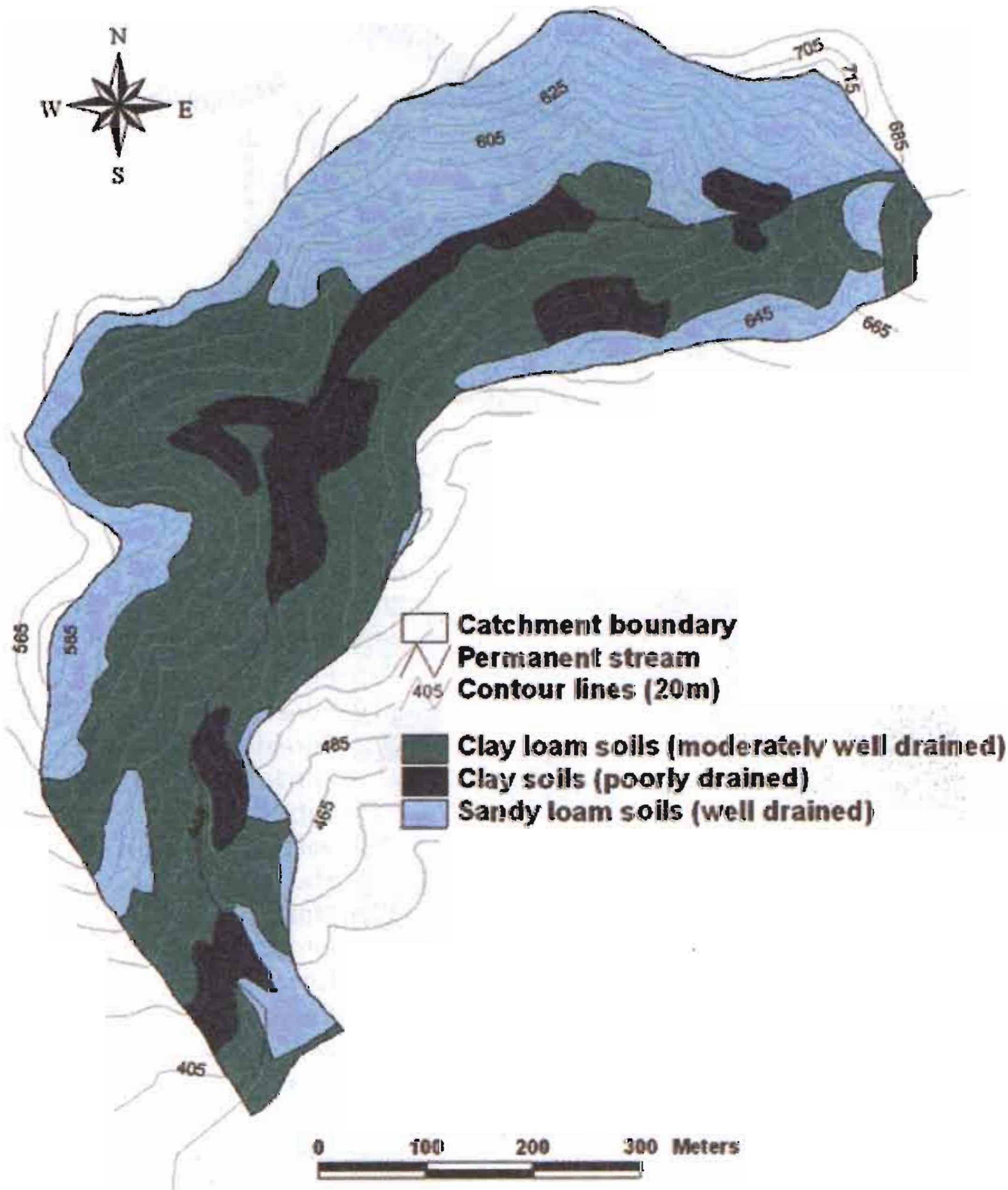

Figure 5 *– Soil texture map of the Houay Pano catchment.*

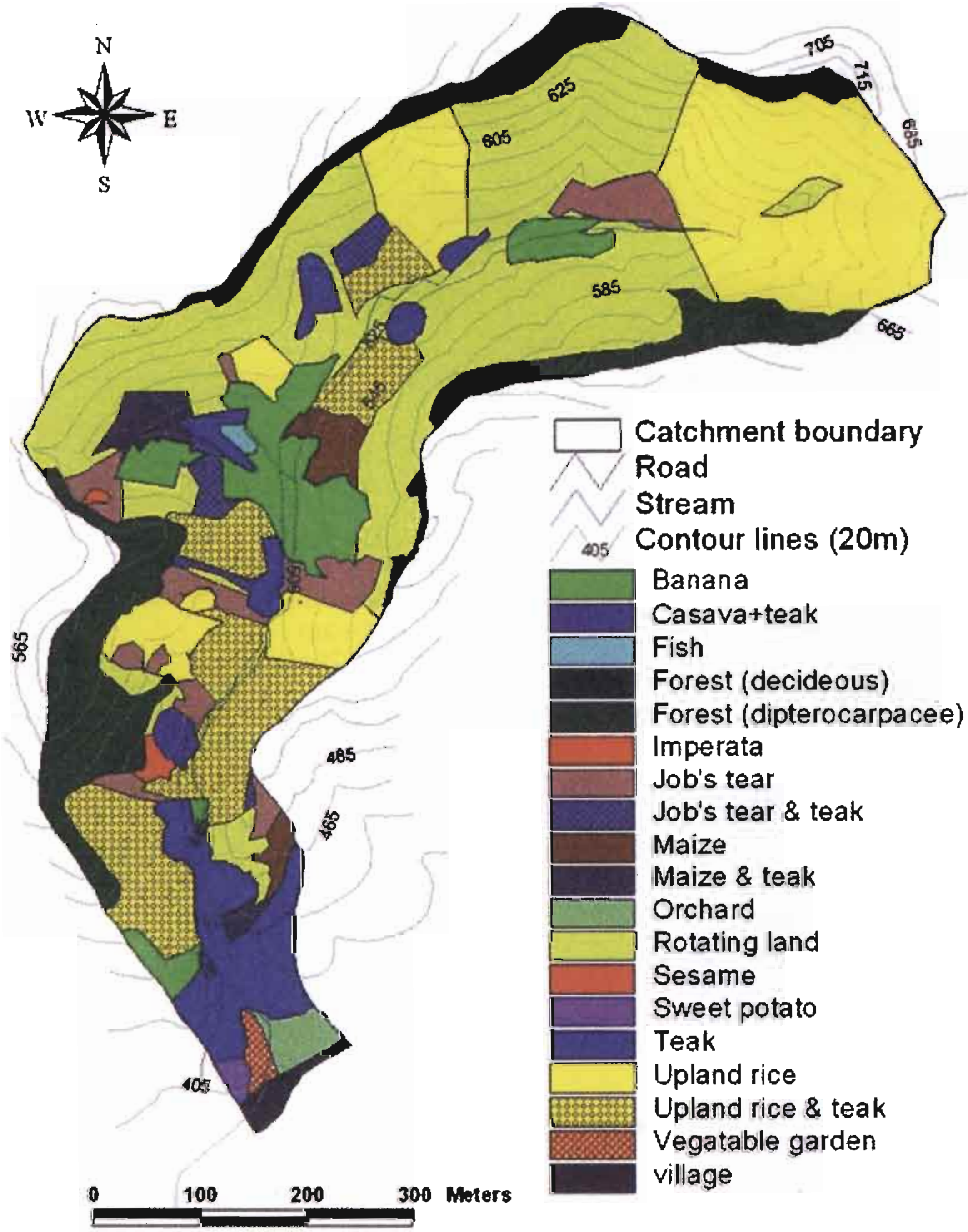

***Figure 6** – Land use map of the Houay Pano catchment in 2007.*

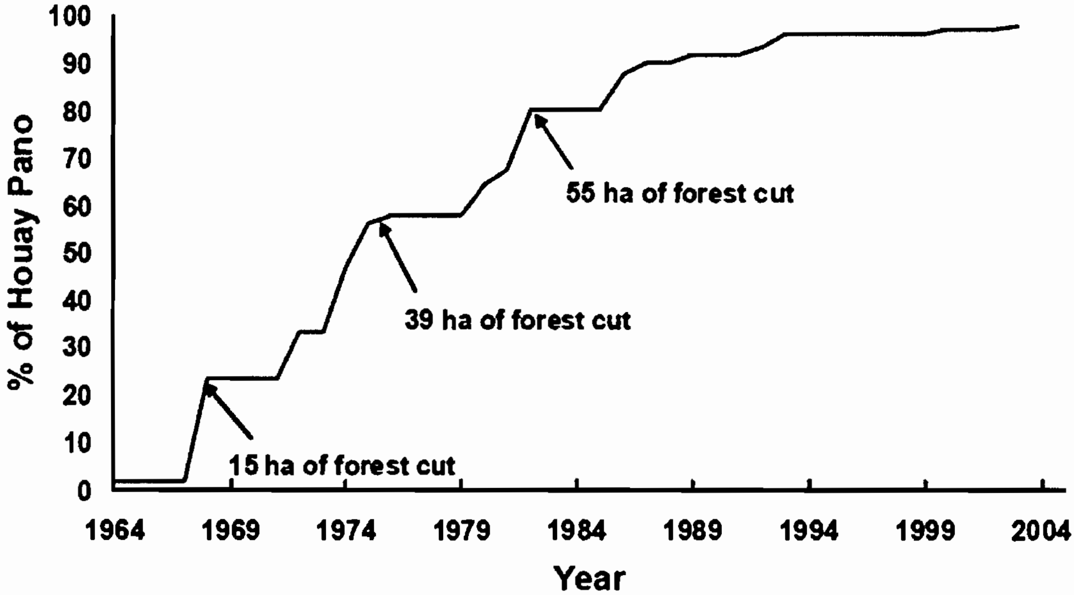

Figure 7 *– Mature forest cut for slash and burn cultivation.*

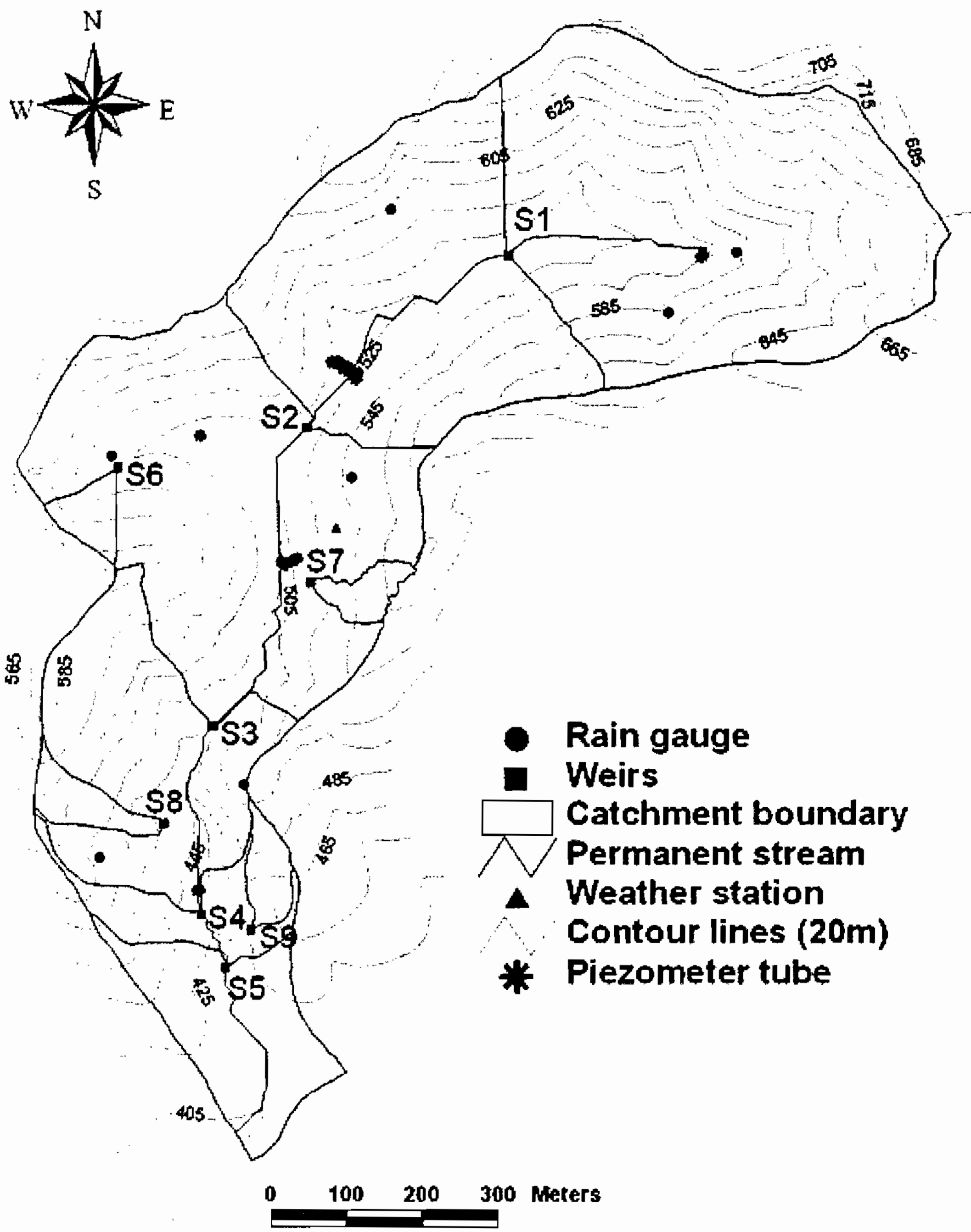

Figure 8 *– Main hydro-meteorological equipment in the Houay Pano cathment.*

ຜົນກະທົບຂອງການຟື້ນຟູປ່າເຫຼົ່າ ຕໍ່ປະລິມານນໍ້າຫວ້ຍ ໃນເຂດອ່າງໂຕ່ງ ທີ່ມີການເຮັດໄຮ່ ຢູ່ ພາກເໜືອ ຂອງ ສ.ປ.ປ ລາວ

ໂອລິວິເອ ຣິໂບນຊີ, ຊັງປີແອ ທີໂບ, ເອມານູແອນ ບວກດົງ, ຊັງປີແອ ບຣິກເກ, ປີແອ ມາກຊັງ, ເອມານູເອນ ມູເຊີ, ອາແລງ ປີເອເຣ, ໂອລີດ ແສງຕາເຮືອງຮຸ່ງ, ຄຣິສຕຽນ ວາເລນຕີນ

ບົດຄັດຫຍໍ້

ແຫຼ່ງສາຍນໍ້າຫ້ວຍຈາກເຂດສູງ ຖືວ່າເປັນເຂດສໍາຄັນໃນເຂດຍອດນໍ້າ. ຈຸດປະສົງຂອງບົດນີ້ແມ່ນເພື່ອສຶກສາຜົນກະທົບ ຂອງການຟື້ນຟູປ່າເຫຼົ່າຕໍ່ລະບົບນໍ້າໃນເຂດອ່າງໂຕ່ງທີ່ມີການເຮັດໄຮ່. ການຄົ້ນຄວ້າແມ່ນແນໃສ່ ວິໄຈໄລຍະຂອງກະແສນໍ້າໄຫຼລະດັບຕໍ່າສຸດ ໃນຊ່ວງລະດູແລ້ງ ແລະ ລະດູຝົນ. ຜ່ານການຄົ້ນຄວ້າເປັນເວລາ 6 ປີ (2000-2007) ສາມາດເວົ້າໄດ້ວ່າ ການຟື້ນຟູປ່າເຫຼົ່າແມ່ນມີຜົນກະທົບທາງບວກ ຕໍ່ລະບົບນໍ້າໃນເຂດອ່າງໂຕ່ງ ດັ່ງນີ້: 1) ການຟື້ນຟູປ່າເຫຼົ່າ ເຮັດໃຫ້ຄວາມສົມດູນຂອງລະບົບນໍ້າມີການປ່ຽນແປງ, ໂດຍສະເພາະ ການກະຈາຍຂອງນໍ້າຝົນ ຜ່ານການລະເຫີຍ ແລະ ການກໍາບັງຂອງພຸ່ມໄມ້; 2) ການເກັບກັກນໍ້າໄວ້ດ້ວຍຮາກ ເພື່ອການຈະເລີນເຕີບໂຕຂອງລໍາຕົ້ນ ແລະ ພາກສ່ວນອື່ນໆ ເຮັດໃຫ້ນໍ້າໃຕ້ດິນຫຼຸດລົງ; 3) ການສູນເສຍນໍ້າໃຕ້ດິນ ເຮັດໃຫ້ປະລິມານນໍ້າໃນຫ້ວຍໜ້ອຍລົງ ຍ້ອນການຫຼຸດລົງຂອງສາຍນໍ້າໄຫຼປົກກະຕິ ໃນລະດູຝົນ ແລະ ລະດູແລ້ງ; 4) ນໍ້າໃຕ້ດິນເປັນຕົວປະກອບທີ່ສໍາຄັນ ພາໃຫ້ມີນໍ້າຖ້ວມ. ນໍ້າໄຫຼບ່າໜ້າດິນ ປະກອບສ່ວນການເພີ້ມຂຶ້ນຂອງນໍ້າ ໃນເວລາມີຝົນຕົກແຮງ.

Effect of fallow regrowth on stream water yield in a headwater catchment under shifting cultivation in northern Lao PDR

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Abstract

Low flow generation from the uplands of has been identified as the one of the most important watershed issues in Southeast Asia. The aim of this work was to examine the effect of fallow regrowth on the hydrological behaviour of a fragmented landscape, under shifting cultivation with short fallows, which is a system typical of the northern Lao P.D.R. uplands. The study focused specifically on analysing and understanding periods of low flow during the dry and wet seasons. After 6 years of hydrological and land use monitoring (2002-2007) in the Houay Pano headwater catchment, we can conclude that fallow regrowth significantly affects the hydrological regime of the catchment. The main results obtained can be summarised as follows: **(i)** Development of fallow vegetation induces remarkable changes in the annual water balance, in particular, it increases the fraction of incident rainfall redirected by transpiration and canopy interception; **(ii)** Increased root water uptake subsequent to perennial vegetation growth, reduces groundwater recharge and subsurface reserves; it also lowers the water table, hence limiting stream feeding by shallow groundwater; **(iii)** This groundwater depletion leads to a drop in the annual stream water yield due to a decrease in wet season inter-stormflow and dry season baseflow; **(iv)** Subsurface groundwater is the major contributor to floods. Overland flow (surface runoff) contributed most significantly to flood waters during rainfall events in the first two years of fallow regrowth.

This study showed that water resources in the uplands of northern Laos are sensitive to land use and hence potentially vulnerable to inappropriate management. The conclusions made in this paper go a step towards predicting the likely consequences of the Government's current effort to eradicate shifting cultivation and replace it with perennial crops such as teak plantations.

Key words: *Runoff; Low flow; Stromflow generation; Water balance; Fallow regrowth; Uplands of Lao P.D.R*

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Introduction

The role of forest and trees in watershed hydrology and the impact of deforestation on hydrological regimes has been widely studied (e.g. Calder, 1998). Generally, although responses vary widely between sites and situations, the removal of forest cover leads to higher water yields. Many studies on evapotranspiration indicate that in both very wet and very dry climates, evapotranspiration from forests is likely to be higher than that from shorter crops and consequently less runoff is generated from forested areas. However, little is known about the hydrological response of headwater catchments following land use and land cover changes that occur during rotational shifting cultivation cycles, which include several years of fallow followed by a one year clearing-burning and cropping phase (Gafur et al., 2003).

In northern Lao PDR, the traditional shifting cultivation system has been evolving over the decades in response to population pressure (Lestrelin et al., 2005). The cultivation cycle, i.e. the time period between two successive clearing/cropping operations on the same site, has been shortened to 2-5 years, whereas ecological sustainability may require a minimum fallow period of at least 10 years (de Rouw et al., 2005). In this agro-ecosystem, the hydrological regime may be changing with potentially increasing negative downstream effects. A few studies reported the consequences of fallow shortening on soil erosion (e.g. Valentin et al., this issue). However, as mentioned by Bruijnzeel (2004) in a review paper, further research is required on the baseflow regime of streams and rivers. The problem of "low flow" generation from the uplands has been identified as the one of the most important watershed issues in Southeast Asia, with numerous human activities, e.g. hydropower production, paddy rice sustainability in the lowlands, depending on this crucial environmental service.

The effect of land use changes on low flow production, dry-season flow in particular, depends on competing processes (e.g. evapotranspiration and infiltration) and is likely to be highly site specific (Calder, 1998). In tropical areas, afforestation can lead to decreased dry-season flows due to increased evapotranspiration, putting hydroelectric plan operations and drinking water supplies at risk (FAO, 1987). In the Mae Thang watershed (Thailand), afforestation programmes led to water shortages downstream, which resulted in reduced water availability for irrigation (Chomitz and Kumari, 1996).

This paper focuses on the effect of fallow regrowth on total annual stream water yield in a fragmented landscape under shifting cultivation with short fallow. Several questions arise in this context. Does the crop/fallow ratio influence rainfall infiltration opportunities and hence groundwater reserves? Are the groundwater reserves replenished sufficiently during the rainy season to sustain the dry season baseflow? The overall objective is to provide information on inter-annual runoff variability at the scale at which farmers operate and at which downstream impacts can be assessed. Special attention was paid to the analysis and understanding of baseflow (low flows) behaviour during the dry and wet seasons compared with land cover and land use dynamics.

We investigated baseflow generation for six years (2002-2007), which corresponded to an entire crop-fallow cycle within the Houay Pano catchment. We surveyed land use (mainly crop/ fallow evolution) and quantified stream water yields at the catchment outlet.

Materials and methods

The biophysical and socio-economic characteristics of the study site (a headwater catchment in northern Lao PDR) are described by Valentin et al. (this issue).

Land use mapping and topography

Annual land use maps were prepared for seven years (2001-2007) from detailed field surveys. Observed land uses included fallow, degraded secondary forest, teak plantation, banana, upland rice, Job's tears (Coix lacryma-jobi L.), sesame, and maize. The percentage of catchment occupied by each type of land use or land cover was derived from land use maps established each year. The boundaries between land use units were mapped in the field using a combination of GPS and theodolite survey points. The mapping accuracy of land use boundaries is estimated to be within ± 2.5 m (Chaplot et al., 2005). The proportion of each land use was estimated using Arc-View software (ESRI, 1997).

Hydro-meteorological measurements

Rainfall was monitored using a network of six manual rain gauges (see Valentin et al., this issue) and an automatic rainfall recorder with 0.5 mm capacity tipping-buckets. Annual reference evapotranspiration (ETo) was estimated following the Penman-Monteith FAO method (http://www.fao.org/docrep/X0490E/x0490e0k.htm#TopOfPage) with the program CropWat4 windows (version 4.3), and using monthly mean meteorological parameters (air temperature, wind speed at 2 m height, relative air humidity, and global solar radiation) collected with a weather station (CIMEL, EMERCO 404) installed at mid-hillslope in the catchment.

The discharge of the permanent stream was measured at the outlet of four nested catchments (S1, S2, S3 and S4) from March 2001 using automatic recording stations consisting of a water level recorder (OTT, Thalimedes) and a V-nor weir. A control rating curve (the relationship between water level and discharge) was determined using the velocity area method at each station. Water-level data were downloaded every week. Among the four weirs monitored along the Houay Pano stream, S3 was installed on the bedrock in a steep-sided reach, and thus may guarantee the control of total outflow and hence will be considered in this study for the stream flow deficit (SFD) estimate (see below).

The water table level was monitored from June 2002 using a network of 12 piezometers (0.055 m internal diameter PVC tubes; screen height = 0.5 m) positioned at a depth between 1 and 6 meters and distributed along three transects (T1, T2 and T3), each including four piezometers .T1 and T3 were settled near the permanent stream in the main valley, while T2 was installed across an ephemeral first-order stream in a lateral sub-valley. The results presented here are for one piezometer (T1-A3) which was representative of the downstream groundwater system.

Estimate of actual evapotranspiration

The impact of land use on total annual runoff is a function of many variables. Actual evapotranspiration (ET) (i.e. evaporation of soil water and transpiration by plants) and interception (I) of rainwater by plant cover are the most important factors in most tropical environments. The estimate of these two variables using classical measurement techniques (e.g. lysimeters, rain gauges) based on local observations is technically complicated to implement and extremely difficult to upscale at the catchment level, especially in heterogeneous upland environments. We preferred to estimate

ET+I indirectly by the "stream flow deficit" (SFD) method with the following water balance equation:

$$SFD = P - (R + \Delta S) \quad (1)$$

Where P is the total annual rainfall, R is the total annual runoff (i.e. stormflow and inter-stormflow) and ΔS is the change in water storage at the surface and/or the subsurface within the catchment (i.e. the amount of water that is being added to or removed from water stored within the catchment). All the terms of this equation are expressed in mm. We hypothesised that the inter-annual changes in soil water storage (i.e. the unsatured zone) were negligible and that only the annual dynamical groundwater volume of storage (S_y) may vary, hence ΔS was estimated as follow:

$$\Delta S = S_{y+1} - S_y \quad (2)$$

while S_y and S_{y+1} were approximated at the end of each year with the following equation:

$$S_y = Q_0 / \alpha \quad (3)$$

Where Q_0 is the stream base flow discharge at time t_0 (31 December) and α is the depletion coefficient, characteristic of the groundwater reservoir, estimated by fitting an exponential decay curve (Maillet, 1905) to observed stream discharge values during a low flow period without any flood disturbances.

Storm-hydrograph separation

In order to estimate the contributions of surface (i.e. rainfall water that fell during the rain event) and subsurface (i.e. water in the ground before the rain event) flows during floods, storm hydrographs were separated using a tracer-based mixing model approach (e.g. Collins and Neal, 1998). In the case of Houay Pano, a strong linear relationship was established between residual alkalinity, a conservative natural tracer (Ribolzi et al., 1996), measured from numerous spot water samples, and electrical conductivity. Electrical conductivity is easy to monitor and inexpensive so it was used as the hydrological tracer for storm hydrograph separation.

Results

Land cover changes

The Houay Pano catchment is part of the farming land of Lak Sip village. It is mainly cultivated following an altered shifting cultivation system with short fallow periods (Figure 1). Annual crops and fallows were the main land cover changes throughout the survey period.

The proportion of other land use types (secondary forest, permanent crops) also varied but within a narrow range. Figure 2 shows the mean 5-year periodicity of the rotational farming system: i.e. one year of slashing-burning-cropping followed by a fallow period of four years. The highest proportion of annual crops, about 51 % of the total catchment area, was observed in 2007. It was a bit more than in 2002 (46%). This percentage decreased regularly the four following years (2003-2006) as almost all the fields of annual crops were left as fallow areas. In 2006, only 6% of the catchment area was allocated to annual crops. Fallow areas evolved with in a converse trend: they decreased first from 66% in 2001 to 33% in 2002 and then increased to reach a maximum of 71% in 2006. Figure 2 also shows the ratio of crop/fallow areas. It increased steeply from 2001 to 2002, then decreased more gradually from 2002 to 2006, and at last increased again sharply from 2006 to 2007. This periodic behaviour indicated that almost all the Lak Sip farmers follow the same rotational cycle. However, this global observation at the catchment scale masks heterogeneities: some of the fields were cultivated more intensively with only two years of fallow (de Rouw et al., 2005), whereas for a low percentage of others (<1.5 %) the period exceeded five years.

Rainfall characteristics

The rainfall distribution during the study period followed the normal rainfall pattern for Luang Prabang, with the rainy season extending from mid-May to mid-October. Annual rainfall was rather stable from 2002 to 2006 (Figure 3), with a low variation coefficient~5% (SD=67 mm). However the annual rainfall values measured in 2001 and 2007 (1738 and 1139 mm, respectively) differed significantly from that of the 2002-2006 period (mean value=1343 mm). Therefore, in order to better discriminate the effect of land cover changes on stream yield from that of annual rainfall variations, the following hydrological analysis focused on the 2002-2006 period.

Variations in the water table level and groundwater reserves

Figure 4 shows the water table level variations over the study period in piezometer T1-A3. It appears extremely variable, especially during the wet season when extremely sharp fluctuations were observed. The minimum and maximum values measured were 319 cm and 102 cm respectively that is, a range of

217 cm. The water table level began to rise mostly in May with the return of the first rainfall events, and the highest values were observed during the climax of the rainy season, i.e. between July and September. The steepest change measured was 165 cm in less than five days in July 2002. Figure 4 also shows the mean overall trend since monitoring began. It clearly indicates a decrease corresponding to a fall in the mean water table level of 39 cm in five years (from May 2002 to May 2007).

In headwater catchments, the range and dynamics of water table variations can vary tremendously from station to station depending on local conditions (e.g. distance to the stream, transmissivity of soil layers). In view of this variability, direct water table monitoring using a limited number of piezometers is difficult to upscale. Because we were aware of this limitation, we estimated the dynamic-groundwater-stock (S_y) that can potentially sustain streamflow during the dry season using equation (3). Figure 4 shows annual ΔS values. The variation was positive in 2002 (+82 mm), meaning that the groundwater stock increased throughout the year which had the highest annual cropping rate during the study period. Then, it decreased (130 mm) in 2003, the year with the highest percentage of one year fallow cover. Finally, the variations remained close to zero for the three following years.

Behaviour of streamflow components

Figure 5 shows the inter-annual variations in the main streamflow components (i.e. surface and subsurface contributions during floods, and inter-stormflow during the wet and dry seasons) and the annual runoff ratio (i.e. streamflow depth/rainfall depth). The annual runoff ratio decreased regularly from 43% in 2002 down to 26% in 2006. As year-to-year annual rainfall variations were very little, the annual streamflow behaved in the same way as the annual runoff ratio: it decreased from 598 mm (i.e. 5976 m3/ha) in 2002 to 325 mm (i.e. 3251 m3/ha) in 2006. This decreasing trend was clearly due to baseflow changes, and in particular the wet season baseflow. Mean values of overland flow, subsurface stormflow, dry season baseflow and wet season baseflow were 17 mm (STD = 13 mm, VC=80%), 133 mm (STD = 25 mm, VC=19%), 96 mm (STD = 18 mm, VC=19%) and 198 mm (STD = 89 mm, VC=45%), respectively. Baseflow was the main component of streamwater yield; it represented 66% of total streamflow for the study period. Subsurface flow (i.e. pre-event soil and ground water) widely dominated stormflow (89±9%). It remained extremely high (>90%) except in 2003 and 2004, the two first years of the fallow regrowth period (~80%).

Discussion

Groundwater recharge and streamflow decline vs fallow regrowth

A significant negative correlation was found between the annual stream flow coefficient and total fallow percentage ($r=-0.94$, $P<0.001$). As shown by Figure 6, the data fitted well with a linear regression ($R^2=0.87$). Hence our findings suggest that annual streamflow changes are the consequence of vegetation changes: annual streamflow decreased as plant growth in the fallow plots increased. This observation is consistent with the main conclusion of most studies of the impact of afforestation on the hydrological regime in headwater catchments that is, a change of land cover from lower to higher-ET leads to a decrease in annual stream flow (e.g. Bosch and Hewlett, 1982). Leaf area index increased during the fallow regrowth period (e.g. Dunin et al., 2007), hence interception and transpiration also increased. In particular, groundwater extraction due to transpiration increased with the growth of root systems, which were deep rooting for fallow plants. As a consequence, by extracting water from the unsaturated zone, root systems decreased groundwater recharge. Reduced recharge led to groundwater table depletion and hence affected baseflow and finally annual streamwater yield (Le Maitre et al., 1999).

Estimating real annual evaporation using the streamwater deficit approach

The strong linear correlation between the percentage of fallow regrowth and streamwater yield (Figure 6) is evidence that real annual evaporation (i.e. soil evaporation + interception + transpiration) can be accurately estimated using the streamflow deficit approach (Equation 1). Figure 3 shows the evolution with time of SFD/ETo (annual streamflow deficit / reference evapotranspiration). This ratio remained lower than 1 suggesting that, within a yearly timeframe the annual rainfall input and groundwater stocks were sufficient to satisfy the climatic demand so that the system was not under water stress. However, this ratio increased from 0.65 in 2002 up to 0.90 in 2006. Assuming that this trend continued, due to the Lak Sip village farmers deciding to continue fallow regeneration for one more year, our results suggest that the stream would have dried up during the following dry season.

Synchronised rotational shifting cultivation

Secondary forest and regrowth fallow fields are favourable habitats for wild fauna (e.g. birds, rodents) and straying livestock (pigs, goat). Because these animals can cause severe crop losses, farmers avoid cultivating paddy rice or any other food crops (corn, Job's tears) in the direct vicinity of fallow lands. A direct consequence of this practice is that farmers of the same village cultivate their land simultaneously and follow their rotational shifting cultivation cycles in phase. The Lak Sip village illustrates well this type of dynamic (Figure 1). Most of the fields were cultivated in the same year (i.e. 2002 and 2007 over the study period) and fallow vegetation re-grew continuously, at the catchment scale, until a maximum of about 71% of the catchment area was fallow in 2006 (Figure 2). This cyclic land use caused a periodic behaviour of the annual streamflow yields. Considering stable inter annual rainfall inputs, the lowest stream discharge was observed when the highest percentage of fallow was seen (i.e. when the real evapo-transpiration is maximal). Thus while the strategy adopted by the farmers does limits crop damage by animals and hence the risk of reduced crop yields, the water yield becomes uncertain. If the year preceding cultivation coincided with an exceptionally low annual rainfall input, stream flow may be extremely vulnerable.

Conclusions and recommendations

The aim of this study was to analyse the effect of fallow regrowth on the hydrological behaviour of a fragmented landscape under shifting cultivation with short fallow, a system typical of the northern Lao P.D.R. uplands. A specific focus of the study was to analyse and understand low flow during the dry and wet seasons. After 6 years of hydrological and land use monitoring in a headwater catchment, we can conclude that fallow regrowth significantly affected the catchment's hydrological regime. The main results obtained can be summarised in four points:

1) Development of fallow vegetation induced remarkable changes in the annual water balance, in particular, it

increased the fraction of the incident rainfall redirected by transpiration and canopy interception;

2) Increased root water uptake subsequent to perennial vegetation growth, reduced groundwater recharge and subsurface reserves; it also lowered the water table, hence limiting stream feeding by shallow groundwater;

3) This groundwater depletion caused a drop in the annual stream water yield due to a decrease in wet season inter-stormflow and dry season baseflow;

4) Subsurface groundwater was the major contributor to floods. The highest contribution by overland flow (surface runoff) to floods during rainfall events was observed for the first two years of the fallow regrowth.

This paper has demonstrated that water resources in the uplands of northern Laos are sensitive to land use and hence potentially vulnerable to inappropriate management. Based on our findings we can predict the likely consequences of the government's current effort to eradicate shifting cultivation and replace it with perennial crops such as teak plantations. These changes, in the context of soaring food prices, may put food production and security at risk. It could also negatively and strongly affect the sustainability of land and water eco-services in the uplands and endanger downstream areas for two main reasons:

1) Some tree canopies are known to enhance splash–induced erosion and modify soil surface features because rain drop size is increased when rain drops merge on leaf surfaces (Hall and Calder, 1993). Species such as Tectona grandis (teak) whose large leaves concentrate rainfall drops may thus cause severe erosion and soil surface crusting.

2) Concurrently, increased root water uptake as plantation trees grow, together with reduced infiltration due to soil surface crusting, will most probably reduce groundwater recharge and limit low flows.

We conclude that the generalized introduction of monocultures over large areas of biophysically and geomorphologically diverse landscapes, including functionally sensitive areas such as riparian areas (Vigiak et al., 2008), although technically simple, will most likely result in vulnerable systems in which water flows, soil stability and crop yields will be highly unpredictable. Therefore it seems vital to allocate increased effort and resources to designing specific policies which will guide the introduction of perennial monocultures without threatening natural resource availability. This will require the informed design and implementation of diversified agro-systems, structured in both space and time, so that the impact of biophysical (e.g. climate variability) and economic (e.g. change in market demand) constraints can be optimally buffered at the scale of smallholder operations.

Acknowledgment

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a

b

Figure 1 – *Pictures showing the Houay Pano catchment **(a)** almost entirely covered with fallow (2001) and **(b)** after slash and burn (2007).*

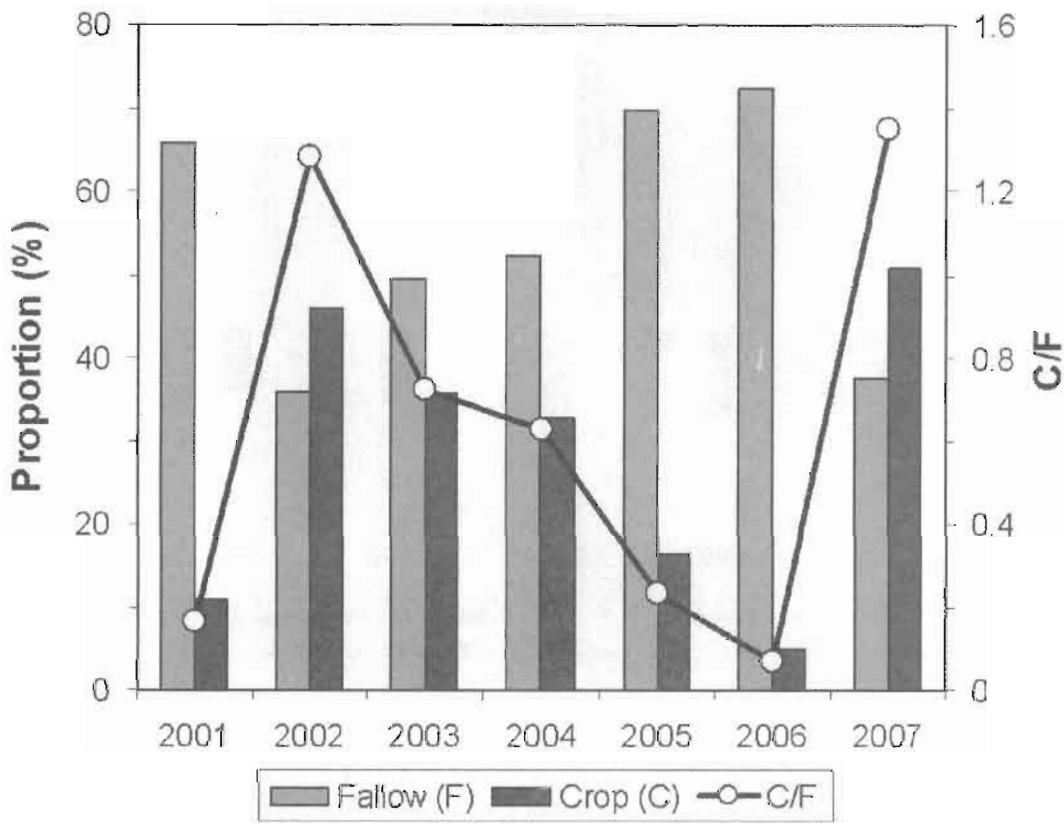

Figure 2 – *Evolution of total fallow and annual crop percentages and the ratio between the two (C/F) areas in the Houay Pano catchment.*

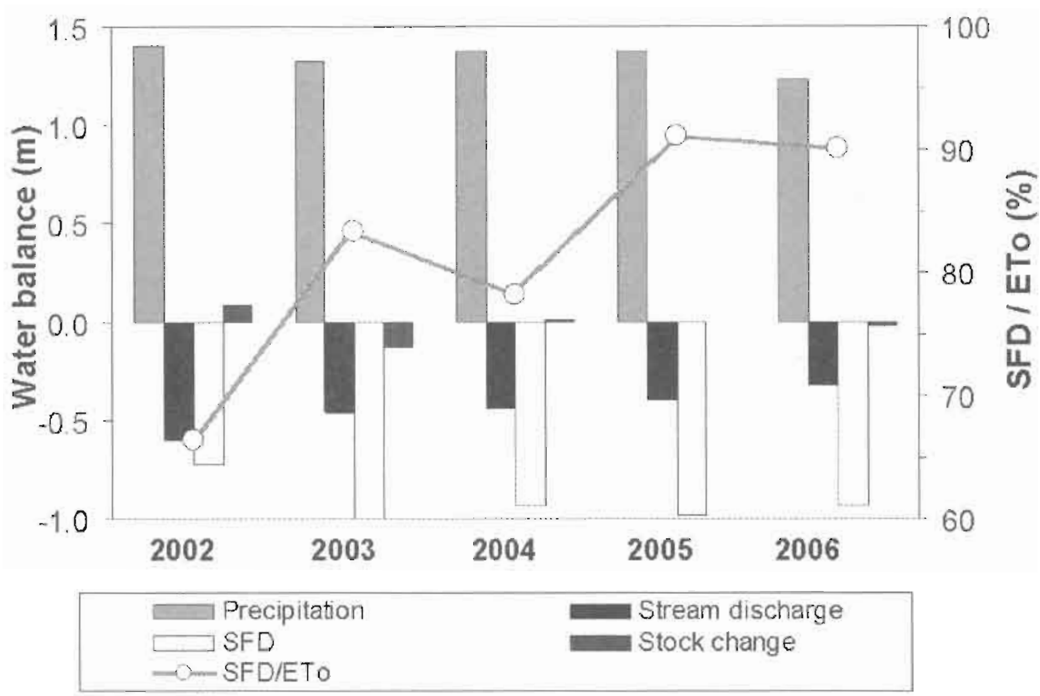

Figure 3 – *Terms of the annual water balance (i.e. precipitation, stream discharge, streamflow "deficit" (SFD) and water stock change) and the ratio between SFD (i.e. estimate of actual evapotranspiration + canopy interception) and reference evapotranspiration (ETo) calculated using the FAO Penman-Monteith method.*

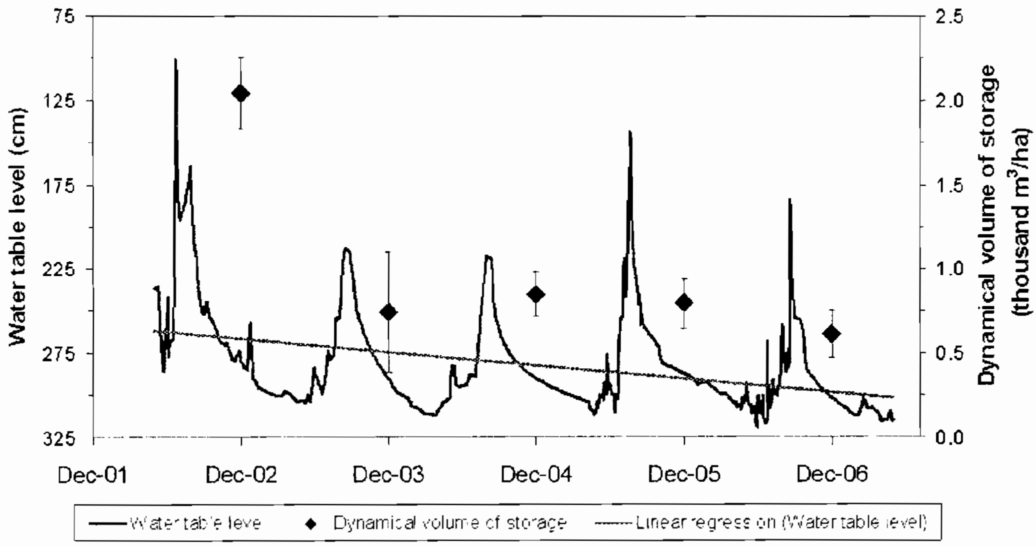

Figure 4 – *Water table level measured in a piezometer (T1-A3) positioned in the downstream part of the catchment with its trend line (linear regression) and estimated dynamical volume of storage (water in the saturated zone) at the end of each year.*

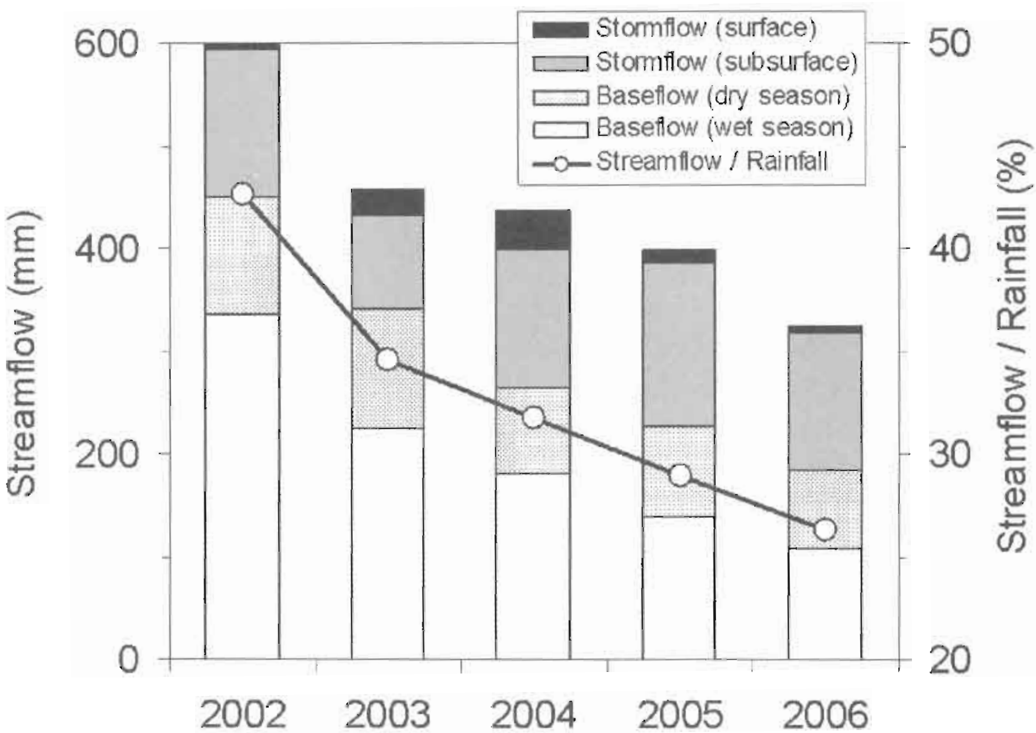

Figure 5 – *Total annual streamflow components (surface and subsurface stormflows, baseflow during the dry and wet seasons) and ratio between total annual streamflow and rainfall in the Houay Pano catchment.*

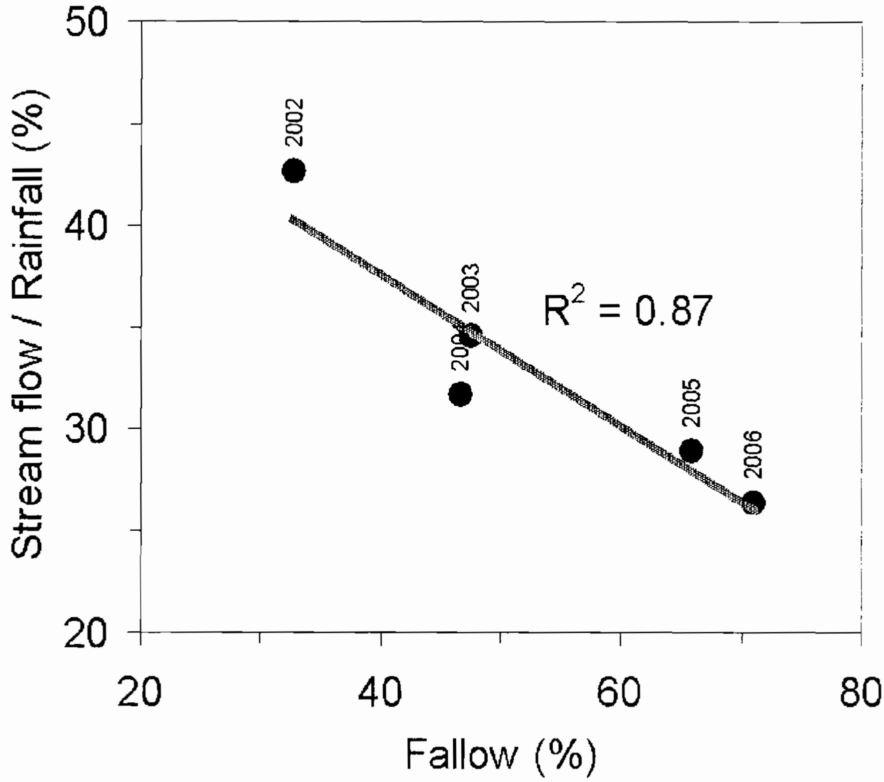

Figure 6 – *The annual stream flow coefficient (Stream flow / Rainfall) as a function of total fallow percentage.*

ເຄື່ອງວັດແທກການຊຶມນ້ຳ ສຳລັບດິນຄ້ອຍຊັນ

ຊັງປີແອ ວັນເດີແອ, ໂອລີວີເອ ຣິໂບນຊີ, ໂອລິດ ແສງຕາເຮືອງຮຸ່ງ

ບົດຄັດຫຍໍ້

ການເຊາະເຈື່ອນຂອງດິນ ແມ່ນປັດໄຈສຳຄັນທີ່ເກີດຂຶ້ນ ໃນເຂດພື້ນທີ່ດິນກະສິກຳ ທີ່ມີຄວາມຄ້ອຍຊັນ ຢູ່ທາງພາກເໜືອ ຂອງ ສ.ປ.ປ ລາວ. ການວາງແຜນນຳໃຊ້ທີ່ດິນ ທີ່ມີປະສິດທິຜົນສູງ ຕ້ອງເຂົ້າໃຈຢ່າງເລິກເຊິ່ງກ່ຽວກັບຂະບວນການ ດ້ານຊີວະ - ດິນ - ນ້ຳ ດ້ວຍການນຳໃຊ້ຮູບແບບຈຳລອງ. ຮູບແບບຈຳລອງທີ່ນຳມາໃຊ້ ຈະຕ້ອງສາມາດຄຳນວນໄດ້ຢ່າງນ້ອຍ ໂຕແປປ່ວນຂອງລະບົບການເຄື່ອນຍ້າຍຂອງນ້ຳໃນດິນ ວິທີການດັ່ງກ່າວ ເປັນວຽກທີ່ຫຍຸ້ງຍາກ ແລະ ໃຊ້ເວລາດົນ ໃນການວັດແທກ. ເຄື່ອງວັດແທກນ້ຳຊຶມແບບໃຊ້ຈານ ແມ່ນໃຊ້ວັດແທກຄຸນສົມບັດຂອງນ້ຳໃນດິນ, ການນຳໃຊ້ເຄື່ອງດັ່ງກ່າວ ແມ່ນຍັງຈຳກັດ ສຳລັບແຕ່ລະປະເພດດິນ. ເຄື່ອງວັດແທກການຊຶມນ້ຳທີ່ໄດ້ກ່າວໃນບົດນີ້ ແມ່ນໃຊ້ສຳລັບວັດແທກລະບົບນ້ຳໃນດິນຄ້ອຍຊັນ. ພວກເຮົາໄດ້ທຳການທົດລອງ ຢູ່ 14 ຈຸດ ໃນເຂດອ່າງໂຕ່ງຫ້ວຍປ່ານໍ່, ບ້ານຫຼັກສິບ, ແຂວງຫຼວງພະບາງ ໃນເຂດທີ່ມີໄມ້ສັກ ຄວາມຄ້ອຍຊັນ 35% ແລະ 67.5%. ຄ່າຄວາມໄວການຊຶມນ້ຳໃນດິນ ແມ່ນຢູ່ລະຫວ່າງ 4 ແລະ 22 ມມ/ຊົ່ວໂມງ.

A new tension infiltrometer to measure the soil hydrodynamic properties on steep slopes

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Abstract

In Northern Laos, there is increasing concern over soil erosion, an important factor of which is linked with land cultivation on steep slopes. Effective remediation or land use policies require in depth knowledge of the hydro-pedo-biological processes involved in these erosion mechanisms, which can only be achieved through the use of models. However, all models must be parameterized with correct estimates of their driving variables. Among those variables, at least one is always devoted to quantifying the soil hydrodynamic behaviour, generally the soil hydraulic conductivity, which is unfortunately complex and time-consuming to measure. Tension disc infiltrometers are often used to characterise this soil attribute but their use is limited to quasi-horizontal areas. A new approach is presented in this paper which aims to measure the soil hydrodynamic properties on steep slopes. The principle of tension disc infiltrometers – measured parameters are related to a known slightly negative pressure head value - was modified in order to combine the advantages of large and small discs. With large discs, a well-conditioned hydraulic conductivity is determined whereas a quasi-homogeneous pressure head condition on a slope is applied with small discs. Thus, the new device was used successfully to estimate hydraulic conductivity in a well-defined slightly unsaturated condition. Fourteen tests were carried out in the Houay Pano catchment in Northern Laos on 35% and 67.5% sloping teak tree stands. Steady state infiltration fluxes, closely related to hydraulic conductivity, ranged between 4 and 22 mm/h indicating a soil a soil predisposed to a high risk of runoff. These preliminary results also indicate that more permeable soils are found on the steeper places in the old teak stands but on the lower slopes in the young teak stands where measurements were made.

Key words: *Disc infiltrometer; Slope gradient; Soil hydrodynamic properties; Teak plantations; Lao P.D.R*

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Introduction

Over the last twenty years, tension disc infiltrometers have become increasingly popular tools for measuring soil hydrodynamic properties close to saturation (Thony et al. 1991; Warrick, 1992; Hussen and Warrick, 1993; Logsdon and Jaynes, 1993 ; Cook and Broeren, 1994). Similar to their well-known predecessor, the Muntz device (Angulo-Jaramillo et al., 2000), the principle consists in applying a constant pressure of water over a small surface of soil and measuring the amount of infiltrating water, the soil having initially a much lower water pressure head (h) than that applied at the surface. With Muntz devices, the pressure head boundary condition (h_0) is positive, i.e. a thin layer of water is maintained above the soil inside a ring which is inserted into the soil to prevent water runoff around the test area. The soil is thus completely saturated. After years of use, soil physicists realised that a major drawback of inserting the ring into the soil is that, in the case of a fragile soil surface, soil crust, roots, stones, etc., measurements will be inaccurate due to damage caused to the soil structure and the creation of artificial macropores. A further negative aspect of the technique is that, by saturating the soil, soil cracks become hydraulically active, increasing hydraulic conductivity (K) by several orders of magnitude (Boolting et al., 1991, Schaap and van Genuchten, 2006) compared to soil without cracks, and thus the actual properties of the soil matrix are masked during the experiment.

Tension disc infiltrometers appeared to solve the two problems cited above. They impose a slightly negative pressure head at the soil surface, i.e. the applied water pressure is lower than the surrounding atmospheric pressure. Thus, well-defined soil parameters at the h_0 pressure head boundary value can be calculated, namely the hydraulic conductivity $K(h_0)$ and the capillary sorptivity $S(h_0)$, (Philip, 1957 ; Elrick and Robin, 1981). However, this is valid only when the boundary condition is uniform, which limits the use of disc infiltrometers to approximately horizontal surfaces. When the aim is to characterise the first centimeters under the soil surface, which is frequently the case, it can not be dug out to create a flat horizontal area because this removes the soil layer which is of interest. The purpose of this paper is to present a modified infiltrometer design that aims at maintaining a quasi-uniform pressure head boundary condition on sloping soil and measuring the surface properties without damaging it at all. Some preliminary results obtained in the Houay Pano catchment (Valentin et al., 2008) in November 2007 are reported.

Theory

Tension disc infiltrometers (Perroux and White, 1988) are made of a disc positioned on the soil surface and a water reservoir closed at the upper end. The air is forced into a resistant path, either a Mariotte vase or a hypodermic needle, which maintains a slightly negative pressure head at the base of the disc what prevents water from flowing freely out of the device. Consequently, the unsaturated porous media (i.e. the soil) on which the disc is placed will pull water out of the reservoir by exerting a capillary force due to the pressure head difference. If the soil is initially at equal or superior pressure head than that applied (which corresponds to a very wet state), no flow will occur.

Because only porous media will make water flow out of the disc, no physical boundary of any kind is required and the disc is simply placed onto the soil. An intimate hydraulic contact is needed between the disc and the soil, which is usually impossible if the soil is not flat and/or covered with vegetation. Thus, all aerial vegetation must be cut off, leaving roots in place to keep the soil structure intact. To smooth out the irregular soil surface, a layer of fine sand is placed and flattened to receive the disc. The effects of this sand layer were extensively discussed by Vandervaere et al. (2000a) who showed that particular attention must only be paid to it at the beginning of the assessment because after approximately one minute of infiltration, the sand no longer influences the observed flow.

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beginning of the assessment because after approximately one minute of infiltration, the sand no longer influences the observed flow.

At short time intervals, water flows into the soil mainly driven by capillarity due to the difference between the initial soil moisture content (θ_i) and that of the boundary condition (θ_0). This effect is represented by the capillary sorptivity S [LT-1/2] which depends on both θ_i and θ_0. As time advances and water progresses into the soil, the capillary force decreases, as does the observed flow, until gravity becomes dominant. After a theoretically infinite time, all the surrounding soil will reach the θ_0 moisture value and the vertical component of the flow equals the hydraulic conductivity K (θ_0). However, because of the laterally moving water at the edge of the circular source (Turner and Parlange,1974),the total flow q_∞ still depends on S(θ_i., θ_0). Wooding (1968) and White and Sully (1987) showed that the steady value of the axisymmetric flow can be expressed by the so-called Wooding's equation:

$$q_\infty = K + \frac{2.2 S^2}{\pi r (\theta_0 - \theta_i)} \quad (1)$$

where r is the disc radius. After measuring q_∞ and estimating θ_0 and θ_i by soil sampling, determination of K requires the estimation of S which can be achieved by analysing the infiltration curve at short time intervals (Smettem et al., 1994; Vandervaere et al., 2000a). Note that, in the case of an infinite disc radius, Eq. (1) would simply reduce to its vertical component:

$$q_\infty = K \quad (2)$$

As the sand must not impede the flow, a highly conductive type of sand is chosen with generally a 100-200 µm homogeneous granulometry. The hydraulic head H is defined as:

$$H = h + z \quad (3)$$

where z is vertical elevation, is quasi-uniform within the whole sand layer since the hydraulic conductivity of the soil is always much lower than that of the sand. Thus, in the case of a horizontal soil surface and a thin sand layer, the pressure head h_0 is also uniform within the whole sand layer and the calculated soil parameters will correspond to their well-defined h_0 values, K(h_0) and S(h_0). The applied pressure head h_0 is freely chosen by the experimenter, usually between -200 mm and -10 mm. A value of -10 mm corresponds to a saturated soil matrix with empty large cracks and macropores (>3 mm). This is the most frequently used value because cracks and large macropores, when present, do not follow a Darcian behaviour and requires specific treatment within flow models. At a -200 mm pressure head, only pores smaller than 0.15 mm are filled with water. Finally, by experimenting with several pressure head values on a given soil, an interesting exploration of the soil structure with respect to flow properties can be achieved.

However, because of the non-flat nature of the soil surface, in reality the applied pressure head cannot be absolutely homogeneous over the sampled area. In the case of a microrelief with a 3 cm difference in elevation between high and low points (Figure 1), the pressure head of the soil will vary within a 3 cm range because the hydraulic head H, not the pressure head h, is homogeneous within the contact layer. A 3 cm variation range is the usual pressure head step between measurements made at different pressure values (Ankeny et al., 1991; Reynolds and Elrick, 1991) and it is thus considered an acceptable uncertainty on h_0. For example, if h0 is set at -5 cm, the applied pressure head at the soil surface will vary between -8 and -5 cm with a 3 cm microrelief (Figure 1). In such a case, it is very important to keep the infiltrometer pressure setting always less than -3 cm otherwise the low points would be at a positive pressure head and water would runoff freely at the soil surface. This illustrates the need for careful observation of the experimental area before choosing the infiltrometer pressure setting, to ensure that the entire sampled plot remains unsaturated. In the example above, a pressure head great than -3.5 cm of water should not be set.

The infiltrometer disc size is generally between 5 and 25 cm diameter. Large discs are more difficult to maintain in good contact with soil surface and require large quantities of water on permeable soils. Small discs are more portable but because a smaller area is sampled it may not be representative of the larger area under study unless many replications are performed. Another important limitation of using a small disc is that more water will flow by capillarity at the edge of the disc compared with water flowing vertically and the second term at right-hand side of Eq. (1) may become dominant over the first one to the point that K cannot be properly estimated. A small disc infiltrometer then becomes a “sorptivitymeter”. It is generally considered that a 15 to 20 cm diameter is an appropriate compromise (Smettem and Clothier, 1989; Elrick et al., 1990; White et al., 1992).

On lands with up to 67.5% slope such as those found in the Houay Pano watershed (Valentin et al., 2008), the use of a 15 cm disc infiltrometer is unsuitable because the pressure head difference between the upper end and lower end points of the sampled area would reach 8.5 cm, which exceeds the desired 3 cm range limit corresponding to a reasonable accuracy. Table 1 summarizes the characteristics of the different devices available for use on a 67.5% sloping soil. The new device proposed here combines the advantages of the classic small and large disc infiltrometers.

Technical specifications

A 15 cm diameter test zone is divided into 7 mini compartments to each of which a separate mini disc infiltrometer with a hypodermic needle air entry is applied. Several needle diameters are available to choose from allowing the boundary conditions to be set between -100 and -5 mm. The 7 mini compartments are separated from each other with a tube guide made out of PVC which was specially designed for this purpose (Figure 2). Very soft split rubber tubing is stuck on the lower side of the tube guide to improve the contact with the irregular soil surface. Each mini parcel has a maximum extension of 45 mm in the direction of the slope to keep the pressure head variations less than 3 cm within the corresponding soil area. In the direction perpendicular to the slope, the mini compartments have the maximum possible extension (Figure 2) so that the area covered by the sum of the 7 mini compartments is very close to a full 15 cm diameter disc.

As described above, with classic horizontal disc infiltrometers, the contact between the disc and the soil is ensured with fine sand. On sloping land, it is very difficult to keep a sand layer parallel to the soil surface without moistening the sand. Moreover, because of the irregular soil surface, sand would move from one mini compartment to another because the rubber tubing cannot keep the compartments totally separated from each other. This would create hydraulic contact above the soil surface between the 7 corresponding zones which must be avoided (otherwise, the experimental conditions would resemble those of the classic 15 cm disc simply posed on a slope). For this purpose hydrophilic cotton is used as the contact material instead of sand (Figure 3). Cotton wool has enough rigidity to remain within one mini compartment without invading the neighbouring one. By gently moistening the lower side with a common water spray hose, it is soft enough to mould into the irregular soil surface encountered inside a mini compartment. The very high hydraulic conductivity of cotton wool ensures excellent water transfer from the device to the soil (Figure 4). Finally, note that another important advantage of cotton wool compared with fine sand is that it does not fall into soil cracks, thus preventing them from becoming artificially active under unsaturated conditions.

The seven individual infiltrometers are maintained perpendicular to the surface using a tripod suitable for slopes (Figure 5). The water levels in the seven reservoirs are monitored with pressure sensors installed at their upper ends. The sensors used have a limited range (0.5 psi) so that sufficient accuracy is guaranteed even in the case of a 45° angle between the reservoir and the vertical plane, which would correspond to a 100% slope. To prevent any error due to sensor electronic shift with time and/or temperature variations, at least two manual readings are taken, during all experiments, on each of the seven reservoirs, to calibrate the seven relations between sensors signals (mV) and water levels. Measurements are recorded every second with a CR1000 Campbell datalogger. Once the seven water levels are calculated, the cumulative infiltration curve for the 15 cm diameter area can be establish by adding the seven values, which can then be analysed using the same methods developed for classic infiltrometer data. Figures 6 and 7 show the infiltration area before and after the PVC tube guide was removed and the cotton remaining untouched. It can be seen from Figure 7 that the contact surface covered with cotton is very close to the full 15 cm diameter disc. The area not covered with cotton wool is visually estimated at less than 10% of the total area. Regardless, it is only at the beginning of the test that this has an effect on the infiltration curve. After a few minutes, the seven soil zones become hydraulically connected, each of them, however, remains at its own hydraulic head value because of the resistance to the flow in the soil.

The test duration is not known, a priori, since it will depend on the desired outcome. If the aim is to measure the steady rate of infiltration, the test will continue until an apparent steady flow is reached, which requires a real time survey of the water levels. If only the first one or two centimeters of soil is being sampled, the test can be shorter than 20 minutes and it is likely then that only a transient regime of infiltration will be available for analysis (Vandervaere et al., 2000b).

Results and discussion

Figure 8 gives an example of a water level recording. Two flow patterns, a fast flow at the beginning of the test (water infiltrating the cotton followed by capillary-driven flow into the soil) followed by a slower gravity-driven near constant flow, can be clearly seen. Short-time variations in the signal correspond to bubbles going through the hypodermic needle. Each time a bubble is released in the reservoir, the pressure suddenly increases. To facilitate the analysis of the transient flow regime, the signal was smoothed by only keeping the lower points (Fig. 8). This was done manually at present but should be achieved with a specially designed computing program in the near future.

At present, only the steady regime will be discussed as the sorptivity estimations are still under analysis. Nevertheless, the hydraulic conductivity can be evaluated as 60 to 80% of the steady flow values, based on field observations of the edge front progression at the periphery of the test areas. Tests were conducted on two teak stands, old teak (OT) and young teak (YT) and two slopes, 35% and 67.5%. Results presented in Table 2 and Figure 9 show markedly different characteristics for each stand.

The most permeable area of the four units was the 35% slope YT soil. In the OT stand, the less permeable soils were found on the 35% slopes whereas in the YT stand these were found on the 67.5% slopes. The OT results concur with previous findings by Janeau et al. (2003) in Northern Thailand regarding runoff decrease with slope. However our finding in the YT plantation do not, suggesting a complex relationship between land use and soil properties. It is likely that the young teak trees have not yet had a marked influence on the soil of this area suggesting that the values found in the YT stand may reflect the previous land use, which was as fallow.

In the above analysis, it was assumed that the infiltration bulbs inside the sloping soil are behaving similarly as in horizontal soil. Indeed, in the sloping geometry the lack of soil material downslope is partially compensated by the upslope soil surplus which probably makes the two bulbs quite equivalent, at least in volume. However, this clearly needs further investigating and quantifying in the future through numerical modelling work.

Conclusion and perspectives

After important modifications to the classic tension disc infiltrometer design, a new device was proposed which was used successfully to provide infiltration measurements with unbiased comparisons between sites with very different slopes. Steady infiltration values ranging from 4 to 22 mm/h were obtained on 35% and 67.5% sloping teak stands showing that the relation between slope angle and infiltration capacity is probably complex and strongly depends on soil use history prior to the tests. These preliminary results, however, were obtained with a limited number of observations.

Although still under processing at present, the analysis of the first stages of infiltration should provide sorptivity estimations that can be used to calculate the hydraulic conductivity from steady state flux values by differentiating vertical and lateral flow components. Finally, forthcoming work will aim to improve quantification of the effects of the sloping geometry on the infiltration bulb, to confirm if it can reasonably be treated as an axisymmetric situation and thus be described with the equations developed in this context.

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Table 1 – *Some characteristics of two pre-existing and the new infiltrometer operating on a 67.5% sloping soil.*

	Classic disc 5 cm diameter	Classic disc 15 cm diameter	New disc 15 cm diameter
Suitable for K estimation	no	yes	yes
Suitable for S estimation	yes	yes	yes
Pressure head homogeneity	acceptable (28 mm)	not acceptable (84 mm)	acceptable (28 mm)

Table 2 – *Steady infiltration flow in mm/h on two Houay Pano stands, Old Teak (OT) and Young Teak (YT). Mean (bold), unbiased standard deviation (std dev) and number of measurements (n) in brackets.*

		OT	YT
35% slope:	**mean**:	**4.1**	**14.8**
	std dev:	1.0	6.2
	(n):	(4)	(3)
67.5% slope:	**mean**:	**12.2**	**4.4**
	std dev:	5.3	0.8
	(n):	(4)	(3)

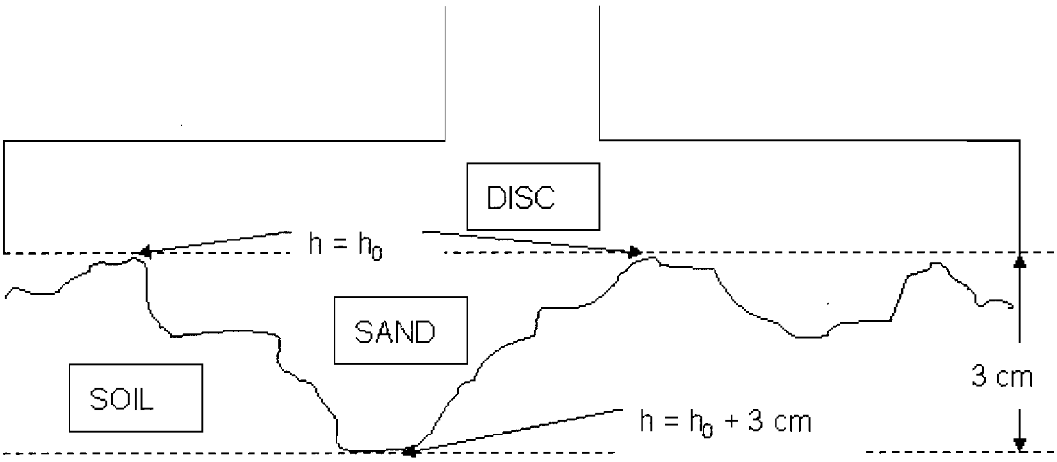

Figure 1 – *Schematic representation of the soil microrelief and its consequences on the applied pressure head.*

Figure 2 – *Tube guide for the 7 infiltrating tubes.*

Figure 3 – *Cotton wool ensuring contact between the infiltrating tubes and soil*

Figure 4 – *The new infiltrometer functioning*

Figure 5 – *The new infiltrometer with tripod on a 67.5% slope.*

Figure 6 – *Wet cotton wool after infiltrometer removal.*

Figure 7 – *Wet cotton wool after infiltrometer use and tube guide removal. Note the well separated infiltration zones.*

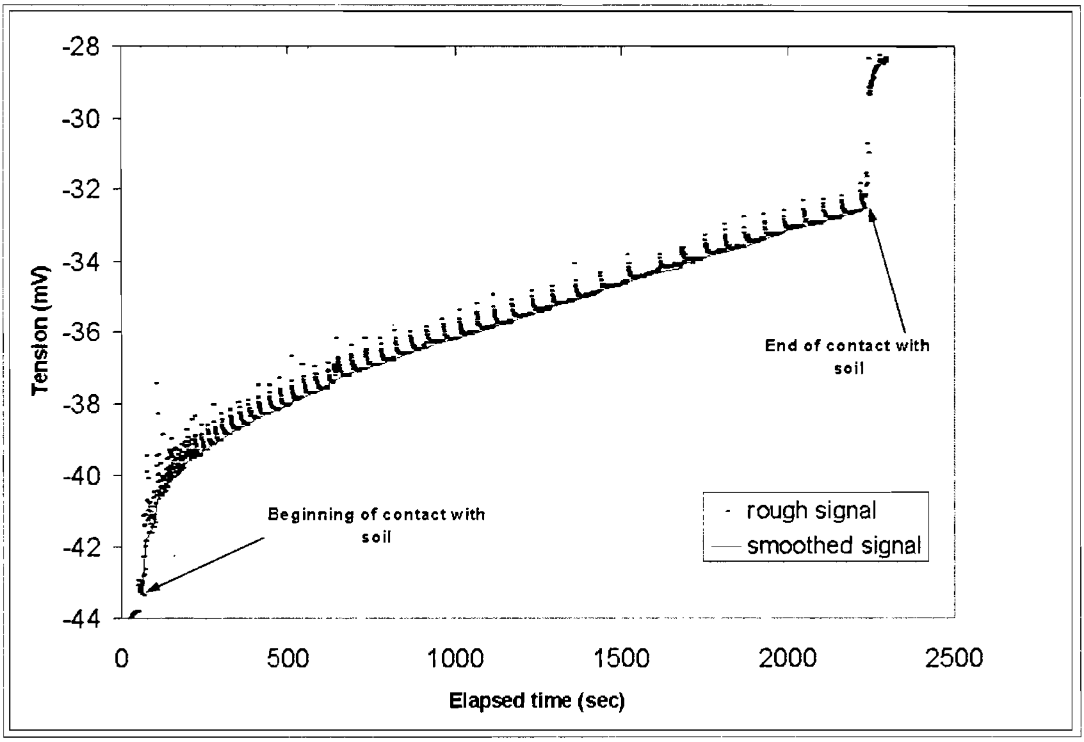

Figure 8 – *An example of water level recording by pressure sensor, rough signal (points) and smoothed signal (plain line).*

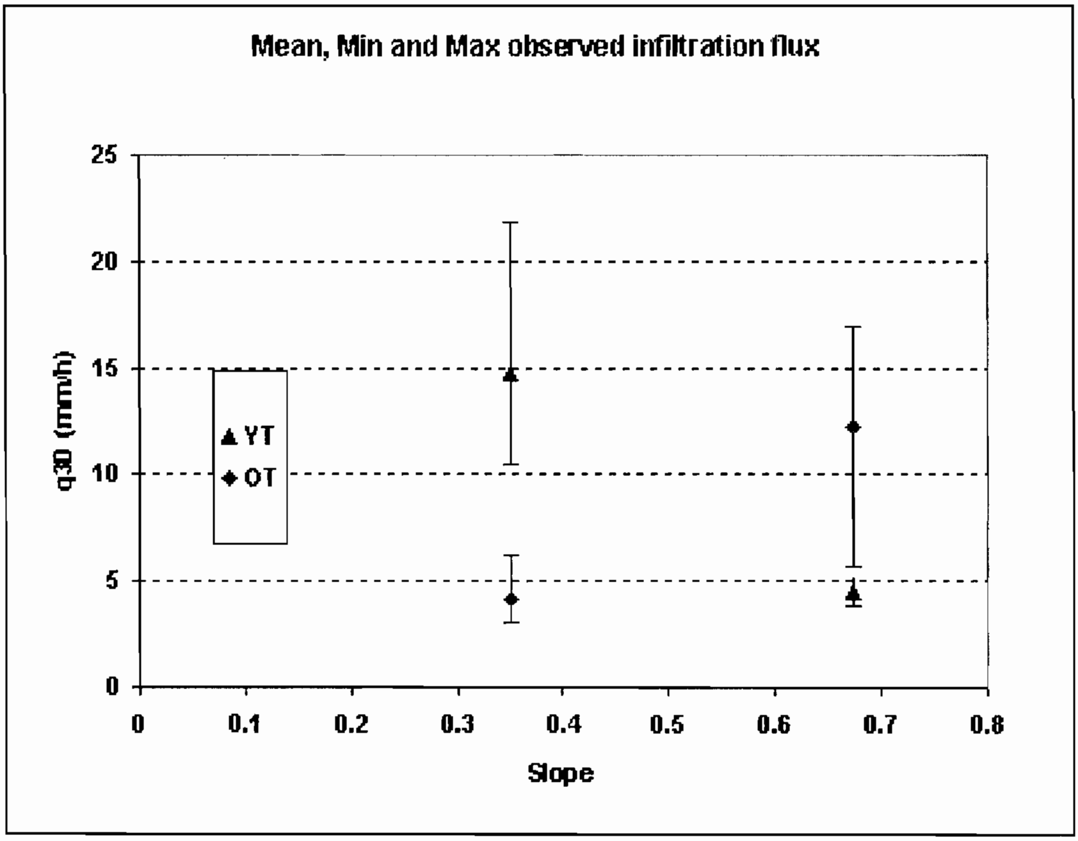

Figure 9 – *Mean, maximum and minimum steady infiltration flux measured within the old teak (red squares) and young teak (blue triangles) stands as a function of the slope.*

ການປະເມີນຄຸນນະພາບນ້ຳ ຕາມສາຂາແມ່ນ້ຳຂອງ ໃນເຂດພູດອຍ ທີ່ມີການນຳໃຊ້ທີ່ດິນແບບປະສົມ

ໂອລິວິເອ ຣິໂບນຊີ, ຢຸລຽດ ກູນີ, ພອນໄຊ ແສງສຸລິຈັນ, ອາແລງ ປີແອເຣ,
ໂອລິດ ແສງຕາເຮືອງຣຸ່ງ

ບົດຄັດຫຍໍ້

ປະຊາຊົນລາວສ່ວນໃຫຍ່ ປະມານ 78% ແມ່ນອາໃສຢູ່ເຂດຊົນນະບົດ, ການເຂົ້າເຖິງນ້ຳສະອາດ ແລະ ສາທາລະນະປະໂຫຍດ ຍັງບໍ່ທັນທົ່ວເຖິງໃນບາງເຂດຫ່າງໄກສອກຫຼີກ ສະນັ້ນ ຄວາມສ່ຽງຈາກບັນຫາຄຸນນະພາບນ້ຳຕໍ່ສຸຂະພາບ ອາດຈະເກີດຂຶ້ນໄດ້. ຈຸດປະສົງຂອງການສຶກສາຄັ້ງນີ້ ແມ່ນເພື່ອປະເມີນຄຸນນະພາບນ້ຳໃນລະດັບເຂດຊຸມຊົນ ໂດຍນຳໃຊ້ຂໍ້ມູນຕົວຊີ້ບົ່ງຈາກສະໜາມ ເຊັ່ນ: ອົກຊີບັນຈຸ, ເຊື້ອບັກເຕຣີ ແລະ ຕະກອນແຂວນລອຍໃນນ້ຳ. ຜົນການສຶກສາເຫັນວ່າ ຄຸນນະພາບນ້ຳແມ່ນຜັນແປ ຂຶ້ນກັບສະຖານທີ່, ການກະຈາຍຂອງປະລິມານນ້ຳຝົນ ແລະ ສະພາບຂອງສາຍນ້ຳ. ການແປປ່ວນຂອງຄຸນນະພາບນ້ຳ ແມ່ນເນື່ອງມາຈາກຄວາມສົມດຸນ ລະຫວ່າງ ຂະບວນການບຳບັດໂດຍທຳມະຊາດ ແລະ ພຶດຕິກຳຂອງຄົນ ເຊັ່ນ: ການຕັ້ງພູມລຳເນົາ, ການຖາກຖາງພື້ນທີ່ແຄມນ້ຳ ແລະ ການປົດປ່ອຍຂອງເສດລົງນ້ຳ. ການກຳເນີດຂອງນ້ຳເສຍ ແລະ ສິ່ງທີ່ເປັນຜົນກະທົບຕໍ່ຄຸນນະພາບນ້ຳມີດັ່ງນີ້: 1) ມີເຊື້ອບັກເຕຣີ ແລະ ມີຄວາມຂຸ່ນສູງ ເນື່ອງມາຈາກການເຮັດຄອກສັດໃສ່ແຄມນ້ຳ; 2) ອົກຊີແຊນບັນຈຸໃນນ້ຳຕ່ຳ ແລະ ການປົນເປື້ອນຂອງເຊື້ອບັກເຕຣີສູງ ຍ້ອນປະລິມານນ້ຳໄຫຼໜ້ອຍ ແລະສຸຂະອະນາໄມບໍ່ພຽງພໍ; 3) ເຊື້ອບັກເຕຣີສູງ ເນື່ອງມາຈາກການຂະຫຍາຍພູມລຳເນົາຕາມແຄມນ້ຳ; 4) ອົກຊີບັນຈຸໃນນ້ຳຕ່ຳ ເນື່ອງຈາກອິນຊີວັດຖຸຈາກສິ່ງເສດເຫຼືອຂອງໂຮງງານ; 5) ຕະກອນດິນ ແລະບັກເຕຣີສູງ ຍ້ອນການເຊາະເຈື່ອນຂອງດິນໃນເຂດສູງຊັນ. ນອກຈາກມົນລະພິດຈາກມະນຸດແລ້ວ ກໍ່ຍັງມີມົນລະພິດທາງທຳມະຊາດ ເຊັ່ນ: ການເກີດສະໜິມໂລຫະຈາກນ້ຳໃຕ້ດິນ. ພວກເຮົາໄດ້ສະເໜີຄຳແນະນຳດັ່ງກ່າວ ເພື່ອປັບປຸງ ແລະ ຮັກສາຄຸນນະພາບນ້ຳ ໃຫ້ຄົງຕົວກັບສິ່ງແວດລ້ອມ ຕະຫຼອດໄປ.

Assessment of water quality along a tributary of the Mekong River in a mountainous, mixed land-use environment of the Lao P.D.R.

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Abstract

In the Lao PDR 78% of the population are classified as rural and efforts to improve access to potable water and sanitation infrastructures are reaching limited areas, these inhabitants may be particularly affected by water quality-related hazards. The objective of this study was to complete a preliminary assessment of stream water quality, at the community-level, using a set of field indicators (i.e. oxygen content, total bacteriological flora and suspended load). Our findings concluded that the water quality is extremely variable depending on the location along the stream and the prevailing rainfall and water flow conditions. Changes in water quality were affected by an uncertain balance between potential self-cleaning processes in the stream environment and human pressure in the riparian zone (i.e. urbanization, riparian vegetation removal, wastewater discharges, stream flow extractions). Several interesting observations were noted that influence water quality: **(i)** high bacteria and turbidity levels were related to free ranging livestock roaming near the stream in isolated areas; **(ii)** very low oxygen content and high bacteriological contamination downstream of small remote villages due to low stream discharge and poor sanitation conditions; **(iii)** high bacteria levels along continuously urbanized reaches; **(iv)** low oxygen content following organic-rich wastewater inflows from a small agro-factory; **(v)** very high suspended load and bacteria levels during flood events due to soil erosion of steep cultivated hillslopes. Besides pollution related to these human activities we also noted "naturally" metal-rich stream water when crossing swampy areas fed by dysoxic groundwater. We propose a set of pro-poor recommendations to improve or maintain good stream water quality in the uplands and for environmentally friendly management of surface water resources.

Key words: *Water quality-related hazards; riparian zone; land uses; wastewater discharges; Mekong river; Lao P.D.R*

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Introduction

Freshwater quality is an issue of concern for human health and the sustainability of environments globally. The risks arise from infectious agents, toxic chemicals and radiological hazards. According to the World Health Organization, the most affected populations live in rural areas of developing regions (WHO-UNICEF, 2006). In 2004, more than three out of every five rural inhabitants, that is over 2 billion people, did not have access to a basic sanitation facility.

In the Lao PDR, 78% of the population lives in a rural setting, and attempts to improve drinking water and sanitation infrastructures are impacting very limited areas, suggesting that communities in these areas may be predisposed to water quality-related hazards. Ten years ago, the United Nations (UN, 1998) reported that human activities have little effect on river water quality in the Lao PDR: "As the country has a low population density, the small amount of wastewater discharged from the towns and industries usually flows through the natural canal systems undergoing self-purification over a long distance before entering the rivers". The UN experts based their conclusions on the country's low population density and a limited number of measurements made (34 for the entire country) in large rivers. Is this diagnostic still valid today in view of the current, still low, population density (24 people per km2; NSC, 2005)? Does an overall assessment based on main rivers which drain large areas reflect community level reality? Besides the major tributaries of the Mekong River, there are hundreds of small order perennial rivers and streams (i.e. "the natural canal systems" cited above). What about the rural people living in villages along these water paths? Rural communities in Laos are often reliant on stream water resources because access is easy and exploitation is less expensive compare to groundwater resources. However, studies have shown that stream water resources encounter problems related to increased turbidity during periods of storm flow (Maniphousay and Souvanthong, 2004), and water and excreta-related diseases are among the most frequently occurring diseases in Laos (Lamaningao and Sugiura, 2004).

The overall goal of this study was to undertake a preliminary assessment of stream water quality at the community level, in a typical mixed land-use area of northern Lao PDR (in the vicinity of

Luang Phrabang city). Measurements were made along a perennial third order stream passing through villages close to the Mekong corridor but having no direct access to the main river. This study does not intend to identify and analyze all factors and processes contributing to surface water quality in the uplands of the Lao PDR. Our objective was to identify the main causes contributing to the spatial variability of water quality indicators (i.e. oxygen content, total bacteriological flora, suspended load) in a watershed that includes some karstic features. Among the underlying factors studied, we paid specific attention to **(i)** land use along the riparian area; **(ii)** wastewater discharges and **(iii)** suspended sediment yield during floods.

Materials and methods

Description of the Houay Xon catchment

The study was conducted along the Houay Xon stream (UTM zone 48, WGS84 coordinates: 197860-204760 E, 2192570-2199820 N), part of the Mekong basin of northern Laos (Luang Prabang Province). This stream drains a catchment of about 22.4 km^2 and flows into the Nam Dong River before its confluence with the Mekong (Figure 1). Table 1 shows the main morpho-hydrological characteristics of the catchment. The source of the Houay Xon is in the upper Houay Pano (Valentin et al., this issue). The stream is 10.6 km long, perennial and has irregular topography since it flows within a mountainous environment which is representative of the sloping lands of the Mekong valley (Figure 2). In the catchment, the altitude ranges from 280 to 1336 m, with a mean slope gradient of approximately 31%. The highest altitudes are found in the south, within the Phu Phung mountain range (Figure 1). The geological substrate is composed of Permian to Upper Carboniferous argillite series (shales, mudstones, and fine-grained sandstones) overlaid by karstified limestone cliffs. The karstic cliffs were observed at the extreme north-east of the catchment (i.e. boundary of the Houay Pano headwater catchment) and in the south (i.e. upper Phu Phung). The landscape and relief features are strongly influenced by a complex network of fault lines which controls the direction of the main stream path. The Houay Xon hydrographic system is highly dissymmetric; most of its tributaries are located on the left bank (southern area) and drain more than 80% of the total catchment area. This area includes the karstic system of the upper Phu Phung massif with its underlying geological formations, and constitutes the main groundwater reservoir of the catchment. Part of this water resource is exploited by a drinking water factory (Nam Papa State Company).

The catchment is a typical mixed-use area of northern Lao PDR. The Houay Xon flows through five villages, successively: Lak Sip, Donkang, Kouathineug, Ma and Phoumok. The overall land use units (Figure 1) are roughly influenced by the morpho-hydrological sets: (1) the south-eastern Phu Phung massif (i.e. highest unit with the steepest slopes) is mainly covered by an old protected forest; (2) the upland areas of the north-eastern dog-ear and the south-western part are under shifting cultivation with short fallow; (3) residential areas surrounded by teak plantations are found along the main stream (Figure 2); and (4) irrigated gardens in the peri-urban area of Luang Prabang City are located downstream in a lowland unit (i.e. gently sloping alluvial terrace of the Mekong).

The mean annual rainfall recorded at Luang Prabang from 1960 to 2006 was 1263 mm, about 77% of which falls during the monsoon season from mid-May to mid-October, with high inter-year variability (SD 345 mm, coefficient of variation 27%) leading to a minimum of 444 mm and a maximum of 2100 mm. In 2007, the year of this study, the cumulative rainfall was 1139 mm.

Hydro-chemical measurements in the field

Temperature (T), pH, electrical conductivity at 25°C (EC), redox potential (Eh), and dissolved oxygen content (DO) were measured using a YSI MPS (Multi Probe System/Data Logger) meter. All of the meter's sensors were checked daily before each sampling survey: the pH probe was calibrated using standard pH 4.00 and 7.00 buffer solutions; the Eh probe was verified in a 220mV (at 25°C) electrolytic solution; and the cell constant of the EC probe was set with 1413 μS/cm standard buffer. The DO sensor was calibrated following the air calibration method. Because of the inherent covariance of water temperature and DO, all DO data were transformed to oxygen saturation (DO-sat) in %, using the formula of Hua (1990) and correcting for atmospheric pressure. Two field surveys were conducted in 2007:

- First, in order to analyse the effects of land use on water quality at baseflow (Figure 3a-3e), 109 observations points were surveyed along the Houay Xon (83 stations distributed at 100-m intervals) and its main tributaries (26 stations), at the end of the dry season (31 May 2007) until the confluence with the Nam Dong River.

- Secondly, to examine the impact of floods (Figure 3f) regardless of domestic wastewater inputs, 11 stations were established in close proximity (about 20-meter distance between each) and located within the Houay Pano catchment (upstream Houay Xon), were sampled on two dates (Table 2): (1) during a period of low flow just before the rainy season (28 May 2007) and (2) during the first storm flow of the rainy season (4 Jun 2007).

Water sample collection and laboratory analysis

Seventy water samples were collected to determine the suspended solid load (SL) and total colony count at 37°C (CC37). Samples were collected on the same day or the day following each of the physico-chemical surveys described above. The positions of the sampling stations were chosen based on the reach characteristics (i.e. riparian land uses, hydro-morphology and physico-chemistry). The samples were collected by submerging the sample bottles upstream; taking care to avoid collecting disturbed bed sediments with the sample (i.e. neck of the bottle pointing upstream). SL, expressed in mg l^{-1}, was estimated as the weight of material retained on a pre-weighed 0.45 µm membrane after filtering a known volume of sample (about 1 litre). In general, sampling was carried out at approximately the same period of the day, i.e. mid morning to early afternoon. Water samples for total flora determinations were stored in the dark, placed on ice in a cool box and delivered to the Nam Papa Lao laboratory in Vientiane within 12 hrs. CC37 was estimated following the standard pour plate method. The results are expressed as colony forming units (CFU) per ml.

Morpho-hydrological determina-tions

The sampling point locations were approximated using a portable GPS (GARMIN XL12) and an altimeter (SUUNTO Instrument). For the detailed surveys along the Houay Pano stream, a combination of a compass (SUUNTO Instrument), a clinometer (SUUNTO Instrument) and a decametre was used to survey elevation changes and distance between sampling points. We systematically duplicated these measurements (vertical and horizontal angles) by taking a forward and a backward sight at each waypoint. Stream discharge measurements at the different sampling points were estimated by chemical tracing following the method recommended by Silvera et al. (2007).

Results and discussion

Most conventional hydrological studies are based on flow monitoring and measurement of water quality parameters at the outlet of a catchment. In a mixed land-use areas, it is difficult, if not impossible, to relate this type of time-series observations to the spatial features of the catchment. In order to overcome this obstacle, we surveyed spatial-series observations along the main channels so that the various spatial features could be directly related to the stream water quality changes. In the Houay Xon catchment, the footprint of human activity increases going downstream (Figure 1). Results are presented by first describing the situation upstream and then our findings as we follow the main water course downstream (Figure 2).

Potential hazards due to naturally contaminated groundwater

In the upper part of the catchment (Houay Pano stream, land under shifting cultivation), we observed orange-coloured iron oxide flocculation at several points within the stream channel. Figure 3a shows these metal-rich colloidal features at station 2, where we measured reducing conditions: low DO-sat (12 %, see triangular label 1 in figure 4) and the lowest pH (6.9) and Eh (88 mV). The Eh-pH pair measured at this station (Figure 4) was within the range for soluble ferrous iron hydroxides ($FeOH^{+}$), near the theoretical equilibrium between soluble $FeOH^{+}$ and ferrous iron (Fe^{2+}). At this point in the catchment, these physico-chemical conditions could not be attributed to local waste water inputs or any human activities. Instead, these corresponded to local ex-filtration of subsurface water with a low pH, Eh and DO-sat (Ribolzi et al., 2005). Soluble iron compounds are common in soil solutions with high levels of organic matter (1-6% in the soil of Houay Pano). When dissolved organic matter enters groundwater, the water may become anaerobic and iron becomes soluble. During the ex-filtration process, groundwater containing Fe^{2+} becomes aerated. Since the oxidation of Fe^{2+} at near neutral pH is very rapid, the ionic form may precipitate as amorphous oxides (e.g. Stumm and Morgan, 1981) which then contribute to lowering the pH in the vicinity of groundwater inflow sites. Oxidizing bacteria may accelerate this flocculation process.

The presence of dissolve iron or colloidal features in streamwater should not be considered dangerous in itself, but rather as a useful indicator of local physico-chemical conditions that can potentially favour the mobility of toxic metals such as the so-called atmophile elements (e.g. Cu, Cd, Zn, As). Farmers often take advantage of these groundwater inflows for various purposes: fish ponds; drinking water collection; small irrigation, watercress beds (Figure 2a). However, such practices may entail health risks as streambed sediments, stream water and aquatic vegetation in the vicinity of subsurface inflows can accumulate metals (Huon et al., this issue). In order to limit the risk, seepage waters from soil containing high levels of organic matter should be used only after aeration and the deposition/sequestration of metal ions (e.g. into the streambed sediment during stream transport).

Impact of land use and human activity along the riparian area

Livestock roaming

In the upper land of the catchment under shifting cultivation, livestock was observed roaming close to and in the stream causing sediment particles to be mobilised (Figures 2b) with SL values which can increase up to 2 $g.l^{-1}$ (Figure 4, triangular label 2). This turbidity increase was associated with a local increase in microbiological pollution (CC37>2000 CFU ml^{-1}). This is consistent with the findings by Randall et al. (2006), who observed a strong correlation between faecal bacteria (Escherichia coli) load rate and turbidity at near base flow in a mixed-use watershed. George et al. (2004) studied stream faecal coliform inputs through soil leaching in a temperate climate. They observed that rural streams, located upstream from any waste water outfall, flowing through areas partly or fully covered with pastures were more contaminated than those flowing through forest and cultivated areas. In our case, the main source of bacteria was from the soil surface and very local, most probably due to a dung piles rolling into the stream from a livestock shelter situated on the stream bank.

It is interesting to note that, due to the filtering effect of aquatic plants in the streambed, only a short distance of downstream flow (~100 m) was necessary to recover acceptable levels of suspended solid content and eliminate most of the sessile (attached) bacteria (Galvez, 2007).

Domestic wastewater and household refuse

The physico-chemical characteristics of the stream water changed dramatically when it passed through the first upland village (i.e. Lak Sip): DO-sat decreased from 88 to 5%, CC37 doubled, EC increased from 298 to more than 400 $\mu S.cm^{-1}$ (Figure 4, triangular label 3), temperature increased from 26.0 to 30.2 °C, pH decreased from 8.2 to 7.2 and Eh decreased from 220 to less than 120 mV. These changes were clearly related to (i) domestic wastewater discharge, (ii) human and animal excrement and (iii) household refuse accumulation in the stream bed (Figure 2c). These factors which were associated with low stream discharge conditions, (Figure 4) led to organic matter enrichment of the stream and a decrease in the stream velocity, which in turn contributed to the anoxic conditions (Figure 4) and a noticeable smell in the vicinity of the stream path.

Between Lak Sip and the following village (DonKang), the Houay Xon flows through the lower Phu Phung protected zone (Figure 1), and is therefore not contaminated by any waste water. Figure 4 shows that after a distance of about 1 km downstream, natural filtration and other processes led to the recovery of stream quality back to the initial characteristics. Than, in and up to 900 m downstream from DonKang, DO-sat remained high (i.e. between approximately 80 and 110%) in spite of the numerous waste water discharge points and domestic activities (Figure 3d). This rather steady oxygenation rate is due to the stream being fed by oxygenated tributaries (dilution effect) and, above all, a turbulent flow regime favourable to maintaining aerobic conditions. After 900m, the DO-sat suddenly decreased down to 32% because of organic-rich waste water discharge from an alcohol distillery (Figure 4, triangular label 5). Once again, it took approximately 1 km for the initial level of DO-sat to return to its original state. Contrary to DO-sat, CC37 increased considerably from Donkang village onwards (Figure 4, triangular label 4), and remained high until the confluence with the Nam Dong. Tributary inflows did not lower the CC37.

Flood Impacts

The stormflow measurements described below were conducted within the Houay Pano catchment during the first main runoff event of the 2007 rainy season. This event occurred a short time after the farmers of the Lak Sip village had slashed and burned approximately

42% of the catchment area for annual cropping. Almost all the riparian zone and large hillslope areas were therefore bare; the soil surface and stream banks were unprotected, hence exposed to erosion. This flood was the result of a sudden intense downpour of 54 mm (maximal rainfall intensity of 110 mm h^{-1} calculated over 6 min time steps) that produced considerable amounts of suspended sediments at the main outlet of the Houay Pano catchment (1.7 Mg ha^{-1}, i.e. ~23 % of the annual suspended yield).

Table 2 presents a comparison between base flow and storm flow observations (i.e. 11 observation points at two dates). No significant differences between base flow and storm flow were found for DO-sat (P value > 0.025). Contrasting this, T, EC and pH values were lower during storm flow while Eh was significantly higher. Dilution of stream flow by rainwater (lower T, EC and pH; higher Eh) explains the differences observed. Unsurprisingly, SL was much higher during the storm flow. These higher values result from various soil erosion processes affecting inter-rill areas (Chaplot et al., 2007), rills and gullies (Chaplot et al., 2005) and the washing-out of free aggregates and part of the fragmented organic matter accumulated at the soil surface throughout the dry season. All the samples collected during the flood and one collected at base flow had SL >1 g/l. Such high values may greatly affect water usages and aquatic life, from phytoplankton to fish, by limiting light penetration. SL, especially when particles are small (less than 63μm), carry many substances that are harmful or toxic. In rivers, these fine particles are a food source for filter feeders which are part of the food chain, leading to biomagnification of chemical pollutants in fish and, ultimately, in man. It can also limit reservoir life through sedimentation of suspended matter.

Microbiological studies of watercourses are usually not carried out during rainfall-runoff events. Even though, during and after such events, there are often significant increases in turbidity and suspended solid loads, which are frequently interpreted as an indication of bacteriological contamination. Table 2 also shows that CC37 were considerably higher during the storm flow sampling survey. These observations are consistent with those of George et al. (2004) who reported that fecal coliform bacteria were linked to particles in small streams and that the fraction increased with suspended sediment content.

Conclusion, research perspectives and recommendations

The observations presented above were conducted along a perennial third order stream passing villages close to the Mekong corridor but having no direct access to this main river. The objective was to undertake a preliminary assessment of stream water quality at the community-level and based on in situ measurements of several operational parameters (i.e. oxygen content, pH, electrical conductivity, suspended sediment load, total bacteriological flora).

This study confirmed that, due to poor sanitation conditions, a high degree of bacteriological contamination occurs in stream water passing villages and peri-urban areas. The most common source of pollution was from urban household wastewater, which may potentially contain pathogens (but also nutrients). Pollution of water sources from industrial effluent was not as common.

The downstream section of the catchment mostly includes irrigated peri-urban gardens (via natural streams or small diversion channels) which supply Luang Prabang city with vegetables. These market gardens rely largely on surface waters that could be increasingly polluted by the rapidly growing population. Thus the question of water quality and the potential associated health risks are an important area of study.

The expansion of Luang Prabang city and its population growth pose a major challenge for city planners. In the near future, it will lead to an increased demand for sanitation infrastructures and freshwater resources, notably for irrigated peri-urban market gardens. The current expansion is characterised by a dynamic from the ancient peninsula city, following the stream water paths and spreading progressively up hill slopes. The following recommendations are suggested in order to reduce or mitigate potential negative impacts on water quality:

• Riparian zones along streams and rivers should be managed in an environmentally friendly and sustainable manner. A strip of natural vegetation on the bank should be preserved and protected in order to maintain the sediment-filtering function of this zone. Encroachment of stream banks by residences, non strengthened fish ponds or informal hydraulic infrastructures should be strictly limited and controlled in order to prevent material or even human losses generated by landslides or flood hazards.

• Environmental discharge thresholds should be estimated and then base on these estimates, water which is extracted from the river system for manufacture activities and irrigation should be regulated following a seasonal schedule taking into account rainfall variability and upstream land use. Over-extraction of stream water will place freshwater resources under stress.

• Authorities should organise and encourage the development of community level decentralised sanitation systems. If not, direct domestic wastewater discharges will rise and stream water passing villages and Luang Prabang will turn into sewage. Local inhabitants and tourists would not only be inconvenienced by bad smells but also health concerns if the polluted water is still used to irrigate food crops.

Extending basic drinking water and sanitation services to peri-urban areas and neighbouring villages in order to reach the poorest people is of the utmost importance to prevent outbreaks of cholera and other water-related diseases. To support the above mentioned recommendations, we suggest that an agreement between the Luang Prabang city and the surrounding villages be implemented. This agreement may follow the Payment for Environmental Services (PES) concept: rural dwellers could loosen the pressure on riparian areas in return for which the urban citizens could finance sanitation infrastructures upstream via, for example, the taxation of profits made on certain tourist activities in Luang Prabang.

Finally, our study raises the issue of the spatial scale relevance of field observations regarding the question that needs to be answered, i.e. do upland people of northern Lao PDR have access to good quality surface water? Strategies that consist in monitoring large rivers generally provide a smooth integrated fingerprint of entire watersheds (e.g. UN, 1998). This is unquestionably useful for global water resource management at the regional scale. However this approach may mask system internal variability and hence part of the local community level reality. Conclusions from such large scale studies should be considered with the greatest care.

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Table 1 – *Selected hydro-morphological characteristics of the Houay Xon catchment: surface (A) and planar (Ap) areas; perimeter (P); minimum (Zmin), maximum (Zmax) and mean altitude (Zmean); length of the main stream (L); Gravelus index of compactness (Gc) which is the ratio of the perimeter to the perimeter of a circle which have the same surface area; drainage density (Dc); mean slope gradient (S).*

A	Ap	P	Zmin	Zmax	Zmean	L	Gc	Dc	S
km^2				m			km^{-1}	$km.km^{-2}$	%
22.4	20.7	26529	280	1336	592	10605	1.6	1.4	31

Table 2 – *Descriptive statistics of some hydrological characteristics of the Houay Pano stream during baseflow and stormflow periods for 11 selected observation points: median; arithmetic mean; standard deviation (sd); minimum (min) and maximum (max) values of stream discharge; temperature (T); electrical conductivity at 25°C (EC); pH ; redox potential (Eh), dissolved oxygen content transformed to oxygen saturation (DO-sat); suspended load (SL); total colony count at 37°C (CC37).*

Flow regime		**Discharge**	**T**	**EC**	**pH**	**Eh**	**DO-sat**	**SL**	**CC37**
(date)		l/s	°C	$\mu S.cm^{-1}$		mV	%	$g.l^{-1}$	$CFU.ml^{-1}$
BASE	median	0.4	25.6	388	8.3	163	70.6	0.23	808
(28 May 2007)	mean	0.4	25.7	374	7.8	158	67.1	0.38	1152
	sd	0.1	0.8	31	–	25	21.3	0.50	861
	min	0.3	24.4	309	6.9	88	12.0	0.06	186
	max	0.6	26.9	417	8.5	181	91.8	1.85	2760
STORM	median	5.0	23.9	195	7.6	227	81.2	8.66	19000
(4 Jun 2007)	mean	4.4	23.9	196	7.6	226	73.1	8.80	42469
	sd	1.4	0.2	16	–	8	23.8	3.98	55984
	min	2.4	23.7	170	7.5	216	23.9	2.42	3840
	max	5.3	24.5	232	7.9	238	93.4	18.72	183000

Differences between base flow and storm flow (threshold of significance: $\alpha/2 = 0.025$) are significant for all the parameters (Wilcoxon test, paired samples) except DO-sat. Mean pH is calculated from H^+ concentrations. $CFU.ml^{-1}$, colony-forming units per ml.

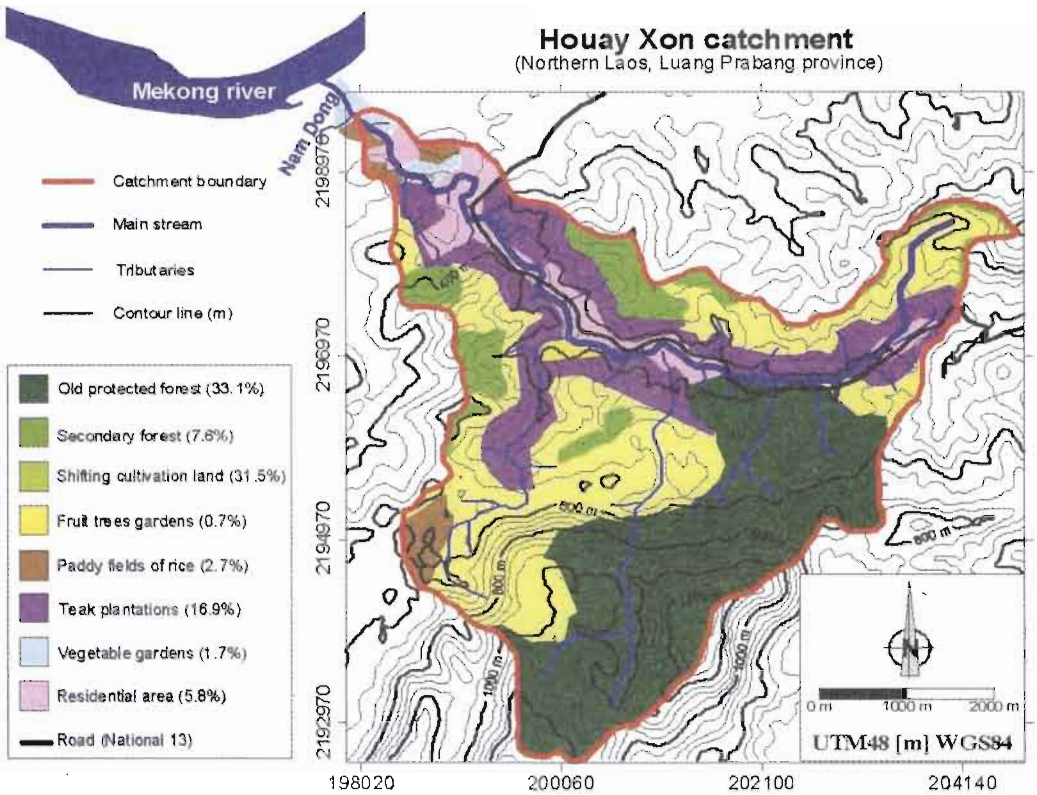

Figure 1 – *Main land uses (percentage of the total catchment area), contour lines and permanent stream paths within the Houay Xon catchment in 2007.*

Figure 2 – *(**a**) Orange-coloured iron oxides flocculation and biofilms in a watercress bed of the upstream Houay Pano catchment; (**b**) Turbid stream water due to livestock straying; (**c**) The Houay Pano stream invaded by household refuse in the Ban Lak Sip village; (**d**) A young lady doing the dishes in the Houay Xon river; (**e**) Corridor of residential blocks recently built on the stream bank of the Houay Xon river; (**f**) Houay Pano during a small flood.*

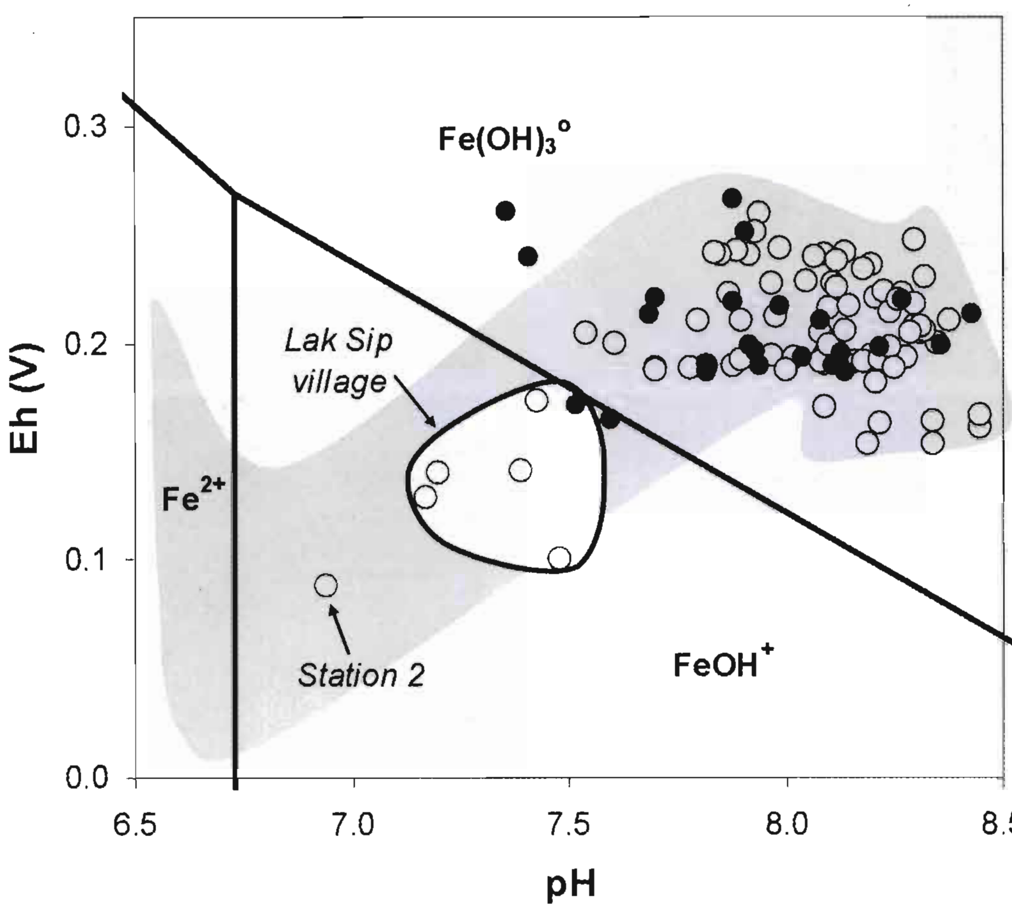

Figure 3 – *Eh-pH diagram of dissolved iron species at 25°C; Stream water of the Houay Xon (o) and its tributaries (•). Continuous black lines indicate the theoretical boundaries of predominance domains between species. the Grey area shows the overall trajectory of pH-Eh conditions from soil water within organic-rich horizons (i.e. lowest pH and Eh values) to downstream water including bicarbonated water originated from calcareous zones (i.e. higher pH values).*

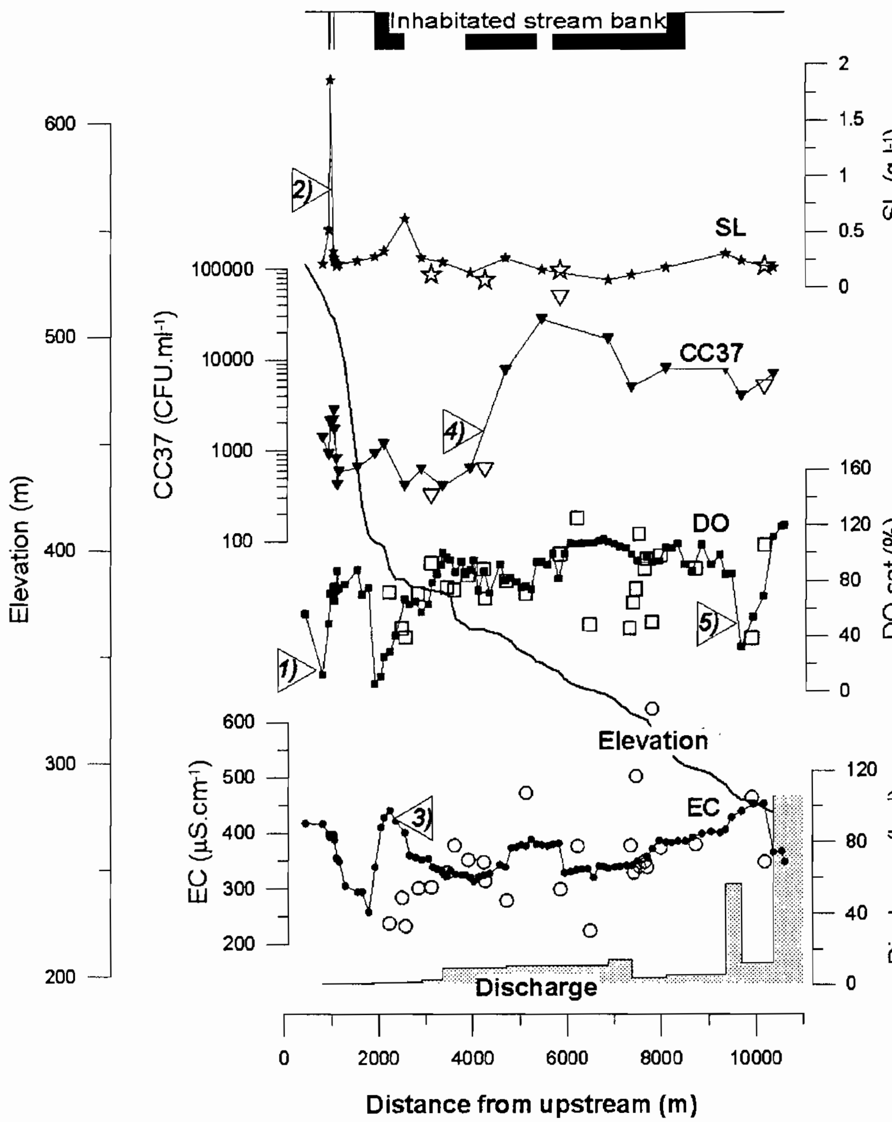

Figure 4 – *Morpho-hydrological characteristics of the Houay Xong river (solid black symbols) and its tributaries (hollow symbols) at the end of the 2007 dry season (i.e. low flow regime): elevation; main river discharge; electrical conductivity at 25°C (EC); dissolved oxygen content transformed to oxygen saturation (DO-sat); total colony count at 37°C (CC37); suspended sediment load (SL); location of the inhabited areas along the stream bank.*
Triangular labels indicate striking positions along the stream: ***1)*** *Reach with subsurface seepage;* ***2)*** *Livestock straying within the riparian zone;* ***3)*** *Domestic wastewater discharge;* ***4)*** *Urbanized area along stream banks;* ***5)*** *Agro-industrial discharge.*

ລະດັບຄວາມເຂັ້ມຂຸ້ນຂອງທາດເຫຼັກ ແລະ ມັງກາແນເຊີ ທີ່ບັນຈຸໃນຜັກນ້ຳ ປູກຢູ່ອ່າງໂຕ່ງ ຫ້ວຍປ່ານໍ່ ແຂວງຫຼວງພະບາງ

ຊົງແວງ ຣວນ, ໂອລິວິເອ ຣິໂບຊີ, ເອມານູເອນ ບວກດົງ, ບຸນສະໄໝ ສຸລິເລີດ,
ມິລານີ ລອງຈຳ, ນີໂກລັດ, ໂອລິດ ແສງຕາເຮືອງຣຸ່ງ

ບົດຄັດຫຍໍ້

ການປາກົດຕົວຂອງໂລຫະໜັກຢູ່ໃນຜັກບາງຊະນິດ ເຊັ່ນ: ຜັກນ້ຳ ອາດສົ່ງຜົນສະທ້ອນທາງລົບຕໍ່ສຸຂະພາບ. ຜັກນ້ຳ ຊຶ່ງມັກເກີດຢູ່ຫ້ວຍນ້ຳໄຫຼ ແລະ ມັກພູມອາກາດຊຸ່ມຊື່ນ ໃນເຂດພູດອຍ. ບົດນີ້ໄດ້ສຶກສາການສະສົມຂອງທາດເຫຼັກ ແລະ ມັງກາແນເຊີໃນຜັກນ້ຳ ທີ່ປູກຢູ່ບໍລິເວນສາຍຫ້ວຍທີ່ມີສະພາບພື້ນທີ່ແຕກຕ່າງກັນ. 2 ຈຸດທົດລອງປູກຜັກນ້ຳ ເຂດທີ່ມີນ້ຳໄຫຼຍອດຫ້ວຍ (ມີອົກຊີຫຼາຍ) ແລະເຂດເບືອມນ້ຳ (ມີອົກຊີໜ້ອຍ) ໄດ້ສົມທຽບເພື່ອສຶກສາຄວາມເຂັ້ມຂຸ້ນຂອງທາດເຫຼັກ ແລະ ມັງກາແນເຊີທີ່ສາມາດລະລາຍ ແລະ ແລກປ່ຽນໄດ້. ຜົນການສຶກສາຊີ້ໃຫ້ເຫັນວ່າ ປັດໄຈສິ່ງແວດລ້ອມ ເປັນຕົວກຳນົດລະດັບຂອງໂລຫະໜັກໃນຜັກ. ຖ້າດິນບັນຈຸທາດໂລຫະໃນປະລິມານຫຼາຍ ຜັກນ້ຳກໍ່ຈະດູດຊຶບເອົາທາດເຫຼັກ ແລະ ມັງກາແນເຊີ ຫຼາຍເຊັ່ນດຽວກັນ. ລະດັບຄວາມເຂັ້ມຂຸ້ນຂອງທາດມັງກາແນເຊີ ບັນຈຸໃນຜັກນ້ຳຈະເພີ້ມຂຶ້ນ 7.5 ເທົ່າ ແລະ ທາດເຫຼັກ 2.2 ເທົ່າ ໃນເຂດເບືອມນ້ຳ (ມີອົກຊີໜ້ອຍ) ເມື່ອສົມທຽບກັບເຂດທີ່ມີນ້ຳໄຫຼຍອດຫ້ວຍ (ມີອົກຊີຫຼາຍ). ສະຫຼຸບວ່າ ຄວາມເຂັ້ມຂຸ້ນຂອງທາດເຫຼັກ ແລະ ມັງກາແນເຊີໃນດິນ ແມ່ນກົງກັນກັບຄວາມເຂັ້ມຂຸ້ນຂອງທາດເຫຼັກ ແລະ ມັງກາແນເຊີ ທີ່ບັນຈຸໃນຜັກ.

Iron and manganese concentration levels in watercress cultivated within the main stream of the Houay Pano catchment, Northern Lao PDR

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Abstract

The bio-availability of metals to currently eaten aquatic herbs such as watercress is of important interest because of its potential impact on human health. Watercress grows in clear running water and is suited to the moist climates of mountainous tropical regions. In this study, the concentrations of Fe and Mn in watercress, stream bottom sediments and ambient stream water were measured in order to evaluate the impact of local environmental conditions on plant Fe- and Mn- accumulation levels. Two sites in the Houay Pano catchment in northern Laos (Luang Prabang province) where watercress is cultivated directly in the stream waters were selected for their contrasting environmental conditions (oxic vs. dysoxic to suboxic oxygen levels). Total, dissolved, exchangeable and potentially exchangeable Fe- and Mn- concentrations were measured. The results indicate that local environmental factors are determinant factors in the availability of these ionic species. Both the total metal content in the sediments and the metal ion speciation status (availability of dissolved species) determine the level of Fe and Mn uptake by watercress. The concentration levels in watercress increased by a factor of 7.5 for Mn and 2.2 for Fe in the dysoxic to suboxic site (swampy area) compared to the oxic site (upstream running water). The exchangeable and potentially exchangeable Fe- and Mn- concentrations in bottom sediments and the dissolved Fe- and Mn- contents of ambient water at both sites were consistent with the accumulation levels measured in the watercress.

The bioaccumulation of these metals should not pose a direct threat in itself, because these elements are not actually very toxic, but rather it is indicative of the local physico-chemical conditions that could be potentially favoring the mobility and accumulation of toxic metals such as the so-called atmophile elements (e.g. Cu, Cd, Zn, As). These elements are the subject of an ongoing study. Because watercress appears to easily accumulate metals it could be used to clean contaminated water by soaking up the toxic elements.

Key words: *Aquatic herbs; Metal bioaccumulation; Mountainous environment; Bioremediation, Lao P.D.R*

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Introduction

Potentially toxic metals may accumulate in soils and sediments along the banks of river systems. Metals are either derived directly from man made waste accumulation (i.e. industrial waste, sewage sludge disposal, fertilizer application on crop fields) or, indirectly removed from naturally occurring metals, located within mineral structures or sorbed onto mineral surfaces. Their natural concentrations in soils define part of the so-called "soil geochemical background", inherited from the composition of the rocks of the geological basement. Metals may contaminate surface and ground waters connected to the river system (Naiman et al., 2005). Health authorities recommend very low metal concentrations in drinking water, for example in France these values are 5 µg l^{-1}, 10 µg l^{-1}, 50 µg l^{-1} and 200 µg l^{-1} for Cd, Pb, Mn and Fe, respectively (Décret 2001-1220, December 12, 2001). Metal bio-availability generally refers to the ability of a given element to be transferred from soil (or sediment) to water. Plants take up most of their trace nutrients from water and can therefore potentially accumulate metals if available. Uptake of Fe and Mn by plants depends mainly on soluble pools and the ability of plant roots to reduce these metals to their mobile forms (i.e. Fe^{3+} to Fe^{2+} and Mn^{4+} or Mn^{3+} to Mn^{2+}). Although these processes are controlled by microbiological activity they may be monitored by environmental parameters: temperature, pH, Eh (redox potential), dissolved oxygen concentration and turbidity, which affect the behavior of metals in natural waters (Stumm and Morgan, 1996). From a purely geochemical point of view, the extent of metal adsorption by plants is controlled by: (1) the total metal content and, (2) the metal ion speciation status in the soil or sediment (Kabata-Pendias, 1993; Alloway, 1995). Both parameters are influenced by the "free metal ion" concentration in the pore water (i.e. the Fe^{2+} concentration with respect to the total Fe concentration), which is linked to the presence of soluble organic and inorganic complexes (Benedetti et al., 1996). Both adsorption onto Fe-Mn-oxides and hydroxides surfaces and complex formation with organic matter reduce the amount of "free metal ions" in the water and thus, the extent of metal uptake by aquatic plants. Several studies have shown that the reactivity of trace metals is strongly linked to the presence of oxides and hydroxides in soil and sediments (e.g. Kabata-Pendias and Pendias, 2001; Dumat et al., 2001).

Antagonist interactions between metals also occur, i.e. excess amounts of Mn in plants, reduces absorption and translocation of Fe, resulting in a decrease of chlorophyll and photosynthesis.

The issue of metal bio-availability to aquatic herbs, in particular watercress (Nasturtium officinale), is of important interest because this cultivated plant is currently eaten raw as salad or cooked as a vegetable. Metal concentrations in commonly consumed watercress are usually very low, ca. 0.009 - 0.3 g kg^{-1} and ca. 0.002 - 0.03 g kg^{-1} for Fe and Mn, respectively (Cumbus et al., 1980; Mohamed et al., 2003; Kawashima and Soares, 2003). However, much higher amounts were reported, up to 7.6 ± 0.7g kg^{-1} for Fe and to 08 ± 0.2 g kg^{-1} for Mn, for iron-contaminated sites in China (Wong, 1985). Watercress grows in clear running waters and is suited to temperate environments or the relatively cool moist climates of mountainous tropical regions (Herklots, 1972). In the province of Luang Prabang (northern Laos), watercress is usually grown from cuttings and planted in waterlogged areas. On the Houay Pano catchment near Luang Prabang, local cultivation is set up directly in the main stream. The aim of this study was to measure the total Fe- and Mn- accumulations in watercress grown in this watershed and to compare these concentration levels with those determined for bottom sediment and ambient water. These determinations provided a first-order estimate of potential metal accumulations in sediments and plants in relation to the local environmental conditions.

Materials and methods

The biophysical and socio-economic characteristics of the study area are described in detail by Valentin et al. (this issue). The geological basement of the catchment is composed of Permian to Upper Carboniferous sedimentary to low grade metamorphic rocks (schists, mudstones and fine-grained sandstones) overlaid by limestone cliffs. Soils are cultivated on steep slopes (average slope: 60 %) by slash-and-burn with no fertilizer input. The soils of the area are dominated by entisols (18.5 %; clay soils with medium fertility, pH = 6.4), ultisols (33.1 %; clay soils with medium fertility, pH = 5.5), and alfisols (48.5 %; heavy clay soils with medium fertility, pH = 6.2). The stream in which watercress is grown is a third order tributary of the Mekong, located 10 km south of Luang Prabang. The permanent flow is fed by groundwater (i.e. 1.6 - 5.2 l s^{-1}; Ribolzi et al, 2005) during the dry season. During the rainy season, the water level is controlled by the amount of rain and the soil saturation status.

Cultivated watercress, bottom sediments and water samples were collected in March 2007 during the dry season from two different sites, located in the upper (site A) and central part (site B) of the catchment (Figure 1). Both sites are included in a monitoring survey of groundwater inflow and outflow in the main stream of the Houay Pano catchment (Ribolzi et al., 2005). The environmental parameters measured the day of sample collection (3/7/2007, 11 am - 2 pm, Table 1) indicate that site A has "oxic conditions" ([O2] > 2.9 mg l^{-1}, Tyson and Pearson, 1991). However, site B is located in a swampy zone where "dysoxic" to "suboxic" conditions prevail (2.9 < [O2] < 0.0 mg l^{-1}; Tyson and Pearson, 1991). For site B, it is of note that watercress only grows in areas where oxygen levels are high (samples B1 - B6, Table 2).

Two different techniques were applied for water sampling: **(1)** a conventional technique with water collection in plastic bottles and filtering through a 0.2 µm acetate filter, in order to separate suspended solid material from dissolved (and colloid) material and; **(2)** in-situ selective metal extractions, based on a DGT procedure (Diffusive Gel Transfer, Zhang et al., 1995). The DGT device uses a specific layer of Chelex resin, impregnated in a hydrogel to accumulate the metals. Ions must diffuse through the filter and the diffusive layer of hydrogel to reach the Chelex resin. The DGT devices were immersed in the stream at sites A and B, very close to watercress cuttings and were recovered after 3 days. This procedure accumulates "free metal ions" on the resin and, thus, very low concentration levels may be determined in natural waters, in particular when these levels are bellow the detection limits of currently used chemical analyzers. Fe and Mn concentrations were calculated using the procedure described in Zhang et al. (1995) with temperature corrections required for the application of diffusion gradients. Total Fe- and Mn- concentrations were determined by Atomic Absorption Spectroscopy (Unicam 989 QZ and Unicam AA series, detection limit: 0.5 ppb).

Watercress samples were dried, weighed and grounded. Aliquots (200 mg) were dissolved in 2 ml of 0.43M HNO3 and 1 ml of 30 % H2O2 for 24 h at 100°C. After dissolution, solid vegetation residues represented less than 10 % of the initial sample weight. The solutions were centrifuged at high speed to remove any solid material and filtered through a 0.2 µm acetate filter. Sediment samples were finely grounded. Selective extractions were carried out on two replicate sample aliquots (2 g) using procedures described in Dumat et al. (2001). Exchangeable (= soluble in water) Fe and Mn were extracted with 0.01M $CaCl^2$ during 24 hours at 20°C. Potentially exchangeable metals (= bound to oxides and/or hydroxides) were extracted from two replicate sample aliquots (2 g) with 0.43M HNO3 and 6M HCl for 2 hours at 20°C. The solution recovered for both extraction procedures were centrifuged and filtered as described for the vegetation samples. The total organic carbon (TOC) and total nitrogen (TN) concentration of sediments were determined using a Carlo-Erba elemental analyzer (Girardin and Mariotti, 1991). All measurements (Tables 2 - 4) were carried out in the laboratories of UMR Bioemco (Université Pierre & Marie Curie) in Paris.

Discussion and interpretation

Fe and Mn concentrations in watercress and bottom sediments

In general total Fe- and Mn-accumulations in plants show remarkable variations depending on the plant species, soil type, stage of growth, as well as ecosystem (Kabata-Pendias and Pendias, 2001). The minimum Mn level for most plants is 0.015 - 0.025 g kg^{-1} but may increase above 1.0 g kg^{-1} for some species. A large range is also observed for Fe in plants, ranging from 0.02 g kg^{-1} up to 3.5 g kg^{-1}. Because watercress grows in waterlogged or aquatic systems, Mn and Fe are more easily available and plant concentrations should fall in the upper range. It was observed that the total Fe and Mn contents in watercress were higher for site B (swampy area) than for site A (upstream). Fe and Mn concentrations ranged from 14.1 - 46.5 and 21.1 - 26.6 g kg^{-1} and 4.4 - 19.6 g.kg^{-1} and 1.0 - 10.0 g.kg^{-1}, for sites B and A, respectively (Table 3). A simple explanation for this difference is the contrasting redox status of each environment. However, significant variations linked to the environmental parameters are also observed locally (Table 2). The dissolved oxygen content and the Eh values are higher for site A (56.4 % < [O2] saturation < 81.1 %; 166 mV < Eh < 270 mV) than for site B (1.4 % < [O2] saturation < 27.3 %; -2 mV < Eh < 271 mV). The dysoxic conditions of site B should favor the transfer of Fe and Mn from oxides-hydroxides or amorphous / colloid phases located in the sediment to "free metal ions" in the pore water in which watercress roots acquire their nutrients. This trend is more pronounced for Mn than for Fe, in accordance with the redox cascade pattern generally described for natural waters (Stumm and Morgan, 1996). For site B the average Mn concentration in watercress increased by a factor 7.5 but the Fe concentration only increased 2.2 times compared to site A.

If the ion metal speciation status explains the difference in watercress Mn and Fe concentration levels between the two sites, there must be Fe and Mn, either available in the sediments or transferred from the local riparian zones. Availability in the sediments (exchangeable and potentially exchangeable fractions) may be assessed using the results of the selective extractions (Table 4). Bottom sediments of site B do contain more Fe bound to oxides-hydroxides (potentially exchangeable Fe) than for site A, 10.0 - 24.0 g kg^{-1} vs. 2.2 - 5.7 g kg^{-1}, respectively. For Mn, the same trend was observed with 4.2 - 20.4 g kg^{-1} and 0.9 - 2.4 g kg^{-1} for site B and A, respectively. Accordingly, sediments contain more Fe and Mn in site B than in site A and the concentrations measured in watercress may be explained by differences in sediment composition. Differences in sediment composition between each site are highlighted by their TOC content (Table 4). Organic matter is well preserved in the swampy area of site B with high TOC concentrations (23.9 - 63.2 mg C g^{-1}). In contrast, site A bottom sediments have lower organic carbon contents (9.1 - 37.2 mg C g^{-1}). Nevertheless, improved preservation of vegetation debris in dysoxic - suboxic conditions with reduced mineralization rates or simply removal of organic debris by stream flow may also explain this difference. Local environmental control is suggested by the contrasted exchangeable Fe- and Mn- concentrations measured for each sites. The proportion of exchangeable Mn at site B was higher at 0.216 - 0.475 g kg^{-1} than for site A, at 0.003 - 0.067 g kg^{-1}. This was not the case for Fe at site B where the exchangeable Fe- concentrations are in the same range as that observed for site A. The differential behavior of Fe and Mn (with respect to local environmental conditions) is supported by the calculated partition coefficients (K; ratio of exchangeable vs. potentially exchangeable concentrations, Table 4). Thus, for Mn in site B a higher rate of exchange between bottom sediments and water is possible whereas only low exchange is expected for Fe. This pattern is also consistent with the redox trends reported for natural waters (Stumm and Morgan, 1996). Overall, both local sediment composition and prevailing environmental conditions explain the difference in the Fe- and Mn-contents of watercress.

Fe and Mn concentrations in ambient water

Because stream waters on the Houay Pano catchment have high pH and low turbidity during the dry season, dissolved Fe- and Mn-concentrations should be very low. High metal concentrations in surface waters are not favored by high pH conditions and the turbidity in the watercress cultivation area is too low to provide particulate sources of metals. Some limitations to our assessment were caused by a local groundwater inflow located at site A (sample A4* in Table 1 - 2). The pH of this groundwater inflow was lower (6.47) than for ambient stream waters (7.49 - 7.94) and the dissolved oxygen concentration were also much lower (11 % at saturation). Major differences were also found between the two water sampling and analysis procedures. Dissolved Fe and Mn concentrations were either in the same range or higher using direct DGT recovery than after water filtration (Table 2). The opposite trend should be found because with the former method only "free metal ions" should be recovered whereas with the later method the dissolved component may contain colloid fractions and possibly also very fine particulate matter (< 0.2 µm). This unexpected behavior indicates that removal of Fe and Mn from the dissolved load with concomitant precipitation of Fe-Mn oxides and hydroxides on the acetate filter took place during water filtration. In order to reduce uncertainty, we decided to only use the concentrations obtained using the DGT procedure when referring to dissolved element concentrations.

The distribution of dissolved Fe- and Mn- concentrations in ambient water mirrored the trends obtained for watercress and exchangeable metals in sediments. High dissolved Fe and Mn contents in ambient water correspond to high concentrations in watercress and bottom sediments. For example, at site B, watercress samples B2 - B5 have "high" Mn content (21.1 - 26.6 g kg^{-1}, Table 3), the corresponding bottom sediments have "high" exchangeable Mn-concentrations (0.216 - 0.475 g kg^{-1}, Table 4) and ambient water has a "high" dissolved Mn content (1404.1 - 4359.3 µg l^{-1}, Table 2). In contrast, watercress samples A2 - A3 and A5 - A10 from site A with a "low" Mn content (1 - 10 g kg^{-1}, Table 3) are linked to "low" exchangeable Mn-concentrations in sediments (0.003 - 0.067 g kg^{-1}, Table 4) and "low" Mn levels in ambient water (13.1 - 53.2 µg l^{-1}, Table 2). The local groundwater inflow at site A (sample A4*, Table 2), characterized by contrasting redox conditions as mentioned above, has a slightly higher dissolved Mn-concentration (480 µg l^{-1}, Table 2) consistent with the more reducing conditions (lower dissolved oxygen and redox potential levels) of ground waters. Additional evidence for a consistent behavior between ambient water, watercress and bottom sediment was displayed by the dissolved Fe-concentrations which were higher for site B than for site A, as already shown for watercress Fe-contents and sediment potentially exchangeable Fe-concentrations. However, locally more reducing conditions also occurred. Water samples B7 - B9 (Tables 1 and 2) collected in a confined part of site B, where watercress no longer grows, displayed an opposite trend with much higher amounts of dissolved Fe (4384.0 - 8556.7 µg l^{-1}, Table 2) with respect to dissolved Mn (264.2 - 1828.1 µgl^{-1}, Table 2). These concentrations were consistent with very low dissolved oxygen content of these waters (1.4 % < [O2] saturation < 3.2 %).

Conclusion and perspectives

Analysis of Fe and Mn-concentrations in watercress, bottom sediment and ambient water for two sites with contrasted environmental conditions (oxic vs. dysoxic - suboxic oxygen levels) showed that metal accumulation levels are linked to the local bottom sediment composition and local environmental conditions (composition of soil waters). The levels of Fe and Mn accumulated in the watercress were high due to the ability of roots to directly take up soluble metals ("free ion") from soil water. Higher levels of Mn were observed in watercress grown in the swampy area compared to the upstream site, which is consistent with both the higher exchangeable Mn-concentrations in the bottom sediments and the higher dissolved Mn-content of stream waters measured at the site. Higher Mn availability is also expected according to the local redox status. A high level of Fe-accumulation in watercress was not favored by the local conditions recorded during the course of this study but might have taken place previously when more reducing conditions prevailed during the dry season. An important outcome of this study is that the total Fe and Mn accumulations in watercress cultivated in the swampy area (site B of our study) might reach and even exceed the levels reported in metal contaminated sites.

The bioaccumulation of these metals should not pose a direct threat in itself, because these elements are not actually very toxic, but rather it is indicative of the local physico-chemical conditions that could be potentially favoring the mobility and accumulation of toxic metals such as the so-called atmophile elements (e.g. Cu, Cd, Zn, As). These elements are the subject of an ongoing study. Because watercress appears to effectively take up and accumulate metals it could be used to clean up contaminated waters as a bioremediation component.

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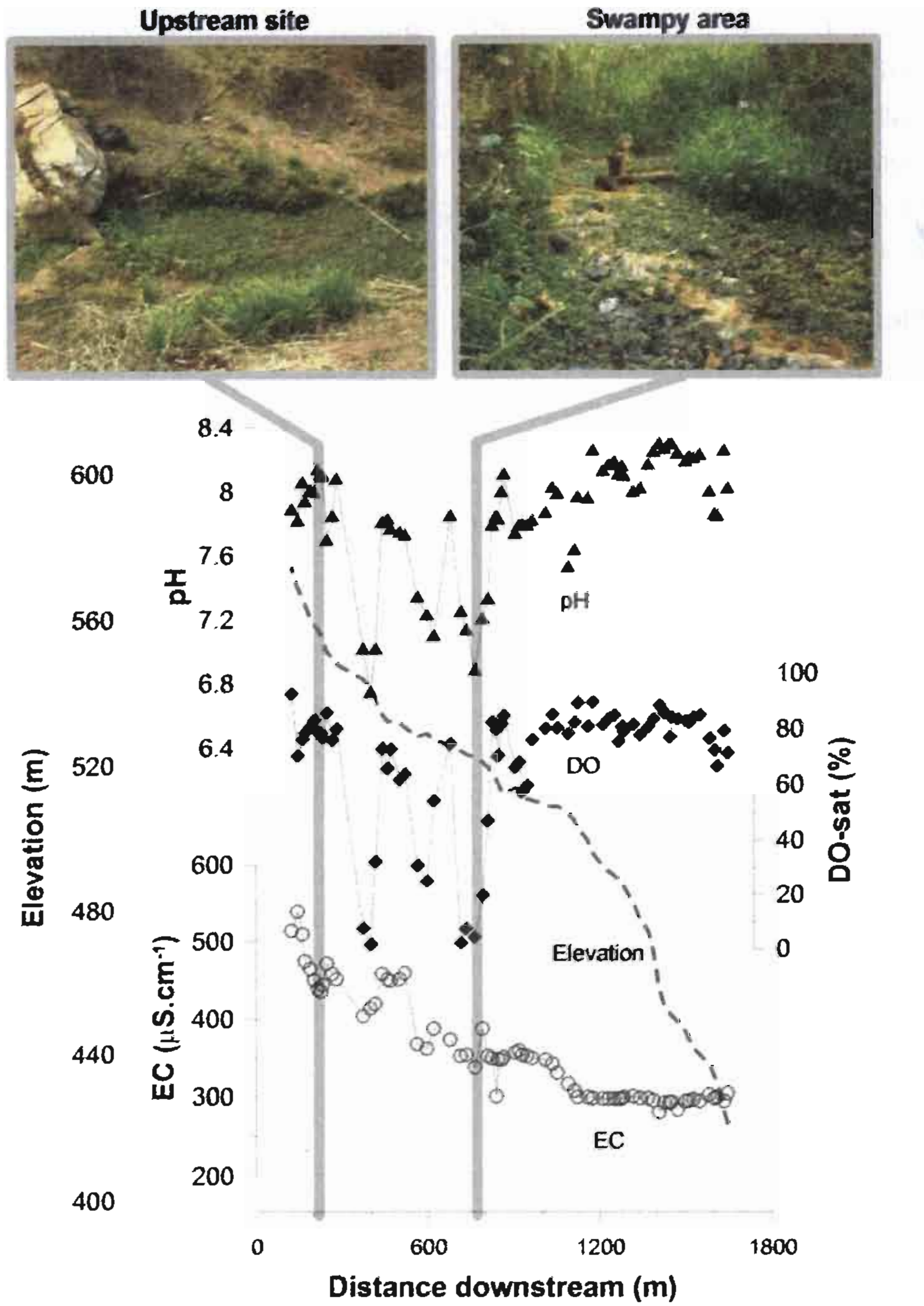

Figure 1 – *Pictures showing the upstream site and the swampy area; Elevation and physicochemical characteristics along the Houay Pano stream during the sampling collection (5 March 2007): pH, dissolved oxygen content transformed to oxygen saturation (DO-sat) and electrical conductivity at 25°C (EC).*

Table 1 – *Major environmental parameters measured on the day of the sampling.*

Sample	Water Temperature (°C)	Water EC (µS.cm^{-1})	pH	Eh (mV)	[O_2] % saturation	[O_2] (mg.l^{-1})
Site A (upstream)						
A1	21.90	534	7.49	166	63.0	5.5
A2	22.34	541	7.54	186	61.5	5.3
A3	23.16	544	7.75	205	65.8	5.6
A4 *	19.53	177	6.47	270	11.0	1.0
A5	23.12	525	7.83	235	70.1	6.0
A6	22.67	517	7.48	244	71.1	6.1
A7	23.12	512	7.58	247	63.6	5.4
A8	23.73	502	7.94	247	81.1	6.9
A9	23.67	501	7.65	252	56.4	4.8
A10	23.58	496	7.97	248	80.4	6.8
Site B (swampy area)						
B1	21.27	371	7.11	271	27.3	2.4
B2	20.30	363	7.03	179	6.0	0.5
B3	20.61	379	7.07	184	16.7	1.5
B4	19.64	378	7.05	169	8.5	0.8
B5	19.34	381	7.19	214	14.3	1.3
B6	18.77	388	7.14	120	18.6	1.7
B7	19.09	382	6.94	104	2.0	0.2
B8	18.55	441	7.23	-2	1.4	0.1
B9	19.21	351	6.83	117	3.2	0.3

* local groundwater inlet

Table 2 – *Fe- and Mn- concentrations measured in water samples after filtration and using the DGT procedure.*

Samples	Filtration [Fe] (μg l^{-1})	Filtration [Mn] (μg l^{-1})	DGT [Fe] (μg l^{-1})	DGT [Mn] (μg l^{-1})
A1	4.4	bd	11.9	2522.2
A2	-	-	4.5	53.2
A3	bd	3.3	6.2	13.1
A4*	3.9	bd	10.9	480
A5	bd	bd	-	-
A6	bd	bd	5.8	2.7
A7**	bd	bd	15.0	49.1
A8	bd	bd	4.5	4.1
A9	7.0	bd	-	-
A10	24.6	bd	2.7	42.4
B1	1.2	200	5.6	2620.1
B2	2.4	190	955.8	1404.1
B3	1.0	220	62.8	4359.3
B4	bd	190	80.6	2156.1
B5**	bd	200	50.7	3553.0
B6	1.3	170	9.0	1983.5
B7	4.6	720	4384.0	1828.1
B8	6.1	340	8556.7	341.2
B9	bd	54	4848.0	264.2

* local groundwater outlet, ** average of 2 replicate samples, bd = below detection limit

Table 3 – *Fe- and Mn-concentrations measured in dry watercress samples (average of 2 replicate samples).*

Samples	Water content (weight %)	[Fe] (g kg^{1})	[Mn] (g kg^{1})
A1	96.2	4.4	2.0
A2	93.7	10.0	10.0
A3	94.8	6.1	2.0
A5	93.0	12.8	1.2
A6	91.1	14.7	1.0
A7	95.0	15.0	7.3
A8	94.7	18.6	1.7
A9	93.9	15.2	1.5
A10	95.1	19.6	2.2
B2	96.4	14.1	26.6
B3	96.4	28.4	22.0
B4	96.4	46.5	26.6
B5	95.8	26.9	21.1

Table 4 *– Total organic carbon, total nitrogen, TOC/TN (= C/N), Fe and Mn-concentration measurements for sediment samples using selective extractions and partition coefficients (K) of exchangeable vs. potentially exchangeable Fe and Mn. (Exchan. = exchangeable = CaCl2 treatment, oxides = potentially exchangeable = HNO3 + HCl treatment).*

Samples	TOC (mgC. g^{-1})	TN (mgN. g^{-1})	C/N	Exchan. [Fe] (mg.kg^{1})	Exchan. [Mn] (g.kg^{1})	[Fe] oxides (g.kg^{1})	[Mn] oxides (g.kg^{1})	K (Fe) (x 10^{6})	K (Mn) (x 10^{3})
A1	12.2	1.4	8.7	bd	0.020	5.7	0.9	-	22.7
A2	22.3	2.3	9.7	0.052	0.067	5.6	1.8	9.4	36.4
A3	23.2	2.1	10.9	0.026	0.009	2.9	1.3	9.1	6.7
A5	18.7	1.8	10.3	bd	0.006	3.6	1.4	-	3.9
A6	17.5	1.7	10.5	bd	0.008	4.2	1.4	-	5.9
A7	37.2	2.9	12.8	0.021	0.003	2.2	2.4	9.3	1.3
A8	25.0	2.1	11.7	0.039	0.036	3.1	2.1	12.7	17.1
A9	16.0	1.5	10.5	0.018	0.003	3.6	0.9	5.0	3.5
A10	9.1	0.9	10.1	bd	0.002	4.6	0.9	-	2.1
B2	53.2	3.7	14.5	0.071	0.289	17.1	9.9	4.1	29.1
B3	41.4	3.0	14.0	0.027	0.359	18.8	11.5	1.4	31.3
B4	63.2	3.9	16.4	0.041	0.475	24.0	20.4	1.7	23.3
B5	23.9	1.9	12.9	0.014	0.216	10.0	4.2	1.5	51.7

bd = below detection limit

ຄ່າຕອບແທນ ສຳລັບວຽກງານການຄຸ້ມຄອງ ແລະ ປົກປັກຮັກສາ ແຫຼ່ງນ້ຳ ໃນເຂດພາກເໜືອ ຂອງ ສ.ປ.ປ ລາວ

ແກຼ ມຸດສະເກ, ອາລານາ ຈອດເຊີ, ພອນໄຊ ແສງສຸລິຈັນ, ແກ້ວອຸດອນ ລາດສະຈັກ, ໂອລິດ ແສງຕາເຮືອງຮຸ່ງ, ໂອລີເວີ, ອາແລັງ ປີແອເຣ

ບົດຄັດຫຍໍ້

ຈຸດປະສົງຂອງບົດນີ້ ແມ່ນເພື່ອສຶກສາຄວາມເປັນໄປໄດ້ ໃນການສ້າງຕັ້ງໂຄງການ ຄ່າຕອບແທນສຳລັບວຽກງານການຄຸ້ມຄອງ ແລະ ປົກປັກຮັກສາແຫຼ່ງນ້ຳ ເພື່ອຄຸ້ມຄອງຄຸນນະພາບ ແລະ ປະລິມານຂອງນ້ຳຫ້ວຍໃນເຂດພູດອຍ. ພວກເຮົາສັງເກດເຫັນວ່າ ທາງດ້ານທິດສະດີແລ້ວ ຄ່າຕອບແທນສຳລັບການຄຸ້ມຄອງ ແລະ ປົກປັກຮັກສາແຫຼ່ງນ້ຳ ສາມາດປັບປຸງເພື່ອໃຫ້ເກີດປະໂຫຍດສູງສຸດ ໃນການປ້ອງກັນການເຊາະເຈື່ອນຂອງດິນ ແລະ ຮັກສາຄຸນນະພາບໃຫ້ໄດ້. ຕາມການສຸ່ມປະຊາກອນໃນເຂດເຫັນວ່າ ຄ່າຕ້ອງຈ່າຍແບບສະໝັກໃຈ (WTP) ປະມານ 0.3 US$ ຕໍ່ຄອບຄົວ ແມ່ນພຽງພໍເພື່ອຢັບຢັ້ງຜົນກະທົບຂອງການເຊາະເຈື່ອນດິນ. ໃນເຂດສຳຫຼວດ ອຸບປະສັກໃນການສ້າງຕັ້ງໂຄງການ ຄ່າຕອບແທນສຳລັບວຽກງານການຄຸ້ມຄອງ ແລະ ປົກປັກຮັກສາແຫຼ່ງນ້ຳ ມີດັ່ງນີ້: 1) ຂາດການປະສານ ລະຫວ່າງການບໍລິການ, ຜູ້ນຳໃຊ້ ແລະ ຜູ້ຕອບສະໜອງ; 2) ຂາດຄ່າຕ້ອງຈ່າຍແບບສະໝັກໃຈ (WTP) ເພື່ອຮັກສາຄຸນນະພາບນ້ຳ ໂດຍການຈັດການກັບສິ່ງເສດເຫຼືອລົງສາຍນ້ຳ; 3) ຂາດຜູ້ຊື້ທີ່ເປັນຂະບວນ ແລະ 4) ການປູກຈິດສຳນຶກ ກ່ຽວກັບບັນຫາສິ່ງແວດລ້ອມໃຫ້ແກ່ຊຸມຊົນ ແມ່ນສິ່ງເອື້ອອຳນວຍ ເພື່ອຄວາມສຳເລັດໃນການສ້າງຕັ້ງໂຄງການ ຄ່າຕອບແທນສຳລັບວຽກງານການຄຸ້ມຄອງ ແລະ ປົກປັກຮັກສາແຫຼ່ງນ້ຳ.

Relevance of Payments for Environmental Services (PES) for watershed management in northern Lao PDR

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Abstract

In this paper we discuss the main results of a feasibility study for the implementation of Payments for Environmental Services (PES) in a small northern Lao watershed. The aim of the work was to assess the relevance of a PES scheme as a way to control both the quality and flow of a small mountain stream. We found that the PES concept, with some adaptations, may offer interesting avenues as a means to maintain water quality through an improved control of soil erosion in the upper catchment: Willingness-To-Pay (WTP) within the sampled population was approximately USD 0.3/month/household which would be sufficient to abate the negative impact of soil erosion. At the whole catchment scale, major impediments to the immediate implementation of a PES scheme were i) the lack an unequivocal relationship between environmental services, users and providers, ii) insufficient WTP to maintain water quality along the stream through waste management and iii) absence of a critical mass of buyers. A precondition of successful implementation of PES in the area is to increase the awareness of environmental issues in the concerned communities.

Key words: *Payments for Environmental Services; Water quality; Soil erosion; Mountain stream; Lao P.D.R*

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Introduction

Environmental Services (ES) are benefits that humans obtain from natural and cultivated environments (Wertz-Kanounninoff, 2006). For example, hydrological services can be obtained through river flow regulation, flood control or protection against soil erosion (Wunder, 2002; Wertz-Kanounninoff, 2006). ES are threatened worldwide, in a variety of ways, by human activities. In response to such threats, the concept of Payments for Environmental Services (PES) has been proposed as a scheme to reward land users who adopt practices that generate ES, hence promoting sustainable land use (Mayrand and Paquin, 2004).

A PES is a payment or direct compensation mechanism by one or more users for the maintenance and/or availability of an ES by one or more suppliers of the ES. The principle as explained by Mayrand and Paquin (2004) is as follows: "Communities that are in a position to provide an ES should receive compensation, and it is those who benefit from these services that should pay [...] PES schemes are aimed at giving a specific value to ES and to set-up effective systems of price setting, institutionalisation and distribution which favour changes in behaviour and the adoption of sustainable land-use practices that benefit the whole community" (Figure 1).

The aim of this study was to assess whether this concept could offer new perspectives for managing the hydrology of a small river basin in northern Laos. Identifying the most appropriate ES for a PES market in watershed services is a complex equation of socio-economic and environmental factors. In addition, it is important to ascertain that a demand for this ES exists among potential buyers. As part of a best practice approach for PES, a study was carried out in order to identify the most appropriate ES for a PES market in Houay Xon. Data required to carry out the successive steps of this approach were collected by i) a survey of the local population's perception of water issues, ii) a critical analysis and compilation of pre-existing biophysical, socio-economical and geographical information and iii) field measurements.

Location and characteristics of the study site

The Houay Xon watershed (Figure 2) covers 22 km^2 and includes 7 villages located along the Houay Xon stream (Ribolzi et al. b, this issue). The stream runs for approximately 15 km and has three main tributaries. The average annual rainfall is 1403 mm (average of the last 30 years), and the mean annual temperature is 25°C. Two distinct seasons characterize the study site: a wet season from April to October, and a dry season from November to March. This catchment's maximum elevation is 584 m a.s.l., near the headwater area (Chaplot et al., 2005).

The study area encompasses a population of 6251 inhabitants mostly of the Lao Lum, Khmu and Hmong ethnic groups. Farming activities are located upstream, in the Houay Pano headwater catchment. In downstream villages, the population is dominated by government employees and agricultural activities are limited to small scale vegetable gardening and fish breeding. Over recent years, the Houay Xon catchment has been subjected to increasing environmental pressure which resulted in degraded water quality and reduced flow. In addition, extreme climatic events, such as a flood in September 2006, have reportedly caused increasingly severe damage to infrastructure essential to the community.

Survey design and implementation

To estimate the supply and demand for hydrological services in the Houay Xon catchment, we selected a sample of 67 people who were interviewed over a period of one month. People included in this sample represented the five main categories of water users identified along the Houay Xon: farmers from upland and downstream areas, gardeners, tradespeople and villagers who only use water from the Houay Xon for domestic purposes (Table 1). Not all categories are represented equally in the sample because not all categories encompass equal numbers of people and some individuals were not willing to participate. In addition, missing or false information made it sometimes difficult to compare all the villages amongst themselves.

All these users, who are scattered along the stream, potentially contribute to water pollution and/or flow decrease. They are therefore potential buyers and suppliers of hydrological services since they participate in water extraction, transformation and discharge. The questionnaire was designed to document interviewees' socio-economical background and that of their dependants, their awareness of water flow and quality changes, their perception of the causes behind these changes, their ability and willingness to participate in a payment scheme and their understanding of institutional and governmental support. This data set was combined with information previously collected by public and private institutions and biophysical data monitored by IRD since 1991.

Results

Table 2 summarizes the information collected during this feasibility study. The need for improved water quality and more constant stream water flow in the Houay Xon catchment was clearly identified. These results can be used to define an ES, such as, for e.g. a guaranteed minimum water flow with precisely defined bacteriological and chemical quality.

Water Scarcity

The survey showed that most of the interviewees have noticed a decrease in the flow of water in the last several years: 62% of interviewees think that the stream has undergone a negative or very negative evolution (Figure 3). However, the quantity of water is not a major problem for the population surveyed: 48% of the sample held the view that the quantity of water is good or very good (see Figure 3). 34.8% did not perceive a change in the quantity of water in the stream. Furthermore, villagers did not appear to be affected by the changes in water quantity within the Houay Xon catchment. In fact most villagers use complementary sources of water, and do not rely upon the river as their only water source. According to the official census, an average of 91.2% of the population in the villages downstream of Ban Don Kang is registered to use the Nam Papa system. The survey also showed that the inhabitants have adopted the network and mineral water for convenience and comfort (it saves time in both transport and there is no need to boil the water), and not because there was not enough river water. Lastly, the cost of water is low for the surveyed communities. Only 2.28% of villagers' annual income is spent on obtaining water from the supply. The budget for mineral water is higher and represents one third of the income. Families are rarely too poor to pay for the private supply and therefore are not dependent solely on river water. A survey in Xiengkhouang showed that the inhabitants spend 4.8% of their annual income on water, which is twice the amount spent in our study area.

The price of water is therefore relatively affordable for the studied population so that a hydrological service to maintain water flow does not emerge as a priority.

Water quality decline

Unlike water quantity, the study revealed significant demand for an ES to control water quality: 67% of the sampled population thinks that the water quality in the Houay Xon is poor or very poor. A further 65% perceive changes in water quality as negative or very negative (see Figure 4). Interestingly, one third of the sample declared not to have seen any changes in water quality. This can in part be explained by the fact that their recent relocation to the area (on average less then 5 years ago) prevented them from observing degradation of the Houay Xon. A decline in water quality has been observed over the past 10 years. In Ban Lak Sip, a 2003 survey showed that 72.2% of the population complained about the deteriorating quality of water in the Houay Xon (based on findings by Lestrelin et al., 2006). In 1999, during a survey by the Rural Development Committee, five villages out of seven declared that the quality of water was "not satisfactory" (RDC, 1999). Water users strongly complained of the bad quality of the stream water and its degradation confirming demand for an ES in water quality control.

Challenges to implementing a PES in the Houay Xon

It has been documented worldwide that, most often, farmers, fishers and foresters do not manage natural resources in ways that increase the provision of environmental services due to a complex combination of social, economic, political and technical factors (FAO, 2007). Likewise, some of the most common barriers to the adoption of improved management practices such as, limited access to information, appropriate technologies and finance, as well as insecure property rights and legal or regulatory constraints (FAO, 2007), are likely to impede a straightforward implementation of a PES scheme along the Houay Xon. Remarkably, our study also found that a major constraint to the implementation of a PES could be that the binary approach to providers and users may not always be valid, which indicates that attentive consideration should be paid to the conceptual definitions of PES.

ES users vs ES suppliers

First, the binary concept of user vs supplier is poorly suited to the situation studied because water extraction and contamination are diffuse along the stream. Complex interactions between the location of users and impact upon hydrological services impede any straightforward implementation of a PES scheme (Figure 5). Farmers and garden owners extract water either all the way upstream or downstream, and the water is used for domestic purposes all along the stream. The consumption of river water occurs randomly from upstream to downstream (Figure 5). Villagers in Ban Lak Sip use more water from the piped supply network than from the river, but the situation is reversed in the downstream villages and the reverse again in Ban Khoy. Therefore potential buyers are distributed erratically throughout the watershed. Likewise, the factors responsible for the deterioration in water quality are not easy to clearly identify. Furthermore, it is not clear which one group of users among the community is (more) responsible for the degradation in water quality. Almost half of the sample thinks that the degradation in water quality is not due to specific usage upstream but rather climatic or other natural causes, which are inevitable. During the 2003 survey, 93% of those surveyed in Ban Lak Sip supported this view (from data collected by Lestrelin). This poses a challenge in implementing PES because the interviewed villagers appear to believe the changes are beyond their control. Education of environmental processes and human impact is critical to overcoming this obstacle. Identifying an ES provider is thus difficult in the studied region because all stakeholders upstream and downstream play a role in degrading the stream. Furthermore, it may be difficult to convince users to modify their usage patterns unless they first accept their responsibility in the deterioration of the Houay Xon.

In theory, the demand for the ES within a hydrological services PES context usually comes from downstream. In this case, the ES appears distributed all along the stream. Furthermore it would seem logical that the buyers of the ES would be those that are most affected by the current situation. However, in this area, the damages suffered vary irrespective of the location of the interviewee along the stream. For example, the villages that suffered the greatest damage during the 2006 flood events were Ban Donkang and Ban Kouathineug. The surveyed inhabitants downstream of these villages were much less affected. Thus there is a demand for an ES all along the stream and it is not confined to downstream. Locating potential buyers downstream leads to an additional two obstacles. Firstly, downstream villagers are not the main water users. These villages are made up of a large majority of employees, factory workers, and shopkeepers, with only 3.7% identifying themselves as gardeners or farmers. A large number of farmers obtain irrigation water from artificial streams and not from the Houay Xon, and the villagers do not use the stream very often. The downstream population is rather unaware of the degradation of the hydrological service, and the villagers would be reticent to buy a service that they do not use.

Unfavourable socio-economic context

The socio-economic context of the Houay Xon catchment is characterised by subsistence economic strategies that also appear to be an obstacle for the implementation of a PES scheme. Farming and market gardens are typically low yielding with corresponding low profitability. 71.91% of the interviewees produce food for their own consumption, which seems to be characteristic of the region (for example, a socio-economic study carried out with 53 households in the neighbouring Nam Kham catchment showed that farmers could only sell their produce for one or two months of the year - personal communication, Mr Keonakhone, NAFREC). The vegetable yields in the study area are relatively low with an average of 2.41 tonnes/ha. The area cultivated is also restricted, with on average 1.33 ha for the farmers we interviewed and 0.44 ha for the market gardeners. The photo in Figure 6 shows the size of the one of the biggest garden plots at Ban Sangkhalok.

Consequently, the income of the inhabitants in the study zone is low, with an average of 500USD/year/household (as a comparison, this is less than half the income calculated during the survey of the Nam Kham catchment - personal communication, Mr Keonakhone). The majority of the population have just enough money to satisfy their basic needs: 95% of income is spent on food. Furthermore, an average of 15% of the studied households does not have access to electricity.

Overall, the downstream users (farmers and gardeners) do not have sufficient income to support a PES market. In the villages of Ban Ma and Ban Sangkhalok the sale of vegetables represents only 46.3% of the income. Furthermore, data from the DAFEO (District Agriculture and Forestry Extension Office) from 2003 shows a clear decrease in the percentage of revenue derived from farming or market gardens of the entire revenue between 1990 and 2003 in Ban Lak Sip and Ban Donkang (data from Lestrelin). This decrease is also observed in the villages downstream of Ban Donkang, which earned almost all their income from agriculture 8 years ago (RDC, 1999). The main economic activity of these villages is now commerce and there has been a large decrease in crop production. Half of the producers interviewed declared that they want to decrease their area under cropping. High-income earning stakeholders in the region do not seem to be the appropriate buyers of the ES. The majority of operating PES markets work with a single buyer of the service and several suppliers. The major companies in the study area, that is Nam Papa and DLPCP (LuangPrabang Pre-Stress Concrete Plant), are potential buyers. However, the quality of the stream water does not pose a major problem to Nam Papa. Furthermore, this company has license to act independently in an area of 3000 ha. It aims to completely reforest the Phu Phung Mountain by banning flooded rice production in the area. The situation appears to be the same for the DLPCP Company that also owns large tracts of land around the spring source. It appears difficult to propose a PES to these companies that already have a huge influence on land usage in the surrounding areas. Thus in principle, there is a lack of buyer(s) for the ES, having determined that the few users downstream do not have the means to pay for such a service, and that the few potential buyers who do have enough money do not use the river or already have control over the usage of land upstream from their spring water source. In the study zone, therefore, we cannot clearly identify the provider of the ES upstream or buyers downstream. As opposed to the simple conceptual framework summarize in Figure 1, the potential buyers and suppliers of this service are scattered in a diffuse manner all along the Houay Xon, as can be seen in Figure 7.

Policy impediments to the implementation of a PES

Finally, while it is a basic principle of the PES concept that land use can be altered with a certain flexibility so as to ensure delivery of ES, the current land allocation system makes it difficult, if not impossible, for farmers to alter land use (National Growth and Poverty Eradication Strategy, cited in NAFRI, NAFES and NUOL 2005). The population relocation policy initiated in the 1970's by the GoL (Lestrelin et al., 2006), also contributed to the emergence of conditions rather adverse to the immediate success of a PES scheme: it resulted in the cohabitation of several ethnic groups within small communities, often leading to tensions, and fell short of establishing good communication between villages and between villages and local authorities. A side effect of the relocation policy was also that displaced populations did not fully bond with their new environment. This resulted in limited awareness of environmental issues and unsustainable use of the natural resource base by the community, naturally leading to a lack of WTP for ES among many.

Conclusion

The need for improved water quality and more constant stream water flow in the Houay Xon catchment was clearly identified. These results can be used to define an ES, such as a guaranteed minimum water flow with precisely defined bacteriological and chemical quality.

This study identified several obstacles likely to impede the straightforward implementation of a PES scheme along the Houay Xon. First, the binary concept of user vs. supplier is poorly suited to the situation studied because water extraction and contamination are diffuse along the stream. In addition, the current land allocation system means that farmers can not independently alter land use although this is a precondition to successful PES implementation.

In spite of these obstacles, the MSEC (Management of Soil Erosion Consortium), program clearly established that alternative farming practices and careful management of sensitive areas (e.g. riparian areas) opens new avenues for the improvement of water quality by reducing sediment delivery (Van Breusegem, 2005; Valentin et al., 2006; van der Helm, 2007). WTP within the sampled population was approximately USD 0.3/month/household which, if put in practice through a PES, would be sufficient to significantly abate the negative impact of soil erosion on water quality. However, at the whole catchment scale, this would not warrant good water quality as it would not be enough to maintain the waste collection system essential to abate the observed distributed contamination of the stream. Therefore, one of the preconditions of successful implementation of PES in the Houay Xon watershed is to increase the awareness of environmental issues in the concerned communities to increase their WTP for ES, as at the moment, they fail to recognize the cost of producing these ES.

Acknowledgment

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Table 1 *– Categories of Houay Xon water users.*

Category of user	**Type of water usage**
Villagers	Domestic activities
Farmers	Crop irrigation
Market gardeners	Garden irrigation
Fish farmers	Supply of water for fish ponds
Trades people (garages and diverse manufacturing)	As part of production process

Table 2 – *Main results of the survey.*

Characteristics of the community	
Socio-economical background	Low average income (USD500/yr/household). Consumption of self-produced food dominates. Most villagers need more than one job. Lack of private property: land use entirely depends on land allocation by the Government of Laos (GoL).
History	Forced relocation (under GoL policy) but newcomers seem attracted by better life conditions in the area (proximity of Luang Prabang is seen as an asset).
Space allocation and management	Population along the stream is increasing. There is no planning of new developments. Farm plot size is decreasing.
Observed water use	
Water extraction	Main form is distributed water extraction. Farming and fish breeding use less water than gardening and domestic activities distributed along the stream. Other sources of water (piped spring and ground- water, bottled water) are used for daily household and production activities.
Water quality	Main form is distributed contamination. Farming and fish breeding contaminate the stream with chemical fertilizers and organic matter. Villagers are responsible for non point source pollution all along the stream (solid wastes and grey water).
Perception of water use	
Water extraction	Decrease in water quantity widely acknowledged but flow still deemed sufficient by many.
Water quality	Unsatisfactory water quality with steady deterioration over years.
Damage related to stream degradation	Economic damage difficult to quantify. Most significant damage ascribed to floods: huge impact of Sept. 2006 floods.
Prospect for change	
Accountability	Villagers are believed to be responsible for water quality degradation. No clear opinion re. changes in water quantity.
Willingness to implement change	Population is ready to pay for waste collection system but not to invest in upstream land use change although WTP sufficient to abate soil erosion.

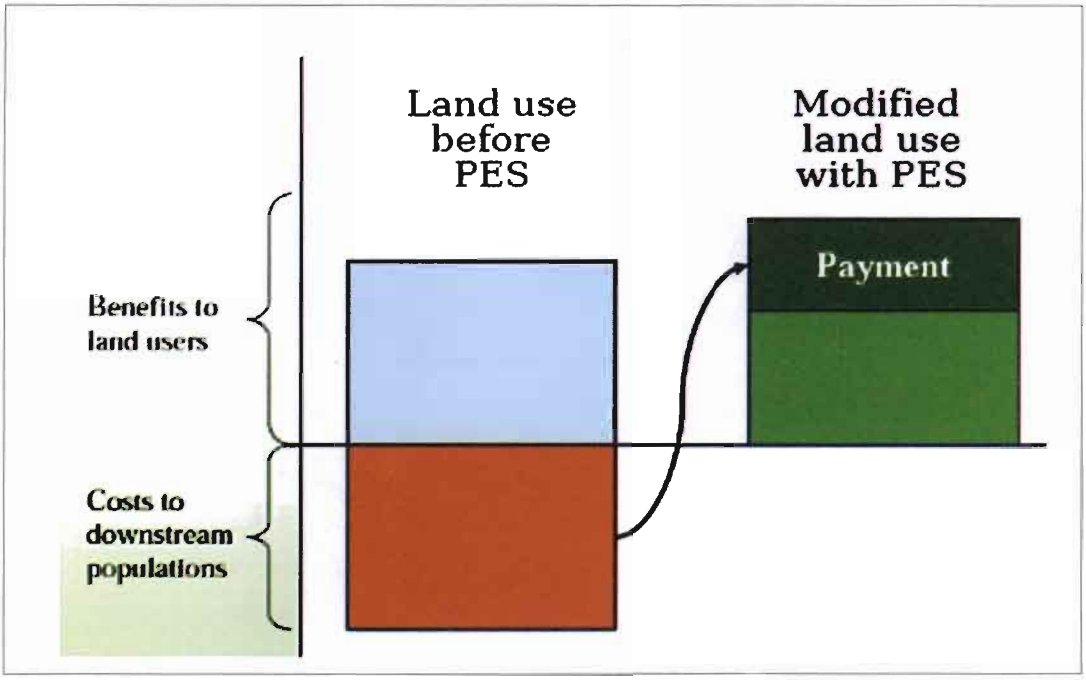

Figure 1 – *Schematic representation of the PES principle (After http://www.itto.or.jp/live/Live_Server/2869/18_Sander.pdf).*

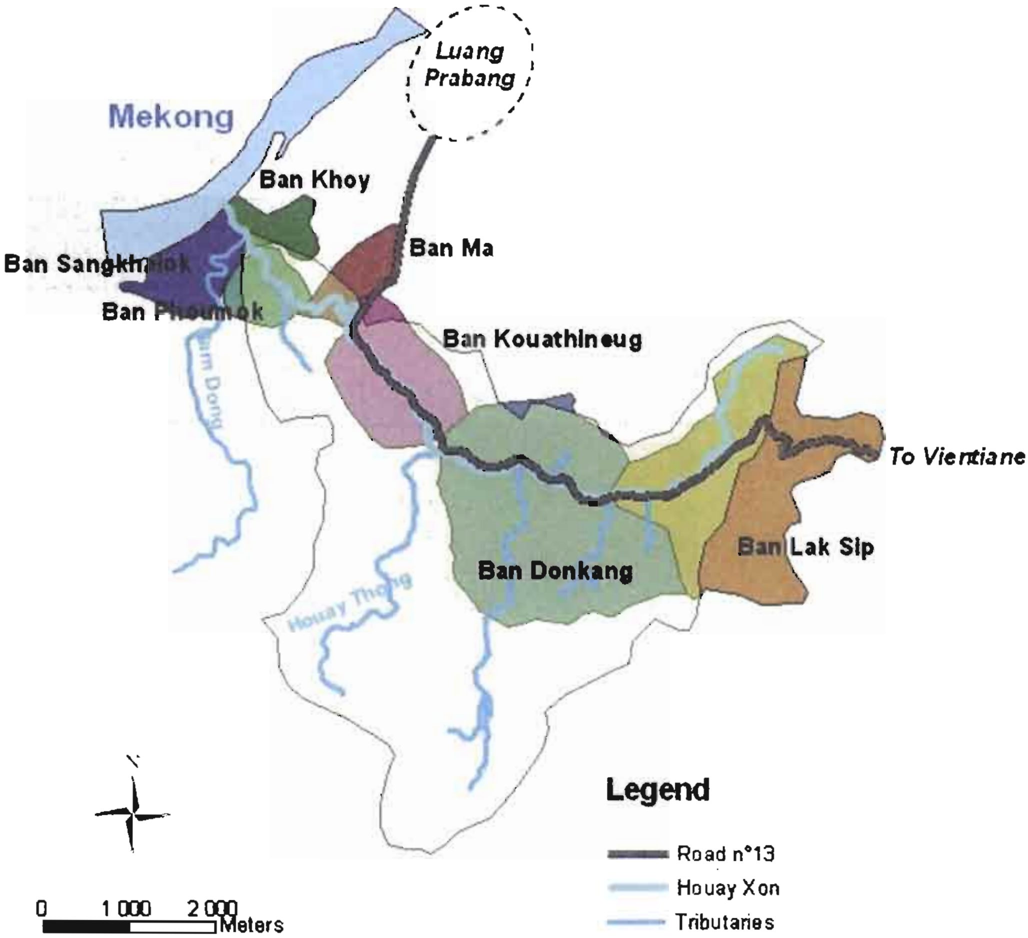

Figure 2 – *Map of the watershed and location of villages*

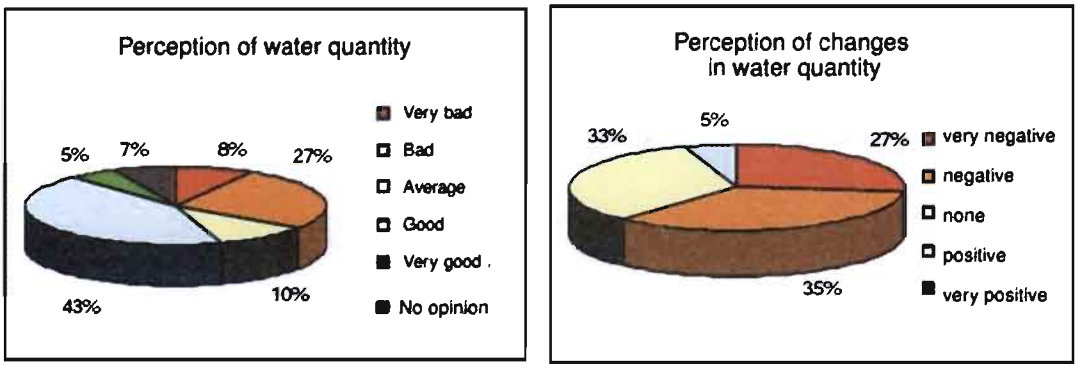

Figure 3 – *Map of the watershed and location of villages*

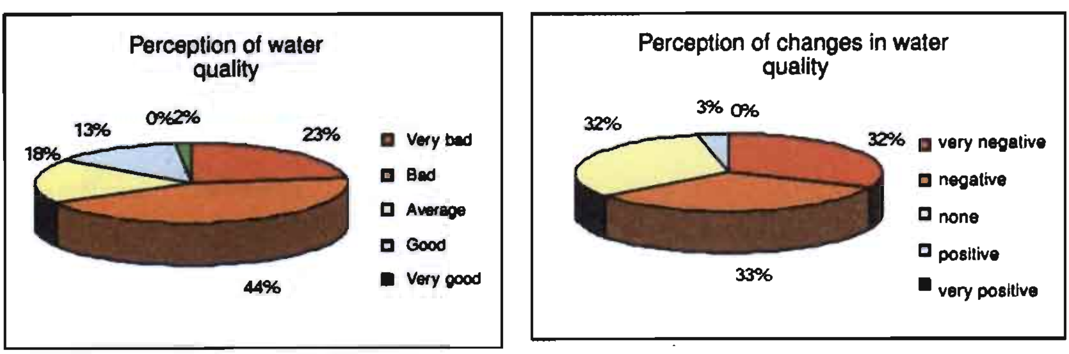

Figure 4 – *Map of the watershed and location of villages*

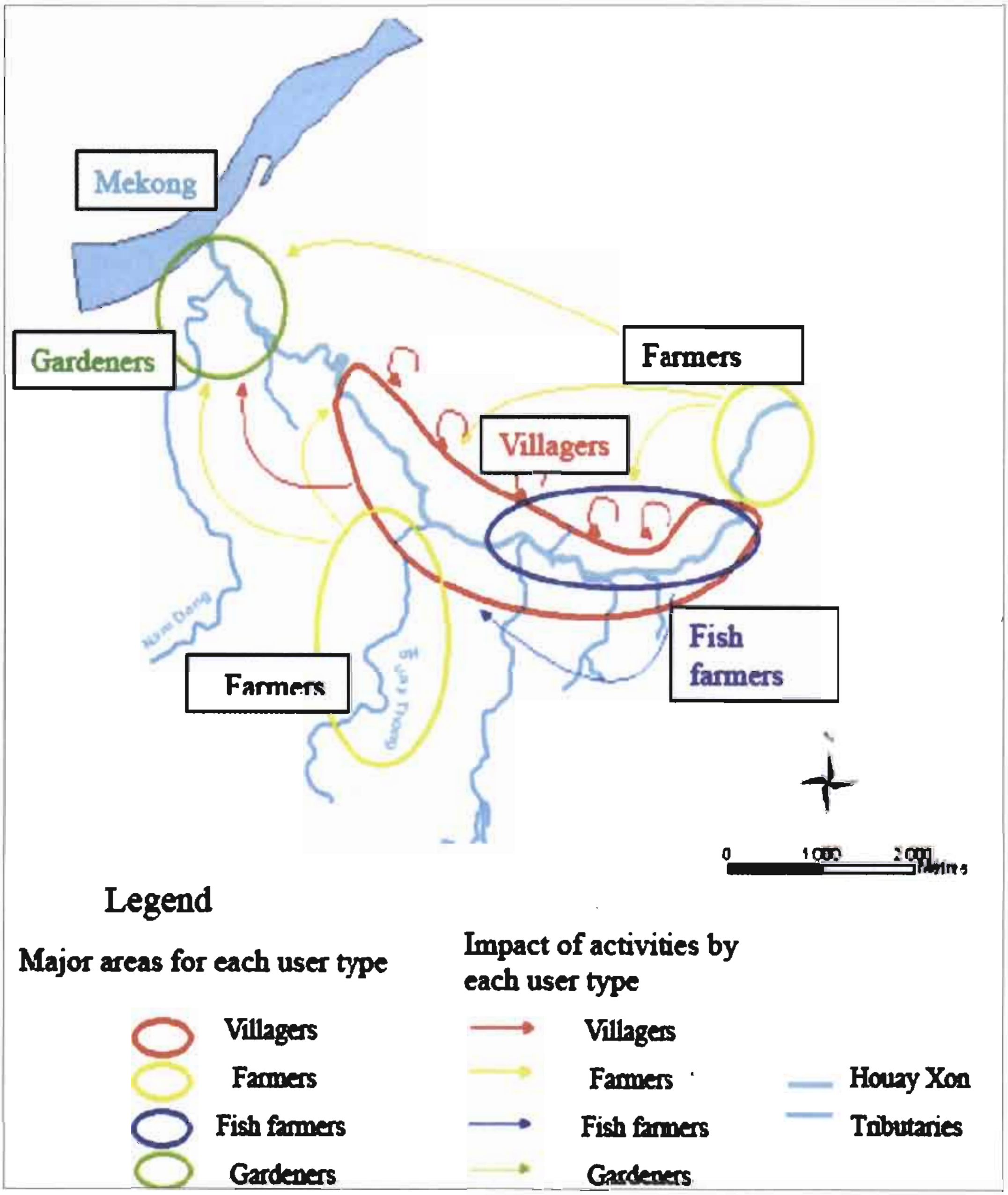

Figure 5 *– Spatial relationship between the different water users along the Houay Xon.*

Figure 6 – Garden plots in Houay Xon.

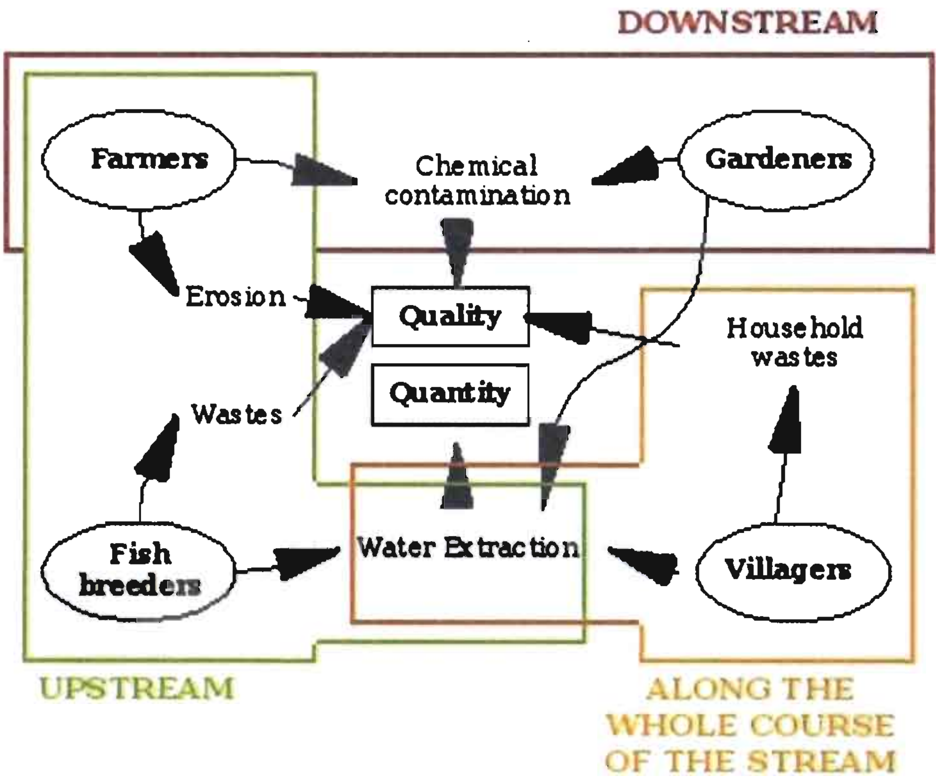

Figure 7 – *Complex water use relationships in the Houay Xon watershed.*

ການປະເມີນຄ່າໄລຍະການບວມນ້ຳໃນດິນ ໂດຍນຳໃຊ້ວິທີການຕີລາຄາສີຂອງດິນ ໃນເຂດອ່າງໂຕ່ງ ພາກເໜືອ ຂອງ ສ.ປ.ປ ລາວ

ເອມານູແອນ ບວກດົງ, ດີດີເອ ບລາເວ, ອຸ່ນລາມ ລວງກອງຄຳ, ບຸນສະໄໝ ສຸລິເລີດ, ອາລຸນສະຫວັດ ຈັນເພັງໄຊ, ອາແລັງ ປີເອເຣ, ໂອລີວີເອ ຣິໂບນຊີ

ບົດຄັດຫຍໍ້

ນ້ຳໃຕ້ດິນ ຈັດເປັນແຫຼ່ງສຳຄັນໃນການຕອບສະໜອງນ້ຳໃຫ້ແກ່ປະຊາກອນ ນອກຈາກນີ້ແລ້ວ ນ້ຳໃຕ້ດິນ ຍັງຊ່ວຍເຮັດໃຫ້ ສາຍນ້ຳຫ້ວຍໄຫຼເປັນປົກກະຕິ ໄດ້ຕະຫຼອດປີ. ຈຸດປະສົງຂອງການຄົ້ນຄວ້າ ແມ່ນເພື່ອປະເມີນຮູບແບບຈຳລອງ 2 ຊະນິດ ເພື່ອຄຳນວນຄ່າໄລຍະເວລາການບວມນ້ຳຂອງດິນຈາກ ນ້ຳໃຕ້ດິນຕື້ນ, ໂດຍອີງໃສ່ການປ່ຽນແປງສີຂອງດິນເປັນຫຼັກ, ວິທີການດັ່ງກ່າວ ໄດ້ພັດທະນາມາຈາກ Blavet (2000) ໃນເຂດອາຟຼິກກາຕາເວັນຕົກ ແລະ ສັງເກດເຫັນວ່າ ວິທີການດັ່ງກ່າວ ແມ່ນເໝາະສົມ ໃນການນຳໃຊ້ ຢູ່ເຂດພູດອຍ ຂອງ ສ.ປ.ປ ລາວ ເຊັ່ນດຽວກັນ. ວິທີການດັ່ງກ່າວ ປະກອບດ້ວຍການ ປຽບທຽບຂໍ້ມູນ (ລະດັບນ້ຳໃຕ້ດິນ, ສີສັນທາງດ້ານກາຍະພາບ, ສີຂອງດິນ) ທີ່ໄດ້ມາຈາກພາກສະໜາມ ແລະ ຈາກຮູບແບບຈຳລອງ. ການທົດລອງໄດ້ເຮັດຢູ່ 2 ຈຸດ ເສັ້ນຜ່າຕັດ ທີ່ມີຄວາມແຕກຕ່າງທາງດ້ານ ພູມສັນຖານ ແລະ ລະບົບນ້ຳໃນດິນ. ຈຸດທີນຶ່ງ ແມ່ນເຂດຮ່ອມພູຕ່ຳ ມີນ້ຳຂັງທັງສອງຂ້າງ ເປັນໂນນພູ ຊັນ ແລະ ຈຸດທີສອງ ແມ່ນເຂດຮ່ອມພູແຄບ ທັງສອງຂ້າງເປັນພູຊັນແບບຫຼຸບໂນນ. ການສຶກສາເບື້ອງ ຕົ້ນ ໄດ້ໄຈ້ແຍກຄວາມສຳພັນລະຫວ່າງສີຂອງດິນ ແລະ ຄ່າສະເລັ່ຍຂອງການບວມນ້ຳໃນດິນ ເພື່ອພັດ ທະນາຮູບແບບທີ່ງ່າຍດາຍ ສຳລັບການຄຳນວນການອີ່ມຕົວຂອງດິນ ໃນເຂດພູດອຍ.

Semi-quantitative evaluation of waterlogging duration using two models based on soil colour in a representative upland catchment of northern Lao PDR

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Abstract

Groundwater is a vital resource for rural populations in tropical areas who depend on seasonal rainfall. Groundwater is often the only source of water feeding streams, allowing them to flow throughout the dry season. The aim of this study was to evaluate two models for estimating the average duration that soil is waterlogged by shallow groundwater table. These models, based on variations in soil colour, were developed by Blavet et al (2000) from observations and measurements made in a semi-arid environment in West Africa. Therefore there is a need to evaluate whether these models are also pertinent in a mountainous context of northern Laos. Our approach consisted in comparing data obtained from field measurements (water table level, morpho-pedological features including soil colour) with predictions made by the models. This study was carried out along two transects with contrasting characteristics in terms of the landscape morphology as well as the soil hydrodynamic: the first was in an open swampy valley with convex hillslopes, the second was in a steep-banked and narrow valley with convexo-concave hillslopes. Preliminary results from our study identified relationships between soil colour and the mean rate of soil waterlogging and are a first step for developing an inexpensive and simple method to predict soil saturation in this environment.

Key words: *Groundwater resources; Waterlogging; Soil colour; Mountainous stream; Lao P.D.R*

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Introduction

Groundwater is a major resource for people living in tropical zones with seasonal rain. In arid and semi-arid environments, it is the only permanent water reserve, whereas in humid mountain climates, it feeds streams resulting in stream flow during the dry season.

Our study is focused on the uplands of northern Laos where groundwater plays a key role in the hydrology of the area. This water resource is used directly in shallow village wells for domestic use or indirectly from the permanent stream for small scale irrigation or to fill ponds for fish farming. Within this context and with the future perspective of predicted global changes in the Southeast Asian region (i.e. global warming, conversion of annual crops to cash crops requiring more water from the underground water table) political decision makers and land managers need to make decisions based on sound scientific data.

A number of morpho-pedological characteristics have been linked with the hydrological functioning of the soil such as the redistribution of carbonate (Bouzigues et al, 1997) or the presence of oxides (Vizier, 1974). The analysis of these indicators often requires expensive and complicated equipment (i.e. scanning electron microscope). A number of studies have shown that the colour of the soil is strongly controlled by the time course of oxidation-reduction cycles linked to the presence of the water table (Schwertmann, 1993; Franzmeier et al., 1983; Veneman et al., 1998; Faulkner and Patrick, 1992). These cycles have an impact on the mobility of elements such as iron, manganese (Fanning and Fanning, 1989) and humic compounds (Duchaufour and Souchier, 1977) which are one the principal factor affecting soil colour in tropical environments (Segalen, 1969). Several authors also described the relationships between oxido-reduction processes and soil colour using different models (Simonson and Boersma, 1972; Megonigal et al, 1993; Genthener et al., 1998; Blavet et al., 2000).

The overall objective of this study was to evaluate soil colour as a simple pedological indicator, which is easy to determine in the field, as a rapid semi-quantitative diagnostic of the water table resources in the mountainous agro-ecosytems in northern Laos. Two models developed by Blavet et al. (2000) predicting soil waterlogging based on soil colour were applied in the Houay Pano catchment.

Materials and methods

This study was carried out in the Houay Pano catchment, the biophysical characteristics of which are described in detail by Valentin et al (this issue). In order to test the models in contrasting situations, two observation and measurement transects were chosen based on of the known hydro-geochemical data of the stream (Ribolzi et al., 2005), morpho-pedological characteristics of the soil (NAFRI, 1999) and existing piezometers (Ribolzi et al., 2008 this issue). The first transect, RIB 48, is characterised by a convex open valley with a swampy area and a stream channel with gentle slope. The second, RIB 33, is in a deep and narrow convexo-concave valley.

Monitoring water table levels

The catchment was progressively equipped with a network of piezometers from 2002 to 2007. The piezometers are made of PVC with a 5.5 cm diameter and are perforated in their base for a distance of 50 cm. The depth at which these were installed depended on the depth of the water table which was determined by auger surveys. These were installed along transects perpendicular to the axis of the river (including RIB33 and RIB48). The depth of water in the piezometers was measured daily during the rainy season and weekly during the dry season. These measurements were made using a probe with an acoustic alarm.

Data collected from 2003 to 2006 were used for a descriptive statistics analysis. The minimums, first quartile maximums, medians, 3rd quartiles and averages were calculated to characterise the water levels measured in the piezometers throughout this period. Furthermore, histograms and cumulated distributions were calculated with a 10cm increment. This analysis was used to determine the time-course of soil saturation. Correlations were sought between these quantitative data and the observed soil colour.

Soil sampling and description

A soil survey with hand augers was carried out during the 2006 dry season. Soil samples were collected every 10 cm along vertical profiles in the vicinity (~1m) of each piezometer in the two selected transects. For each sample the morphology of the material was described in terms of conditions - wet colour, texture, porosity and stoniness. Morphological features associated with hydromorphy were also described (i.e. redoxic coloured spots and lines, pellicular coatings, concretions). These pedological characteristics were used to delimit the volumes of soil along transects which had been affected by the waterlogging (Figure 1).

Soil colour determinations

The soil colour was determined using Munsell colour chart (Munsell, 1976) including Munsell Hue (i.e. shade, noted Hue), Munsell Value (i.e. colour saturation, noted V) and the Munsell chroma (i.e. brightness level, noted C). The Hue is a mixture of one primary colour, white (saturation) and black (brightness). The letters referring to each Hue indicate the following colours: red (R), yellow (Y), green (G), blue (B), purple (P). The colours correspond to alphanumerical values (e.g. 10R 3/6, 10YR 3/4, 2.5Y 4/4) spread around the circle on the Munsell colour cylinder. The shades are converted into an angular coordinate, H°. By convention the colour Red Purple (10RP) is equal to 360°. The formula used for this conversion is the following:

$$H^{0} = 36 * \left(I1 + \frac{I2}{10} \right) \quad (1)$$

where I1 is the numerical coordinate of the hue (i.e. R = 0; YR=1; Y = 2; GY = 3; G = 4; BG = 5; B = 6; PB = 7; P = 8; RP = 9) and I2 is the number associated with the hue (e.g. 10 for 10YR ; 5 for 5YR etc). Table 1 shows the major hue and their corresponding angular notation H° measured in the field. H° of each hue, V and C recorded for the soil are then combined to give the redness rating (RR) proposed by Torrent et al (1983). This ratio describes the forms of iron oxides in the soil and in particular the hematite content (Schwertmann, 1993). It is defined by the following formula:

$$RR = \frac{(360 - 5\,H^{0}) * C}{18V} \quad (2)$$

Table 1 shows the correspondence between H° and RR. Correlations were then sought between these two variables and the cumulated distributions of the water levels measured in the piezometers to establish the prediction models.

Relationship between soil colour and water table levels

In experiments carried out in the semi arid environment of West Africa on granito-gneissic bedrock, Blavet et al (2000) showed that the cloud of points obtained by comparing the variables H° and RR with the mean annual rate of soil waterlogging (in %) could be described by a sigmoid type curve using the following equation:

$$\overline{WLG} = \frac{100}{1 + (ae^{bx})} \qquad (3)$$

where x is the value of H° or RR, a and b are the model constants obtained by adjusting the models using the least squares method (Table 2). Confidence intervals associated to the models follow the normal distribution were estimated as follows:

$$E\overline{WLG}_{0.95}[x] = 1,96\,g(x) \qquad (4)$$

with the hypothesis of a normal distribution of ; g(x) being the function that allowed to calculate the 95% confidence error margin from all the x values observed for H° or RR. Correlation coefficients were obtained by comparing the % values from the models with the measured values.

Results

Water table level behaviour

Figure 1 illustrates the characteristics of the water table depending on the topographic position of the two transects included in the study. On the slope in RIB 48 (Figure 1a, piezometer T3A3), the water table is found at an average depth of 118 cm (median = 110 cm), with an interquartile deviation around the median of 25 cm. The depth of the water table varied from 25.7 and 138.7 cm, thus with a maximum difference of 100 cm. Next to the stream (piezometer T3A2), the average depth of the water table was 12.7 cm (median = 12.4 cm), the interquartile deviation was only 10 cm and the water table level fluctuated between a depth of 24.4 cm and a height of 11 cm above the soil surface, thus a maximum difference between the extremes of 35 cm. On the slope in RIB 33 (Fig.1b, piezometer T1A4), the water table is found at an average depth of 445.4 cm (median = 436 cm), with an interquartile deviation of 20 cm and the difference between the extremes reached 200 cm. Next to the stream (piezometer T1A1), the average depth was 41.8 cm (median = 42.4 cm), the interquartile difference was only 5 cm and the difference between the extremes was only 69 cm (the level of the water table fluctuated between 15 and 54 cm).

Characterisation of the soils near the piezometers

On the slopes (Figure 2a), the soil close to the piezometer T3A3 (transect RIB48) was reddish grey (2.5 YR 3/2, 4/2) to reddish brown (2.5YR 4/4) down to a depth of 70cm while, near piezometer T1A4 (transect RIB33), it was reddish brown (5YR 3/4 to 5YR 4/4) down to a depth of 200 cm. The soil texture at these two piezometers is silty clay. These soils are saturated for 0 to 36 days out of 365 (0 to 10 % of the year).

Deeper into the soil horizon, from 70 cm for piezometer T3A3 and 200 cm for the piezometer T1A4, the particle size distribution of the material was more heterogeneous with a sandy-silt to sandy-clay texture. The processes of oxidation and reduction are more pronounced and are indicated by shades of dark brown (7.5YR 5/6) to greyish brown (10YR 5/2), yellowish brown (10YR 5/8) and/or yellowish olive brown (2.5Y à 5 Y 5/1) associated with reddish brown colours (2.5YR 4/6). These soils are saturated for 169 to 202 days out of 365 (46 to 55% of the year). The reduction processes are indicated by shades of greenish grey to bluish grey (5GY, 5B).

In the proximity of the stream (Figure 2b) at piezometer T3A2 the oxidation and reduction processes appeared from 10 cm in depth and from 20 cm at piezometer T1A1. These processes are highlighted by brown (7.5YR 4/2), reddish grey (2.5 YR 4/2) to dark grey shades (10YR 3/1, 5/1). These soils are saturated for 40 to 193 day in the year (11 to 53 % of the year). The particle size distribution of the material is from a silty-clay to a sandy-clay texture. Below the first 20 cm the two profiles showed morphological characteristics suggesting reduction. The shades are generally greenish grey (5GY 4/1) to bluish grey (5G 4/1).

Correlations between soil colour and water table level variations

Correlations were calculated using the values obtained from field observations for H°, RR and WLG and those predicted by the models. A first comparison (Table 2) using all the values obtained for H^0 and RR resulted in linear correlations with r2 values of 0.82 and 0.87, respectively. This result was obtained using the coefficients a and b from Blavet et al (2000) and those adjusted using the data from the transects. A second comparison taking into account the topographic position of the piezometers calculated linear correlations near the stream, with correlation coefficient r^2 values of 0.93 for H^0 and 0.98 for RR. On the slopes these cœfficients were 0.57 and 0.54, respectively. By adjusting the a and b constants from the two models with the data from the piezometers located on the slopes the linear correlation coefficient, r^2, increased to 0.78 for H^0 and 0.72 for RR (Table 2).

In Figure 3 the H^0 and RR values which were in agreement with the prediction models are indicated. This was a function of the topographic location and the duration of soil saturation at the piezometers.

Correlation between the measured H° and the model predictions

Near the stream (Figure 3a), the following H° values were the same as those proposed by the model: 63° for a saturation period of 11%; 72° for a saturation period between 6% and 53%; 126°, 162° and 234° for a saturation period between 92 and 100%.

On the slopes (Figure 3a), the following Ho values were the same as those proposed by the model: 90° for a measured saturation period of 50 to 60% is close to the model; 72° for a saturation period of 1 to 46%. However, an angular value of 45° does not agree with that proposed by the model for a soil saturated period greater than 20 %. This analysis carried out on the dominant shades of the soil indicated wide ranges of WLG between the angular value 72° and 45°.

Correlation between the measured RR and the model predictions

The piezometric measurements (Figure 1) indicated that in the first case the water table was at an average depth of 445±20 cm with a RR= 0 between 420 and 440 cm for a saturation period of 28 to 46 %. In the second case for RR=0 at 50 cm the water table was at an average depth of 41.8 cm ± 10 cm and a saturation period of 36%.

Near the stream (Figure 3b), the following values agreed with those proposed by the model: RR=0 for a saturation period of 36%; RR=1.3 for a saturation period of 11%; RR=-3.75 and -6.3 for a saturation period from 96 to 100 %. However, the values did not fit closely with those of the model for RR = 0 and a saturation period of less than 6% or equal to 53 %.

On the slopes (Figure 3b), the following values agreed with those proposed by the model: RR=0 for a saturation period between 21 and 46 %; RR=5.0 for a saturation period of 3 to 7%: RR=-1.0 which corresponded to a saturation period of 55%. However, the following values did not agree with those proposed by the model: RR=11.3 for a saturation period of 16 to 39%; RR=0 for a saturation period of less than 21%.

Discussion

On the slopes, our observations of the dominant colours and piezometric measurements agree in part with H° predicted by the model adjusted with observations from transects. But we could improve the model by taking into account other parameters such as the proportion of the dominant shade compared with and the presence of spots and/or gleyic volumes (Figure 2a). This would complete the correlations between measured values and those predicted by the model.

When we recorded the colour in the field an inaccuracy may have been introduced by the fact that all the soil profiles were not examined in exactly the same sunlight conditions. This bias could be avoided, at least partly, by using a field spectrophotometer.

The model based on the redness rating can be used to specify the degree of colour saturation (Value) and brightness (Chroma) for each soil colour shade, which can have a strict correlation with the period of waterlogging experienced by the soils due to fluctuations in water table level. At RIB 48 (Figures 2b and 3), on the hillslope and near the stream, for a saturation period ranging from 21 to 46%, the angular value and RR are about 72 and 0 respectively. This indicated that for these two situations, the soil colour had the same dominant shade (i.e. 10 YR) but a different hue and chroma: on the slope the soils were a light yellow brown colour (i.e. 10 YR 5/8) whereas near the stream they were greyish brown (i.e. 10 YR 5/1).

In this study, we only took into account the annual average duration of soil saturation. In a study carried out on a toposequence in North Carolina, He et al (2003) showed that soils must be saturated for 21 consecutive days in the year for iron reduction to be seen as lasting morpho-pedological feature.

Conclusion and perspectives

Our study showed that the prediction models developed on data obtained in a semi-arid African environment can be applied to a mountainous tropical region of northern Laos. Significant correlations between soil colour and piezometric measurements have been identified, which allowed us to use existing models of waterlogging prediction based on colour indicators. This work represents a first step towards developing an inexpensive, simple and indirect method for predicting soil waterlogging. Future research should focus on the cycles of reduction or oxidation in the soils throughout the year on the morpho-pedological characteristics in the dry season.

Acknowledgements

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Table 1 – *Correspondences between the alphanumerical values for the soil colour observed in the field (i.e. Hue, value and chroma), with their angular notation (H°) and red ratio (RR).*

Hue	Value	Chroma	H° (degrees)	RR
10 R	3	6	36	20
2.5 YR	3	2	45	5
	4	2	45	3.75
	4	6	45	11.3
5 YR	4	4	54	5
7.5 YR	4	2	63	1.3
	5	6	63	3
10 YR	4	1	72	0
	3	1	72	0
	5	8	72	0
2.5 Y	5	1	81	-3
5Y	5	1	90	-1
5GY	4	1	126	-3.75
5B	4	1	234	-11.25

Table 2 – *Coefficients a and b from the model by Blavet et al (2000) and adjusted values using data from RIB48 and RIB33. Comparison of the correlation coefficients (r2) for the two transects (s & rb), on the hillslope (s) and near the stream (rb). The input value used in the models was either the angular coordinate Ho or the red ratio (RR).*

Variables	*a*	*b*	*n*	r^2	Position
Coefficients a and b from Blavet et al (2000)					
H°	382353	- 0.16	40	0.82	s & rb
			29	0.57	s
			11	0.93	rb
RR	2,07	1	40	0.87	s & rb
			29	0.54	s
			11	0.98	rb
Coefficients a and b adjusted					
H°	382353	- 0,16	40	0.82	s & rb
		- 0,14	29	0.78	s
		- 0,16	11	0.93	rb
RR	2.07	1.2	40	0.87	s & rb
	3.9	1.4	29	0.72	s
	2.07	1	11	0.98	rb

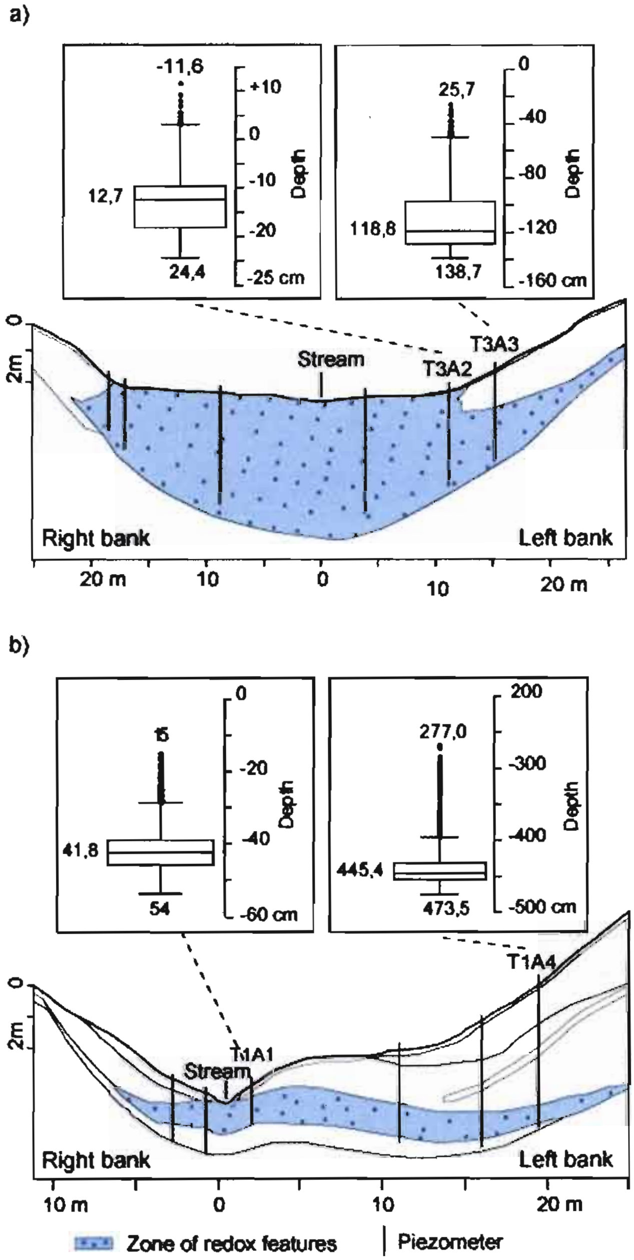

Figure 1 – *Schematic showing a transversal section of the interaction zone between the stream and the water table for the traverses RIB48* ***a)*** *and RIB33* ***b)****; Location of the piezometers (T3A2, T3 A4, T1A1, T1A4) along the transects; Map of the subsurface zones showing redoximorphic features. Whiskers plot (1st quartile, mediane, 3rd quartile, minimum and maximum) of water table levels measured in the two piezometers at each site.*

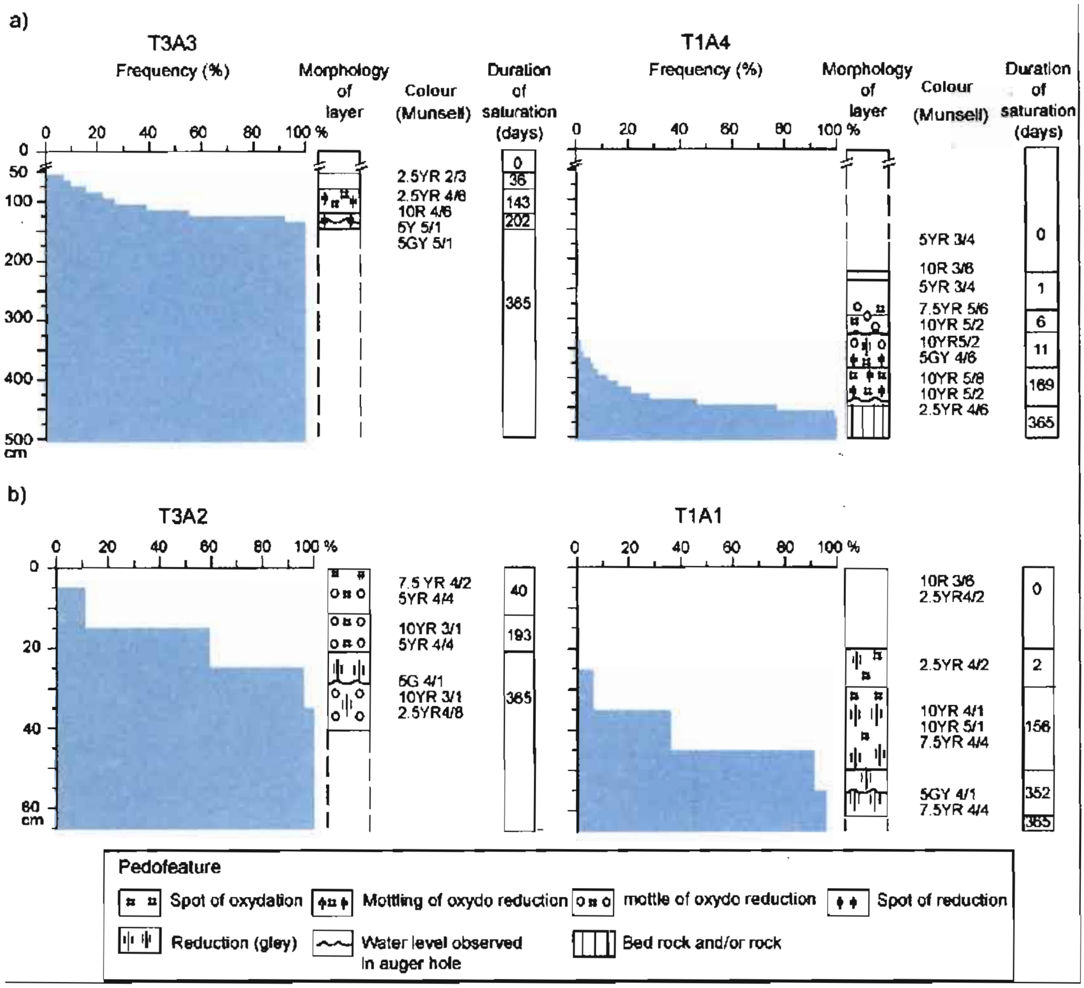

***Figure 2** – Histograms showing the combined frequencies and pedological characteristics linked to the duration of soil saturation **a)** on the slopes (piezometers T3A3 at transect RIB48 and T1A4 at transect RIB33) and **b)** on the stream bank (T3A2 piezometers at transect RIB48 and T1A1 at transect RIB33).*

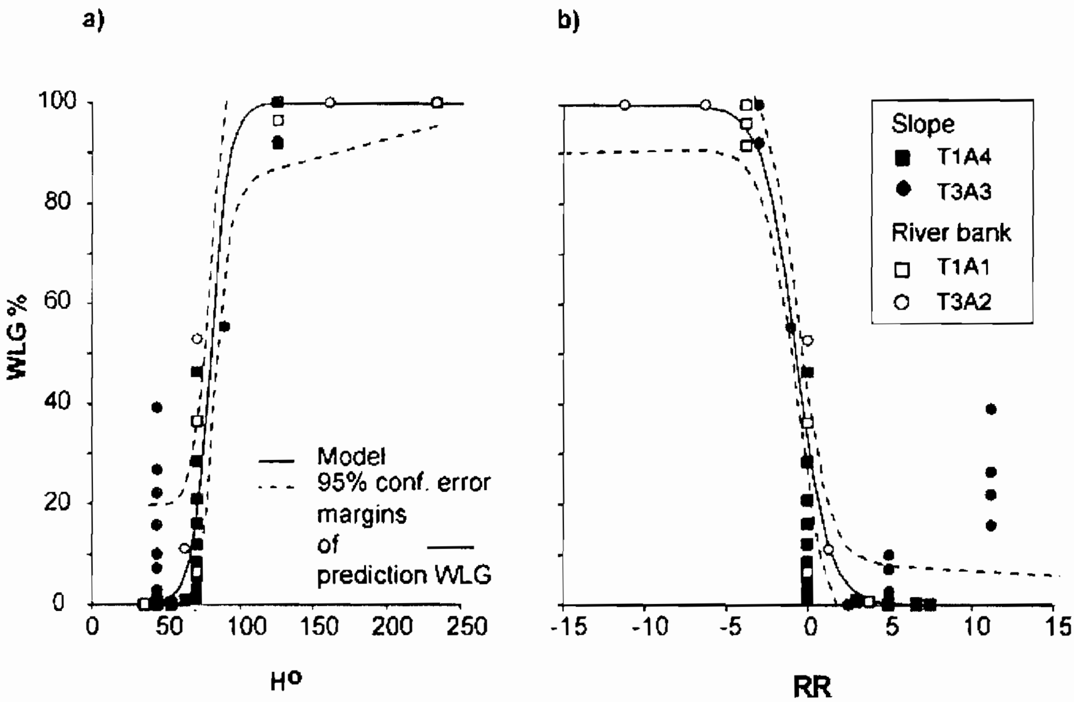

Figure 3 – *Frequency of soil saturation (WLG %) as a function of a) the angular value (Ho) and b) the red ratio (RR).*

ການປະເມີນໂຄງປະກອບຂອງດິນ ແລະ ການຕິດຕາມການບັນຈຸນ້ຳໃນດິນ ໂດຍການນຳໃຊ້ເຄື່ອງວັດແທກ (ERT) ໃນເຂດພູດອຍຂອງ ສ.ປ.ປ ລາວ

ອອງ ໂຣແບງ, ແຢນ ເລີໂຕແກ, ພາວິໄລ ສູນຍະວົງ, ບີຊົງ ຈາກົວ,
ເອມານຸ ບອກດົງ ແລະ ໂອລີວີເອ ຣິໂບຊີ

ບົດຄັດຫຍໍ້

ເຄື່ອງວັດແທກ (ERT) ໄດ້ນຳໃຊ້ເພື່ອຕິດຕາມນ້ຳບັນຈຸໃນດິນ ໃນເຂດອ່າງໂຕ່ງ ຫ້ວຍປ່ານໍ່ ແຂວງຫຼວງພະບາງ. ໄດ້ນຳໃຊ້ຂໍ້ມູນທີ່ໄດ້ມາຈາກເຄື່ອງວັດແທກ ແລະ ຈາກການເຈາະດິນຕາມໜ້າຕັດດິນມາສົມທຽບກັນ. ເຄື່ອງວັດແທກດັ່ງກ່າວ ສາມາດວັດແທກການຜັນແປຂອງລະດັບນ້ຳໃຕ້ດິນຕາມຄວາມຄ້ອຍຊັນຂອງພື້ນທີ່ໄດ້ຢ່າງຖືກຕ້ອງ. ຈາກການທົດລອງ ສາມາດຢືນຢັນໄດ້ວ່າ ປະລິມານ ຂອງນ້ຳຫ້ວຍແມ່ນຂຶ້ນກັບປະລິມານນ້ຳທີ່ສະສົມໄວ້ໃນດິນ ໂດຍຜ່ານການຊຶມລົງດິນຂອງນ້ຳຝົນ ແລະ ນ້ຳໃຕ້ດິນຈະປ່ອຍນ້ຳອອກມາຫຼາຍ ໃນເຂດດິນທີ່ມີປ່າເຫຼົ່າປົກຄຸມ ສ່ວນເຂດດິນທີ່ໄດ້ນຳເຂົ້າໃນການປູກຝັງ ຈະປ່ອຍນ້ຳໃຕ້ດິນອອກມາໜ້ອຍກວ່າ.

Assessment of soil organisation and monitoring of soil water content using Electrical Resistivity Tomography in the Uplands of Lao PDR

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Abstract

An Electrical Resistivity Tomography monitoring experiment was carried out in the uplands of Lao PDR in the Houay Pano experimental catchment. By comparing data obtained from the calculated cross section of electrical resistivity with hand auger observations, the detailed soil organisation in such a complex mountainous environment was characterised. By comparing the seasonal variation of ground electrical resistivity with the monitoring of groundwater level through a series of piezometer monitoring points, ground water fluxes along hillslopes can be measured precisely. Our study confirmed that stream water mainly corresponds to pre-event water stored in soils that is forced out by the infiltration of fresh rain water. The study also indicated that ground water recharge is larger for hillslopes with fallow vegetation than for cultivated hillslopes where soils are bare at the beginning of the rainy season suggesting the importance of surface cover on infiltration.

Key words: *Shallow groundwater resources; Geophysical measurement; Soil resistivity; Mountainous stream; Lao P.D.R*

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Introduction

In the uplands of the Lao PDR population growth and resettlement policies have led to recent changes in land use. In this region, cultivated areas on marginal sloping lands have greatly increased, fallow periods have become shorter and new cash crops such as plants for biofuel (e.g. jathropha) or plantation timber (e.g. teak) are competing with former food-producing farmland or forest land.

In this context, knowledge of soil water content is of major importance to implement new sustainable agricultural practices that conserve soil ecological services. It is well known that within a small catchment, the soil water content may vary considerably both in space and time. In an agricultural context, these variations are controlled by complex interactions between i) surface water inputs (rainfall and streams), ii) soil structure which controls water infiltration and storage and iii) water uptake by plants. The last two factors are strongly influenced by changes in land use and agricultural practices.

Generally, variations in soil water content are measured using invasive methods which disturb soil conditions (e.g. measurements of the gravimetric water content require sample removal, water content measurements with Time Domain Reflectometry or neutron probes require that holes are drilled). Furthermore it is often difficult to establish generalities concerning large areas based on these local measurements.

Due to improvements in the feasibility of performing intensive calculations with personal computers, Electrical Resistivity Tomography (ERT) has been used in many recent soil research studies (e.g. Dahlin, 1996; Reynolds, 1997, Samouëlian et al. 2005). Indeed, this innovative geophysical method operated from the soil surface is not invasive, easily reproduced and the different soil layers can be rapidly characterised with very dense sampling. The measured parameter is ground electrical resistivity which depends on i) the type, size and arrangement of solid constituents; ii) water content; iii) the ion concentration in soil water and iv) soil temperature (Campbell et al., 1948; Rhoades et al., 1976; Kalinski and Kelly, 1993). The different soil layers are delineated by measuring variations in electrical resistivity along a cross section (e.g. Griffiths and Barker, 1993; Robain et al. 1996; Tabbagh et al., 2000), and water content changes in each layer are characterised by determining variations in electrical resistivity with time (e.g. Daily et al. 1992; Ramirez et al. 1993; Benderitter and Schott, 1999; Hahesy et al., 2000; Aaltonen, 2001; Zhou et al., 2001; Michot et al., 2003).

This paper presents some results obtained in the Houay Pano experimental catchment using an integrated approach combining high resolution non-invasive ERT measurements and low resolution invasive measurements made with auger holes and piezometers. The study aimed to i) assess the detailed soil organisation and ii) obtain a comprehensive understanding of the connexions and fluxes between groundwater in hillslopes and river banks, on the one hand, and stream surface water, on the other hand.

Material and methods

Site Description

The biophysical characteristics of the surveyed site, namely the Houay Pano catchment, are described in detail by Valentin et al (this issue).

The traverse RIB48 presented in this article is located in the central part of the catchment (Figure 1a) where the valley is rather large and corresponds to a swampy area. The land use on the right hillslope was fallow and the left hillslope was cultivated (rice). The geographical coordinates of the traverse were recorded with a hand GPS (GARMIN XL12) and the topography determined with a laser theodolite (NIKON DTM 332). The elevation AMSL of the traverse was referenced to a DGPS survey (TRIMBLE 5700) undertaken along the Houay Pano stream in 2006.

The groundwater level variations presented in this article were measured with 4 piezometers (Figure 1b) located approximately 0.5 m and 1 m above the stream base level on the right and left banks, respectively. Groundwater level monitoring was made with a manual probe, weekly until mid May 2007 and then daily after that.

Electrical Resistivity Tomography (ERT)

ERT is based on the measurement of ground electrical apparent resistivity. To perform the measurements, an electrical current of known intensity (I in Amperes) is released into the ground using a pair of metallic electrodes (C_1 and C_2) and then the resulting difference of electrical potential (ΔV in Volts) is measured between another pair of electrodes (P_1 and P_2). The electrical resistivity is given by the following equation:

$$\rho_a = K \cdot \frac{\Delta V}{I} \text{ (in } \Omega\text{.m)}$$

with $K = \frac{2\pi}{\frac{1}{C_1P_1} - \frac{1}{C_1P_2} - \frac{1}{C_2P_1} + \frac{1}{C_2P_2}}$

with C_1P_1, C_1P_2, C_2P_1 and C_2P_2 the distances (in m) between the electrodes of the measurement quadrupole.

P_a corresponds to a value normalised by the geometrical characteristic of the measurement array and is called the apparent resistivity. For homogeneous ground it is equal to the actual ground resistivity. For heterogeneous ground it is a convolution of the different resistivities. A set of measurements using quadrupoles with increasing size is required to calculate the distribution of actual resistivities. The curve of apparent resistivity as a function of array size is known as the Direct Current Vertical Electrical Sounding (DCVES). This curve allows a 1D geoelectrical model to be calculated (i.e. the variation of electrical resistivity along a vertical axe) using specific software. ERT consists of measuring numerous soundings close to one another along a linear traverse. This data set allows a 2D model of ground resistivity variation to be calculated - i.e. the variations of electrical resistivity along a cross section (Lines and Treitel, 1984; Ellis and Oldenburg, 1994; Loke and Dahlin, 2002).

The data set presented in this study was obtained with a multi-electrode resistivity meter (SYSCAL R2 – MULTINODE equipment, Iris Instruments). With this device the apparent resistivity for numerous quadrupoles of increasing size can be measured automatically with an array of 64 equidistant electrodes. For this study the unit inter electrode spacing was 1.5 m which corresponds to a traverse total length of 94.5 m.

The quadrupole configuration used is known as the Wenner-Schlumberger configuration. It corresponds to a quadrupole $C_1P_1P_2C_2$ where the distances C_1P_1 and P_2C_2 are equal and where distance P_1P_2 is a fraction of distance C_1C_2. When this fraction is equal to 1/3, the configuration is called Wenner *a*.

SYSCAL R2 uses a commutation program to connect sequentially chosen $C_1P_1P_2C_2$ quadrupoles among the 64 electrodes. The 828 apparent resistivity measurements obtained are represented on a conventional graph (Figure 2). For the Wenner-Schlumberger array, the X coordinate is the centre of bipole P_1P_2. The Y coordinate is a pseudo-depth equal to half distance between C_1 and C_2.

Each resistivity measurement was repeated at least 3 times and up to 6 times, when the experimental deviation was greater than 1%. Measurements that still had an error factor of more than 1% were not used in the analysis. In the most unfavourable cases, the rejected measurement points represented approximately 5% of the total set of measurements along the traverse.

This paper presents ERT measurements obtained in 2007 at the end of the dry season (19/01), at the beginning of the rainy season (24/04), and the middle of the rainy season (01/08) (Figure 3). This data set was processed using the commercial software RES2DINV (Geotomo Software, Malaysia). Since measurements were made in the same location at different dates, a 2D model of the underground resistivity distribution as well as its variation with time could be calculated (Loke, 1999; Leroux and Dahlin, 2006).

Results

Variations in the groundwater level

Rainfalls and groundwater levels monitored during the period are presented in Figure 4. Groundwater fluctuations appear to be strongly influenced by rainfall events with very rapid rises in the groundwater level upon rain and then sharp exponential decays. This behaviour is linked to the storm floods observed in the stream.

Readings from the piezometers close to the stream (48R2 and T3A2), showed that groundwater levels were almost constant and lower than the stream baseline until mid June. After this date, levels increased gently and only surpassed the stream baseline after the heaviest rainfall events. A strong difference between readings from distant piezometers placed on the left and right banks was observed. For the right bank (48R1), the fluctuations were the same as those observed with the close piezometers. For the left bank (T3A3) the variation amplitude was much larger. A decrease starting above the stream baseline was seen until the end of the dry season. Then increases were observed just after the beginning of the rainy season, at first these were gradual (until the end of June) and then became more rapid with very sharp fluctuations of more than 0.5 m in amplitude.

ERT monitoring

The 2D models calculated from the resistivity data are shown in Figure 5. Three main layers can be seen in the cross sections: a top resistive layer, a conductive intermediate layer and a resistive layer at the bottom. The more complex soil organisation is also included on the models. Important differences were observed between the right and left bank of the stream. These differences concern both the shape and resistivity of the layers.

The cross section shows several anomalies of high resistivity deviating from the general resistivity pattern along hillslopes in the top layer. These were more pronounced on the right bank than on the left bank. The conductive layer extends over the whole cross section and reaches the surface under the swampy area. The resistivities are lower under the hillslopes than under the swampy area. An anomaly of low resistivity is observed in the intermediate layer at the foot of the right hillslope. The top of the bottom resistive layer rises at the right end of the swampy area.

Variations in resistivity with time did not significantly change the general aspect of the cross sections. Nevertheless the differences relative to the initial resistivities are significant. Their statistical characteristics are presented in Table 2. The mean measured apparent resistivities did not vary between January and April (transition between dry and rainy season) but decreased between April and August (transition between the beginning and the middle of rainy season). On the other hand, the standard deviations of measured apparent resistivities decreased for both time intervals with a larger drop between January and April than between April and August.

The mean calculated resistivity decreased for both time intervals. The drop was lower between January and April than between April and August. The standard deviations also decreased for both time intervals but, as in the case of the measured apparent resistivities, the drop was larger between January and April than between April and August.

Regarding the distribution of the changes in resistivity in the cross section relative to dry season, some general trends can be inferred:

- The transition between the dry and rainy seasons corresponded to a decrease in resistivity at the top of the cross section, a more or less pronounced increase at intermediate depth and a complex pattern at the bottom of the cross section. It is also noted that increases in resistivity in the intermediate layer were connected with the soil surface between the high resistivity anomalies observed along hillslopes in the top layer. This indicates that the pattern of the resistivity variations with time is influenced by the differentiations in the top layer of soils which are shown by the anomalies in resistivity.

• The transition between the beginning and the middle of the rainy season corresponded to an extension, both in amplitude and in thickness, of decrease in resistivity at the top of the cross section, a diminution of the increase observed at intermediate depth and a conservation of the complex pattern observed at the bottom.

• Important differences were observed for the increase in resistivity at intermediate depth between the left and right banks. At the beginning of the rainy season, the increase in resistivity was continuous across the whole section and extended to depth under the swampy area. The amplitude of the increase was more pronounced for the right bank than for the left bank. At the middle of the rainy season, the resistivity increase almost disappeared for the left bank and was confined to several areas for the right bank.

Conclusion

This study shows that ERT provides relevant data to address the spatial variations of soils in a complex context such as a mountainous environment. In particular it appears that using this technique, landslides and bedrock inhomogeneities, which strongly influence the organisation of soils along hillslopes, are clearly detected. This information is very useful to guide the implementation of observation and/or experimentation plots.

By monitoring resistivity variations with time the water fluxes can be assessed in this type of environment. On one hand, it confirms that in this catchment rain water infiltrates very rapidly and pushes out the pre-event groundwater which principally contributes to the storm floods observed in the stream. On the other hand, it appears that the general pattern of water content variations in the top layers is strongly influenced by plant cover. High levels of water uptake occur in vegetated soils and hence water content during the rainy season is highly variable. Bare soils present lower variations in water content and consequently are more subject to surface runoff which decreases the budget of catchment groundwater recharge.

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Table 1 – *Elevation of piezometers relative to the local stream base level*

Piezometer	Elevation	Delta Elev
T3A3	525.92	1.42
T3A2	524.81	0.31
Stream	524.50	
48R2	524.94	0.44
48R1	525.57	1.07

Table 2 – *Statistical parameters of measured and calculated electrical resistivities. The changes in resistivity models are both calculated relative to January.*

Date		19/01/2007	24/04/2007	01/08/2007
Data : Apparent Resistivity (Ohm.m)	Number	828	828	828
	Number	836.6	463.8	403.3
	Max	24.0	22.0	20.4
	Mean	69.8	69.9	61.5
	STD	78.4	59.5	46.3
Model : Calculated Resistivity (Ohm.m)	Number	1344	1344	1344
	Max	1189.6	591.2	495.9
	Min	7.8	8.5	8.3
	Mean	107.5	95.0	79.3
	STD	174.1	117.5	94.0
Model Changes (%)	Max		146.4	103.1
	Min		-62.2	-65.1
	Mean		3.2	-9.8
	STD		24.2	21.6

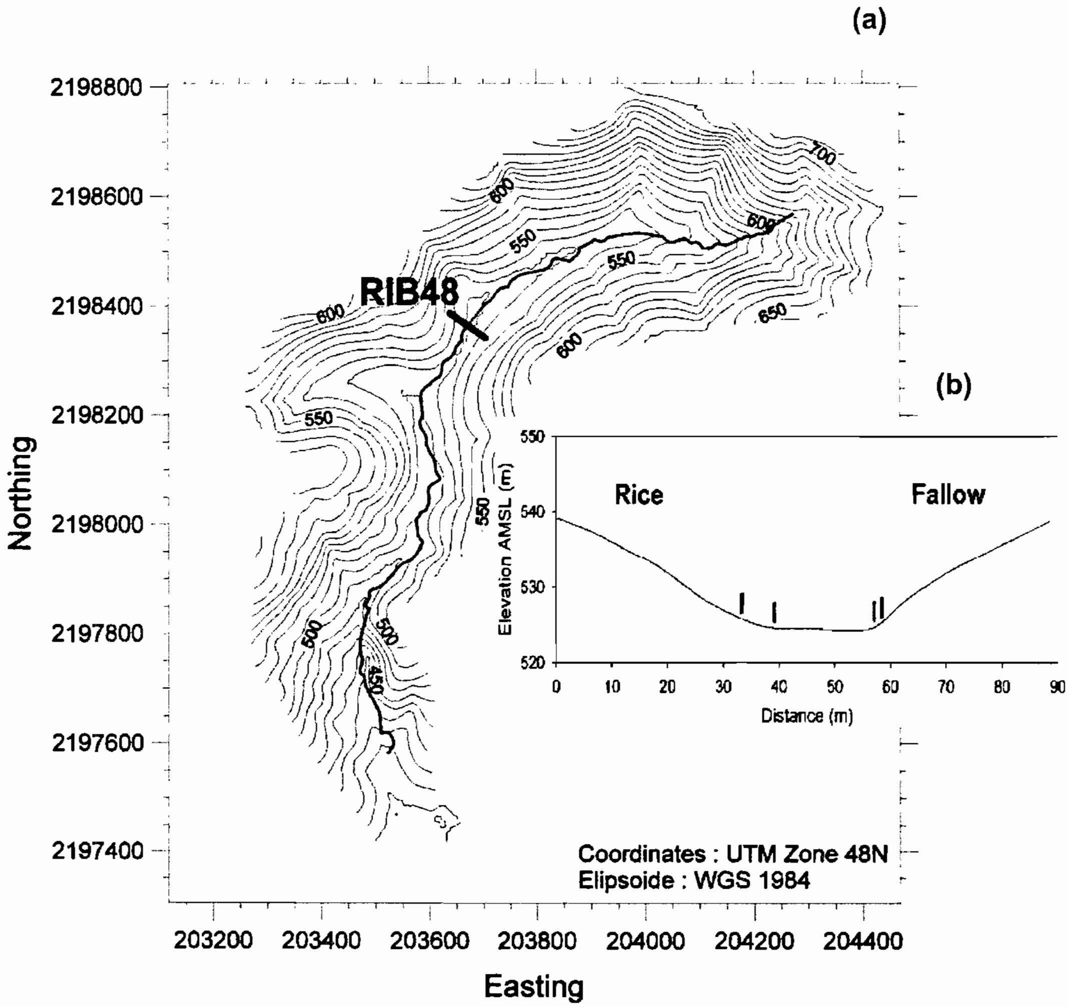

Figure 1 – ***(a)*** *Traverse RIB48 location and topography.* ***(b)*** *Elevation profile showing the location of piezometers (blue vertical lines).*

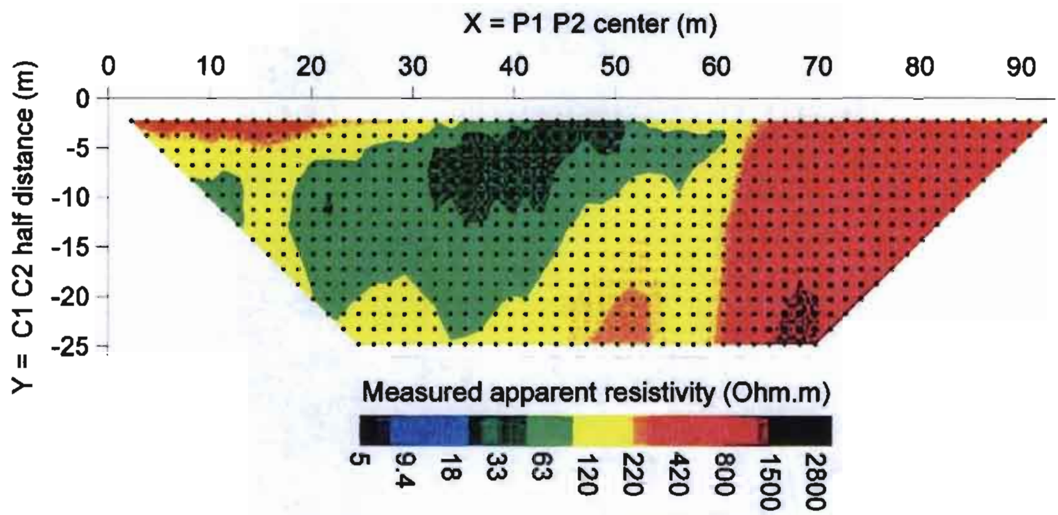

Figure 2 – *Conventional representation of a set of apparent resistivity measurements.*

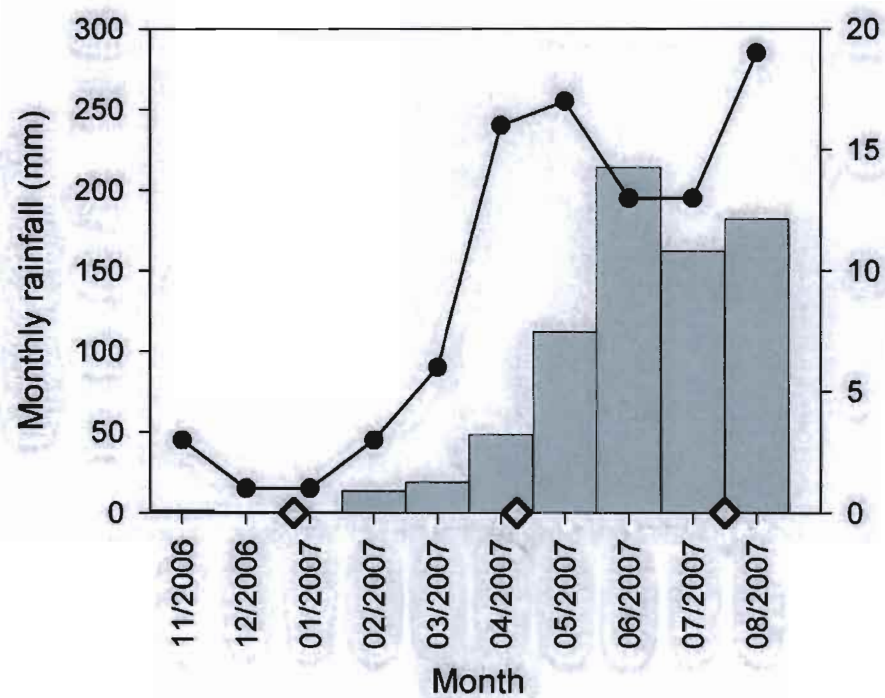

Figure 3 – *Monthly rainfall in the Houay Pano catchment. The bar chart represents monthly rainfall; the line plot, the number of rainy days; the three dates on which ERT measurements were made are indicated along x axis by the diamond symbols.*

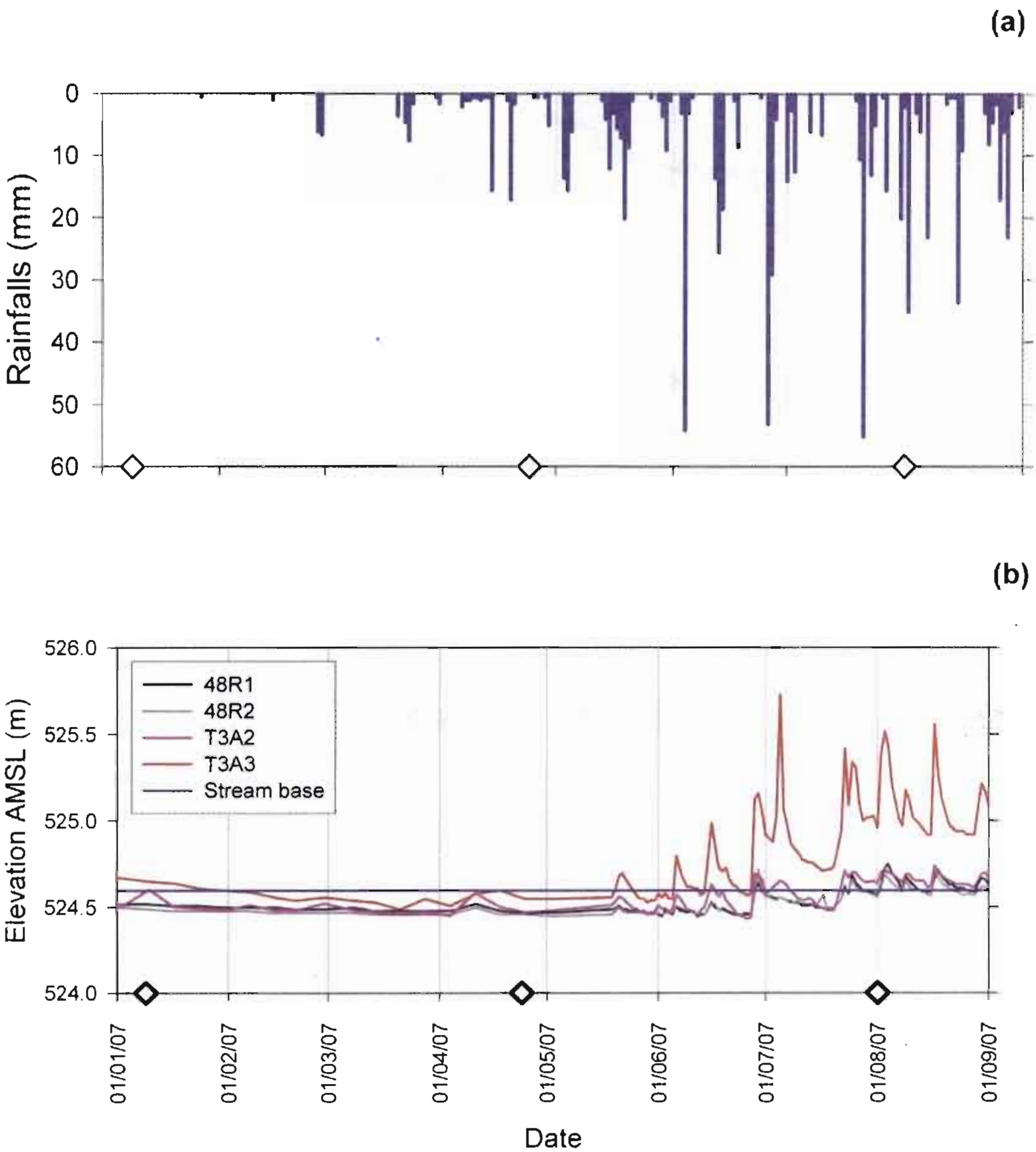

Figure 4 – *Daily rainfall **(a)** and groundwater level variations **(b)**.*

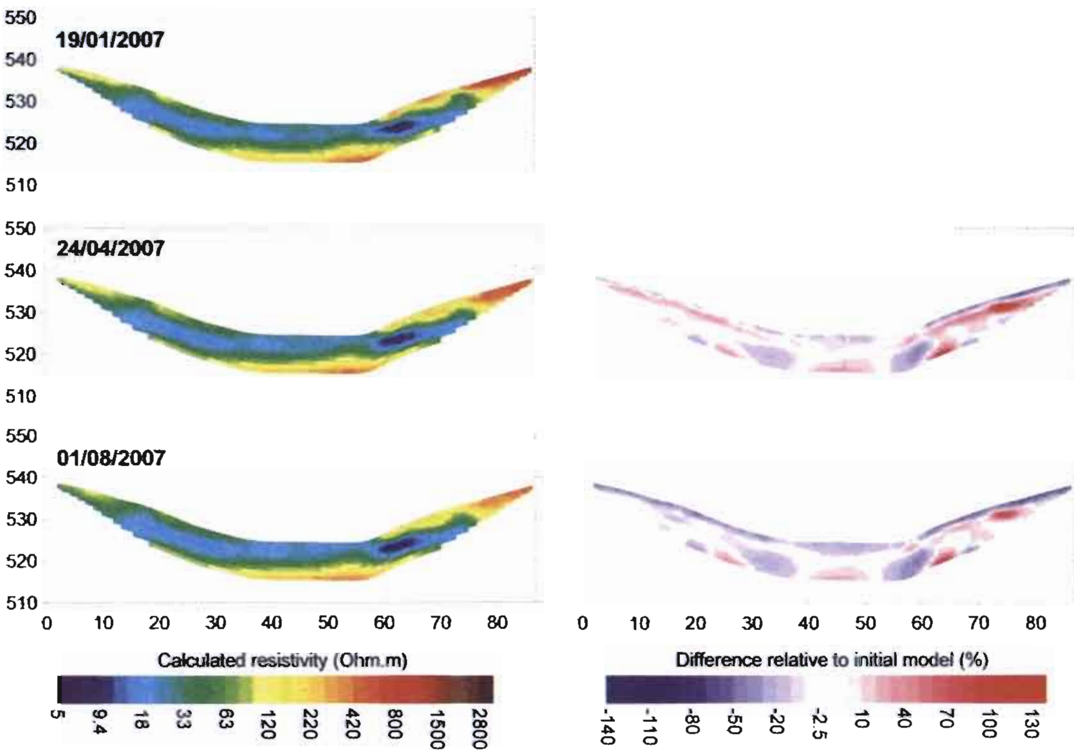

Figure 5 – *Calculated 2D resistivity models (left) and variations relative to the end of dry season (right).*

ການນຳໃຊ້ຄວາມຮູ້ທ້ອງຖິ່ນ ແລະ ວິທະຍາສາດ ໃນການແກ້ໄຂ ບັນຫາດິນເຊື່ອມຄຸນ: ການສຶກສາແບບມີສ່ວນຮ່ວມ ກໍລະນີ ຢູ່ ບ້ານຫູ້ກສິບ, ແຂວງຫຼວງພະບາງ

ເລສເຕີລິນ, ເປເຕຣ, ວິຊຽກ, ແກ້ວທາວົງ, ວາເລນຕິນ

ບົດຄັດຫຍໍ້

ບົດນີ້ ໄດ້ເວົ້າເຖິງການປຽບທຽບຂໍ້ມູນທາງດ້ານກາຍະພາບ ແລະ ຄວາມຮັບຮູ້ຂອງຄົນທ້ອງຖິ່ນ ກ່ຽວກັບບັນຫາການເຊື່ອມຄຸນຂອງດິນ ທີ່ບ້ານຫູ້ກສິບ, ແຂວງຫຼວງພະບາງ. ຂໍ້ມູນ 2 ຊະນິດ ໄດ້ນຳມາໃຊ້ ເພື່ອຕັ້ງບັນຫາທີ່ກ່ຽວພັນກັບການເຊື່ອມຄຸນຂອງດິນ ໃນເຂດດັ່ງກ່າວ. ຈາກນັກວິຊາການ ແລະ ອົງການພັດທະນາສາກົນໃນລາວ ເຫັນວ່າ ການເຮັດໄຮ່ ເປັນສາເຫດເຮັດໃຫ້ດິນເຊື່ອມຄຸນ. ຈາກການເກັບກຳຂໍ້ມູນທາງດ້ານກາຍະພາບ ເຫັນວ່າ ການສູນເສຍດິນຈາກການເຊາະເຈື່ອນ ແມ່ນໄປຄຽງຄູ່ກັບການຂະຫຍາຍເນື້ອທີ່ປູກພືດປະຈຳປີ. ເຊັ່ນດຽວກັນກັບຄວາມເຫັນຈາກປະຊາຊົນທ້ອງຖິ່ນ ເຫັນວ່າ ການເຊື່ອມຄຸນຂອງດິນ ແມ່ນມາຈາກການເຮັດໄຮ່. ແຕ່ກົງກັນຂ້າມ ການກັດເຊາະດິນ ບໍ່ແມ່ນປັດໄຈຕົ້ນຕໍທີ່ເຮັດໃຫ້ດິນເຊື່ອມຄຸນ. ປະລິມານການສູນເສຍດິນ ຈາກການເຊາະເຈື່ອນ ທີ່ໄດ້ເກັບກຳມາເປັນເວລາ 5 ປີ ແມ່ນຖືວ່າ ບໍ່ຢູ່ໃນຂັ້ນອັນຕະລາຍ. ໃນຕົວຈິງ ຄົນທ້ອງຖິ່ນເຂົ້າໃຈວ່າ ການເຊື່ອມຄຸນນະພາບຂອງດິນ ແມ່ນມາຈາກໄລຍະປ່າເຫຼົ່າສັ້ນລົງ ເຮັດໃຫ້ຄວາມອຸດົມສົມບູນຂອງດິນ ແລະ ຜົນຜະລິດຫຼຸດລົງ ແລະ ຕ້ອງໃຊ້ແຮງງານເພີ້ມຂຶ້ນໃນການເສຍຫຍ້າ. ສະຫຼຸບໄດ້ວ່າ ຕ້ອງເຂົ້າໃຈບັນຫາສິ່ງແວດລ້ອມຂອງທ້ອງຖິ່ນໃຫ້ເລິກເຊິ່ງ ໂດຍນຳໃຊ້ວິທີການສຶກສາແບບປະສົມ ເພື່ອສຶກສາການປ່ຽນແປງຂອງສະພາບແວດລ້ອມ.

Integrating scientific and local knowledge of land degradation: a participatory case study in Ban Lak Sip, Lao P.D.R.

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Abstract

The results of a study comparing biophysical measurements and local perceptions of land degradation in Ban Lak Sip, Luang Prabang Province, Lao PDR are presented. Two data sets were used to question the role of environmental policy in the uplands with respect to the land degradation issues. In line with the view shared by the Laotian authorities and a number of international development agencies, upland shifting cultivation does appear to be a primary cause of land degradation in our study area. Biophysical measurements have indicated a significant statistical correlation between the spatial extent of annual crops and sediment yields. Similarly, a large majority of farmers interviewed perceive that the main causes of land degradation are all related to shifting cultivation practices. However, in contrast with a frequent viewpoint, soil erosion is not necessarily a primary factor in land degradation in Ban Lak Sip. Sediment yields recorded over a 5-year period at the outlet of the Houay Pano catchment dô not appear to be at a critical level. In fact, villagers' perceptions suggest that land degradation is related to shortened fallow periods and hence to reduced soil fertility and yields, and increased labour, than perceived soil erosion. We conclude that a better understanding of local environmental issues can be gained by using a 'hybrid research' approach to study environmental change.

Key words: *Participatory approach; Land degradation; Farmer perception; Upland shifting cultivation; Soil fertility Lao P.D.R*

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Introduction

Since the late 1980s, the Laotian state has placed environmental conservation at the core of its rural development strategy and emphasised the importance of natural resources for economic growth and poverty reduction. Laotian authorities and international development agencies active in the country, agree that Laos' development is threatened by a 'chain of degradation' which includes deforestation, increased runoff, soil erosion and related downstream impacts such as the increased frequency and intensity of floods and droughts, sediment accumulation in streams and siltation of wetlands and reservoirs (e.g. GoL 1999, 2003; UN 2000; UNEP 2001; MRC 2003).

The upland areas of Laos are often described as having embarked on a 'downward spiral' of environmental degradation and poverty, and are therefore attributed a particular role and importance in this issue. In a general context of ecological fragility, arable land scarcity and endemic poverty, traditional shifting cultivation practices are believed to combine with population growth to engender deforestation and land degradation which, in turn, undermines farming activities and exacerbates poverty. Increased poverty may drive upland populations to further intensify their pressure on natural resources in order to maintain a decent living (e.g. GoL, 1999; UN, 2000; UNEP, 2001). This 'chain of degradation' is believed to threaten the national economy; in particular, two of the country's major sources of revenue: lowland agriculture and hydroelectricity. Indeed, siltation of wetlands and reservoirs, downstream water shortages and floods are often cited as the main consequences of 'improper' management of the uplands (e.g. GoL, 2003; MRC, 2003). The main objectives of this study were 1) to gain insight into the 'local reality' of land degradation in the uplands and 2) based on these findings, to assess whether upland agriculture really represents a threat to downstream activities and, more generally, the Laotian national economy.

Centred on a case study in Ban Lak Sip, an upland village in the Luang Prabang province, our methodological approach involved both quantitative monitoring of biophysical indicators of land degradation and the collection of more qualitative insights from local land managers. Two reasons motivated this 'hybrid research' approach. Firstly, as pointed out by various authors (e.g. Murdoch and Clark 1994; Ericksen and Ardon 2003; Stringer and Reed 2007), neither scientific nor local knowledge of land degradation is comprehensive. Biophysical monitoring provides very precise measurements related to land degradation processes. However, these measurements are often limited to a particular set of indicators and/or a short time scale. They are also difficult to link to broader social, contextual information that is necessary to understand how and why degradation is occurring. Complementing biophysical approaches, local knowledge provides an alternative perspective on land degradation. However, the use of local knowledge is not straightforward. Practical experience and local perceptions can be quite different, even contradictory, depending on e.g. individuals' social background. Thus, relying exclusively on local accounts may reflect changes in local populations' concerns and expectations rather than actual land degradation dynamics. Hence, combining biophysical measurements with an approach that draws on local perceptions allows information triangulation, verification and complementation, thus leading to a more accurate and comprehensive understanding of land degradation.

Secondly, while it is now widely recognised that farmers possess an important body of knowledge concerning soils and their use for agriculture (e.g. Blaikie and Brookfield 1987; Zimmerer 1994; Wrinklerprins 1999), this knowledge is often only partially exploited. As Niemejer and Mazzucato (2003) pointed out, most of the studies related to local knowledge of soils "focus on either correlation and comparison of local classifications with scientific soil classification systems and methods or on agricultural adaptation and decision-making in relation to local soil classifications" (2003: 404). By contrast, very few studies focused on the 'theories' that local populations have on soil formation and land degradation processes. While commendable, the few attempts made to capture local soil knowledge in Laos clearly reflect these shortcomings (e.g. Douangsavanh et al. 2006; Saito et al. 2006). Lastly, adopting a research approach that integrates not only local perceptions of soil differences but also local actors' definition of land degradation is one way of working towards the empowerment of local populations.

Biophysical measurements

A survey of linear soil erosion in the Houay Pano watershed was conducted from 2001 to 2003. The survey consisted of rill and gully counts, length measurements and assessment of their volumetric evolution during the rainy season (Chaplot et al., 2005a). Fourteen, twenty-five and thirteen rills and gullies were observed during the first, second and third year of survey, respectively. Most of the rills appeared in fields cropped with annuals during aggressive rainfall events and stretched from mid-slope to footslopes (Valentin et al., this issue). While a few rills expanded and deepened gradually over the three years to form gullies, sometimes exposing bare rock on the surface, most rills disappeared within one year, either because they got filled in with branches and vegetation debris brought in by farmers or because they were covered by fallow vegetation. In this watershed, overall annual soil losses due to linear erosion were estimated to be 2.4, 1.5 and only 0.1 ton per hectare in 2001, 2002 and 2003, respectively (Table 1). A significant correlation between linear erosion and the spatial extent of annual cultivation was found in 2001 and 2002, but not in 2003. Even though 2002 and 2003 had similar annual and monthly rainfall amounts and comparable proportions of land covered by annual crops, linear erosion decreased in 2003 rather substantially. These results illustrate the major role played by rainfall intensity in triggering linear erosion. In fact, the positive correlation between the area of annual cropping and rill formation exists only when rainfall events reach a particular intensity threshold and, in 2003, rainfall events were of consistently low intensity throughout the year.

From 2001 to 2005, soil losses at the outlet of the Houay Pano watershed were measured continuously. Total sediment yields per hectare ranged between 0.7 tons in 2005 and 3.4 tons in 2001 (Table 1). Sengtaheuanghoung et al. (2006) investigated the relationships between soil losses and various environmental factors (i.e. annual rainfall, mean slope, soil structure, soil depth, land use distribution) monitored at this main outlet station and in another seven weir stations, set up in eight nested sub-catchments. Annual and monthly rainfall amounts did not have a significant influence on sediment yields. Statistical analysis showed a clear correlation between sediment yields and land use. In particular, the areal extent of annual crops in sub-catchments appears to be the best predictor of soil erosion. However, in contrast with linear erosion, no correlation with rainfall intensity was identified.

Depending on the reference they are compared to, these sediment yields can be considered low to average (e.g. Pimentel and Kounang 1998; Douglas 1999; Gafur et al. 2003), but because a 'universal' scale of erosion rates does not exist, this does not add much to our understanding of the local significance of these values. In fact, due to their limited temporal extent, such biophysical measurements provide limited information on long-term environmental change in the village. Does the observed positive correlation between soil erosion and the extent of annual cultivation mean that the land is undergoing significant degradation? Or are we simply observing a cycle whereby land is exploited during a period of extensive cultivation and later regenerated by a period of extensive fallow? In this regard, experience from local populations can provide essential information.

Local perceptions

A survey of local perceptions of soil erosion and land degradation was undertaken in Ban Lak Sip over a 3-year period (2004-2006) based on two questionnaires, seven group discussions and many informal conversations with farmers. During the first questionnaire survey carried out in March 2004 with 16 of the 27 farmers working in the Houay Pano watershed, 87 percent answered that erosion had generally increased in their fields. The questionnaire did not include an investigation of the links made by farmers between soil erosion and agricultural yields. However, 85 percent of the interviewees also reported that their yields had declined over the previous fifteen years.

To collect more detailed information, group discussions were organised in July 2004 and December 2006, each time involving three or four key informants selected among the farmers working in the Houay Pano watershed. Discussions focused on the identification of local indicators, factors and impacts of soil erosion. According to the farmers interviewed during the first series of discussions, an 'ideal' upland field satisfies the following criteria: gentle slope, dense and green vegetation cover (i.e. old fallow or forest) and moist and black soils. By contrast, they consider a red soil surface, the development of gullies, the presence of stones and particular weed species (e.g. Erigeron sumatrensis, Microstegium ciliatum, Thysanoleana maxima) as the main indicators of erosion. Using pictures of the watershed, the second series of group discussions gave comparable results. The farmers again identified the density and colour of the crops, the presence of stones on soil surface, the presence of rills and/or gullies and the colour of the topsoil as main indicators for determining the soil erosion level of a plot (Table 2).

Regarding the causes and consequences of soil erosion, farmers identified and sorted in order of importance: intense rainfall events, long history of agricultural rotations, annual cultivation on steep slopes and high elevation areas, and short fallow periods as the main factors leading to high soil erosion rates. Decreasing crop yields (due to impoverished soils and land lost to gullies) and increasing workload (due to invasion by hardier weeds and, to a lesser extent, the time spent filling rills) were identified by farmers as the main adverse impacts of soil erosion on their farming activities. Reconstruction of upland rice yield and annual cultivation workload based on survey data shows a notable decline in rice yield since 1990 and a significant increase in workload after 1995 (Figure 1). At the same time, fallow periods have decreased by almost two thirds since 1970 and cropping periods (number of years a field is cropped before being fallow) have nearly doubled since 1995 (Figure 2 and, for further details, Lestrelin and Giordano 2007).

A second questionnaire survey was undertaken in November 2005. It reiterated the set of questions used during the 2004 survey but included an investigation of the causality linkages perceived by the villagers. Two direct links clearly emerged: one between increased rainfall intensities and soil erosion, and the other between shortened fallow periods, decreasing soil fertility and declining crop yields. Out of 31 individuals interviewed on the development of soil erosion in the entire village land, 52 percent reported increased erosion. This change was attributed primarily to more intense rainfalls (62 percent of the respondents), short fallow periods (18 percent of the respondents) and increased weeding frequency (12 percent of the respondents). Again, a large majority of the villagers interviewed (i.e. 94 percent of the interviewees) reported a decrease in soil fertility essentially reflected in declining agricultural yields. However, soil erosion was not identified as a major driver of fertility loss. In fact, among the 29 farmers who reported decreasing yields, 23 mentioned short fallow periods as the main proximate cause, while soil erosion was cited only once. More generally, as illustrated in Table 3, while short fallows, in relation to land shortage and high population density, were considered as significant issues by 16 percent of the villagers interviewed, soil erosion appeared clearly as a secondary issue.

To Ban Lak Sip farmers, soil erosion is not the only or the primary factor of land degradation. In fact, while the group discussions showed that farmers considered that soil erosion negatively impacts agricultural productivity, the results of the second questionnaire survey suggested agricultural yields depend most on the quality of the vegetation cover that is cut and burned so as to make up part of the substratum for crops. As the following quote illustrates, this perceived link between fallow vegetation, soil/land fertility and crop yields appeared rather explicitly in a number of interviews:

"Compared with ten years ago, current annual crop yields are much lower. The products are good but the production is low. If the fallow vegetation is not dense enough and if the trees are too small, then the fertility of the fields will be low" (Mr. Lae, 33, farmer).

Group discussions also focused on the definition of different stages of land degradation representative of the past, present and future of the watershed. The farmers defined five successive stages ranging from brown soils, dense-green crop cover and no noxious weeds to red-orangey soils, sparse-yellow crop cover, surfacing stones, and high densities of hardy weeds and gullies (Figure 3). Once this last stage is reached, fields are unproductive and must be abandoned. The interviewees reconstructed the history and predicted the evolution of the Houay Pano watershed, showing a continuous degradation trend that, without land use change, would lead to the impossibility of cultivating upland annual crops in ten to forty years' time. For instance, one of the farmers interviewed in 2004 estimated that, under the current land use cycles (i.e. on average, a three-year fallow period followed by two years of annual cropping), his field would reach the last degradation stage by the end of the next cultivation cycle, that is, within six years.

Overall, the aggregated information indicated that a majority of villagers believe that: (1) the village land has followed a degradation trajectory over the past forty years, (2) soil erosion has increased over the past fifteen years, (3) soil fertility and annual crop yields have declined during the same period, and (4), if soil losses have definitely played a role, the main cause of degradation is the shortening of fallow periods (Figure 4).

Comparison of the two data sets

According to local perceptions, the village land is on a continuous degradation trajectory characterised by two dynamics: an increase in soil erosion rates over the past fifteen years and a gradual loss of fertility of the upland fields. With regards to the first perceived trend, biophysical measurements do not exactly confirm a regular increase in soil erosion rates. Indeed, both linear erosion rates and sediment yields appear to vary importantly from year to year, without a clear trend of increase over the five years of survey. This inconsistency should not be considered as discrediting entirely local knowledge. Firstly, the time scale of the biophysical records and that of villagers' perceptions are different. Five years of biophysical monitoring is insufficient to characterise environmental dynamics while local populations have experienced these dynamics for several decades. Secondly, local perceptions may reflect the importance of soil fertility transfers which occur within the watershed, when soil erodes from the cultivated slopes to sedimentation areas located downhill. As shown experimentally, the quantity of soil that is displaced from the upper part to the bottom of the slopes can be very significant, but it may only have a minor impact on sediment yields at the watershed outlet (Dupin et al. 2002; Chaplot et al. 2005b). Nevertheless, the mismatch between the two data sets suggests that, rather than being used as unquestionable evidence, local knowledge is probably best employed to provide further insight into measured processes and/or identify new scientific hypotheses.

The second environmental trend perceived by the villagers cannot be directly addressed by the scientific experiments carried out in Houay Pano because the measurements made do not give a clear indication of the cumulative impact of soil erosion on land fertility. However, even if the sediment loads monitored at the outlet of the Houay Pano catchment are low in absolute terms, analysis of their composition shows that an important transfer of carbon (i.e. a crucial element conditioning soil fertility) has occurred from the watershed to downstream areas (Chaplot et al. 2005b; Rumpel et al. 2006). In this regard, the very short fallow periods currently practised by farmers are not likely to counterbalance the process.

This last observation brings us back to an important causality linkage perceived by villagers, that is, the major role played by shortened fallow periods in the reduction of soil fertility and the associated decline in annual crop yields. This perception is in line with scientific experimentation undertaken elsewhere in the Luang Prabang province. As highlighted by Roder et al. (1995, 1997b), in slash-and-burn shifting cultivation systems practised on relatively poor soils only a minor part of the soil fertility decline could be attributed to soil erosion . In contrast, the quality of the secondary vegetation growing during the fallow period appeared to strongly influence fertility. With litter degradation, vegetation regrowth plays an essential role in the production of soil organic carbon which, in turn, is crucial for maintaining the physical, biological and chemical properties of the soil. Once slashed and burned, fallow biomass provides a stock of nutrients easily assimilated by the crops. Furthermore, if its duration is longer than the dormancy period of weed seeds present in the soil, the fallow period also plays a significant role in limiting weed germination and potential competition with the crops (de Rouw 1995; Roder et al. 1997a). Thus, even if the relationship between fallow length, soil fertility, soil erosion and crop yield is neither simple nor linear (Mertz 2002; Ickowitz 2006), the fallow period appears to be an important driver of land productivity in shifting cultivation systems, possibly more significant than soil erosion.

Conclusions

If we consider the case of Ban Lak Sip in light of the general issue of land degradation in Laos, we can draw two main conclusions. Overall, the generally accepted view that shifting cultivation is a major cause of land degradation also appears to be the locally relevant situation. In Ban Lak Sip, both biophysical measurements and local perceptions indicate that this practice is the main proximate cause for land degradation. On the one hand, there is a significant statistical correlation between the areal extent of annual crops and sediment yields recorded along the Houay Pano stream. On the other hand, a large majority of farmers think that the main causes of land degradation are all related to cultivation practices.

However, our results also raise questions as to whether upland agriculture is really the main culprit of the 'chain of degradation'. In Ban Lak Sip, sediment yields recorded over a 5-year period at the outlet of the Houay Pano catchment do not appear critical. They can even be considered as relatively low when compared to similar studies in the uplands of northern Thailand (e.g. Douglas 1999). Besides, while soil erosion may have significant impacts at the catchment scale (i.e. the erosion of organic matter and nutrients redistributes soil fertility along the hillslope, thus depriving upslope farmers and possibly 'enriching' farmers downhill), it is not necessarily the only nor the primary issue for upland farmers. Villagers' perceptions suggest that, rather than the shifting cultivation system per se, it is the ever shortening length of the fallow period, and its negative impact on soil fertility and yields, that lies at the core of the upland degradation issue in Laos. Studies in Nepal (Ives 2004) and northern Thailand (Forsyth 2007) draw similar conclusions regarding the excessive emphasis placed on the issue of upland soil erosion in the political agenda of these countries. Thus, rather than asking "how can we limit the downstream impacts of upland shifting cultivation", a more relevant question for policy-makers should perhaps be "how can we circumvent the shortening of fallow periods in the uplands?" In this regard, reconsidering the actual land allocation process may help (e.g. Ducourtieux et al. 2005; Evrard 2004). Farmers could also be encouraged to adopt improved land management systems. Finally, encouraging economic diversification in the uplands could also contribute to reduce land use pressure and maintain sustainable shifting cultivation systems (Lestrelin and Giordano 2007).

While this study remained limited to an examination of a generally accepted viewpoint on upland degradation, 'hybrid research' approaches can also be used as a valuable practical tool. By integrating both local and scientific views into a common framework, communication between development agents and local populations is likely to be greatly facilitated. And so are development interventions. In the end, such an integrated approach appears to be an essential, yet often neglected stage of any approach to combat land degradation.

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Table 1 – *Annual rainfall, linear erosion and annual crop distribution in the Houay Pano watershed, sediment yields in the Houay Pano watershed (Station 4). 2001-2005 (Source: Sengtaheuanghoung et al. 2006).*

Year	Annual rainfall (mm)	Linear erosion (tons/hectare/ year)	Sediment yields (tons/hectare/ year)	Annual crops (% of the total surface)
2001	1774	2.3	3,36	9,6 %
2002	1221	1.4	6,83	40,4 %
2003	1308	0.1	2,03	31,5 %
2004	1383	n/a	4,67	32,1 %
2005	1377	n/a	0,74	14,7 %

Table 2 *– Main indicators of soil erosion identified and sorted by order of importance by the farmers of Ban Lak Sip interviewed during two series of group discussions. Note: the actual ranking has been calculated by summing the classifications determined during each group discussion.*

Rank	1st series (July/August 2004)	2nd series (December 2006)
1	Colour of the topsoil	Crop cover (density and colour)
2	Gullies	Surface stones (presence)
3	Surface stones (size)	Gullies, rills and landslides
4	Weed species	Colour of the topsoil
5	Rills	Weed species
6	Vegetation cover (density)	Surfacing roots of crop
7	Landslides	-
8	Weed density	-

Table 3 – *Main livelihood issues perceived by the population (percent of households interviewed), 2005.*

Main livelihood issues in Ban Lak Sip	Total
Drought	52%
Decreasing rainfall amounts	52%
Low agricultural yields	42%
Labour shortage	35%
Land shortage	19%
Shortened fallow periods	16%
Poverty	16%
High population density	13%
Food shortage	13%
Lack of income sources	13%
Hot weather	10%
Theft	6%
Soil erosion	6%
Difficult environmental conditions	6%
High dependency ratio	6%
Lack of access to credit	3%
Remoteness	3%
Prices fluctuation (production)	3%
Increased weed density	3%

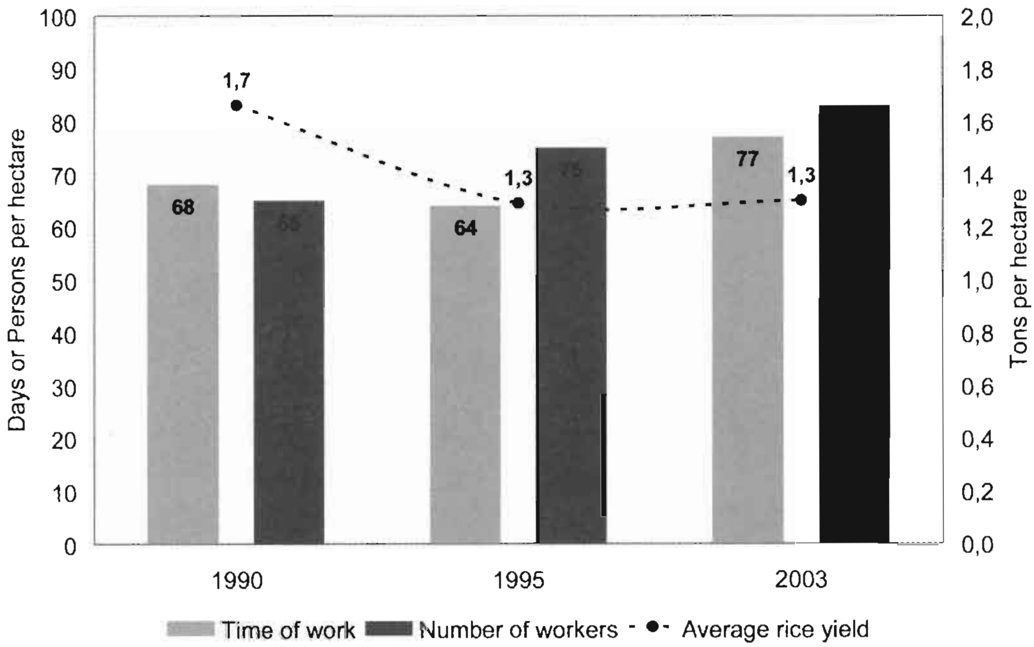

Figure 1 – *Annual cultivation average work time, number of workers and upland rice yield, per hectare and per year, 1990-2003.*

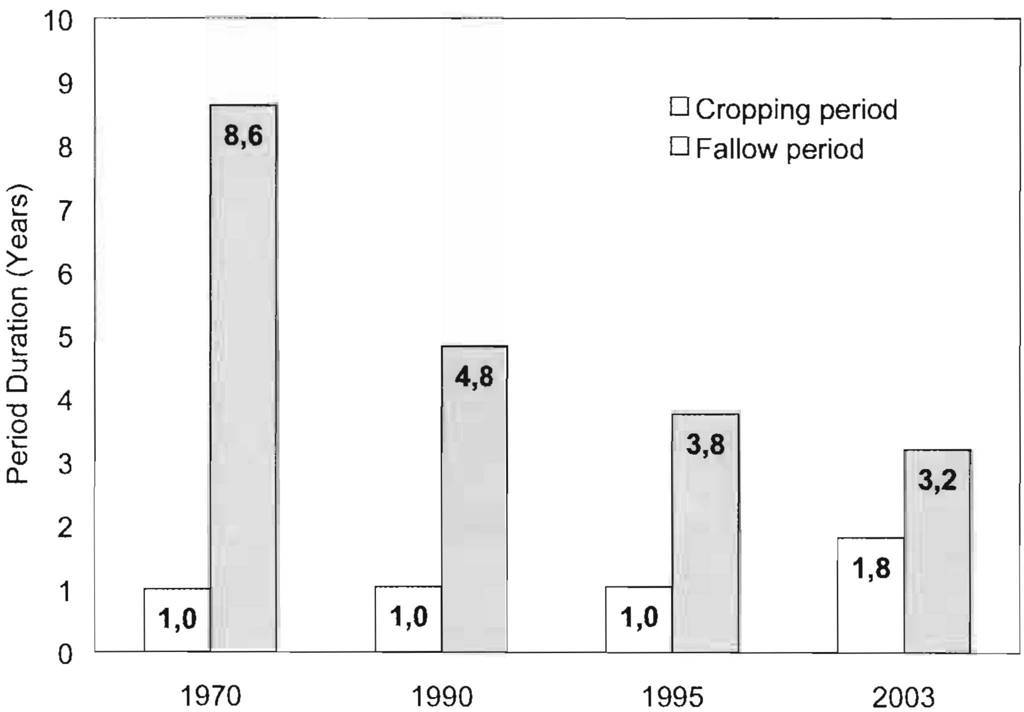

Figure 2 – *Average fallow and cropping periods for the fields under shifting cultivation, 1970-2003.*

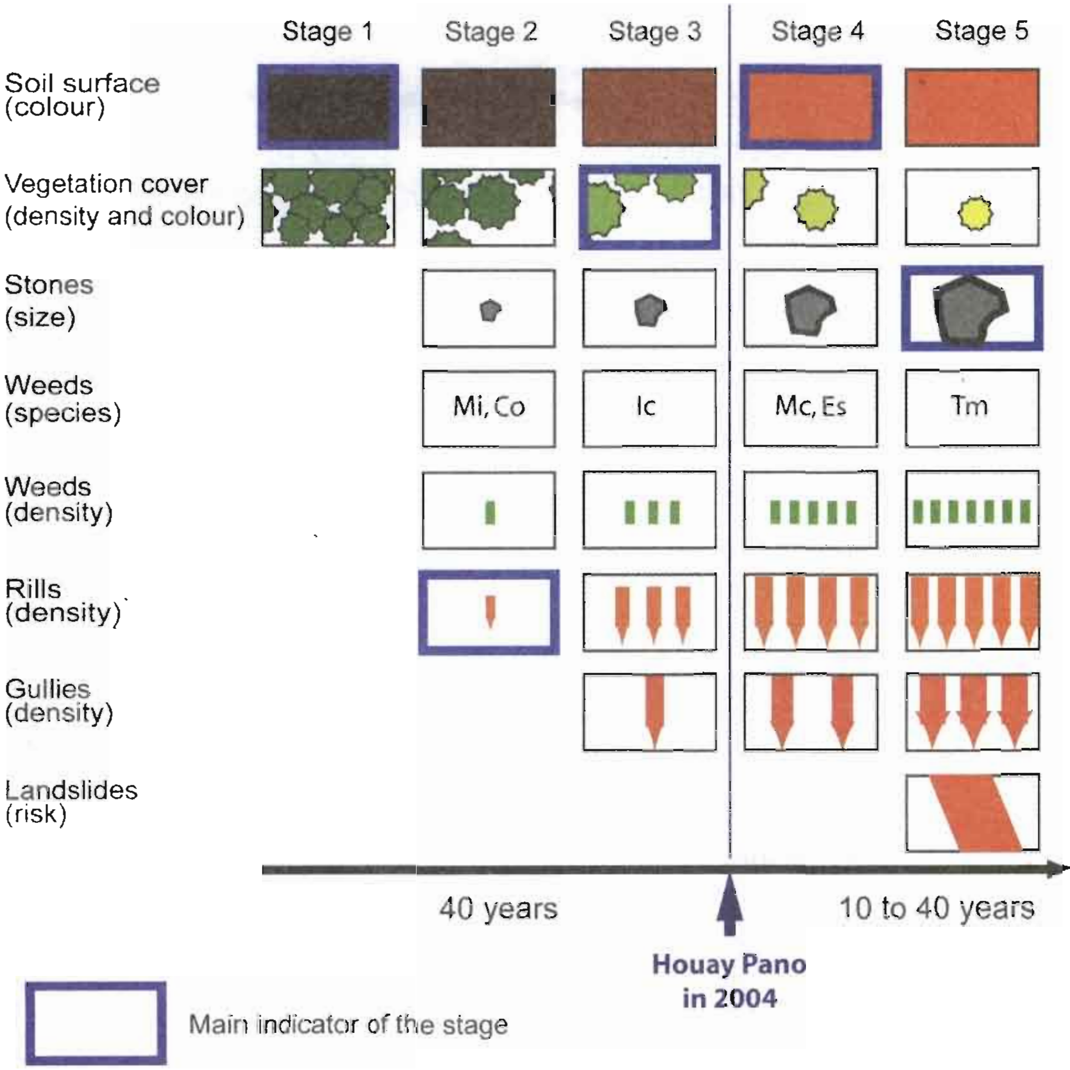

Figure 3 *– Perceived stages of land degradation in the Houay Pano catchment (adapted from Pelletreau 2004). Note: Mi, Mimosa invisa; Co, Chromolaena odorata; Ic, Imperata cylindrica; Mc, Microstegium ciliatum; Es, Erigeron sumatrensis; Tm, Thysanoleana maxima.*

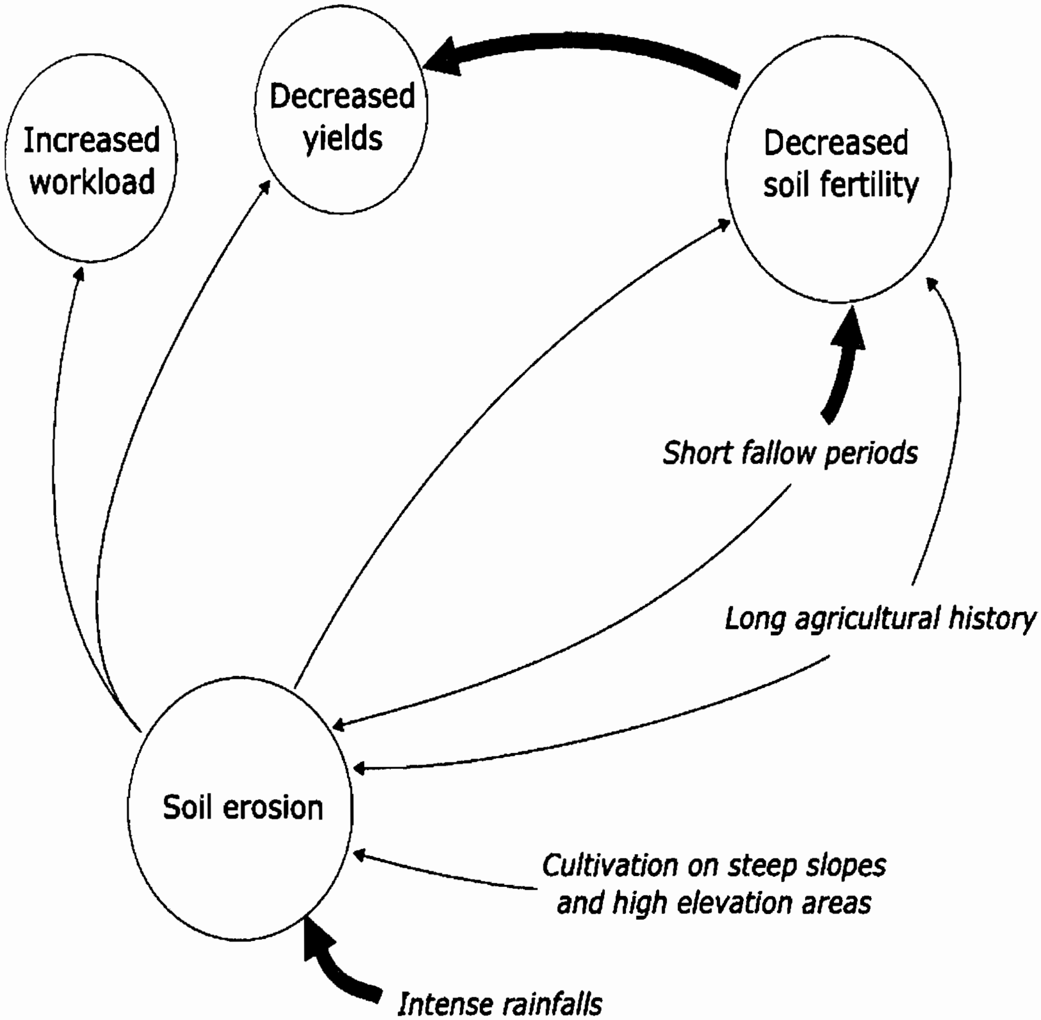

Figure 4 – *Land degradation-related causality linkages perceived by the farmers in Ban Lak Sip.*

THE LAO JOURNAL OF AGRICULTURE AND FORESTRY

The Lao Journal of Agriculture and Forestry is a journal of Ministry of Agriculture and Forestry. It aims to disseminate technical information relating to agriculture and forestry within the Lao PDR. The journal is published twice a year. The publication of the journal is being supported by the Upland Research and Capacity Development Programme (URCDP). The journal is distributed among all agencies of the Ministry of Agriculture and Forestry. Subscriptions are available to all other agencies wishing to receive the journal on a regular basis. Abstracts of papers are expected reproduced in various international abstracts. Papers in both Lao and English will be accepted for publication; an abstract in the second language (Lao or English) is also to be published. Only papers with specific relevance to the Lao PDR will be considered for publication.

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Units:

The metric system for units of measure should be used.

Abstract:

Abstract of no more than 200 words in both the English and Lao languages and key words should be provided.

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Anandhana, B. 1989*. The amount and distribution of soil organic matter in Thailand. Technical Bulletin No. 168. Soil Survey and Land Classification Division. Land Development Department. Ministry of Agriculture and Cooperative. Thailand.*

Anon. 1993*. Basic statistics about the socio-economic development in the Lao PDR 1992. State Statistical Center.*

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Schiller, J.M., Phoudalay Lathvilayvong and Dr. Ty Phommasack 1993*. Green Manure (INSURF) study in the Lao PDR. Proceeding of INSURF Planning Meeting, Fuzhou/ Guangzhou, People's Republic of China, 14-21 June 1993.*

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Tables should be numbered consecutively and referred to the text. A brief title for each table should be provided. Each table should be typed on a separate page. Column headings and descriptive matter in tables should be kept brief. Only tables that complement rather than duplicate information in the text will be accepted for publication. Combining tables that present different types of information should be avoided.

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