Integrated modelling for land use planning and policy recommendation in the Northern Uplands of Vietnam

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Table of Contents

Chapter 1

Introduction

Introduction

1.1 The Northern Uplands of Vietnam

Despite significant economic growth and increases in living standard from *"doi moi"* and successive development policies since the 1980s, the rural areas of Vietnam, especially the Northern Uplands (NUV), still face major development problems related to livelihood and natural resource management. As in neighbouring countries in South East Asia, rapid population growth and favourable economic development in Vietnam resulted in rapidly increasing demands for food and other commodities. Still, Vietnam remains one of 30 poorest countries in the world (Minot et al., 2006) and poverty continues to be a serious problem in areas like NUV where it averages 15.5% and reaches as high as 31.6% of the population (GSO, 2009). With family farming systems still common in the region, household livelihood depends heavily on agricultural production. Rice is the most important food crop, contributing up to 46% of the total crop production value (Minot et al., 2006). The previously sustainable swidden, a.k.a. slash and burn, production systems used for centuries are no longer appropriate within the context of increased population pressure and demand for land resources. To improve farmers' livelihoods and long-term natural resource management, an integrated approach to inform and support decision making and encourage adoption of more sustainable land use practices is greatly needed.

The NUV region is characterized by hilly to mountainous topography, high diversity in other biophysical conditions (Castella, 2009; Vien, 2003) and more recently significant land and water degradation. Furthermore, the region is inhabited by approximately 30 different ethnic groups, each with its own specific culture and agricultural habits, and its own distinctive farming system (Castella and Quang, 2002). The combination of high diversity in household orientations and the heterogeneous physical environment results in a wide range of different farming systems being applied. Although over the last 20 years, the Vietnamese government has given special attention to improvement of land management systems in the NUV through economic development and environmental conservation policies (Castella, 2009; Clement and Amezaga, 2008), land and water degradation has been an increasing problem. The transformation of sloping land to agricultural use has resulted in significant degradation which has consequently led to declining agricultural productivity and unsustainable livelihoods (Bat, 2001; Maglinao, 2000). The degradation of natural resources in the mountain region of Vietnam is most clearly demonstrated by the increase in soil erosion. Currently, 38% of the country area has become denuded hills and open wasteland (Dower, 2004). The associated very high soil erosion risk has been confirmed in many studies and varies from 40 – 100 ton ha^{-1} y^{-1}, depending on the slope, vegetation cover and soil type (Bat, 2001; Can and My, 1982; Maglinao, 2000; Trinh, 2007).

1.2 The gap between land use policy and adoption

Changing current land use practices in the upland regions is one of the solutions for improving the livelihood of farmers, protecting natural resources and ensuring sustainable development. However, many of the Vietnamese government's long term policies on land use do not take into consideration the traditional approaches of farmers. As a result, many of the policies have been in conflict with the traditional use of land resources by the ethnic communities (Clement and Amezaga, 2009; Clement et al., 2006; Vien et al., 2005) with the result that actual land use change has not followed the plans of the policy makers (Castella et al., 2005). For example, in some areas, the land use rights devolution policy resulted in increased degradation of the forest land, due to the revoking of the rights of the community to manage the resource (Sikor, 1998). Also, there is evidence that farmers' decisions to use sloping land for agricultural purposes were not affected by government bans or through reforestation incentives (Clement et al., 2006; Sicat et al., 2004).

At the landscape–community level, the upland agricultural management system can be defined as the sum of the many individual strategies within all the different stakeholder groups (Castella, 2009). The household is considered as the unit that makes decisions, determines the objectives, mobilizes resources and influences the transformation process (Vien, 2003). Therefore, wide scale dissemination of precise agricultural policies is very difficult, if not impossible.

1.3 The need for an integrated modelling approach

Based on the assumption that appropriate land use policies will improve agricultural production and consequently the livelihood of farmers, the Vietnamese government has always emphasized natural resource conservation together with livelihood improvement in development of strategies and policies. However, with various constraints related to natural and social environments, the adoption of such top-down policies in the NUV is generally low. It has been argued that, in order to develop appropriate land management policies that will stimulate farmer adoption, it is imperative to understand the goals and circumstances of upland farmers, the range of farming systems they have developed, and the variability in socio-economic factors and trends influencing the dynamics of these systems (Cramb, 2004). Through investigation of both the cultures and the farming systems of the farmers, we can learn from their indigenous knowledge about natural resource management, as well as increase our understanding of the processes by which these populations adapt to changing environmental and societal conditions. Such information will greatly improve the appropriateness, adoption and therefore effectiveness of land use policies.

It is well known that land management comprises aspects of complex ecological-economic systems (Arhonditsis et al., 2005; Costanza and Ruth, 1998). Therefore land use planning is not only a bio-physical analysis of the technical possibilities, but also includes a trade-off analysis of a range of socio-economic objectives and ecological sustainability (Roetter et al., 2005; Trung et al., 2006). Furthermore, stakeholder involvement in land use planning allows inclusion of local knowledge, which is important for sustainable development, and participation studies increase chances to transfer scientific knowledge directly into decision making processes (van Ittersum et al., 2004). Interaction with stakeholders can reveal many important factors, which were not seen at the planning phase due to actual biophysical and social complexities. Therefore, when combining land use optimization models with participatory tools, a broader range of social and technical aspects are taken into account in the development of feasible land use plans to increase the likelihood of adoption of the proposed land use options.

1.4 Research aims and objectives

The need for an integrated solution to support decisions on sustainable land management, especially in fragile upland environments, has been strongly advocated by several authors (Castella et al., 2002; Nhapi et al., 2005; Toan et al., 2002). However, little progress has been made in the NUV. A toolbox to analyse the interactions among different elements of the complex land management system would be of great value for improved understanding of the key interactions between the agro-ecological and socio-economic dynamics at the watershed level. As an innovative step in this direction, the main objective of this research is to integrate modelling of 1) erosion assessment, 2) land use optimization and 3) land use decision making in order to improve the effectiveness and adoption of recommendations that contribute to the improved livelihood of farmers and sustainable natural resource management. This will be achieved through following sub-objectives:

- Increasing understanding of the interactions between agro-ecological and socio-economic dynamics at watershed scale;

- Facilitating emergence of a common agreement on ecological sustainability, social equity and economically sound solutions;
- Stimulating dialogues among various stakeholders and actors (farm households, local institutions, researchers, policy makers) to achieve a shared responsibility of the common resources

1.5 Approaches for integrated land use planning

A close look at the current agricultural land use in the NUV reveals several problems, which reflect the conflicting interests of farmers, local authorities, land use planners and policy makers. In an effort to determine future optimal land use plans, the Land Use Planning and Analysis System (LUPAS) was developed under the Systems research Network for eco-regional land use planning in tropical Asia (SysNet project). LUPAS is a Multiple Goal Linear Programming (MGLP)-based modelling framework, enabling agricultural experts and planners to explore the outer boundaries of agricultural potentials, as well as the trade-offs between various socio-economic objectives and ecological sustainability (Roetter et al., 2005; Trung et al., 2006; Van Paassen et al., 2007). The LUPAS model integrates biophysical and socio-economic factors through three major components: (i) land evaluation including assessment of resource availability, land suitability, yield and input-output estimation; (ii) formulation of scenarios based on policy views and development plans; and (iii) land use optimization in the form of MGLP models (Hoanh and Roetter, 1998; Roetter et al., 2001; Van Ittersum et al., 2004). The LUPAS methodology has been applied for determining regional land use options in support of natural resource management in a mountainous province in northern Vietnam (Kam et al., 2002). Therefore, LUPAS was considered a suitable tool to generate land use scenarios for negotiating objectives of stakeholders in this research. The recommended land use plans, however, remain just pretty pictures if they are not adopted by the local people. Therefore, in a further step, a land-use scenario should be evaluated by stakeholders using their own knowledge (Sicat et al., 2004). Agent Based Modelling (ABM) was developed to facilitate knowledge integration across scales and disciplines. ABM is an approach to simulate and identify relationships between agro-economic conditions, policy and farmers' behaviour (Kam et al., 2000). The use of ABM includes execution of the following set of activities (Bousquet et al., 2007; Bousquet et al., 2005):

- Framing: Identification and understanding of the system’s ecological and social dynamics and of key issues, concerns, and intervention points with stakeholders. Identification of knowledge gaps to be filled through specific surveys;
- Prioritization and visioning: Establishment of a common vision shared by all key stakeholders through role-playing games (RPG) and participatory simulation workshops;
- Participatory field work and modelling: Implementation of an iterative, integrated, flexible and user-friendly modelling approach, combining participatory workshops and laboratory work;
- Collective exploration and discussion of trade-offs displayed by the simulated scenarios;
- Assessment of local impact: Assessment of the local impact of the approach for participatory and integrated renewable resource management (Bousquet and Trebuil, 2005).

In agricultural economics ABM has been used to assess the impact of various government policies on the adoption of new agricultural practices and the structure of the farm economy (Parker et al., 2002). In this research, the ABM approach is applied to explore land use decision making by farmer groups and the adoption possibility of recommended land use scenarios in the NUV.

Being located in the humid tropics with highly variable inter- and intra-annual rainfall (generally from 1000 to 2300 mm y^{-1}) and deeply weathered soils, Vietnam is at very high risk for soil erosion as has been confirmed in many studies (Bat, 2001; Can and My, 1982; Maglinao, 2000; Siem and Phien, 1999). In order to reduce soil loss by erosion, scientists have put a lot of effort into understanding the processes behind erosion. In the last decade, studies in Vietnam have focused on the computation of soil losses over large areas using several soil erosion models (Dang et al., 2009; Ha, 1996; Trinh, 2007). However, most of these studies do not consider the impact that the large diversity in agricultural land use and annual variability of seasonal landscape factors has on the vulnerability for soil erosion. In other words, the spatial and/or temporal distribution of a range of factors that influence soil erosion (Van Dijk and Bruijnzeel, 2003; Verbist et al., 2002) were not taken into account. Overcoming this limitation was important for achieving the objectives of this study as well as the long term goals of more sustainable natural resource management and improved farmer livelihood.

The Predict and Localize Erosion and Runoff (PLER) model, developed by the Management of Soil Erosion Consortium (MSEC) using the Griffith University Erosion System Template (GUEST) (Rose et al., 1983), describes the most important hydrological and erosion processes. Because of its innovative functions, PLER was initially selected for this research to estimate daily soil erosion at the watershed scale taking into consideration the spatial and temporal variables. However the validation of PLER showed that, while the model can predict quantity of soil loss quite well at the outlet, the estimation of eroded material over the watershed surface is less precise. Furthermore PLER's predictions depend very much on spatial distribution of land use types (e.g. crops on the up or down slope), which is unspecifiable in LUPAS's land use scenarios. This leads to a mismatch between the PLER and LUPAS models. For these reasons, in place of PLER, the Revised Universal Soil Loss Estimation (RUSLE) model (Morgan, 2005; Wischmeier and Smith, 1978) was eventually chosen and adapted to estimate the soil erosion for possible land use scenarios. Factors selected for use in RUSLE were calculated following methods suggested by Mulengera and Payton (1999), Phien and Siem (1998), and Vezina et al. (2006) In this application of RUSLE, potential soil loss during crop seasons and tilling periods could be taken in to account to overcome the limitations of the original equations (Mulengera and Payton, 1999; Vezina et al., 2006).

The research was carried out in small agro-forestry watersheds in the NUV. To work toward an integrated toolbox a methodological approach was followed comprising four main steps: 1) Data Collection on biophysical and socio-economic conditions and policy views; 2) Soil Erosion Modelling 3) Land Use Optimization; and 4) Agent Based Modelling. Figure 1.1 shows a flow diagram of the methodological approach to the study.

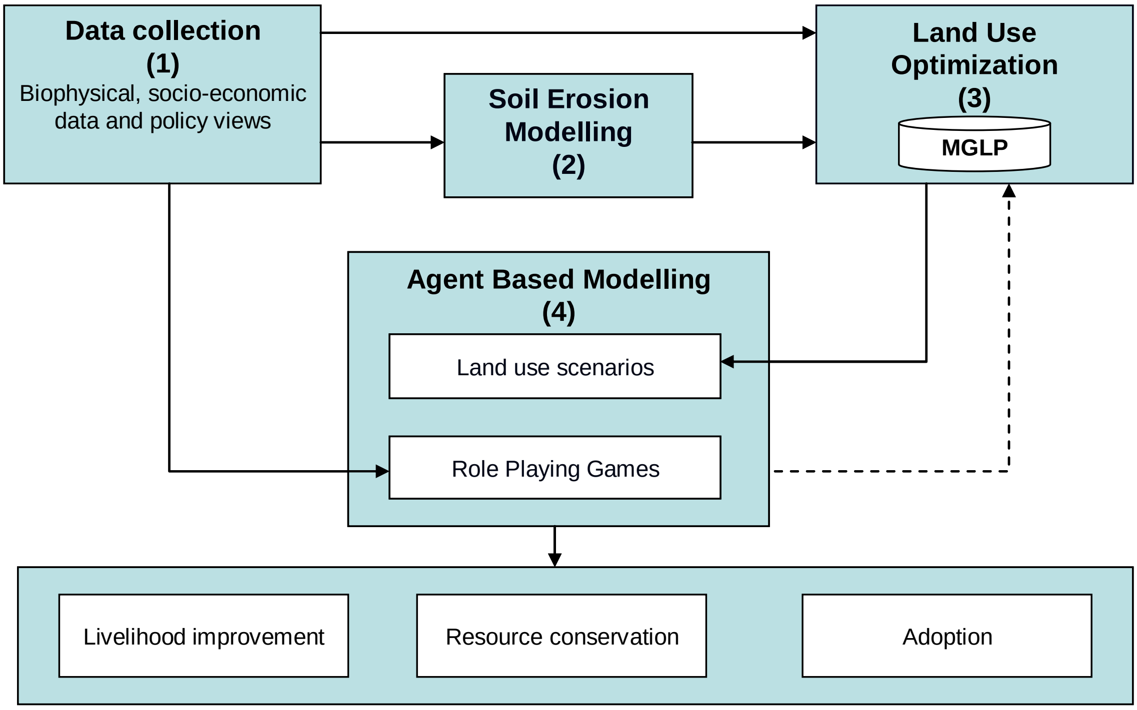

Figure 1.1. Conceptual framework of the study.

In the first step, the current biophysical and social conditions in the study area are described (Box 1 in Figure 1.1). The output of this first step, consisting of land quantity and quality, crop suitability, and current and potential crops yields is used as input in the next analysis steps. Factors that describe socio-economic conditions and policy goals, such as households' capital, labour, investments, land use targets and governmental development strategies are also obtained in step 1.

In step 2, soil loss rates for each land unit are predicted under normal climate conditions with different cropping patterns (Box 2). All land use factors together with the simulated soil loss rates are used to generate input-output relations, which are used in step 3 for land use optimization simulations (Box 3). The land use optimization process provides alternative land use options for a range of scenarios. Based on the achievement values of options and trade-offs between land use objectives, recommendations can be developed to satisfy multi land use targets.

Finally, in step 4 farmers and other stakeholders are invited to participate in a Role Playing Game (RPG) following the Agent based modelling (ABM) approach (Box 4). During the RPG the land use optimization model is used as a support tool to facilitate discussion among participants. The biophysical and socio-economic factors defined in Box 1 are used to define components of ABM and to design game sessions. Results obtained through the ABM approach can be used as feedback to improve the used tools.

It is expected that insights on land use decision processes and *"emerging phenomena"* captured from this case study will be of value to scientists, government and policy makers in the development of livelihood improvement and resource conservation plans with a higher likelihood of adoption in the NUV.

1.6 Thesis outline

This thesis is organized in 6 chapters, comprising this general introduction chapter, 4 scientific articles and a synthesis. An overview of the problems and opportunities in agricultural land use in the NUV is given in Chapter 2. The Predict and Localize Erosion and Runoff (PLER) model initially developed to provide insight into the erosion risk at watershed scale is discussed in Chapter 3. Analyses of alternative scenarios and possible solutions for reaching desired land use targets generated by the Land Use Planning and Analysis System (LUPAS) are presented in Chapter 4. An application of the Revised Universal Soil Loss Equation (RUSLE) which provided estimations of potential soil loss under different land use scenarios is also described in this chapter. The application of the Agent Based Modelling approach is covered in Chapter 5 which also explains the land use strategies developed by farmers and the reality of recommended land use plans. The last chapter (6) is the synthesis - a presentation and discussion of the major conclusions, the newly generated knowledge, limitations and future recommendations that came from this study. Chapter 6 also discusses how PLER, RUSLE, LUPAS and RPG were integrated and used in an ABM framework, and the implications of the integrated approach for livelihood improvement and natural resource conservation in the NUV.

Chapter 2

Constraints in agricultural production in the Northern Uplands of Vietnam

This paper is under review as:
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Constraints in agricultural production in the Northern Uplands of Vietnam

Abstract

The Northern Uplands of Vietnam (NUV) is one of the largest ecological regions in the country characterized by complex biophysical conditions and a high diversity in ethnic minorities, culture and farming systems. The “Doi moi” (renovation) program from early 1980s has resulted in significant changes in agriculture production and related economic issues. However, poverty, low agricultural productivity and degradation of natural resources are still major problems. This paper provides understanding of the driving factors that cause these problems in the NUV. We present insights on the relation between agro-ecological and socio-economic dynamics with respect to agricultural land use in Suoi Con, a representative watershed within the NUV. We first explored the current land use situation and analysed constraints in agricultural production. The results underline that although low soil fertility and land degradation are considerable problems, availability of household capital, current level of agricultural technology and land fragmentation are major constraints that hold back agricultural development in the region. These constraints were analysed from different points of view to identify mismatches between the applicability of top-down government’s policies and specific conditions in the NUV. Such mismatches are reasons that actual land use change in NUV deviates from development plans of the government. Based on land use analysis in the Suoi Con watershed, we conclude that participatory and bottom-up approaches are needed to better understand problems and opportunities in agricultural production of households in order to develop appropriate land use plans and policies.

Keywords: Northern uplands, land use constraints, land evaluation, resource use efficiency, Vietnam

2.1 Introduction

The Northern Uplands of Vietnam (NUV), also called the Northern Midlands and Mountain areas, is one of the largest ecological regions of Vietnam. The region covers 29% of the national land area and has 11 million inhabitants (GSO, 2009). It is characterized by a hilly and mountainous topography and a high diversity in ethnic groups, culture and farming systems (Castella and Quang, 2002; Wezel *et al.*, 2002; Vien, 2003). Being influenced by the “*Doi moi*” (renovation) and agricultural de-collectivisation policies (from the early 1980s to the mid-1990s), there have been significant economic and societal changes in the NUV (GSO, 1996; Castella and Quang, 2002; GSO, 2011). One of the major changes involves land use rights, which have been taken from large scale agricultural cooperatives and given to households. Consequently a household has become the smallest unit in land use decision making process.

Existing top-down government policies (Akram-Lodhi, 2002) have led to a number of political and social conflicts (Cramb, 2004). Household land use decisions are not in line with the market-oriented strategy of the government, and the family-based agricultural system created several negative impacts on resources. For example, the establishment of new agriculture regions from the 1960s to 1980s has led to a serious decline in natural forest and an increase in land degradation (Vien et al., 2005). According to (McElwee, 2010), stricter conservation enforcement in Vietnam has led to increased opportunity costs for local communities.

Despite efforts of government, poverty is still a major problem in the NUV. With an annual per capita income of less than US$ 500 y^{-1}, the NUV is the poorest region in Vietnam. In 2008, 32% of this population still lived under the poverty line (GSO, 2009). In agriculture, farmers are faced with uncertainties in relation to weather, markets and policies. Steep sloping land, scarcity of arable land, water shortage, lack of information on new technological developments, and cultural isolation are factors that holdback agricultural development (MARD, 2006; Sekhar, 2007).

In order to develop rational agricultural land use plans, there is a need to assess limitations and potentials of land. The method that uses physical, social and economic information to assess the potential use of land is commonly known as land evaluation (LE) (FAO, 1976). Following the basic LE method introduced by the Food and Agriculture Organization of the United Nations (FAO) (FAO, 1976), a number of LE approaches, ranging from empirical and qualitative to mechanistic and quantitative expressions, have been developed with the support of computing technologies and GIS software (Sanchez *et al.*, 1982; Janssen *et al.*, 1990; Littleboy *et al.*, 1996; Cools *et al.*, 2003; Van Keulen, 2007; Recatalá Boix and Zinck, 2008; Sonneveld *et al.*, 2010). In general, a more complex LE method provides more accurate descriptions of land potentials but also corresponds to a higher quantity and quality of input parameters and higher costs (Rossiter, 1996; Manna *et al.*, 2009). Despite the fact that the old FAO's LE framework has limitations in characterising dynamics and spatial variability of biophysical factors (i.e. soil properties, climate and crop requirements) (Kam *et al.*, 2002; Manna *et al.*, 2009) the method has been adapted worldwide to support land use planning because it is based on simple qualitative procedures that require only basic knowledge of land resources. With the 2007 revision of FAO's 1976 LE Framework (FAO, 2007), LE became appropriate not only for regional scales (national or agro-ecological zones) (Manna et al., 2009) but also for local scales (watershed, village, community and household). Therefore, the FAO framework for land evaluation is still useful and appropriate for resource management studies, especially in developing countries.

This paper uses results obtained from FAO's 2007 LE, literature review, stakeholder meetings and a household survey in Suoi Con, a representative watershed, to analyse limitations in agricultural development of the NUV from different points of view. The paper also aims to underline the mismatches between land use objectives of the government and of households in the NUV, which make land use change in the NUV generally not in line with long term development plans of the government.

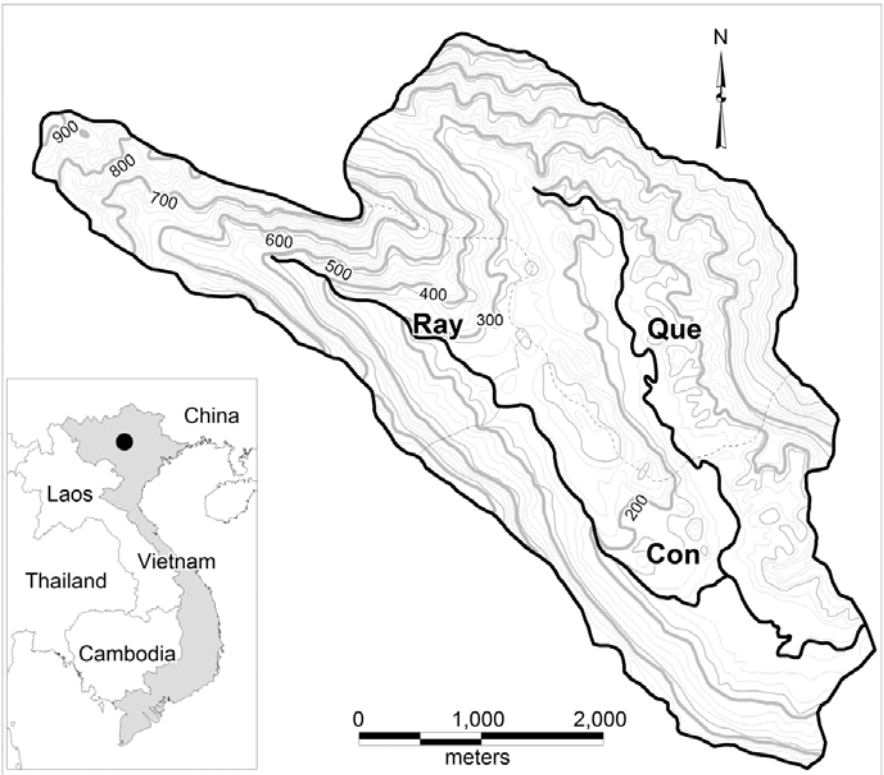

Figure 2.1. Topographic map of the Suoi Con watershed and its location (black circle) on the map of Vietnam.

2.2 Materials and methods

2.2.1 Study site

Suoi Con (Figure 2.1) is a small agro-forestry watershed situated in Thu Cuc commune, Tan Son district, Phu Tho province, North of Vietnam (104° 49' 42" E to 104° 53' 41" E and 21° 16' 1" N to 21° 19' 17" N) with the total area is about 1760 ha. The lands of the Suoi Con watershed are shared by three villages: Con, Que and Ray with a total of 399 households, belonging to two main ethnic groups: the Muong and Dao people. Only 21% of the total area is used for agriculture. Irrigation systems can only cover 17% of the agricultural lands. Water shortage often occurs in the dry season and creates several disadvantages for agricultural production.

The annual rainfall is high, around 1600 mm y^{-1} but distributed unequally over the year, forming two distinct seasons (Figure 2.2). The rainy season (from mid-April to the end of September) contributes up to 76% of the annual rainfall. The average monthly air temperature ranges from 15°C to 28°C but extremes can be 33°C in summer (from May to July) and 10°C in winter (from November to January). Dynamics of rainfall and temperature create three main cultivation seasons in a year: spring (S_p, from February to June), summer (S_m, from July to October) and winter (W_t, from November to January).

2.2.2 Identification of bio-physical constraints

The latest land evaluation framework by FAO (FAO, 2007) was used to determine land suitability for 8 main annual crops: irrigated rice, rainfed rice, grain maize, groundnut, soybean, vegetables, sweet potato and cassava. In the first step of this land evaluation, only static land variables such as slope, soil, irrigation, drainage and village borders were used to distinguish Land Units (LU). In order to retain spatial variability of continuous variables (i.e. slope) and to reduce homogeneity in LU delineation, land characteristics are represented in geo-registered gridded maps (Kam *et al.*, 2002) with the resolution of 30 x 30 m.

In the next step, dynamic variables (rainfall and temperature), properties of the top soil horizon (0-20 cm) and land requirements for crops, given by Sys et al. (1993), were used to determine suitability classes for the selected crops. The matching between crop requirements and land characteristics was done for each possible crop-season combination. The weighting-rating method (Rossiter, 1996) and the maximum limitation method (Sys *et al.*, 1991b; Rossiter, 1996) were then applied to produce overall suitability for crop-seasons. For each LU, possible crop rotations can be identified based on suitability and duration of combinations of crops and seasons. For example, if a LU is suitable for rice in S_m and for maize in S_p and S_m then possible rotations can be S_p.maize + S_m.rice or S_p.maize + S_m.maize or S_p.fallow + S_m.rice or S_p.fallow + S_m.fallow, etc.

A field survey was conducted to capture characteristics of agricultural land in the study area. Twenty four primary (soil pits) and 32 secondary (auger holes) soil profiles (0-120 cm) were collected in the whole watershed (30 ha per profile), following the handbook for soil survey and land evaluation (Chieu et al., 1999). Surface soil samples (0-20cm) taken at 5 positions within a perimeter of 100 m around each primary soil profile were used to determine soil properties. The morphological, physical and chemical properties of soils together with pre-existing soil information (soil map 1 : 50,000 of Phu Tho province) (NIAPP, 2006) were used to build the soil map of the Suoi Con watershed, following the FAO's guidelines for distinguishing soil subunits (FAO, 1990).

Other necessary data were obtained from different sources: monthly climate data from the Vietnam Institute of Meteorology, Hydrology and Environment; satellite images from the Vietnam Remote Sensing Centre; the land use map of Thu Cuc commune from the Forest Inventory and Planning Institute; and a Digital Elevation Model (resolution of 30 x 30 m) from the Earth Remote Sensing Data Analysis Centre (ERSDAC, 2009).

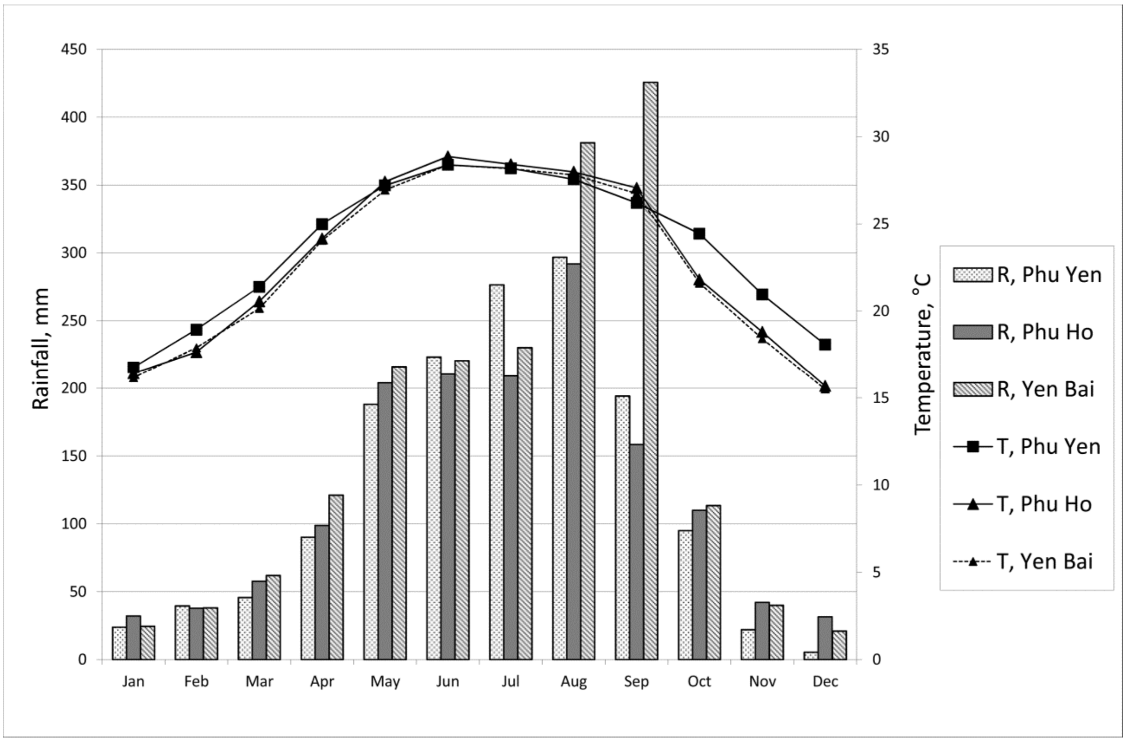

Figure 2.2. Average monthly rainfall (R, mm) and air temperature (T, °C) of three climate stations around the Suoi Con watershed, Vietnam.

2.2.3 Identification of socio-economic constraints

A household survey (HHS) was conducted to collect socio-economic data. In the Suoi Con case study, HHS focused on land use under traditional practice and constraints of households. The survey was based on the face-to-face interview method with participation of 100 households (25% of the total households in the watershed). The households were listed by village chiefs based on levels of agricultural investments (land area, fertilizer use, cropping technique and labour) and then invited to the village's hall to join the survey. Land use information on each plot of land was split into 3 periods (1995-2000, 2000-2005 and 2005-2008), corresponding to the current land use planning scheme (every 5 years) of the government. An average of values provided by households was used to describe farmers' current practice (Cr = current technology level) and the level of inputs and outputs required under similar soil and climate conditions to reach attainable production levels (as suggested in the literature) was used to describe the recommended technology level (Rm).

To evaluate socio-economic constraints from other points of view, various sources of information such as government documents, research articles, project reports, local newspaper, etc. were referred. In addition, stakeholder meetings with the participation of local authorities, agricultural department of the commune, the Women's Social Union, the Youth Union and farmers were conducted to discuss on constraints in agricultural production based on information collected from the HHS and from literature review. The constraints were then ranged in order of priority, according to agreement of participants.

2.3 Results

2.3.1 Land characteristics

The field survey identified a number of limitations related to soil, topography and water availability in the Suoi Con watershed. The watershed has 12 sub-soil units, belonging to 4 groups: Fluvisols (FL), Acrisols (AC), Luvisols (LV) and Regosols (RG) (Table 2.1). Up to 92% of the watershed surface belongs to the Acrisols, which have low fertility, high acidity and several degradation problems. Large spatial variation in the top soil characteristics occurs over short distances and can be related to the high diversity in soil type and management practices. The steep slopes and the heterogeneous topography are also major limitations for agricultural production. Nearly 40% of the 366 ha of agricultural land has a slope that exceeds 15 degrees, which is considered as marginally suitable for many crops (Sys et al., 1993).

Table 2.2 presents the area of suitable land (as a proportion of total agricultural land) for the main annual crops in the three growing seasons. Most lands are in the S2 and S3 classes. According to climate regime in the region (Figure 2.2), water and temperature are more suitable for crops in summer than in others seasons. As a result, many fields that are classified as S3 and N (e.g. irrigated rice, grain maize, soybean and vegetables) in S_p and W_t seasons become more suitable (mostly S2) in summer.

Table 2.1. Soil types of the Suoi Con watershed (FAO classification)

Soil code	Soil groups	Sub-soil unit	Area	
			ha	%
	FLUVISOLS		**15.9**	**0.9**
1		FLeu.st	15.9	0.9
	ACRISOLS		**1642.4**	**92.5**
2		ACsk.le2	398.6	22.6
3		ACsk.dyh	531.4	30.1
4		ACst.sk	30.2	1.7
5		ACst.dyh	30.4	1.7
6		ACha.sk	369.6	20.9
7		ACha.fr	28.1	1.6
8		ACha.dyh	254.1	14.4
	LUVISOLS		**96.2**	**5.4**
9		LVha.um	75.3	4.3
10		LVha.ct	20.9	1.2
	REGOSOLS		**10.7**	**0.6**
11		RGgl.st	8.7	0.5
12		RGst.sk	2.0	0.1

Table 2.2. Suitability (in % of total agricultural land) for main annual crops obtained from land evaluation of the Suoi Con Watershed.

Crops	Crop season (a)	% of agricultural land(b)			
		S1	S2	S3	N
Irrigated rice	S_p	12	5	81	2
	S_m	12	49	37	2
Rainfed rice	S_m	43	55	2	-
Grain maize	S_p	33	63	4	-
	S_m	13	83	4	-
	W_t	13	2	2	83
Groundnut	S_p	3	74	23	-
	S_m	5	72	23	-
Soybean	S_p	55	45	-	-
	S_m	-	100	-	-
	W_t	15	2	-	83
Vegetables	S_p	13	78	9	-
	S_m	-	91	9	-
	W_t	2	15	-	83
Sweet potato	S_p	-	87	13	-
	S_m	-	87	13	-
	W_t	-	87	13	-
Cassava		17	46	29	8

(a) Crop seasons: S_p = spring; S_m = summer and W_t = winter

(b) Land suitability classes: S1 = highly suitable, S2 = moderately suitable, S3 = marginally suitable and N = not suitable

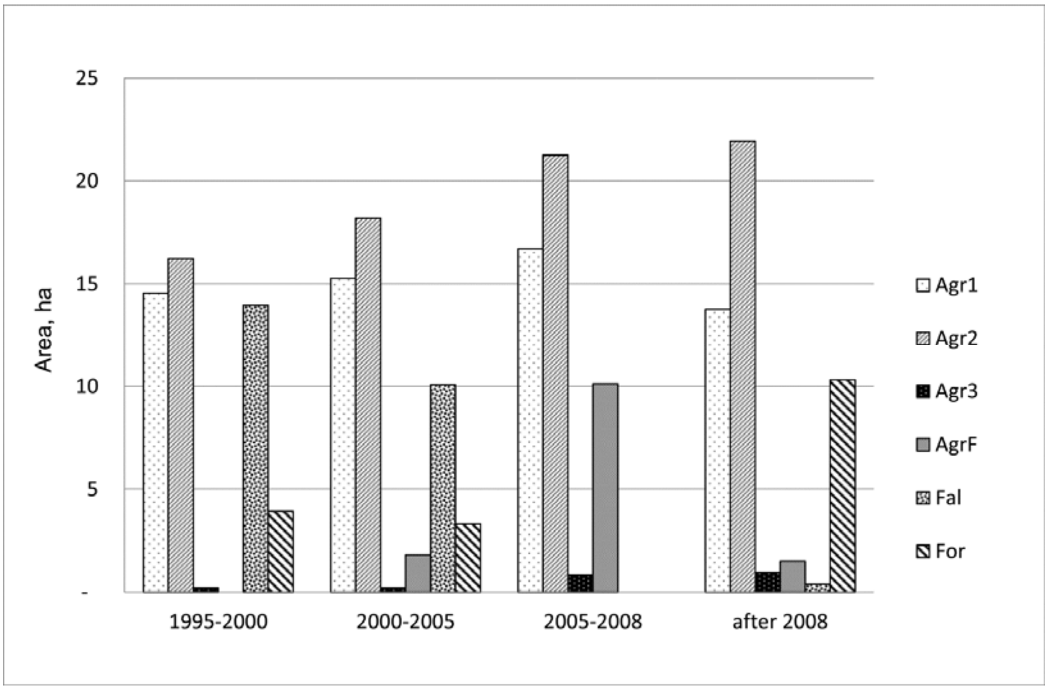

Figure 2.3. Land use in the Suoi Con watershed for 4 periods. Agr = Agriculture (with 1 = single cropping, 2 = double cropping and 3 = triple cropping), AgrF = Agro-forestry, Fal = Fallow and For = Forestry.

2.3.2 Land use

Total area of lands for cultivation (rainfed and irrigated) is 366 ha, including 60 ha of irrigated rice and 306 ha of rainfed crops (i.e. rainfed rice, maize, soybean, groundnut and cassava). Figure 2.3 shows the land use split into 4 periods (1995-2000, 2000-2005, 2005-2008 and > 2008) based on records of 461 plots (49 ha) that were used for annual crops by 100 households in the Suoi Con watershed. Overall, agricultural lands have expanded between 1995 and 2008, especially the area with single and double cropping. The expansion of agricultural lands has resulted in the reduction of forest lands and fallow land. In the period between 2000 and 2005, various fallow and forest lands have been replaced with agriculture and agro-forestry. Correspondingly, a number of shrub and fallow plots in 1989 (Figure 2.4a) have disappeared altogether with the establishment of large agricultural areas in 2008 (Figure 2.4b). In addition, dense forests have been degraded and converted to young planted forest or other land uses.

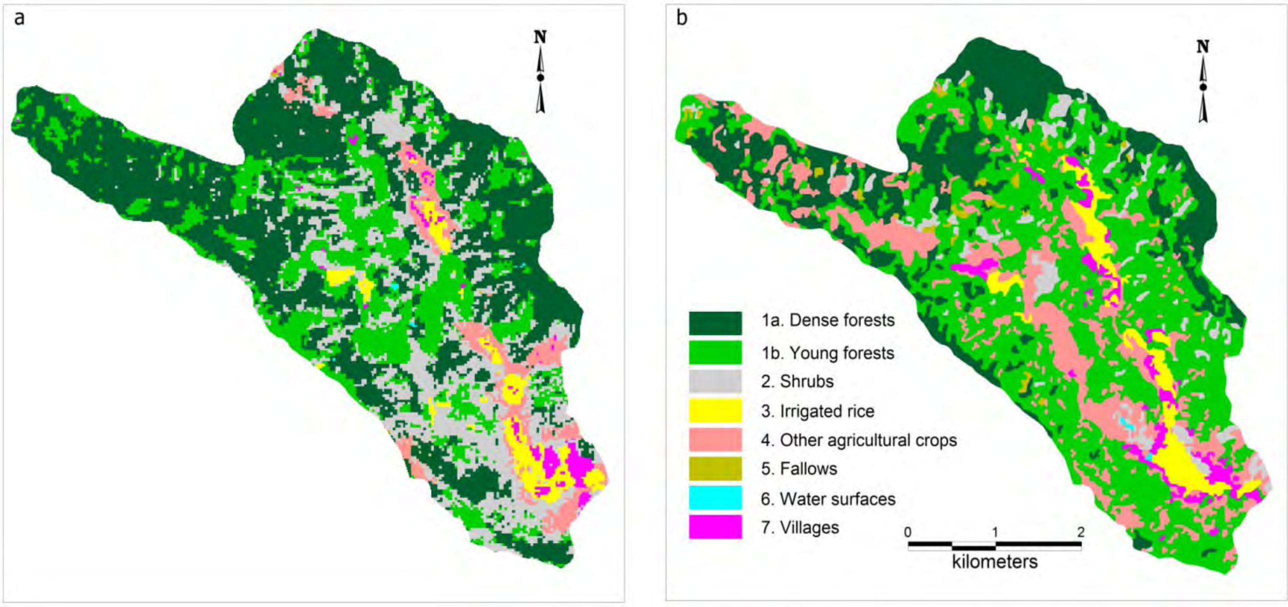

Figure 2.4. Vegetation cover of the Suoi Con watershed in 1989 (a) and in 2008 (b).

2.3.3 Current agricultural production

The result of HHS shows that 84% of household income is from on-farm production and 16% is from off-farm sources (i.e. wood processing, construction work, etc.). Within the agriculture and forestry sector, crop cultivation contributes most of agricultural income. In general, investments for crops under actual farmers' practice are very much lower than under the recommended techniques (Table 2.3). For example, actual rice yield varies from 3-4 Mg ha^{-1} while the average of attainable yield under otherwise similar conditions (climate, soil, etc) is above 5 Mg ha^{-1} (Siem and Phien, 1999; VAAS, 2008; Vien and Nga, 2008).

The watershed has 22 ha under perennial crops, but these crops currently contribute a minor proportion in household income. For example, most of tea fields are in the first or the second year of their development stage, so that shoot production is not considerable. Other perennial crops (longan, litchi and citrus) are often grown scattered within the villages, mainly for self-sufficiency.

Since the de-collectivisation in agriculture (1980s), fish ponds and livestock (buffalo, native cow, pig and poultry) have been managed by individual households. Most costs relate to the purchase of young animals (calf or piglet or chick). Only a few households buy commercial feed. Although total production is low, this sector contributes up to 47% of the agricultural income of households.

Table 2.3. Investments for annual crops with farmer practice (Cr) and with recommended technology (Rm) in the Suoi Con watershed.

Crop code[a]	Season[b]	Labour d ha^{-1}		Total cost[c] USD ha^{-1}		Crop yields Mg ha^{-1}		Revenue USD ha^{-1}	
		Cr	Rm	Cr	Rm	Cr	Rm	Cr	Rm
RiceD1	S_p	209	272	150.0	356.3	3.8	5.5	1175.0	1687.5
	S_m	195	272	143.8	337.5	3.6	5	1125.0	1562.5
RiceD3	S_p	209	272	168.8		3.9		1218.8	
	S_m	195	272	143.8		3.7		1156.3	
RiceH	S_p	209	272	212.5	443.8	4.1	6.5	1275.0	2031.3
	S_m	195	272	193.8	381.3	3.6	6	1106.3	1881.3
UpRice	S_m	333	354	112.5	231.3	1.6	2.3	487.5	718.8
GmaizeH	S_p	216	328	137.5	450.0	3.9	6	862.5	1312.5
	S_m	216	328	143.8	450.0	3.9	6	862.5	1312.5
	W_t		328		450.0		6		1312.5
GrNut	S_p	334	397	100.0	412.5	2	4.5	1375.0	3068.8
	S_m	306	369	93.8	375.0	1.4	4.5	937.5	3075.0
Soyb	S_p	244	314	112.5	375.0	1.4	4	1043.8	3000.0
	Sm	244	314	150.0	375.0	2.8	4	2087.5	3006.3
	S_m		314		393.8		4		3006.3
Cabb	W_t	460	467	318.8	943.8	6.9	30	1737.5	7500.0
SpoR	S_p		265		437.5		16.7		3131.3
	S_m		265		437.5		16		3000.0
	W_t		265		437.5		16		3000.0
SpoL	S_p	322	334		412.5	8.5	27	187.5	700.0
	S_m	322	334		412.5	8.5	27	187.5	718.8
	W_t	322	334		412.5	8.5	27	187.5	718.8
Cas		333	431	62.5	306.3	13.9	40	312.5	875.0

[a] Crop codes: RiceD1 = Commercial traditional rice, RiceD3 = Self-breed traditional rice, RiceH = Hybrid rice, UpRice = Upland rainfed rice, GmaizeH = Hybrid grain maize, Grnut = Groundnut, Soyb = Soybean, Cabb = Cabbage, SpoR = sweet potato for root, SpoL = sweet potato for leave, Cas = Cassava.

[b] Crop seasons: S_p = Spring, S_m = Summer and W_t = winter.

[c] only expenses for seeds and fertilizers are used to calculate total cost.

2.3.4 Agricultural constraints

To be able to satisfy food demand for about 2000 people in 2015, the watershed needs to provide at least 424 Mg y^{-1} of rice. In addition, to move beyond the national poverty line (GOV, 2011), annual income needs to rise (for the watershed as a whole) from US$ 225 thousand y^{-1} in 2008 to US$ 375 thousand y^{-1} in 2015. From stakeholder meetings, local authorities indicated that traditional techniques, limited land area, water shortage and lack of market information are most considerable constraints that prevent the watershed to reach given land use targets. However, solutions were not accordantly defined in land use strategy of the local government.

From local authorities' point of view, the order of priority of the constraints is: technique > land > irrigation > market > capital > labour. However, the household survey showed that limited household capital was mentioned by 90% of the interviewed households, followed by limited land area and quality (45%), lack of agricultural techniques (40%), labour shortage (38%), not enough irrigation water (18%), low yielding crop varieties (14%), pest and diseases (10%) and lack of market accessibility (8%). From the farmers' perspective, the availability of capital is the major constraint. About 50% of the interviewed households said that they are using loans from formal and informal credit sources (government banks, private credit services, relatives, neighbours, etc.) to maintain production activities. This does not mean that the available capital of the other 50% of the farmers is sufficient. Rather, they have little opportunity to access credit sources and therefore have to stay with current production techniques and levels. Many households do not have land tenure rights documents or valuable properties to mortgage in return for agricultural loans. During the survey, we suggested that the policy may change so that every household could have sufficient access to credit sources. As a result, 70% and 30% of households are willing to use such loans to invest in livestock and cultivation, respectively.

2.3.5 Alternative land use options

The high diversity in soils, topography and a dynamic climate create flexibility in farmers' land use decisions. In a season, a plot of land is often suitable for various crop types. Therefore, farmers can have various alternatives of cropping system on the plot. Based on actual conditions (e.g rainfall, market price and availabilities of capital and labour), farmers may choose an appropriate alternative to alleviate their biophysical and socio-economic constraints. In practice, farmers have replaced the spring rice in the rice-based system with spring maize, groundnut or soybean on many terraced fields to adapt water shortage. Results of the household survey showed that availabilities of household capital and labour also influence intended crop variety and investment level in the coming crop-season.

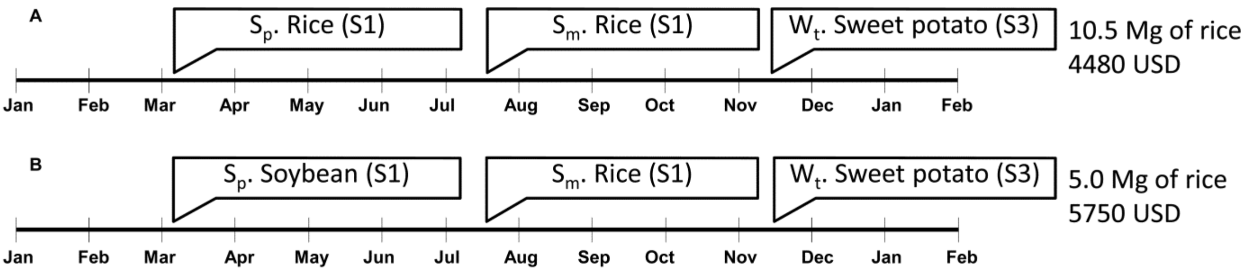

Figure 2.5. Selected alternative land use options based on crop suitability. A: maximizes rice production by growing rice in both S_p and S_m seasons. An alternative crop rotation (B) can be applied to maximize income while maintaining enough rice production for food self-sufficiency. (Crop seasons: S_p = spring ; S_m = summer, W_t = winter. Land suitability classes: S1 = highly suitable, S2 = moderately suitable, S3 = marginally suitable. Rice productions and total revenue are estimated for 1 ha).

Figure 2.5 illustrates an example of two land use options corresponding to two possible production targets. For increasing food production, rice can be grown in both Sp and Sm (crop rotation A in Figure 2.5). Alternatively, crop rotation (B) can be applied to improve income while maintaining enough rice production for food self-sufficiency. The diversity in land suitability and crop-season combinations creates opportunity for farmers to quickly change their copping systems adapting changes in biophysical and socio-economic conditions.

2.4 Discussion

Results shown in Table 2.3 indicate that traditional technology results in low crop yields (about 40-75% of attainable yields expected under the recommended technology level). Therefore, low soil fertility, steep slope or low land suitability indicated by land evaluation has minor impacts on agriculture production in the region. Various experimental studies (Phien *et al.*, 1998; Siem and Phien, 1999; Bo *et al.*, 2003) proved that such land constraints can be overcome by improving cultivation techniques. According to an agricultural extension officer in the watershed, farmers can easily assess to various sources for modern technologies. In spite of this it is very difficult to convince farmers to apply the recommended techniques. As a result, crop production and economic returns for the households are not improved. That is why 14% of interviewed households were not satisfied with existing crop varieties. Thus, the technology constraint should be described as low adoption rate of improved technology.

Despite efforts of the government since 1998 to reallocate agricultural land (GOV, 1998), land fragmentation is still a serious problem for agricultural production, especially in mountainous areas (Lan, 2001; MARD, 2006; Hung *et al.*, 2007). In the Suoi Con watershed the average farm size is 0.5 ha. Each household typically owns 4 – 7 separated parcels, which may have different soil types, terrain and/or irrigation conditions. With regard to long term land use, land fragmentation may limit the large scale implementation of agricultural mechanization, a market-oriented agriculture (Markussen et al., 2012) and the national target programs on rural development. This makes land fragmentation another major constraint for improved agricultural production. However, this problem was not mentioned by farmers.

Although 90% of surveyed households reported the capital shortage problem, local authorities pointed out that capital availability is not really a constraint according to them, because there are various credit services in the region, and possibilities for extending household capital are available. From the point of view of local authorities, agricultural techniques and farmers' adoption are more important than extending capital. In fact, it is agreed that without enough capital, farmers have less chance to renovate their production and to apply new technologies and varieties (GOV, 2003). According to Hao (2005), nearly 30% of Vietnam rural households in 2001 were unable to access formal or semi-formal credit. Dower (2004) identified that the current high interest rate and the strict mortgage requirements are main reasons. In the NUV, most small and poor households typically do not have much collateral, so they often rely on small loans from informal sources such as neighbours, relatives, private financial services, etc. Households demand capital, formal credit sources are available but households are unable to access such credit sources.

We agreed with local authorities that labour is not an existing constraint. Labour shortage only occurs at the beginning and the end of crop seasons but the problem appears to be manageable within the labour exchange group that is established between relatives or neighbouring households. Moreover, existing limitations on household capital prevent farmers from expanding their agricultural activities and, therefore, the need for extra labourers.

While irrigation water and markets are not of urgent concern to farmers, they are considered important factors for agricultural development by the People Committee of Thu Cuc commune. The local authorities put higher priority on these factors than on availabilities of capital and labour. From their point of view, this is true because when agriculture in the region shifts to a higher level of production (i.e. market-oriented or mechanized agriculture), a better infrastructure and market access will be required.

When constraints are ranged in the order of priority obtained from the household survey, the order is: capital > land > technique > labour > irrigation > crop variety > pest control > market. From the local authorities' point of view, however, the order is: technique > land > irrigation > market > capital > labour. This difference reflects the mismatches in defining core problems and leads to mistakes in determining cause-effect relations and action plans. In order to generate effective action, objectives and interventions need to be determined with consideration for the above constraints. Defining constraints, delineating intervention measures and building land use objectives are links in a development chain. Therefore, land use planning must be developed with involvement of multiply disciplines to avoid biased views on the limitations and the potentials of available resources.

According to Rerkasem and Rerkasem (1998), soil erosion alleviation has never been a land use objective of farmers in the upland regions of Southeast Asia. HHS showed that although households in the study site can recognize the appearance of surface crusts, gullies and stoniness on their fields, no conservation measure has been applied. The increase of agro-forestry and forest land (Figure 2.3) was not for land conservation purpose but rather reflects the flexibility in land use decisions made by households to adapt to changes in natural and economic conditions. Considering the diversity in biophysical conditions and availability of alternative land use options, using cropping systems that satisfy both economic and land conservation targets could be a viable approach for sustainable land use in the upland regions.

2.5 Conclusions

The study in the Suoi Con watershed demonstrates that people's livelihoods and agricultural production in the NUV are problems - and sheds light on some of the factors involved. Rural households rely on agricultural production for food and other demands. Considering the limitations of the land resources an integrated management technique is needed to improve crop production, economic return and land conservation. The above discussion also makes it clear that agricultural techniques, household capital, and land fragmentation are the most important factors holding back agricultural development in the mountainous regions. Apart from these disadvantages and challenges, the high diversity in soils, climatic conditions and crop suitability is a great advantage for the region. There are a number of alternative land use options that can be implemented in order to reach multiple land use objectives. This case study has also shown different points of view on land use constraints and the gap that exists between land use decisions by government and by farmers in the region. Therefore, participatory and bottom-up approaches are needed to better understand problems and opportunities in agricultural production of households in order to develop appropriate land use plans and policies.

Chapter 3

Lumped surface and sub-surface runoff for erosion modeling within a small hilly watershed in Northern Vietnam

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Hydrological Processes

Lumped surface and sub-surface runoff for erosion modelling within a small hilly watershed in northern Vietnam

Abstract

Developing models to predict on-site soil erosion and off-site sediment transport at the agricultural watershed scale represents an on-going challenge in research today. This study attempts to simulate the daily discharge and sediment loss using a distributed model that combines surface and sub-surface runoffs in a small hilly watershed (< 1 km^2). The semi-quantitative model, PLER, integrates the Manning-Strickler equation to simulate runoff and the GUEST equation to simulate soil detachment, sediment storage and soil loss based on a map resolution of 30m x 30m and over a daily time interval. By using a basic input data set and only two calibration coefficients based respectively on water velocity and soil detachment, the PLER model is easily applicable to different agricultural scenarios. The results indicate appropriate model performance and a high correlation between measured and predicted data with both Nash–Sutcliffe efficiency (*Ef*) and correlation coefficient (r^2) having values > 0.9. With the simple input data needs, PLER model is a useful tool for daily runoff and soil erosion modelling in small hilly watersheds in humid tropical areas.

Keywords: Surface runoff, Subsurface runoff, Erosion, Hydrological modelling, Land Use, Sloping Land, PCRaster, Vietnam

3.1 Introduction

Land-use and agricultural practices have a strong impact both on surface runoff and soil loss due to water erosion (e.g. Wischmeier and Smith, 1978; Turkelboom *et al.*, 1997; Morgan, 2005; Breuer *et al.*, 2009), especially in sloping lands (e.g. Maglinao and Valentin, 2003; Valentin *et al.*, 2008). On-site water and soil losses reduce crop yields and thus threatening the livelihoods of rural families (Ananda and Herath, 2003). Water and sediments can also pose problems off-site in adjacent waterways and reservoirs (e.g. Dang Thi Ha *et al.*, 2009). It is therefore clear that soil conservation strategies must be developed to manage the impact of agricultural practices both in- and off-site.

In North Vietnam, soil erosion is a critical issue in the mountainous areas due to increasing population pressure on agricultural lands (Valentin *et al.*, 2008). The World Development Report 2008 argued that agricultural development policies should focus on raising smallholder competitiveness in highest potential farming activities, as well as accelerating the adoption of new agricultural technologies. However, adoption of new technologies in Southeast Asia is often limited due to barely adequate subsistence livelihoods and risk aversion to new practices (Noble *et al.*, 2006; Orange et al., 2008).

Numerous studies have highlighted that a decision support tool such as erosion models that are easy to apply over a large variety of areas and that provide accurate and simple results is a requirement in order to illustrate the potential of new practices in reducing soil erosion and thus to enhance adoption by farming communities (e.g. Orange *et al.*, 2002). Then a quantitative approach at the watershed scale with a comprehensive analysis of hydrogeomorphic processes, hydrological pathways and spatial-scale effects is required to identify source and sink areas for runoff and sediment (De Roo *et al.*, 1996; Jetten *et al.*, 1999; Walling, 1999; Chaplot *et al.*, 2005; De Vente and Poesen, 2005). Many studies (Beven, 2001; e.g. Renard *et al.*, 1997; Morgan *et al.*, 1998; Jetten *et al.*, 1998) have developed hydrological and erosion models within land-use scenarios, but this approach is still under discussion (Clark *et al.*, 2009); a comprehensive overview is presented in Sidorchuk (2009). From a global perspective, physics-based models are extremely complex. These models often require large amounts of precise data which tends to limit their application to few areas (Breuer *et al.*, 2009). Moreover it is well known that information on the spatial heterogeneity and temporal dynamics of surface conditions is fundamental for erosion modelling in cultivated areas (Poesen, 1986; Bresson and Valentin, 1992; Chaplot *et al.*, 2005; Nearing et al., 2005; Visser and Sterk, 2007; Podwojewski *et al.*, 2008). As a result, runoff and erosion simulation on the watershed scale are conceptually limited due to the complexity of hydrological processes and to the often high data input requirements.

In humid, tropical climates and particularly within the hilly watersheds common to Southeast Asia, surface runoff is mainly generated by two hydrological processes (Xie *et al.*, 2003): the Hortonian flow which is due to an infiltration of excess runoff (Horton, 1993) and the Dunne flow which is due to a saturation excess runoff (Dunne *et al.*, 1991). The distribution in time and space of these two processes is largely forced by the spatial variability of soil properties, land-use practices, antecedent soil moisture, topography and vegetation cover (McGlynn and McDonnell, 2003; Xie *et al.*, 2003; Buda *et al.*, 2009; Weill *et al.*, 2009). Subsequently, the allocation of flow volumes due to the overland flow and the subsurface flow is quite impossible at watershed level. However, the determination of contribution of relative surface and subsurface water to stream flow is of primary importance when studying runoff and erosion at watershed scale (Nearing *et al.*, 2005). On the other hand, Van der Kwaak and Loague (2001) then Weill et al. (2009) have shown that the integrated simulation of overland flow through coupling surface/sub-surface flow is a useful tool for the study of the hydrological processes at plot scale (1–100 m^2) or on small watershed scale.

Based on that, this paper presents the results of a study with the following objectives: (i) to simulate, calibrate and validate the hydrological response of a small hilly watershed (below 1 km^2) using a combination of surface and subsurface runoff by implementing the PLER (Predict and Localize Erosion and Runoff) model; (ii) to simulate, calibrate and validate water erosion processes based on the results of the previous objective; and (iii) to identify the minimum basic data set of relevant input parameters that is required to apply a hydrological model to identify the erosion impact of land-use change at small watershed scale.

3.2 Materials and methods

3.2.1 The Predict and Localize Erosion and Runoff (PLER) model

PLER model was specifically built to be applied on steep slopes in Southeast Asia for small agricultural watersheds (with an area below 1 km^2). The PLER model is designed to produce runoff and soil erosion simulations using a limited amount of input data and calibration parameters thus making it easy and cheap to apply in a wide range of small agricultural hilly watersheds. Moreover, the model is accurate enough to clearly show the relative impact of different land-use practices on soil losses to farmers and decision-makers.

PLER model is a raster model written in PCRaster, which is a dynamic modelling language for distributed spatio-temporal environmental models (Karssenberg, 2001). PCRaster has the advantage in that it takes into account both temporal and spatial dynamic processes to produce serial and cartographic outputs. Furthermore, it allows simulation of hydrological and sediment transport processes occurring in a three-dimensional landscape.

PLER model is a conceptual semi-physical based erosion model with two combined modules (Figure 3.1). The first module is based on the hydrological processes and calculates the lumped surface and sub-surface runoff in each grid-cell and calculates stream discharge at any possible outlet of the studied watershed. The second module uses the lumped runoff to calculate the quantity of detached and transported sediment in each grid-cell. The mass of eroded sediment that is moved out of the watershed by the stream flow is considered as total soil loss and is dominated by suspended material, which is in agreement with field observations (Orange *et al.*, 2007). PLER outputs are thus a time series of stream discharge and sediment loss at any grid-cell inside the studied watershed with maps of runoff, peak flow velocity, soil detachment, sediment storage and suspended matter loss, by event (Figures 3.2 and 3.3) or for annual budget (Figure 3.4).

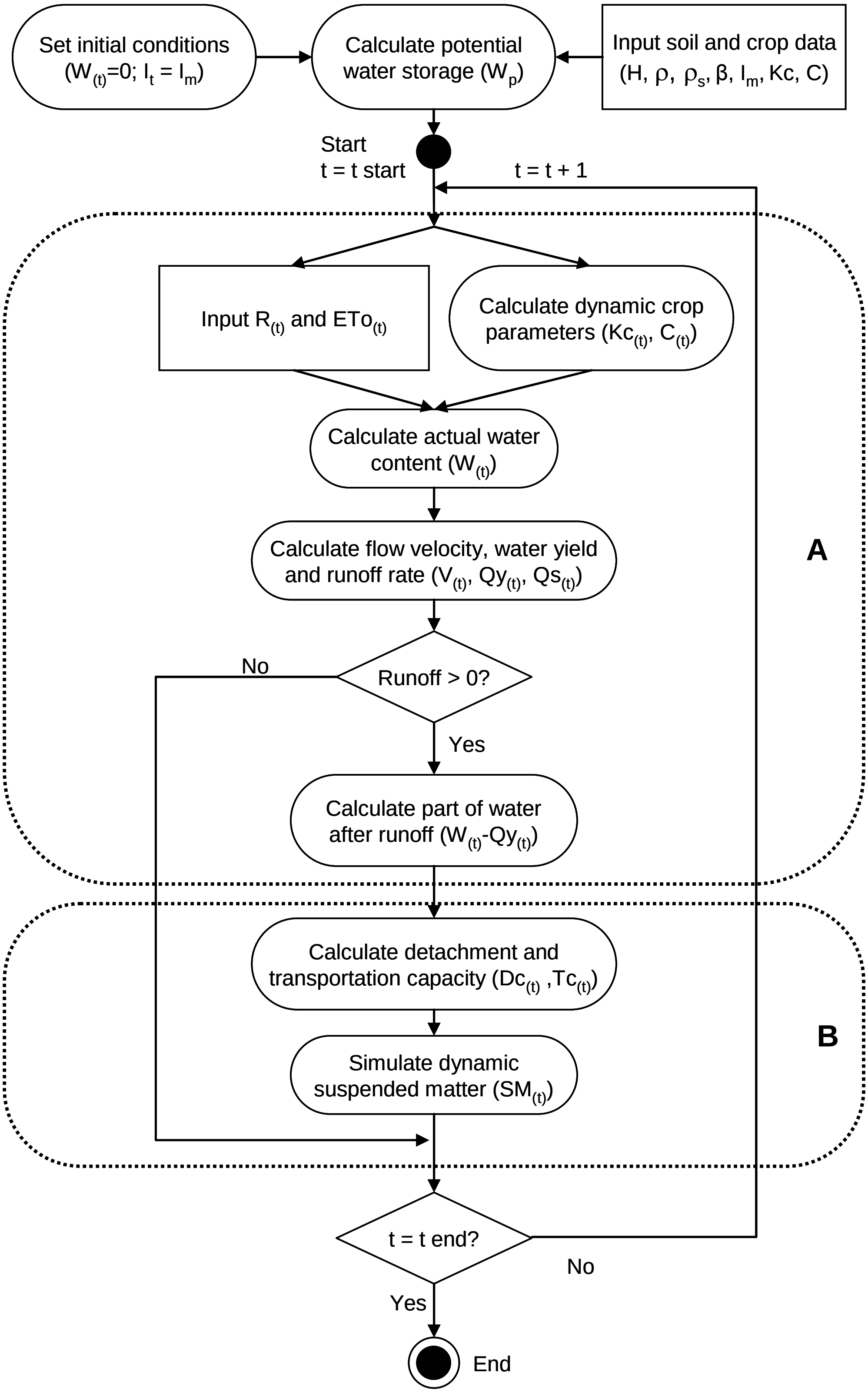
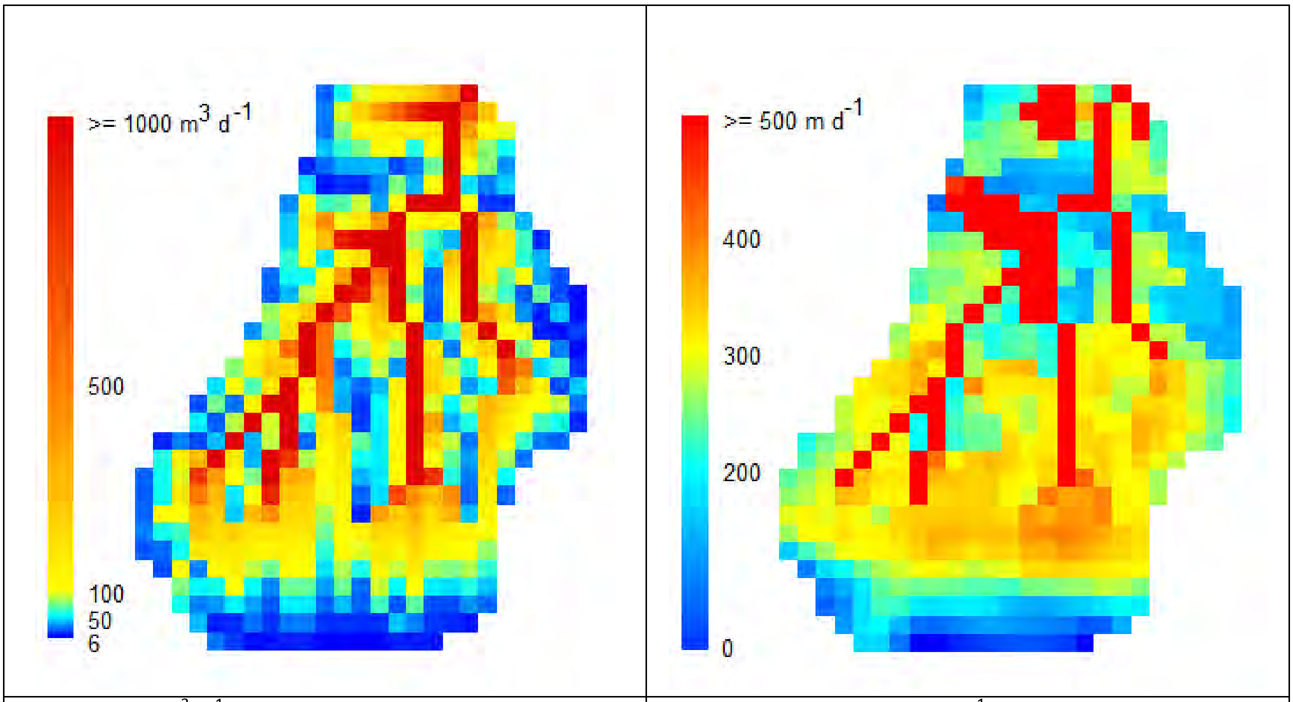


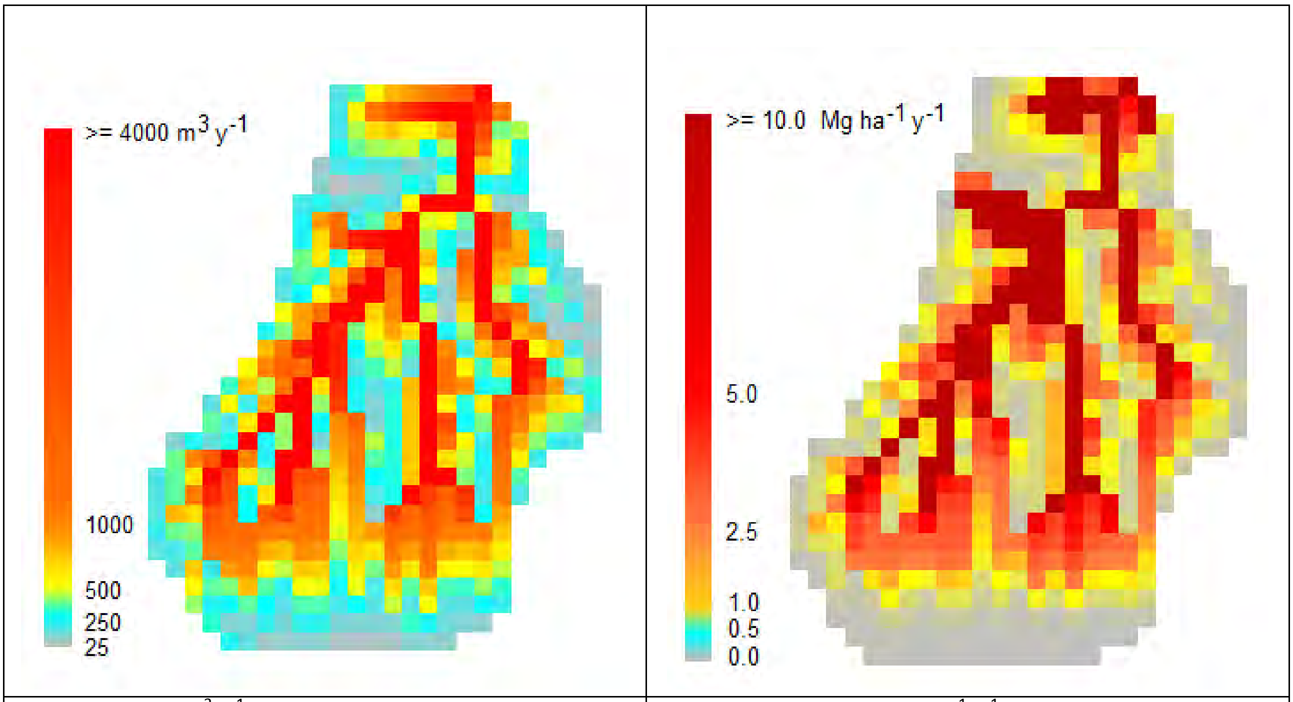
Figure 3.1. How-to-work schematic diagram of the PLER model.



Daily runoff (m^3 d^{-1})

Daily peak flow velocity (m d^{-1})

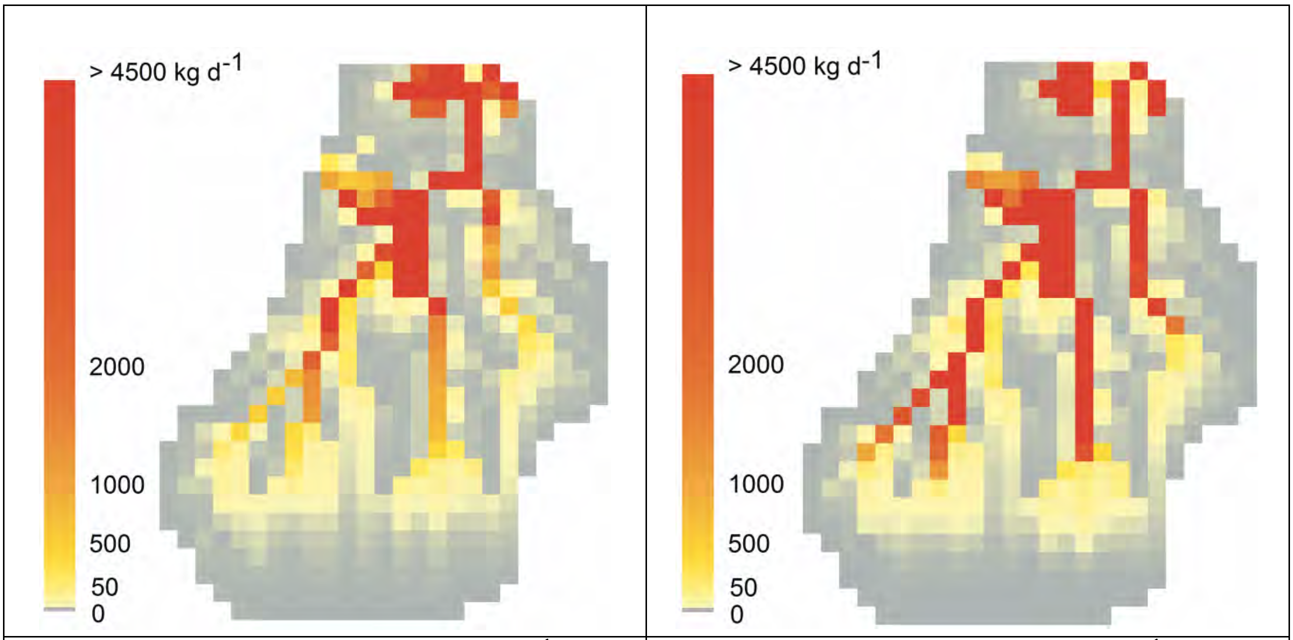
Figure 3.2. Output maps of daily runoff and daily peak flow velocity from PLER running, example of the rain event occurred on 18th August 2006 (Julian day 230).



Annual runoff (m^3 y^{-1})

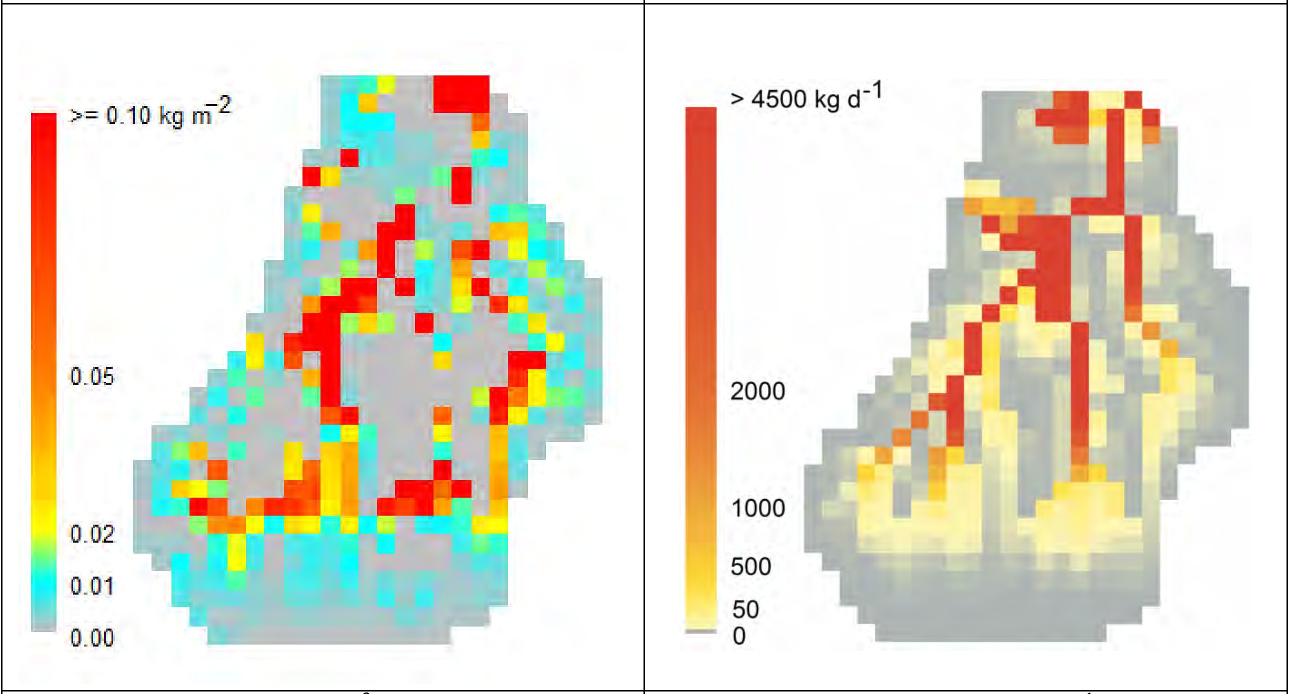
Annual erosion flux (Mg ha^{-1} y^{-1})

Figure 3.4. Output maps of annual runoff and annual erosion flux from PLER running, example of the year 2006.



Daily detachment capacity of the flow (Dc) (kg d^{-1})

Daily transport capacity of the flow (Tc) (kg d^{-1})



Daily deposited materials (kg m^{-2})

Daily suspended matter loss (SM) (kg d^{-1})

Figure 3.3. Output maps of daily detachment capacity (Dc), daily transport capacity (Tc), daily deposited materials and daily suspended matter loss (SM) from PLER running, example of the rain event occurred on 18th August 2006 (Julian day 230).

3.2.2 Hydrological module

The hydrological module calculates of water volume in each grid-cell and the water discharge of each grid-cell reaching the outlet. For each grid-cell, the *potential water storage capacity of the soil*, W_p (mm), is defined as entire volume of space obtained if the soil column were completely be compacted (Figure 3.5). Because both surface and sub-surface flows (Figure 3.5a) contribute to discharge, runoff may still occur even if *the current water content in soil column*, $W_{(t)}$ (mm d^{-1}), does not exceed W_p. Under small rain events, assumed to be under the effective rainfall amount, *the part of water that is moved out of the soil column*, $Qy_{(t)}$, is mostly composed of sub-surface flow (Figure 5b). Whereas, when the soil becomes fully saturated under a large rain event, surface flow is the dominant element in creating runoff (Figure 3.5c).

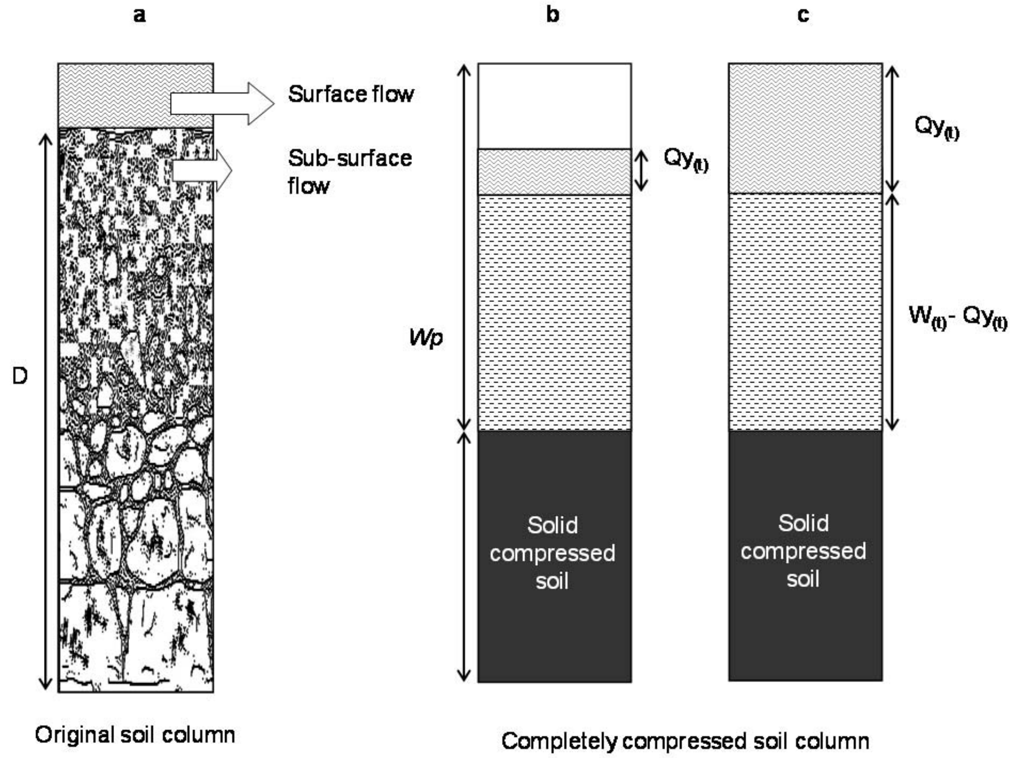


Figure 3.5. The water storage capacity of the soil column (Wp) is considered as the volume of water that can be stored in a conceptual space when the original soil column (a) was compressed completely (b, c). The volume of water that contributes to runoff, $Qy_{(t)}$*, implies only sub-surface runoff (b) or both surface and sub-surface runoff (c) depending on rainfall and soil characteristics.* $W_{(t)}$ *is the quantity of water remaining in the soil column and is called the actual water content. D is the depth of the soil column.*

The potential water storage capacity W_p is defined according to Equation 3.1.

$$W_p = \left(1 - \frac{\rho}{\rho_s}\right) D * 1000 \qquad [3.1]$$

Where:
ρ ($kg\ m^{-3}$): soil bulk density;
ρ_s ($kg\ m^{-3}$): sediment density;
D *(m)*: the soil depth.

By definition, *soil water availability*, $Wa_{(t)}$ (mm d^{-1}), is calculated by *the rainfall of the current time step*, $R_{(t)}$ (mm d^{-1}), *the in-flow from the upstream cells*, $Wi_{(t-1)}$ (mm d^{-1}), and *the remaining water in the soil*, $W_{(t-1)}$ (mm d^{-1}), in the previous time step using Equation 3.2.

$$Wa_{(t)} = W_{(t-1)} + Wi_{(t-1)} + R_{(t)} \qquad [3.2]$$

$R_{(t)}$ is read into model from the input data. $W_{(t-1)}$ and $Wi_{(t-1)}$ are calculated from the previous time step. Their values are assumed to be zero ($W_{(t-1)} = 0$ and $Wi_{(t-1)} = 0$) for the initial time step in the dry season as rainfall is zero ($R_{(t)} = 0$).

The current water content at time step *t*, $W_{(t)}$ (mm d^{-1}), is the remaining quantity of water after crop evapotranspiration, $ETc_{(t)}$ (mm d^{-1}), and deep infiltration, $I_{(t)}$ (mm d^{-1}) of each soil column (or grid-cell). The current water content is calculated according to Equation 3.3.

$$W_{(t)} = Wa_{(t)} - ETc_{(t)} - I_{(t)} \qquad [3.3]$$

The $ETc_{(t)}$ is calculated in the model as a function of the crop coefficient, $Kc_{(t)}$, and potential evapotranspiration, $ET_{0(t)}$ (mm d^{-1}) (Allen *et al.*, 1998). Value of $ET_{0(t)}$ is pre-calculated as input data for the model. The *daily deep infiltration*, $I_{(t)}$ (mm d^{-1}), depends on maximum infiltration rate I_m (mm d^{-1}) of the soil multiplied by the ratio of $Wa_{(t)}$ by W_p, and is calculated according to Equation 3.4.

$$I_{(t)} = I_m \left(\frac{Wa_{(t)}}{W_p} \right)^{1/2} \qquad [3.4]$$

Once Equation 3.3 is calculated, the obtained $W_{(t)}$ is used to calculate the flow velocity that crosses the grid-cell. We assume that all $W_{(t)}$ contributes to the lumped runoff, i.e. the sum of surface and sub-surface runoff. Then the flow velocity of the lumped runoff, $V_{(t)}$ (m d^{-1}), is calculated following the Manning-Strickler equation (3.5) (Azmon, 1992).

$$V_{(t)} = 86400 \ \varepsilon_f \ \frac{Rh_{(t)}^{\ 2/3} \sqrt{S}}{n} \qquad [3.5]$$

Where:
86400: number of seconds in a day;
S: the slope gradient (%);
n: Manning's roughness coefficient (s $m^{-1/3}$);
ε_f: velocity coefficient ($0 \leq \varepsilon_f \leq 1$);
$Rh_{(t)}$: hydraulic radius of the stream section (m) at time step *t*.

$Rh_{(t)}$ is defined as the ratio of stream section area to the wetted perimeter, assuming that all $W_{(t)}$ contribute to runoff. Because the Manning-Strickler equation is only developed for the surface runoff estimation, the *velocity coefficient*, ε_f, is used as a calibration coefficient, which is required to estimate the lumped runoff.

Based on the estimated flow velocity and the friction-distance between individual grid-cells and the outlet, *L* (m), the time that water needs to travel to the outlet, $Tm_{(t)}$ *(d),* is then estimated using Equation 3.6.

$$Tm_{(t)} = \frac{L}{V_{(t)}} \qquad [3.6]$$

The water yield from the grid-cell reaching the outlet, $Qy_{(t)}$ (mm d^{-1}) is computed according to Equation 3.7.

$$Qy_{(t)} = W_{(t)} \frac{t}{Tm_{(t)}} \qquad [3.7]$$

And the quantity of remaining water in the grid-cell from the current time step is used as soil water content $W_{(t-1)}$ for the following time step (Equation 3.2). This can be calculated according to Equation 3.8.

$$W_{(t-1)} = W_{(t)} - Qy_{(t)} \tag{3.8}$$

Finally the lumped runoff, $Qs_{(t)}$ (m^3 s^{-1}), and the total daily runoff, $Qf_{(t)}$ (m^3 d^{-1}) for each grid-cell are directly calculated from $Qy_{(t)}$ and the grid-cell area.

3.2.3 Erosion module

To estimate the mass of soil loss transported by the overland flow, a simplified equation from the Griffith University Erosion System Template (GUEST) (Misra and Rose, 1996; Yu et al., 1997; Yu, 2003) was applied in the erosion module of PLER. This equation describes the concentration of sediment that can be maintained in flowing water at equilibrium between the rates at which particles settle out of the suspension and new particles are entrained, respectively. In other words, the GUEST approach is based on the recognition of a maximum sediment concentration sustainable for a particular combination of runoff, topography and soil characteristics (Van Dijk *et al.*, 2005). A combination of two equations on the soil detachment capacity, $Dc_{(t)}$ (kg d^{-1}), and the transport capacity, $Tc_{(t)}$ (kg d^{-1}), can be computed to provide the suspended load, $SM_{(t)}$ (kg d^{-1}), exported by the stream at the outlet.

From Paningbatan *et al*. (1995), Yu *et al*. (1997) and Van Dijk *et al*. (2003), the GUEST equation for the soil detachment under the presence of the soil surface with contact cover is Equation 3.9.

$$Dc_{(t)} = k^{\beta} Qe_{(t)}^{0.4\beta} Qf_{(t)} e^{-KsC_{(t)}} \tag{3.9}$$

Where:

$Qe_{(t)}$ (m^3 s^{-1}): the effective runoff.

With a daily time step, the effective runoff $Qe_{(t)}$ represents the mean daily runoff $Qs_{(t)}$ ($Qe_{(t)} = Qs_{(t)}$);

$Qf_{(t)}$ (m^3 d^{-1}): the total daily runoff;

Ks: a non-dimensional coefficient ($5 \leq Ks \leq 15$) (Yu *et al.*, 1997);

$C_{(t)}$ (%): the fraction of soil surface with contact cover;

β: the runoff erodibility coefficient ($0 \leq \beta \leq 1$),

β=1 indicates that the soil cohesion is weakest, the soil particle is easily detached by the flow energy and consequently the sediment concentration in the flow, i.e. the suspended load, is highest.

The parameter *k* (kg m^{-3} $s^{2/5}$ $m^{-6/5}$), qualifying the erosion force, is given by Equation 3.10.

$$k = \frac{F\rho_s SL^{-0.4}}{\left(\frac{\rho_s}{\sigma} - 1\right)\varphi} \left(\frac{\sqrt{S}}{n}\right)^{0.6} \tag{3.10}$$

Where:

F: the fraction of stream power effective in erosion with $F \approx 0.1$;

ρ_s: the sediment density (kg m^{-3});

σ: the water density (σ = 1,000 kg m^{-3});

S: the slope gradient *(%)*;

L: the slope length (m);

φ: the average sediment settling velocity (m s^{-1}), and

n: the Manning's roughness coefficient (s $m^{-1/3}$).

In order to take into account the effect of the lumped runoff in the detachment equation, a second calibration parameter, ε_e, named the *erosion coefficient*, is introduced in the mass equation (3.9). The equation to calculate the *detachment capacity*, $Dc_{(t)}$, thus becomes Equation 3.11.

$$Dc_{(t)} = \varepsilon_e k^{\beta} Qs_{(t)}^{\;0.4\beta} Qf_{(t)} e^{-KsC_{(t)}} \qquad [3.11]$$

Following the same hypothesis, the *transport capacity* $Tc_{(t)}$ that is calculated with runoff discharge is therefore corrected with the same erosion coefficient ε_e for the effect of the lumped runoff when soil cohesion is weakest (*β*=1 for any sediment and river), according to Equation 3.12.

$$Tc_{(t)} = \varepsilon_e k \; Qs_{(t)}^{\;0.4} Qf_{(t)} e^{-KsC_{(t)}} \qquad [3.12]$$

The runoff erodibility coefficient β is equal to 1 in the transport capacity equation, then $Tc_{(t)}$ is by definition always higher than $Dc_{(t)}$. Moreover the mass of sediment transported downstream is limited by the transport capacity of the drainage channel. Indeed the flow can only carry out an amount of detached sediment that is smaller or equal to its transport capacity. And the excess amount will be deposited on the soil surface. Then the sediment concentration in the flow at time step *t*, expressed by *Suspended Matter loss* $SM_{(t)}$ (kg d^{-1}), is the cumulative of sediment flux transported from upstream cells to downstream cells at time step t. And this quantity has to be equal or minus the transport capacity of the considered cell.

3.2.4 Evaluation of model performance

Numerical methods were used to evaluate the model performance. Two classic indicators, the correlation coefficient, r^2, and the Nash-Sutcliffe efficiency, *Ef*, (Nash and Sutcliffe, 1970) were used to quantify the systematic and dynamic errors of the model simulation.

The correlation coefficient is the ratio between the covariance and the multiplied standard deviations of the observed and simulated values according to Bravis-Pearson (Krause *et al.*, 2005). It describes the dispersion of the observed and simulated series. A value of zero denotes no correlation whereas a value of 1 means the prediction is equal to the observation. The correlation coefficient is calculated according to Equation 3.13.

$$r^2 = \left(\frac{\sum_{i=1}^{N} (O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{N} (O_i - \overline{O})^2} \sqrt{\sum_{i=1}^{N} (P_i - \overline{P})^2}} \right)^2 \qquad [3.13]$$

Where:

O_i and P_i are observed and simulated values at time step *i*, respectively;

$\overline{O}$ and $\overline{P}$ are means of N observed and simulated values.

The model efficiency (E_f) proposed by Nash and Sutcliffe (1970) expresses the quality of model performance. E_f is calculated according to Equation 3.14.

$$E_f = 1 - \frac{\sum_{i=1}^{N}(Oi - Pi)^2}{\sum_{i=1}^{N}(O_i - \overline{O})^2} \qquad [3.14]$$

Where:

O_i, P_i, $\overline{O}$, $\overline{P}$ as defined above.

E_f ranges from 1 to $-\infty$. An efficiency value of 1 shows a perfect relation between prediction and observation; value of 0 occurs when an equal performance relative to the reference and a negative value indicates that the model predictions are worse than the average of observation.

The performance of the erosion model was also analysed by a two-way analysis of variance (ANOVA) with erosion events (characterized by presence of suspended load in the stream) considered as independent variables. The erosion events were classified by class: large events > 100 kg ha day^{-1} of soil loss concentration (SL), medium events from 10 to 100 kg ha day^{-1} of SL and small events < 10 kg ha day^{-1} of SL. The LSD test was performed to assess differences between class means. All statistical analyses were carried out using R (RDCT, 2008). The level of significance was at $P < 0.001$.

3.2.5 Dong Cao watershed

The study was carried out in the Dong Cao watershed, which has a total surface area of 47 ha and is situated in Hoa Binh province, North Vietnam (20 57’N, 105 29’E), approximately 50 km from Hanoi (Figure 3.6). The watershed is a typical cultivated mountainous watershed, has an elevation of 125 m to 485 m and slopes ranging from 15 to 120% (Toan *et al*., 2003; Phai *et al*., 2007). According to FAO soil classification (1998), the dominant soil type in the watershed is Ferralic Acrisol with a soil depth of approximately 1 m. Some Cambisols and Fluvisols occur along the stream course. The main characteristics of these soils are: a heavy texture with clay contents around 50% and are rather porous with an average bulk density of 1.24 g cm^{-3} (Podwojewski *et al.*, 2008). During the two experimental years used for the PLER calibration and validation, 2006 and 2007, the Dong Cao watershed was mainly covered by young planted forest (*Acacia mangium*) on former cassava plantations, with small contributions from cassava and with old fallow or secondary forest at the top of the catchment.

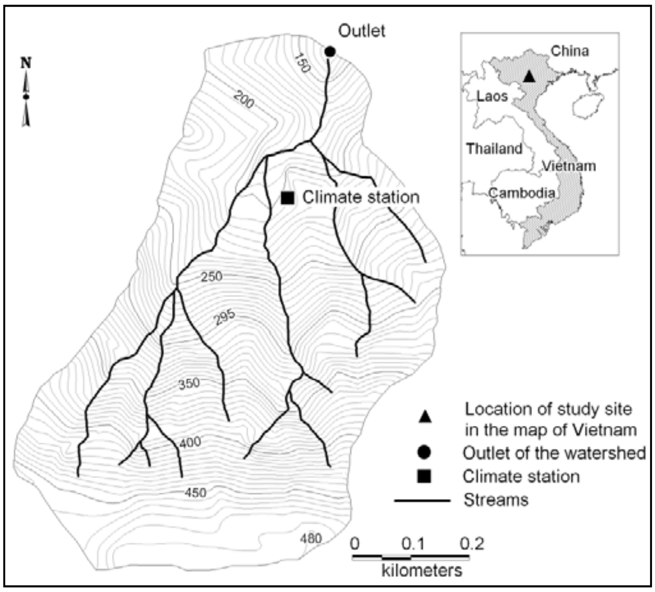


Figure 3.6. Location of study site and topographic map (elevation lines in 10 m intervals) of the Dong Cao watershed with the location of the climate station and the outlet.

The Dong Cao watershed is situated in the humid tropical climate zone of Vietnam and annual rainfall ranges from 1,200 – 2,300 mm y^{-1}. The rainy season starts in April and lasts till the end of September with 80 – 85% of the annual rainfall. High intensity rainfall events occur with a high frequency from July to August. The daily average temperature varies from 10ºC in January and February to 39ºC from June to July. The humidity is always high with daily average around 80% to 100%, and the annual potential evapotranspiration is approximately 960 mm y^{-1}.

3.2.6 *Field measurements and data collection*

The monitoring network of Dong Cao watershed includes a weather station and a weir at the outlet of the watershed equipped with a water level recorder (Thalimedes) and an automatic water sampler (AWS) (Toan *et al.*, 2003). The automatic weather station (CIMEL) measures rainfall at six-minute intervals, minimum and maximum hourly temperature, minimum and maximum hourly air humidity, hourly wind speed and hourly solar radiation. This weather data was used to calculate daily rainfall amounts and potential evapotranspiration as inputs for the model. Previous studies, based on several rain gauges distributed over the whole watershed, have shown that this rain gauge is representative of rainfall in the watershed (Orange et al., 2007). Daily potential evapotranspiration, $ETo_{(t)}$ (mm), was calculated by using Penman-Monteith formula. Water level is recorded every 3 minutes to calculate runoff discharge at the watershed outlet. The AWS automatically collects one litre of water in the stream for each increase of 2 cm of water level during peak flow. The water samples were then filtered to measure the suspended matter concentration (g l^{-1}).

A Digital Elevation Model (DEM) with a grid size of 30 m was acquired from the Earth Remote Sensing Data Analysis Centre (ERSDAC, 2009). Other spatial layers, including a land-use map, a soil map, a slope map and a stream network map, are created with a resolution of 30 x 30 m. In the Northern Vietnam, field-to-field variability occurs over short distances of about 20 to 100 m (Witt *et al.*, 2007). Therefore, we consider that a resolution of 30 x 30m is appropriate for taking into account the soil, topography and land-use variability. In the model, the land-use map is linked to a database describing characteristics of land-use type in four stages (initial, development, middle and last stages) of vegetation growth (Allen *et al.*, 1998). Monthly vegetation cover rate of land-use types measured in the Dong Cao watershed were used as fraction of soil surface with contact cover (Paningbatan *et al.*, 1995; Van Dijk *et al.*, 2003). Crop coefficients and Manning's roughness coefficients of land-use types were obtained from the literature (Azmon, 1992; Allen *et al.*, 1998; Hessel *et al.*, 2003). Rainfall and potential evapotranspiration are used as the temporally variable input data. Data concerning the soil characteristics of the watershed are taken from the soil study of Podwojewski (2003): soil depth, bulk density, sediment density, sediment setting velocity, clay content and maximum infiltration rate. All variables and parameters used in the model are listed in Table 3.1.

3.3 Results

The daily rainfall (mm d^{-1}) and the discharge ($m^3 s^{-1}$) measured at the watershed outlet in 2006 and 2007 are presented in Figure 3.7. Despite numerous small rainfall events in early 2006 (40 events below 20 mm d^{-1} occurred from January to April), the significant peak flows occur only from end-July till mid-September and during the single event at the end of November 2006 due to a 65 mm d^{-1} rainfall event. During 2007, the rainfall pattern was quite different. The rains were significant in March and April and weak in July-August, leading to a stream discharge in early April and a very low discharge during the summer. The largest event in 2007 occurred in October with a rainfall of 100 mm d^{-1}.

The largest daily discharge at the outlet ranged from 0.0001 to 0.0005 $m^3 s^{-1}$ (i.e. 8 to 40 $m^3 d^{-1}$). The highest daily discharge (0.35 $m^3 s^{-1}$) was recorded on 18th August 2006 corresponding to a rainfall of 154 mm d^{-1}. In 2007, similar ranges of rainfall (110 mm d^{-1} and 125 mm d^{-1}) occurred on 10th September and 5th October, respectively, but resulted in lower peak flows, 0.06 m^3 s^{-1} and 0.13 m^3 s^{-1}, respectively.

PLER model was calibrated by using data of 2006 and then validated with data of 2007. Fourteen floods in 2006 and thirty two floods in 2007 with measured suspended matter, $SM_{(t)}$ (outlet, location in Figure 3.6) were used to calibrate and validate the hydrological and the erosion modules.

Table 3.1. Parameters, variables and calibration coefficients used in the PLER model.

Symbol	Description	Unit	Source	Range Value
t	Time step	d		
ε_f	Coefficient to adjust flow velocity	-	Calibration coefficient	
ε_e	Coefficient to adjust mass of suspended matter	-	Calibration coefficient	
I_m	Maximum infiltration rate	mm d^{-1}	Field measurement	18 – 67 mm h^{-1}
ρ, ρ_s	Density of soil, of sediment	kg m^{-3}	Field measurement	1200 kg m^{-3}
σ	Density of water	kg m^{-3}		1000 kg m^{-3}
φ	Average sediment settling velocity	m s^{-1}	Field measurement	0.63 – 1.12
D	Soil depth	m	Field measurement	0.2 – 1.5
β	Runoff erodibility coefficient ($\beta = 1 -$ clay content)		Field measurement	0.55 – 0.63
$R_{(t)}$	Daily rainfall	mm d^{-1}	Field measurement	
$ETo_{(t)}$	Potential evapotranspiration	mm d^{-1}	Calculated from climate data	
$C_{(t)}$	Vegetation cover rate of growth stages	%	Field measurement	0.15 – 0.95
n	Manning's roughness coefficient	s m$^{-1/3}$	(Azmon, 1992; Hessel et al., 2003)	0.03 – 0.2
$Kc_{(t)}$	Crop coefficient	-	(Allen et al., 1998)	0.3 – 1.2
Ks	Non dimension coefficient	-	(Paningbatan et al., 1995)	
F	Fraction of stream power	-	(Misra and Teixeira, 2001)	
S	Slope gradient	%	Derived from DEM	
L	Slope length	m	Derived from DEM	
$Etc_{(t)}$	Current evapotranspiration	mm d^{-1}	Calculated in model	
Wp	Potential water storage capacity	mm	Calculated in model	
$Wa_{(t)}$	Water availability	mm	Calculated in model	
$W_{(t)}$	Current water content	mm	Calculated in model	
$W_{(t-1)}$	Remaining water in soil after previous runoff	mm	Calculated in model	
$Wi_{(t-1)}$	In-flow from upstream grid-cells after previous runoff	mm	Calculated in model	
$I_{(t)}$	Actual deep infiltration rate	mm d^{-1}	Calculated in model	
$V_{(t)}$	velocity of the flow	m d^{-1}	Calculated in model	
$Rh_{(t)}$	Hydraulic radius of the flow	m	Calculated in model	
$Tm_{(t)}$	Time for water to reach the outlet	d	Calculated in model	
$Qy_{(t)}$	Water yield from grid-cell	mm d^{-1}	Calculated in model	
$Qs_{(t)}$	The runoff rates	m^3 s^{-1}	Calculated in model	
$Qf_{(t)}$	Total daily runoff	m^3 d^{-1}	Calculated in model	
k	*k* factor	kg m$^{-21/5}$ s$^{2/5}$	Calculated in model	
$Dc_{(t)}$	Detachment capacity of the flow	kg d^{-1}	Calculated in model	
$Tc_{(t)}$	Transport capacity of the flow	kg d^{-1}	Calculated in model	
$SM_{(t)}$	Daily suspended matter loss	kg d^{-1}	Calculated in model	

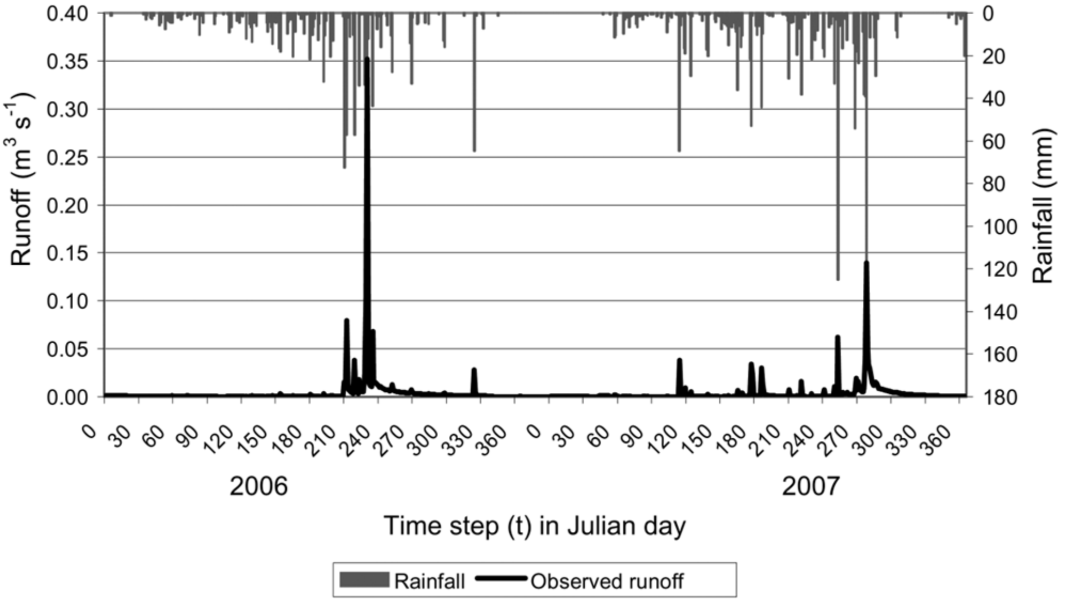


Figure 3.7. Observed rainfall (mm d^{-1}) and runoff (m^3 s^{-1}) at the outlet of the Dong Cao watershed in 2006 and 2007, in Julian days.

3.3.1 Calibration and validation of the runoff module

From December to January in both 2006 and 2007, rainfall was very low and no overland runoff occurred. During this period, the soil moisture was at its lowest level and the deep infiltration capacity was at its highest level. The initial conditions of the simulation are set as $I_{(t)} = I_m$ (maximum infiltration rate); $Wi_{(t)}$=0 and $Qf_{(t)}$=0 corresponding to the conditions at the beginning of the year. While it often starts to rain in March, significant rain events (the efficient rainfall threshold is fixed above 20 mm d^{-1}) generally do not occur before April. Thus, the simulation during the first 3 months of the year was used to stabilize the daily parameters of the model.

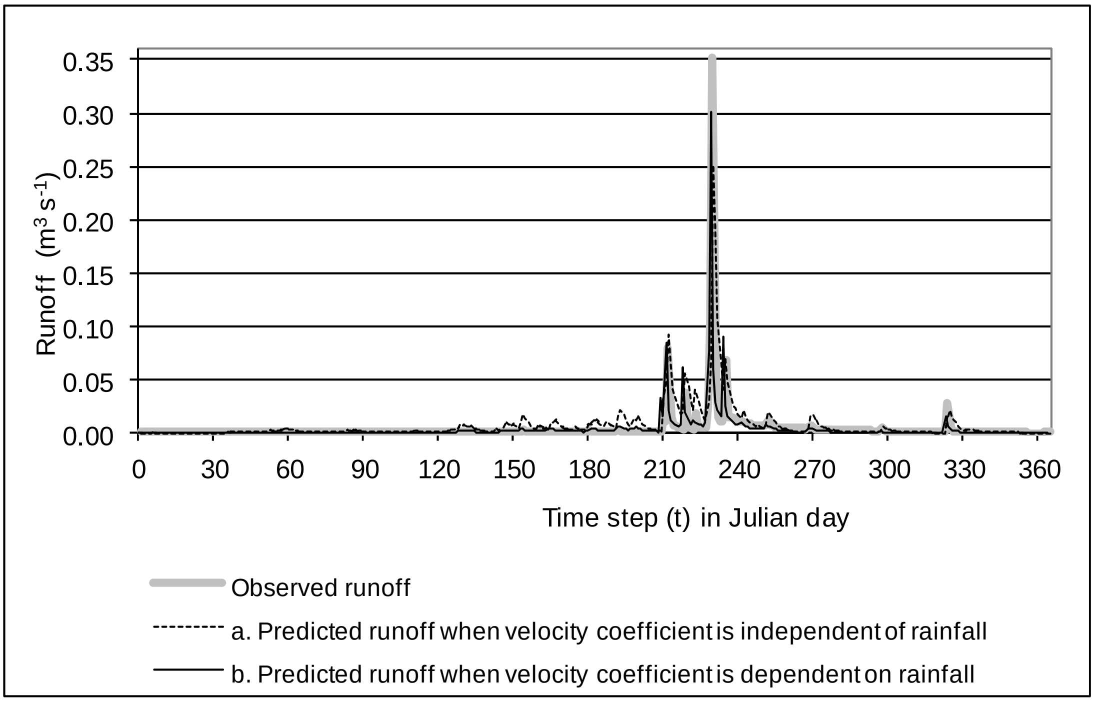


Figure 3.8. Comparison of predicted mean daily runoff (m^3 s^{-1}) in 2006 using two different calibration methods for the flow velocity: (a) calibration coefficient is independent of the daily rainfall amount, and (b) calibration coefficient is dependent on the daily rainfall amount (R <= 40mm d^{-1} and R >40mm d^{-1}).

Table 3.2. Values of the calibration coefficient for the hydrological module of PLER model (ε_f, the velocity coefficient) and performance indicators (correlation coefficient r^2, Nash-Sutcliffe coefficient E_f, and the Measurement/Prediction ratio in % to evaluate the performance of the runoff simulation in the Dong Cao watershed, Northern Vietnam, using measured discharge data from 2006.

Indicators	ε_f is independent of rainfall					ε_f is dependent on rainfall	
	0.005	0.0045	0.004	0.0035	0.003	$R_{(t)}$ ≥40 (mm d^{-1})	$R_{(t)}$<40 (mm d^{-1})
						0.004	0.001
r^2	0.67	0.68	0.65	0.63	0.60	0.96	
E_f	0.54	0.56	0.57	0.58	0.57	0.96	
Measurement/Prediction ratio (%)	46	48	51	55	60	97	

ε_f: calibration coefficient to adjust the flow velocity; two values of ε_f are used when rainfall threshold of 40 mm d^{-1} is taken into account.

The calibration of the runoff module was done by tuning the velocity coefficient ε_f (Equation 3.5) with and without influence of rainfall (Table 3.2). Data analysis showed that high peak flows always occurred when rainfall events exceeded 40 mm d^{-1}, thus a threshold of daily rainfall of 40 mm d^{-1} was used to reflect the change of flow behaviour at this rainfall level. When ε_f is independent of rainfall, the Nash coefficient was always below 0.6. Whereas, when rainfall was taken into account, two values of the velocity coefficient, ε_f =0.01 and ε_f =0.04, were found for when daily rainfall was below or above 40 mm d^{-1}, respectively. Using these values significantly improved the model performance (Nash coefficient of 0.97 and a coefficient correlation of 0.96 (Table 3.2). In addition, the overestimation of stream flow after smaller rainfall events was significantly reduced (Figure 3.8). This regulation of the velocity coefficient is consistent with the hydrological behaviour of the sub-surface and surface runoff as observed in the field. At last the map of daily peak flow velocity and the map of daily runoff (Figure 3.2) underline that the flow velocity is highest inside the stream course or on the highest slopes with the weakest vegetation cover; and the daily runoff can be different to the flow velocity due to the slope length. These mapping observations are strongly consistent with field behaviour.

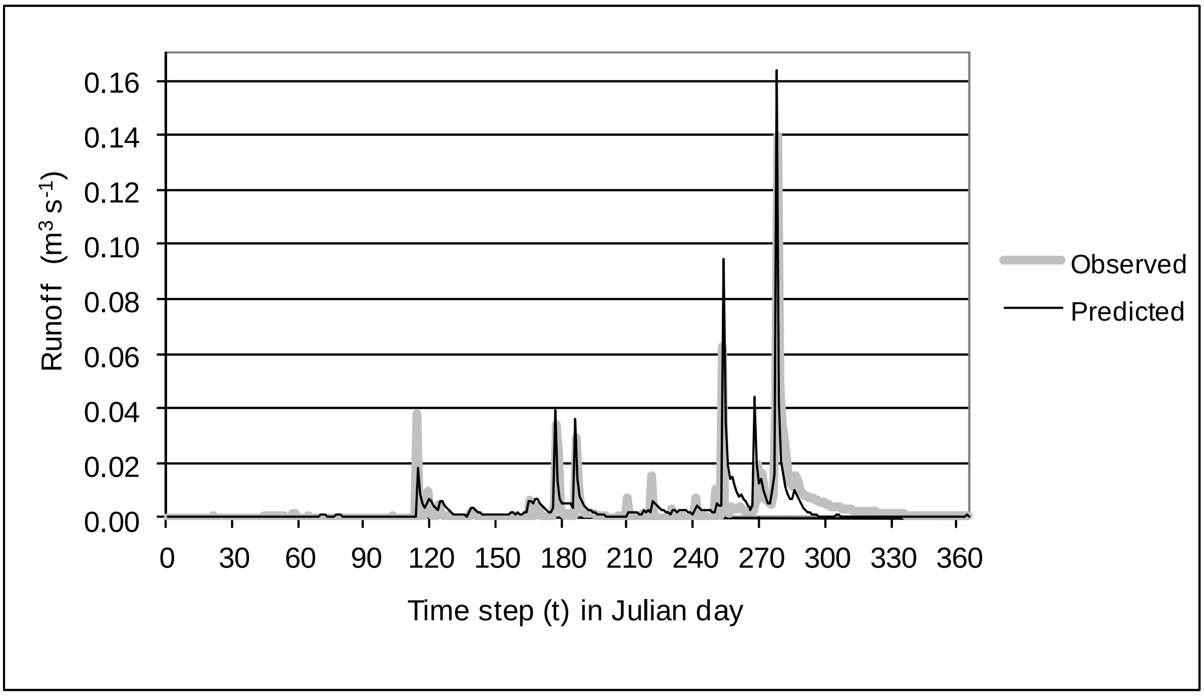


Figure 3.9. Comparison between observed and predicted runoff at the outlet of the Dong Cao watershed in 2007.

Applying the obtained values of ε_f to the year 2007 for validation, resulted in a Nash coefficient of *Ef* =0.76 and a correlation coefficient r^2 =0.82. The simulated and observed flows have the same pattern in term of peaks and base flow over the two years (Figures 3.8 and 3.9). More precisely, the best fit was found for peak flows and after the larger events, the base flow was often overestimated. The model does not seem to simulate the rapid decrease of the peak flow well, which may be due to the fast drainage from the surface or through infiltration. However, the numerous peak flows in autumn that were due to some exceptional heavy rain events in October 2007 were well simulated by the PLER model, since the base flow is smoothly underestimated. In order to provide adequate estimates of simulated daily soil losses, it is essential that peak flows are well simulated as discussed by Morgan et *al*. (1998). Therefore, it is probable that the PLER model provides a good tool for determining hydrological calculations of the outlet discharge from a small hilly watershed on a daily time scale using based on a free digital elevation model obtained from the internet. Despite very low base flows as compared to heavy rain events, the daily discharge is adequately simulated. Given these robust predictions of peak discharge, we propose that this hydrological model provides a good basis for the calculation of soil losses by runoff.

3.3.2 Calibration and validation of the erosion module

The erosion module was calibrated by tuning the second calibration coefficient, the *erosion coefficient* ε_e (Equations 3.11 and 3.12). The calibration using a constant value did not provide acceptable results. Further analysis of the measured data showed a link between the rainfall event value and the soil loss amount (Phai et al., 2007; Orange *et al*., 2007) following the same conclusion obtained with the calibration of the hydrological module. The regression analysis software TABLECURVE (Tablecurve 2D, 2002) was used for variables $SM_{(t)}$, $R_{(t)}$ and $R_{(t-1)}$. The best value for the erosion coefficient ε_e was provided through a function of the rainfall (mm d^{-1}) of two successive days, using Equation 3.15.

$$\varepsilon_e = \frac{3}{(0.07 + \frac{20}{R_{(t)}^{\ 1.5}})} * \frac{1}{(0.95 + 0.06 R_{(t-1)})} \qquad [3.15]$$

Where:
$R_{(t-1)}$: rainfall (mm d^{-1}) in previous day *t-1*;
$R_{(t)}$: rainfall (mm d^{-1}) in predicting day *t*.

The qualitative results can be observed on the mapping outputs that PLER model can provide for any time step. In the example selected for the Figure 3.3, for the rain event occurred on 18th August 2006, the daily suspended matter transported by each cell has been quite similar to the transport capacity due to the fact that the rain event chosen is a very strong event, the highest of the year. And the map of deposited materials indicates that the sedimentation has occurred this day mainly in some parts of the stream channel and over the lands with the lowest slopes. Then these mapping outputs underline the qualitative sense of the PLER results.

For the 14 events recorded in 2006, the Nash coefficient and the correlation coefficient show very significant correlations between observed and simulated $SM_{(t)}$, *Ef* = 0.99 and r^2 = 0.99, respectively (Figure 3.10). As the observed data were not well distributed over the range value, the classic correlation analysis cannot be used. The data was therefore ranked by erosion intensity from small to large soil loss events. Independence of the transformed data was confirmed by the LSD test and the ANOVA analysis demonstrated the high significance level of simulated data in comparison with the observed data in each erosion class (P = 0.998 for the model; Figure 3.11).

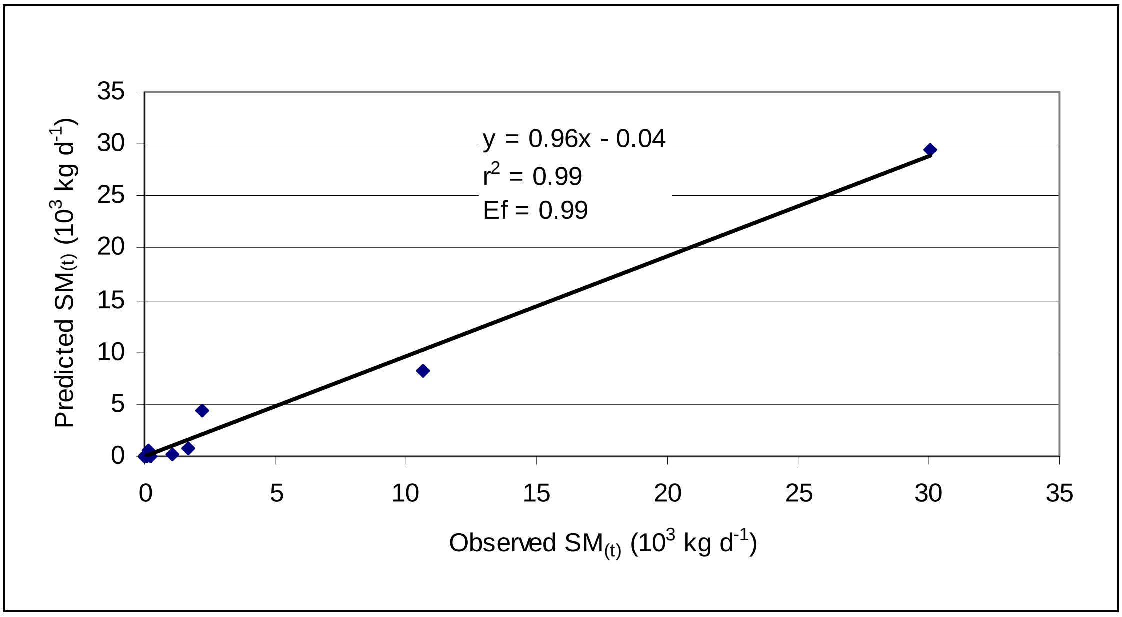


Figure 3.10. Correlation between observed and simulated suspended matter at the outlet of the Dong Cao watershed calibrated with data from 2006.

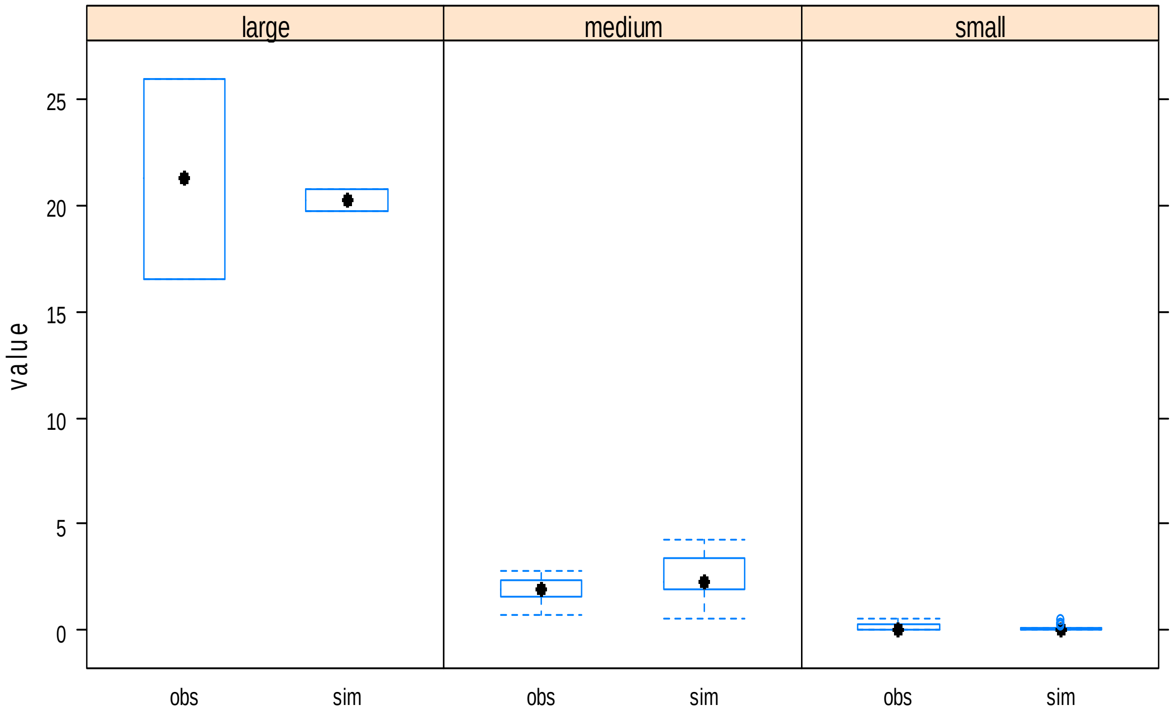


Figure 3.11. ANOVA analysis on observed (obs) and simulated (sim) suspended matter data from large, medium and small rain event classes for the model validation with data from 2007 at the outlet of the Dong Cao watershed.

3.4 Discussion

Runoff calculated by the PLER model is defined as the sum of surface runoff and sub-surface runoff. Therefore, the simulated runoff of a grid-cell, which is the quantity of water leaving the soil column in a time unit, is the lumped surface and sub-surface runoff. This water quantity corresponds to the rainfall minus deep infiltration and the evapotranspiration. The deep infiltration variable has been added to the model since field observations suggested that an important amount of water can be lost by infiltration to the deep aquifer in the flat lands, even on slope gradients above 30% as demonstrated by Janeau *et al.*

(2003). Moreover, Podwojewski *et al*. (2008) showed that the physical soil properties and the geology of this watershed facilitate the infiltration process by driving the waters to deep infiltration.

The soil characteristics coupled with the topography characterized by steep slopes led to the combination of Hortonian and Dunne flow processes. Indeed measurements in gullies and small streams in the Dong Cao watershed with surface runoff detectors showed that surface runoff in a gully can appear in the upper part, then disappear by infiltration and appear again at the surface some distance downward from exfiltration. Thus surface runoff and sub-surface runoff are continuously mixed over the time and along the hillslope. In fact, the infiltration process shifts from a Hortonian mechanism governed by infiltration excess to a Dunne mechanism governed by saturation excess. Thus the Green and Ampt method often used to simulate the infiltration within the runoff models, e.g. LISEM (Jetten *et al.*, 1998), is not adapted to the studied watershed as an explanation for the loss of water through deep infiltration as recorded here. Consequently, the infiltration, named *deep infiltration* in PLER model, is linked to the water storage capacity of the soil column of the grid-cell divided by the quantity of sub-surface and surface water available (Equation 3.4).

The instantaneous cell water content, $W_{(t)}$ calculated by PLER model, is based on the Manning-Strickler equation, originally developed for uniform rough open channel flow (Hergarten and Neugebauer, 1997). We assume that the Manning-Strickler equation can be applied for lumped sub-surface and surface runoff with a velocity coefficient ε_f (Equation 3.5) ranging from 0 to 1 as the calibration coefficient. A value of $\varepsilon_f = 0$ indicates that there is no runoff and $\varepsilon_f = 1$ means that the entire $W_{(t)}$ contributes to runoff. Thus the ε_f value depends on the water potential of the soil column under the influence of both rainfall characteristics (amount, intensity and time pattern) and soil characteristics. Since the velocity of sub-surface flow is significantly slower than the velocity of surface flow, a lower value for the velocity coefficient was expected for the case of only sub-surface flow ($\varepsilon_f = 0.001$). Based on field observations, it appears that the hydrological response of the stream differs with rainfall amounts over 40 mm d^{-1}. Peak flows are much more important in showing a very quick increase of the water level. To represent this behaviour, with higher rainfall (above 40mm), the calibration coefficient has a higher value ($\varepsilon_f = 0.004$), which simulates faster transfer of runoff water from the cell to the outlet.

The erosion module is calibrated with the erosion coefficient ε_e (Equation 3.11 and 3.12) as a function of rainfall amount over two successive days (cf. Equation 3.15). Based on the measured suspended load dataset, it appears that $SM_{(t)}$ is very low when rainfall is around 20 mm d^{-1}, but $SM_{(t)}$ increases significantly when rainfall exceeds 40 mm d^{-1}. Field observations showed that daily rainfall alone is not sufficient to explain the variability in the suspended matter content of the discharge. It was shown that rainfall in the previous day, $R_{(t-1)}$, also strongly influenced the quantity of $SM_{(t)}$ (Orange *et al.*, 2007). Misra and Rose (1996) indicated that the mass of eroded sediment comes from two types of particles: the particles from original soil with a strong cohesion and some aggregates, and the newly deposited particles. Thus, when the rain occurred, the soil detachment under $R_{(t)}$ is initially composed of newly deposited particles due to the previous rain event, $R_{(t-1)}$, followed by the in-place soil. Due to the soil softening effect caused by $R_{(t-1)}$ and previous runoff, unstructured soil is detached easily, and so $SM_{(t)}$ increases. Alternatively, when a large part of easily detached soil has been transported downstream by $R_{(t-1)}$, the surface flow created by $R_{(t)}$ will have a lower sediment concentration, and $SM_{(t)}$ reduces accordingly. Therefore it is reasonable to describe ε_e as a function of $R_{(t)}$ and $R_{(t-1)}$. The high model efficiencies in both calibration and validation demonstrate the robustness of the erosion coefficient calculated through the Equation 3.15.

The application of the PLER model to another watershed requires a basic dataset of some relevant input parameters (Table 3.1). Besides the parameters for which values can be found in literature such as Manning's roughness coefficient and the crop coefficient, a basic catchment specific data are needed such as land-use maps, soil maps, slope maps and stream network maps. These maps are all strongly influenced by the topographic map, which in our case was derived from a DEM. Applying PLER model in Dong Cao demonstrated that a 30 x 30m grid-cell is a suitable resolution. Moreover, DEM with a resolution of 30 x 30 m can be downloaded freely from internet, which greatly simplifies the application of PLER model to other small hilly watersheds (< 1 km^2). Land-use map are often complicated to obtain since the land-use can change quickly from year to year. Moreover the land cover is also rather dynamic in the tropical monsoon climate. Other input data on soil properties (soil depth, bulk density, sediment density, average sediment setting velocity, clay content and maximum infiltration rate) must be collected from field measurements or from regional bibliography. And daily rainfall rates are usually available at monitoring locations. Other climate parameters as minimum and maximum temperature, air humidity, wind speed and solar radiation are needed to calculate the potential evapotranspiration. So the presence of a weather station in the watershed is probably essential for the application of the model. Finally, in order to determine the applicability of the model to other watersheds, it is essential that some flow measurements and suspended sediment data are available for model calibration and validation at the chosen outlet of the studied watershed. Nevertheless, the data requirements for PLER model are still simple compared with the requirements for other soil erosion models such as LISEM model (Jetten *et al.*, 1998) or WEPP model (Flanagan *et al.*, 2001). The key challenge of the next step of our study is to evaluate the PLER model in other small watersheds without any gauging and erosion measurements.

3.5 Conclusion

Although Manning-Strickler and GUEST equations are designed to address runoff and sediment detachment during short rainfall events, they were adapted in the PLER model to perform simulations on a daily time scale. The combined application of these equations in PCRaster has resulted in a distributed model (the PLER model) that simulates daily runoff and daily suspended matter load at the outlet of small hilly watersheds (i.e. < 1 km^2). Daily maps and cumulative maps of overland water, erosion and deposition are dynamic outputs of the model. The map resolution of 30 x 30 m, freely accessible on the web, is appropriate to capture field to field variation of soil and land-use characteristics. The main advantage of the PLER model is that it can be calibrated with only two parameters, the velocity and erosion coefficients, both of which are related to rainfall.

The main hypothesis of PLER model is to assume that the cumulative of surface runoff and sub-surface runoff can be used to apply these two physics-based equations by applying two calibration coefficients. The velocity coefficient, incorporated into the Manning-Strickler equation, is used to tune the model outputs to match with the daily flow at the watershed outlet. The erosion coefficient, calculated as a function of daily rainfall at time step t and t-1, is used to adjust the outputs to match with the suspended matter observed at the watershed outlet. The simplicity of data requirements allows the model to run over many years without long calculation times. Above all, PLER model allows the production of g numerous maps such as runoff rate, detachment rate, soil transport capacity, etc. These maps can then be used to identify the hydro-geomorphic functioning as a function of land-use, thus providing a better estimation of the application of agricultural management strategies. .

With its simple input data needs as compared with other models, the PLER model could be applied for small hilly watersheds in humid tropical areas as an easy and useful tool for long term runoff and soil erosion modelling in relationship with land-use change. The key challenge of the next step for PLER model development is to evaluate its capacity to be transportable in other small watersheds that are lacking in water flow and erosion measurements.

Chapter 4

A modelling approach for evaluating constraints in agricultural production in the Northern Uplands of Vietnam

This paper will be submitted as:
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To: Land Use Policy

A modelling approach for evaluating constraints in agricultural production in the Northern Uplands of Vietnam

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Abstract

Changes in poverty alleviation and economic growth in the Northern Uplands of Vietnam (NUV), where 80% of rural households rely on agriculture, appear to be very slow and not in line with government plans. One of recognized reasons is the mismatch between perspectives of government officials, researchers and farmers on problems of the region. The reason has led to insufficient or inappropriate interventions for agricultural development in recent decades. The constraints in agricultural production in the NUV are commonly described by stakeholders, including lack of land area, land fragment, lack of capital and agricultural labour and traditional technology, but they are often seen in different points of view. A modelling approach described in this paper supports policymakers and researchers to describe the constraints in a quantitative manner. The Land Use Planning and Analysis System (LUPAS) was used to generate current and future land use scenarios for a representative watershed in the NUV. Trade-offs among the scenarios showed that traditional technology level and land fragmentation are largest constraints at current natural and social conditions while land area, capital and labour seem to have inconsiderable impacts. Towards reaching future targets, capital becomes an important factor and household capital needs to be extended. However, land use scenarios specify that a small loan size is likely more significant for households than larger loans. The results imply that shifting agricultural technology from traditional to recommended level together with developing microfinance are the most important keys of economic development and poverty reduction in the NUV.

Key words: Modelling, land use planning, constraints, LUPAS, Northern Uplands, Vietnam

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4.1 Introduction

The Northern Uplands of Vietnam (NUV) is a habitat of 11 million people, approximately 13% of national population. 80% of rural households in the region are relying on agricultural production and facing with various challenges in their livelihood. Low agricultural production, serious land degradation and high poverty rate are mentioned as fundamental problems of NUV (Castella and Quang, 2002; GSO, 2011; Minot et al., 2006; Orange and Noble, 2010; Vien, 2003). Successive government' land use policies implemented since the beginning of "Doi moi" (renovation) program in 1980s (McPherson, 2012) show that Vietnamese government has put a lot of efforts on the way to reach national goals for food security, poverty alleviation and economic growth, especially for rural area. Although such policies have made significant national economic growth, changes in NUV, however, appeared to be very slow (MARD, 2006) and not in line with government plans (Clement et al., 2006; Sicat et al., 2005). Although there have been a lot of studies in order to explore the root causes of the existing problems, the constraints in agriculture production and people livelihood are not clearly defined.

An overview of Ministry of Agriculture and Rural Development of Vietnam (MARD) (2006) for land use planning underlined that low soil fertility, steep slope and inconvenient topography are main natural disadvantages of the region. In addition, low education and traditional land management practices of rural people in NUV are also considerable social constraints. In looking at current circumstance of NUV, other authors highlighted the connection between above problems with highly heterogeneous conditions. According to Vien (2003), NUV has more than 30 different ethnic groups and each group, with its own traditional culture and habits, has developed distinctive farming systems. Therefore, diversity in culture is also a factor that influences economic development. Among an ethnic group or a small community (villages) the diversity is also remarkable. Clement and Amezaga (2008) and Orange et al. (2008) indicated that land use strategy in NUV is often made by individual households according to situation of their fields, capital endowments and also the human belief on land management. Accordingly, agriculture production of whole NUV appears to be the sum of consequences of individual strategies (Castella, 2009).

At the household scale, a smallest unit of land use decisions, the heterogeneity is reflected by both inter-farm fragmentation, in which several households share an area of land, and intra-farm fragmentation, in which land of each household includes many discrete plots. Although a farm size is typically less than a hectare, a household in NUV owns up to 10 – 20 discrete plots (Lan, 2001). Overall, land fragmentation is not only a households' constraint but also a concerned limitation of the region (Hung et al., 2007; Lan, 2001; MARD, 2006). The government of Vietnam considers land fragmentation as a significant barrier to achieving further productivity gains in agriculture.

From farmers' point of view, land degradation, heterogeneous environment and a high diversity in culture and farming system, however, are not their concerns. It is easy to understand because in NUV, rural households are dealing with a number of more urgent real-life challenges such as food for self-sufficient, expenses of family, education of children, etc. An analysis Minot et al. (2006) showed that the poor and better-off rural households in the NUV cited lack of land area, low knowledge and education level, large number of children and lack of capital as their current problems, which are main causes of poverty. According to a recent report of the Vietnam Academy of Social Sciences (VASS, 2011), lack of credit sources is also seen by rural households as common constraints. The fact that most of households highly appreciated the benefits from higher crop yields and more profit-able crops (Minot et al., 2006) implies that agricultural techniques play an important role in agricultural development in NUV. That is also in accordance with results obtained from a household survey conducted by Yen et al. (2012).

It is obvious that there are mismatches between perspectives of government, researchers and farmers on existing constraints of rural households in NUV. These perhaps led to insufficient or inappropriate interventions for agricultural development. For example with land administration field, the Prime Minister's Decision 10/1998/CT-TTg, dated 20 February 1998, which encourages households to exchange land plots to reduce land fragmentation, has been largely adopted in lowlands and large deltas but seemed to be not successful in many NUV's provinces because of a high diversity in land quality between plots and high cost requirement for land use right allocation. Consequently, other national programs for NUV such as agricultural mechanization or market-oriented production are likely not applicable. In financial aspect, although the government has developed a rural credit system since 1990s with three formal financial institutions: Vietnam Bank for Agricultural and Rural Development (VBARD), Vietnam Bank for Social Policies (VBSP) and People's Credit Fund (PCF), collateral requirements such as value properties or land use right certificate has prevented households from access to such sources (Marsh et al., 2006). Consequently, capital remains a major constraint of rural households in NUV (Minot et al., 2006; VASS, 2011). In order to develop appropriate policies for the NUV, the questions need to be answered are what actual problems are, and how to specify the most crucial once for making interventions?

A large gap between development and implement of land use policies in NUV has been commonly recognized by many authors as a result of the perspective mismatches and top-down management scheme in Vietnam (Akram-Lodhi, 2002; Clement, 2010; Cramb, 2004; Vien et al., 2005). Therefore, there is an agreement that new tools are needed to support land use planning (Castella et al., 2007). In recent decades, a number of methodologies and tools have been developed to explore land use decision process from individual household to regional scale (Castella and Verburg, 2007; Chen et al., 2008; Jin et al., 2008; Laborte, 2006). However, few can take multi-scales and multi-aspects of land use into account. Some methodologies mainly focused on physical factors (climate, soil and topography), some others only address social and economic aspects (households' perception, market, transport facilities, labour, access to capital, etc.). As mentioned above, agricultural land use of NUV is a result of a complicated combination of diverse cultures, heterogeneous environment, strategies of individual households and government plans. Therefore, land use studies for this region need a methodology that both biophysical and socioeconomic influences are taken into account and cause-effect relations of land use decision process is carefully investigated.

The Land Use Planning and Analysis System (LUPAS) is a modern methodology that is designed as a decision support system (DSS) for strategic land use planning (Roetter et al., 2005). The system provides a possibility to analyse short-term land use changes and propose alternative land use options, which is very useful for policymakers, researchers and local managers. In practice, LUPAS can be used as a system to suggest optimal land use scenarios using the Interactive Multi Goal Linear Programing (IMGLP) as a tool to analyse land use factors based on the trade-off analysis. By using this technique (Stoorvogel et al., 2001), the role of different ecological and economic indicators of agricultural systems can be clearly explained. LUPAS supports integrated land use analysis in various cycles in close collaboration with local stake-holders and has been evaluated in heterogeneous environment of NUV (Castella and Verburg, 2007; Yen et al., 2002).

This paper presents a modelling approach that is used to evaluate land use constraints in agricultural production in NUV. The LUPAS methodology was used to analyse trade-offs among major constraints in agricultural production. Through land use scenarios, the five constraints including limited land area, land fragmentation, availability of agricultural labour and household capital and agricultural technology were included in the analysis process. By analysing results we aim to highlight the role of each constraint and then propose recommendations that can effectively motivate agricultural development and livelihood improvement in the rural of NUV. Through land use analyses described in this paper, we expect to provide policymakers and researchers a different view on problems and opportunities in agricultural land use. The findings described in this paper may contribute materials to bridge the gap between top-down and bottom-up land use planning in Vietnam.

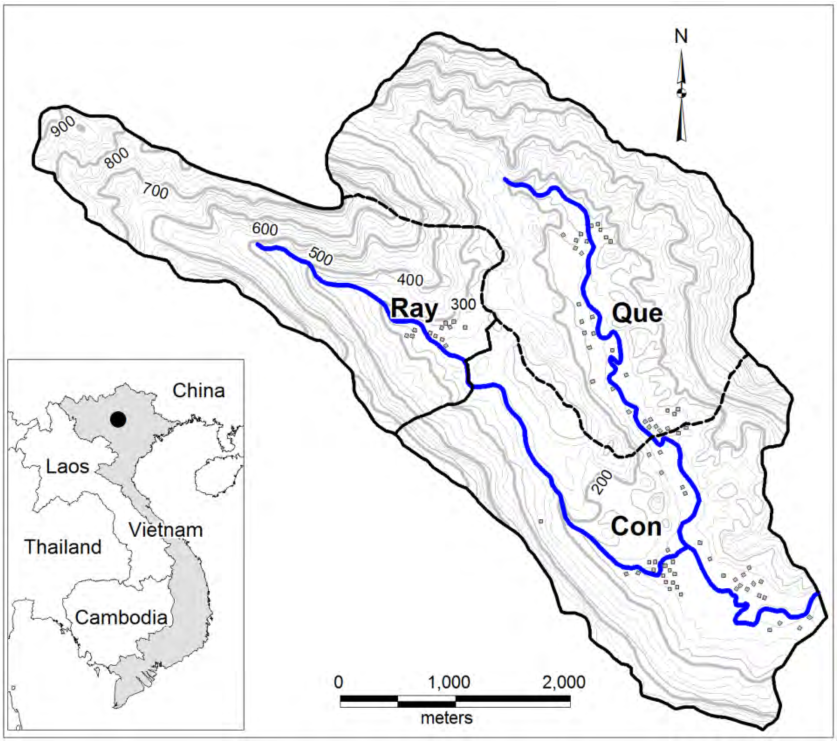

Figure 4.1. Topographic map of the Suoi Con watershed and its location (black circle) on the map of Vietnam

4.2 Materials and methods

4.2.1 Study site

The land use analysis was carried out in Suoi Con (Figure 4.1), an agro-forestry watershed in Thu Cuc commune, Tan Son district, Phu Tho province (104° 49' 42" E to 104° 53' 41" E and 21° 16' 1" N to 21° 19' 17" N). The total area of the watershed is 1760 ha, of which, only 60 ha can be used to cultivate irrigated rice, the most important food crop of Suoi Con people. Land for other annual crops (cassava, soybean, groundnut, maize and vegetables) is 306 ha. Perennial crops (tea, longan, litchi and citrus) and fishery are mostly situated within villages. Agricultural land often includes a number of discrete plots. Inter and intra fragmentations of agricultural land are commonly seen in the Suoi Con watershed. On average, each household owns 4.6 plots with a total area of about 0.5 ha. In recent years, there was the trend that forestry and fallow lands have been shifted to agricultural land. As a result, area of agricultural lands has increased continuously while the farm size is generally stable.

Nearly 40% of agricultural land has a slope that exceeds 15°, which is commonly considered as lowly suitable land for agricultural crops. Acrisols is the common soil type (based on FAO-UNESCO classification system) of Suoi Con characterized by low fertility, high acidity and several degradation problems.

Other soil types (i.e. Fluvisols, Luvisols and Regosols) just cover 8% of total area but they are very important for agricultural production in the watershed. Crops can be grown in three main crop-seasons: (1) spring, S_p (from February to June), (2) summer, S_m (from July to October) and (3) winter, W_t (from November to January). Most of crops are moderately or marginally suitable with land conditions of Suoi Con. Due to variation of temperature and water supply regime over a year, more suitable land for crops in summer than in others seasons. Such high diversity in crop, soil, topography and climate conditions create a high flexibility in farmers' land use decisions.

The Suoi Con watershed has three villages with a total of 399 households of Muong and Dao people. Currently, agricultural production in Suoi Con contributes 84% of household income, of which cultivation is the most an important sector as it covers 52% of agricultural income of the household. In 2008, 25% of total households are still facing with food shortage (2 months or less) and 29% are under the natural poverty line (annual income per capita below 2.4 million VND or 150 USD) (Government, 2005). Regarding to environmental impact of agricultural production, land degradation is popularly seen on slopping land of Suoi Con. Symptoms of soil fertility decrease, surface crust, the appearance of gullies and stoniness were stated by most of households.

Above natural and social conditions of the Suoi Con watershed create several challenges in agricultural development and livelihood improvement. The constraints in capital, land, agricultural techniques and labour were mentioned by 90%, 45%, 40% and 38% of interviewed households, respectively. From the manager's point of view, however, the People Committee of the Thu Cuc commune (PCC) underlined that capital shortage is not a considerable constraint and emphasized important roles of agricultural techniques, land fragmentation, irrigation and market in agricultural production. Accordingly, land use strategies given by the PCC are to accumulate and stabilize land for food crops, improve irrigation system, disseminate new crop varieties and to develop livestock and perennial crops for the income target (PCC, 2008).

4.2.2 LUPAS methodology

The Land Use Planning and Analysis System (LUPAS) is a methodology developed under the Systems research Network (SysNet) for land use planning in tropical Asia (Roetter et al., 2005). LUPAS focuses on land use analysis based on the potential of the land and other available resources. Technically, LUPAS does not use a single tool but a group of different computer models and knowledge-bases corresponding to its operations. Major parts of LUPAS have been well introduced by Roetter et al. (1999) (Figure 4.2), including (P1) resource assessment; (P2) scenario construction and (P3) the land use optimization.

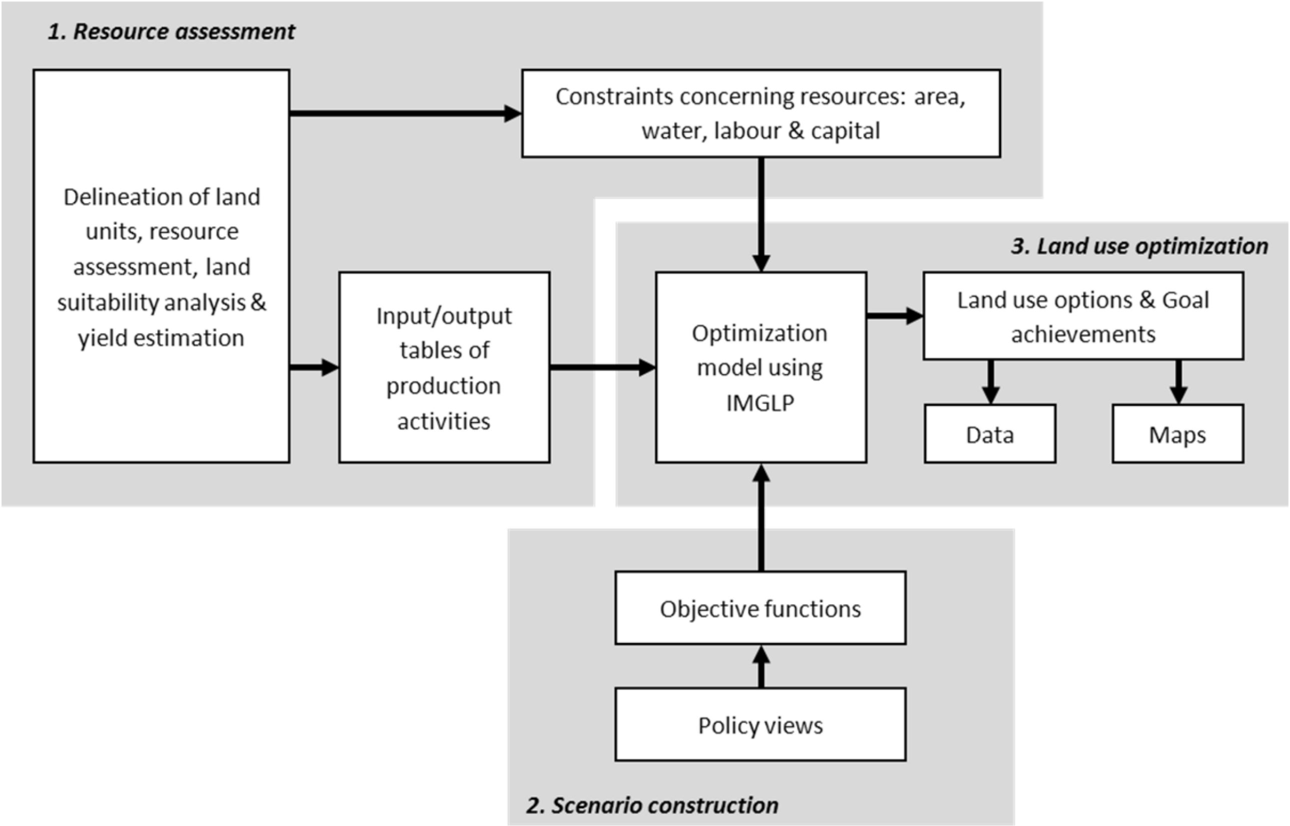

Figure 4.2. The operation structure of Land Use Planning and Analysis System (LUPAS) (Roetter et al. 1999).

Resource assessment

P1 consists of three activities: quantitative and qualitative land evaluation; yield estimation and input-output estimation (Hoanh et al., 2000). Based on surveys conducted in the Suoi Con watershed (Yen et al., 2013) and information collected from various sources (ERSDAC, 2009; FIPI, 2007; IMHEN, 2008; VNRSC, 2007), availability and characteristics of resources such as agricultural land, soil, topography, climate and irrigation were determined. A land use map (created in 2007) and satellite images (captured in 1989, 2000 and 2007) were used to allocate land use types within the watershed. Because this application of LUPAS focuses on analysis of short-term land use (1-5 years), land for permanent land uses (i.e. perennial crops and fishery) was not taken into consideration.

The monthly availability of labour (man-day) for cultivation was estimated for each village in two steps. In the first step, labour requirement for off-farm employments, livestock, forestry and perennial crops by month were determined from the household survey. In the next step, that amount was then subtracted from the monthly available labours, assuming that every labourer can work 24 days per month. Because labour sharing is typical in Suoi Con, there was an assumption that available labour within a village can be shared among households.

The current availability of capital for annual crops (Cap0) was estimated as the maximum cost spent among three crop-seasons in the last year. Besides, we assumed that every household can get loan from external credit sources. Currently, there are several formal and informal credit organizations in rural of Vietnam, i.e. the Vietnam Bank for Agricultural and Rural Development (VBARD), the Vietnam Bank for Social Policies (VBSP), the People's Credit Fund (PCF) and the Women's Society Foundation (WSF). Among those, WSF and VBSP have lower interest rates (6.5% and 7.8% per year, respectively) and provide better opportunities for poor households to extend their capital. The loan sizes estimated by Hao (2005) and Takashi (2009) and from the survey were used for this assumption. Accordingly, each household in Suoi Con can borrow 2 million VND (125 USD y^{-1}) from WSF (Cap1) or 4.6 million VND (287.5 USD y^{-1}) from VBSP (Cap2).

The FAO's land evaluation method (FAO, 1976, 2007) was used to evaluate land suitability following the FAO's guideline. A method to delineate land unit (LU) for heterogeneous environments introduced by Kam et al. (2000) was adapted to built 1809 LUs over agricultural land of Suoi Con. The quantity and quality of resources described in LU's attributes were matched with requirements (Sys et al., 1993) of 8 annual crops that are popularly used in the watershed. The matching process was done for each crop-season combination instead of entire land use type (LUT) due to a highly dynamic of climate condition in the region.

Crop yields are normally estimated through direct field surveys or using simulation models (De Wit, 1965; Laborte, 2006; Van Ittersum and Rabbinge, 1997). Yields can also be estimated through correlations between crop yields and agro-environment factors (De La Rosa et al., 1981; Mandal et al., 2005; Olson and Olson, 1985). However these methods often require a number of observation data and experimental parameters. Therefore, a simple yield estimation method introduced by Sys (1991a) and (van Diepen, 1993) was adapted in the Suoi Con case study. This method was first developed by FAO in 1981 under the FAO Agro- Ecological Zones (AEZ) Project and then used in many studies in European Community (van Diepen, 1993). The method describes a relative relation between yield levels and crop suitability classes, whereby, attainable yield can be 75-100% of maximum yield under highly suitable condition (S1), 50-75% under moderate suitability (S2), 20-50% under marginal suitability (S3) and below 20% under non-suitability (N). By this method, potentials and limitations of land can be described as different levels of crop yields.

Soil erosion caused by cultivation activities is considered as an output of land use, especially in the upland region. Thus, estimation of soil loss under possible land use options was included in P1, using the Revised Universal Soil Loss Equation (RUSLE) (Wischmeier and Smith, 1978). In the Suoi Con case, we assumed that each LU is a unique plot and used LU-based to estimate potential soil loss. We adapted methods to calculate factors used in the RUSLE equation from literatures, considering environmental similarity. Accordingly, calculation of monthly rainfall factor (R) was based on the regression found by Siem and Phien (1999); The equation suggested by Mulengera and Payton (1999) for tropical soils was used to determine the soil factor (K); the slope and slope length factor (LS) was calculated following equations introduced by Morgan (2005); and methods given by Wischmeier and Smith (1978) and Vezina (2006) were used to estimate management factor (P) and crop factor (C). Consequently, potential soil loss (Mg ha^{-1}) was estimated for every possible crop-season combination.

Inputs and outputs of agricultural activities in Suoi Con were collected through a household survey. A direct interview method with open-ended questionnaires was used during the survey. 100 households (25% of the total) from 3 villages in whole Suoi Con were invited to describe their cultivation, livestock, fishery, and forestry activities. The quantities of inputs (e.g. labour, capital, fertilizer and pesticide) and outputs (e.g. grain, root, meat, egg, crop residues and soil loss), so-called 'technical coefficients' (Roetter et al., 2005), were described for each land plot of the household. Two technology levels of agricultural production were defined: the current technology level (Cr), which is actual farmers' practices obtained from the survey and the recommended technology level (Rm), which is introduced by agricultural extension agencies and in literatures. Using results obtained from the survey and from the land evaluation, input-output relations were built for each crop-season. In addition, constraints in resources (land, labour and capital) were also quantified.

Scenario construction

In LUPAS, a land use scenario is defined as a combination of an objective function under a set of constraints and a set technology levels (Roetter et al., 1999). Land use scenarios for the Suoi Con watershed were built in P2 based on three sources of information. Firstly, we referred the recent development strategies of the government (Government, 2003, 2010) and of NUV (MARD, 2006) together with a wide range of available literatures. Secondly, we used annual reports of the People's Committee of the commune (PCC) and villages in Suoi Con, which clearly specified detail targets and actions plans for coming years. Finally, the scenarios are also based on the land use perspectives of stakeholders obtained through the household survey and two meetings in Suoi Con. All information on land use objectives, targets and constraints were analysed and used to build conceptual scenarios. These scenarios were then transferred into functions of the Interactive Multi Goal Linear Programing (IMGLP) in a land use optimization model (P3).

Land use optimization

The land use optimization model was developed in GAMS-IDE environment (Rosenthal, 2007) using the CONOPT solver. The operation of P3 includes several iterations so-called operational rounds, which are cycles of exploring the optimal solution for land use objectives and targets. The first iteration is called 'Round 0', with only one objective is considered in a time (e.g. minimizing soil erosion). The purpose of Round 0 is to define upper and lower limits of each objective. In the next iterations (Round 1), one other objective (e.g. maximizing rice production) is added to set a target while the previous objective is optimized (e.g. minimizing soil erosion while rice production must be at least 1200 Mg y^{-1}). In subsequent iterations (from Round 2 towards), other objectives (e.g. maximizing income) join in optimization process and list of targets is expanded accordingly.

Each operational round consists of a number of runs, in which, the combination of constraints and/or values of targets are changed while objective and number of targets are remained. For example with Round 0, only land area constraint is considered in the first run, land area and labour constraints in the second run, and land area and capital constraints in the third run. Each run produces an optimal solution. Therefore, each round can generates a series of solutions. When value of a certain target is slightly reduced to narrow down the 'solution space', trade-off between objectives can be expressed as a curve. The more restrictions are taken into account, the curve closer to reality is found.

Trade-off analysis

Trade-offs between objectives can be used to explore priorities of objectives (van Ittersum et al., 2004) and the difference between curves generated under different set of constraints can be used to describe the role of such constraints in achieving desire targets. To highline problems and opportunities in agricultural land use of Suoi Con, two steps of analysis were presented in this paper. Firstly, trade-offs between objectives in Round 1 were used to discussion on priority of objectives in land use planning. Secondly, the cost-to-income ratio (CIR) was used in Round 2 to measure efficiency of land use scenarios and the role of constraints. The CIR is calculated by dividing the total costs by the attained income. The lower value of CIR shows the more profitability of the land use scenario.

4.3 Results

4.3.1 Resource availability

Table 4.1 presents estimations of availability of land, labour and capital in the Suoi Con watershed. As being explained, land area was limited to 366 ha, including 60 ha of irrigated rice and 306 ha of other annual crops. These lands were divided into 1890 LUs with LU area ranges from 0.1 to 8 ha. Currently, there are 965 labourers in the Suoi Con watershed. If farmers work 24 days per month, the availability of labour of the watershed is 23,160 man-days. Labour used for cultivation varies from 43-57% of the total, depending on growth periods and seasons of crops. Capital spent for cultivation also varies by season. As estimated, a maximum cost spent for annual crops was 23,500 USD in summer season. It means that potential investment of households is 70,414 USD a year. If all households could access to credit from WSF and VBSP, the capital availability of Suoi Con will be 220,039 USD and 414,563 USD, respectively.

Table 4.1. Land, labour and capital availability of the Suoi Con watershed in 2008.

Resources	Unit	Availability
Number of households	household	399
Population	person	1845
Labourer	person	965
Labour for cultivation *		
January	%	57
February	%	55
March	%	43
April	%	52
May	%	54
June	%	55
July	%	56
August	%	54
September	%	47
October	%	51
November	%	55
December	%	55
Land		
Dense forest	ha	386
Young forest	ha	846
Shrubs	ha	88
Irrigated rice	ha	60
Other annual crops	ha	306
Bare lands	ha	21
Water surface	ha	3
Resident areas	ha	50
Capital		
Current availability	USD y^{-1}	70,414
Possibility 1**	USD y^{-1}	220,039
Possibility 2***	USD y^{-1}	414,563

* Percentage of total labour

** Adding a loan of 2 million VND (125 USD) per household from the Women Society Foundation

*** Adding a loan of 4.6 million VND (287 USD) per household from VBSP bank

The difference between two technology levels, Cr and Rm, is described in Table 4.2. The total cost spent for cultivation only includes permanent expenditures, i.e. seed and fertilizers because other costs, such as pesticide, herbicide, hired labour, etc. depend very much on production condition during a season and financial ability of households. In general, total cost, crop yields and net income in Cr are clearly lower than Rm. Under Rm level, some crops like maize, sweet potato and soybean are suggested to be grown in winter season to improve household income. And contrarily, self- produced in-bred rice (RiceD2) that popularly used by farmers is not recommended.

4.3.2 Land use objectives and targets

The three main land use objectives of Suoi Con are (Obj1) to increase rice production, (Obj2) to maximize agricultural income and (Obj3) to minimize soil erosion.

Land use achievement in 2008 and targets in 2015 of the watershed are shown in Table 4.3. Accordingly, with current 60 ha of paddy land and averages of actual yields presented in Table 4.2, total rice production of Suoi Con was estimated as 381 Mg y^{-1}. If each person consumes 465 gr of rice per day (Kennedy et al., 2002), annual rice production for self-sufficiency should be 392 Mg y^{-1}. And if population growth rate remains 1.1% per year, food demand of 2000 people in 2015 will be 424 Mg y^{-1}. In addition, to provide food for livestock (1 or 2 cattle, 2 pigs and 5-10 poultry per household), production of maize and cassava must be 434 and 340 Mg y^{-1}, respectively.

Table 4.2. Investments for annual crops with farmer practice (Cr) and with recommended technology (Rm) in the Suoi Con watershed.

Crop code[a]	Season[b]	Labour d ha^{-1}		Total cost[c] USD ha^{-1}		Crop yields Mg ha^{-1}		Revenue USD ha^{-1}	
		Cr	Rm	Cr	Rm	Cr	Rm	Cr	Rm
RiceD1	S_p	209	272	150.0	356.3	3.8	5.5	1175.0	1687.5
	S_m	195	272	143.8	337.5	3.6	5	1125.0	1562.5
RiceD3	S_p	209	272	168.8		3.9		1218.8	
	S_m	195	272	143.8		3.7		1156.3	
RiceH	S_p	209	272	212.5	443.8	4.1	6.5	1275.0	2031.3
	S_m	195	272	193.8	381.3	3.6	6	1106.3	1881.3
UpRice	S_m	333	354	112.5	231.3	1.6	2.3	487.5	718.8
GmaizeH	S_p	216	328	137.5	450.0	3.9	6	862.5	1312.5
	S_m	216	328	143.8	450.0	3.9	6	862.5	1312.5
	W_t		328		450.0		6		1312.5
GrNut	S_p	334	397	100.0	412.5	2	4.5	1375.0	3068.8
	S_m	306	369	93.8	375.0	1.4	4.5	937.5	3075.0
Soyb	S_p	244	314	112.5	375.0	1.4	4	1043.8	3000.0
	Sm	244	314	150.0	375.0	2.8	4	2087.5	3006.3
	S_m		314		393.8		4		3006.3
Cabb	W_t	460	467	318.8	943.8	6.9	30	1737.5	7500.0
SpoR	S_p		265		437.5		16.7		3131.3
	S_m		265		437.5		16		3000.0
	W_t		265		437.5		16		3000.0
SpoL	S_p	322	334		412.5	8.5	27	187.5	700.0
	S_m	322	334		412.5	8.5	27	187.5	718.8
	W_t	322	334		412.5	8.5	27	187.5	718.8
Cas		333	431	62.5	306.3	13.9	40	312.5	875.0

[a] Crop codes: RiceD1 = Commercial traditional rice, RiceD3 = Self-breed traditional rice, RiceH = Hybrid rice, UpRice = Upland rainfed rice, GmaizeH = Hybrid grain maize, Grnut = Groundnut, Soyb = Soybean, Cabb = Cabbage, SpoR = sweet potato for root, SpoL = sweet potato for leave, Cas = Cassava.

[b] Crop seasons: S_p = Spring, S_m = Summer and W_t = winter.

[c] only expenses for seeds and fertilizers are used to calculate total cost.

Table 4.3. Current achievements and land use targets in 2008 and 2015 of the Suoi Con watershed

Indicators	**Unit**	**Current**	**Targets**	
			2008	**2015**
Population	person	1,845	1,845	2000
Income per capita	USD y^{-1}	280	maximize	300
Total income	USD y^{-1}	516,600	maximize	600,000
Off-farm income	%	16	-	22
On-farm income	%	84	-	78
Cultivation income	USD	225,650	maximize	234,360
Rice production	Mg y^{-1}	381	392	424
Maize production	Mg y^{-1}	75	434	434
Cassava production	Mg y^{-1}	312	340	340
Soil loss	Mg y^{-1}	3,495	Minimize	Minimize

Total income of the watershed was 516,600 USD in 2008, of which, agriculture contributed 84%. Within agriculture sector, annual crops provided up to 52% of total value. As estimated, income from annual crops in 2008 was just above 225,650 USD. At current land, labour, capital and technology conditions in Suoi Con, the share of livestock, fishery and perennial crops is not expected to increase in coming years. Therefore, to move beyond natural poverty line (Government, 2011) with an average of annual income per capita is 4.8 million VND (300 USD) and expected proportion of on-farm income is 78% (MARD, 2006), income from annual crops needs to be at least 234,360 USD in 2015.

Current cropping systems on 366 ha of annual crops produce about 3,495 Mg of potential soil loss per year. Cassava and summer crops (i.e. maize, rainfed rice and groundnut) cause a highest soil loss risk. Estimations showed that maximum soil loss rates of these crops range from 67 to 458 Mg ha^{-1}. Although soil erosion was not a concern of farmers (only 7% of households applied at least one measure to protect their land), reducing soil loss was mentioned as one of targets in the land use strategy of the NUV (MARD, 2006).

4.3.3 Analysis of land use constraints

Figure 4.3 shows a trade-off between attainable income (1000 USD) and rice production (Mg y^{-1}) obtained from Round 1 of the optimization process. In this round, main objective is to maximize income and a target is desire rice production. The upper limits of the targets were acquired from the Round 0. The four combinations (C1, C2, C3 and C4) of constraints (land, labour and capital) were added successively.

If only land area is limited (C1), attainable rice production or income reach maximum values of 1214 Mg or 1,520,000 USD, respectively. When other constraints are added the curve is shifted towards actual situation of production values (the point A) and the distances from the point A to the curve presents the weight of constraints. The figure clearly shows that constraint in capital (C3) is stronger than in labour (C2). It implies that if capital constraint exists, the increase of labour has no meaning in improving production values. However, when capital demand is satisfied agricultural production of the watershed will be bounded by current availability of labour. This analysis proved that capital and labour are two of considerable constraints in Suoi Con. Indeed, these three constraints together (C4) can reduce about 42% of maximum rice production and 70% of potential income.

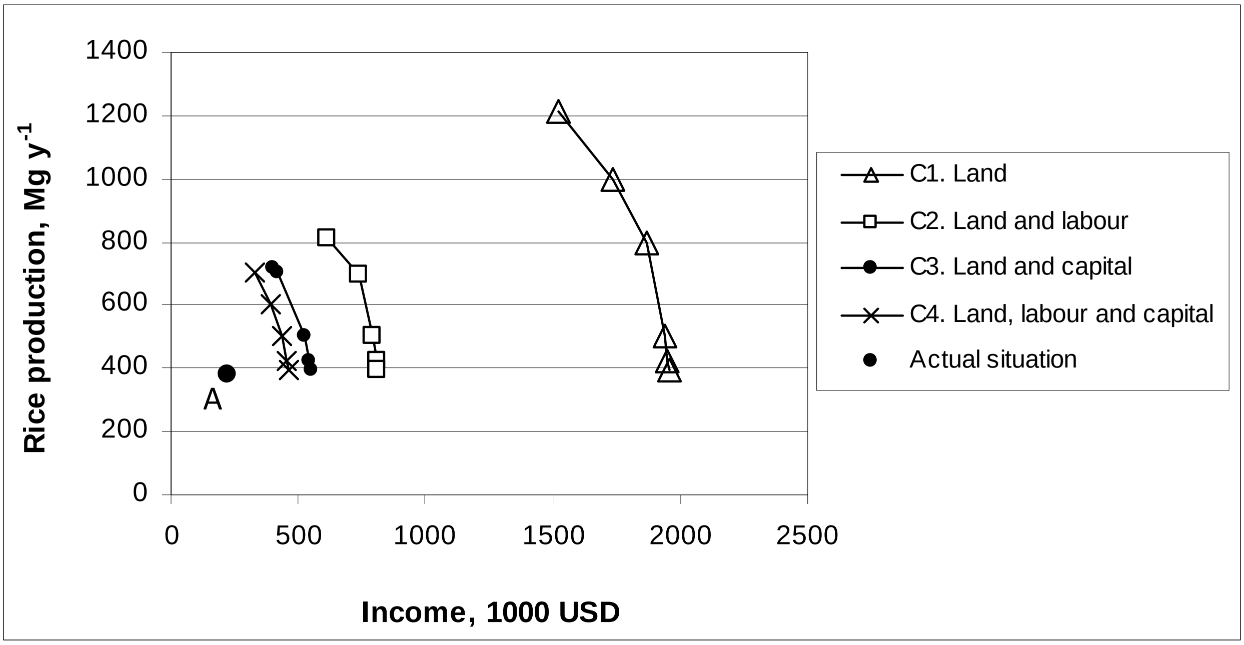

Figure 4.3. Trade-off between annual income (1000 USD) and total rice production (Mg y^{-1}) of the Suoi Con watershed.

Table 4.4. Land use targets and achievements of the Suoi Con watershed under capital and technology conditions.

Scenarios	Objectives			Capital		Total cost	Technology	Attainments					
				source	availability		levels	Rice	Maize	Cassava	Income		soil loss
	Income	Erosion	Food		USD y^{-1}	USD y^{-1}		Mg y^{-1}	Mg y^{-1}	Mg y^{-1}	USD y^{-1}	CIR	Mg y^{-1}
LSR0	-	-	-	Cap0	70,414	41,843	Cr	381	75	312	225,625	0.19	3,533
LSR1	Opt	Opt	-	Cap0	70,414	54,835	Cr	381	75	312	301,187	0.18	5,447
LSR2	Opt	Opt	-	Cap1	220,039	58,550	Cr	381	75	312	313,938	0.19	5,807
LSR3	Opt	Opt	-	Cap0	70,414	70,414	Rm	381	75	312	435,625	0.16	4,521
LSR4	Opt	Opt	Opt	Cap0	70,414	70,414	Rm	392	434	340	201,438	0.35	5,277
LSR5	Opt	Opt	Opt	Cap1	220,039	145,351	Rm	392	434	340	498,282	0.29	4,740
LSR6	Opt	Opt	Opt	Cap2	414,563	156,388	Rm	392	434	340	503,977	0.31	4,152
LSR7	Opt	Opt	Opt	Cap1	220,039	145,789	Rm	424	434	340	484,594	0.30	4,787
LSR8	Opt	Opt	Opt	Cap2	414,563	156,450	Rm	424	434	340	489,352	0.32	4,419

LSR= Land use scenario, Opt = optimised, Cap = capital source
Cr = Current technology level, Rm = recommended technology level
CIR: The cost-to-income ratio

The nine land use scenarios (LSR) presented in Table 4.4 highline the influences of capital constraint and technology levels in agricultural production of Suoi Con. LSR0 reflects actual circumstance, whereby agricultural land is fragmented, land use is decided by individual households and only current capital availability (Cap0) and technology level (Cr) were used. Other scenarios were optimised in Round 2 of the optimization process with involvement of land, capital and labour constraints. Resources used in LSR0 was optimised and showed in LSR1 to LSR3. Possibilities to reach expected targets for 2008 and 2015 are described in scenarios LSR4 to LSR8.

While maintaining attained crop production of LSR0, optimizing the use of resources without external capital or new agricultural techniques (LSR1) can reduce the CIR from 0.19 to 0.18. Under current technology level, extending household capital (LSR2) does not change the IND value. In the first three LSRs, total cost is always lower than capital availability. However, if changing technology level from Cr to Rm (LSR3) with the same resources (land, labour and capital), all capital are fully used. Among above scenarios, LSR3 significantly increases income to 435,625 USD with a lowest CIR value. These comparisons demonstrate that land use under current family-based farming system obviously limits agricultural production due to the fragmentation of land, labour and capital resources. Sharing resources among households within a village appears to be a promising approach for livelihood improvement. The difference between the CIR of LSR2 and LSR3 shows that improving technology level is more important than extending of household capital. The total cost only reaches limit or capital constraint appears when Rm is applied (LSR3).

However, changing technology level alone will not bring a good outcome. Indeed, although crop production targets in LSR4 can be reached, food demand of 1845 people and forage demand for livestock are satisfied but income is lower than the expected value (225,650 USD) (see Table 4.3). By using Cap1 income in LSR5 increases significantly, and the CIR reduces significantly from 0.35 to 0.29. The CIR of LSR5 indicates that capital shortage at this condition becomes more serious than the current technology. However, only 66% of capital availability is used. Adding more capital (Cap2), used capital in LSR6 reduces to 38% and the CIR increase to 0.31. In LSR5 and LSR6, labour becomes more serious than capital and technology. Labour used in these scenarios, especially in summer and winter seasons reaches the limit.

Regarding future targets, attainments of LSR7 and LSR8 prove that availability of land and labour resources allows Suoi Con to produce enough crop production for self-consumption in 2015. However, extending capital and recommended technology level are required in order to reach both food and income targets.

4.4 Discussions

Land use scenarios show that current availability of land resource of the Suoi Con watershed is sufficient to satisfy food demand and desire agricultural income. However, in actual while many households leave their land at fallow, others have to rent land to cultivate or to find off-farm employment. Lack of land still occurs to 45% of households. This situation is understandable because the ‘equitable’ allocation of agricultural land among households, which has been made in 1990s, is now unable to remain. The 1993 land law allows farmers to transfer, exchange, lease, inheritance and mortgage their land assets. Therefore, rapid population growth and sub-division of land among household heirs, which are traditionally seen in South Asia (Niroula and Thapa, 2005), have led the decrease of land area per capita and the increase of land fragmentation. These resulted in a paradox that overall land resource is available but many households, especially young households, do not have enough land for agriculture production. However, the outputs of the LSR1 prove that this constraint could be reduced through land sharing. Indeed, this approach brings a better outcome (food production and income) for whole region and, thus, for individual households. By sharing land resource, level of land fragmentation will be reduced and disadvantages of family-based farming system in NUV (Vien, 2003) could be overcome. Accordingly, larger fields enable farmers to mechanize cultivation and facilitate the use of new agricultural techniques. Furthermore, this opens a feasible opportunity to produce market-oriented products, which was emphasised as a priority in strategies of the government (Hayami, 1994; Müller and Zeller, 2002). Therefore, land consolidation will be a promising solution for agricultural development in NUV.

Although farmers in the NUV often consider capital shortage as the most constraint (Minot et al., 2006; The et al., 2004), land use scenarios presented in this paper denote that extending household capital without improving agriculture techniques has an inconsiderable impact on attainments. At current farmer practice, extending household capital seems to have no meaning in improving income (the CIR of both LSRs equal 0.19). The appearance of capital constraint is reflected by the reduction of the CIR when technology shifts from traditional to recommended level.

In spite of several formal credit sources exist in rural of the NUV (Takashi, 2009), these sources are often reluctant to extend loans to low-income households due to transaction costs, risks and collateral (Hao, 2005). In addition, collateral and other criteria (e.g. certification for the poor) to get a loan is a major barrier from the households' side. Outputs of land use scenarios underline that a loan size of 125 USD (Cap1) is adequate to demand of households and such small loan size is more significant than the larger loan (i.e. Cap2). Developing microfinance, the financial services for poor and low-income households and their micro-enterprises (ADB, 2000), is necessary in order to promote economic development and poverty reduction in the NUV.

Enabling the poor to access and to make use of financial services is significant to the goal of poverty reduction (Morduch and Haley, 2002). However, there is the fact in the NUV that many households have not used all bank's loan for productive investments as stated in the loan application but spent for consumption needs (Minot et al., 2006). The result obtained from analysing scenarios in this study also proves that providing a loan size greater than the actual need of households will reduce the capital efficiency.

The 9 LSRs specify that at present food production and income of households depend very much on technology level although most of households in Suoi Con cited availability of capital as the major constraint. However, a stakeholder meeting showed that technical guidelines for individual crops are disseminated to farmers yearly through the agricultural extension agency. A survey conducted in the NUV by Minot et al. (Minot et al., 2006) also showed a high proportion of the rural households that had received guidance or assistance from an extension agent. It means that access to agricultural techniques is obviously available for farmers. Concerning the way to shift agricultural technology from traditional to recommended level, adoption appears to be a considerable issue. This implies the need for an integration solution that includes a productive contribution of agricultural extension agencies and improvement of access to credit sources in the NUV.

Agricultural labour is an important factor in agricultural development (Figure 4.3). However, LSR1 to LSR3 indicate that it is not a current constraint in the Suoi Con watershed. In deeded, only 38% of households state that they lack agricultural labour and in actual, a lot of labourers leave the watershed to find off-farm employments. Labour constraint only occurs when capital demand is satisfied and recommended technology is adopted.

4.5 Conclusions

This study provides a modelling approach to evaluate constraints in agricultural land use. The five major constraints, including the limited land area, land fragmentation, available of agricultural labour and household capital and traditional technology are taken into analysis. Trade-offs among major constraints of households in the Suoi Con watershed are described through the nine scenarios of current and future land uses. These results highlight the influence of different constraints in reaching desire food production and income targets.

At current land use circumstance, traditional technology level appears to be a largest constraint that significantly holds back agricultural production of the watershed. Land area, capital and labour are important factors but they are not constraints at current technology level. On the contrary, land fragmentation appears to be a considerable constraint. With available land area and without any new agricultural technique, crop variety and external capital source, land consolidation can help households to significantly improve income while maintaining current crop production. So that the order of priority of constraints is: technology > land fragmentation > capital > labour > land area.

Once recommended technology level is adopted, capital shortage becomes a largest constraint. However, land use scenarios show that extending capital with a small loan size is more significant than the larger loan. A loan size of 125 USD y^{-1} (about 2 million VND) is adequate to current demand of households and providing a loan size greater than the actual need of households will reduce the capital efficiency. This implies that developing microfinance is necessary. Together with enabling access to credit sources of households, improving adoption of agricultural techniques should be considered by the government and institutions. Shifting agricultural technology from traditional to recommended level is the most important key of economic development and poverty reduction in the NUV.

Chapter 5

Integrated modelling for improved land use planning in rural upland areas of Vietman

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Integrated modelling for improved land use planning in rural upland areas of Vietnam

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Abstract

The land use planning process in Vietnam is administrative-based and often follows a top-down approach, although agricultural land use change strongly depends on decisions of individual households. This mismatch has led to various challenges in policy implementation. Experience has learned that participatory approaches with support of integrated modelling can provide insights in farmers' decision-making and therefore, can serve as a basis for the formulation of viable land use plans. This paper presents an integrated land use optimization model and a Role Playing Game to support land use planning for Suoi Con, a hilly watershed in the Northern Uplands of Vietnam. Based on land use scenarios developed in the game, participants identified feasible solutions to existing constraints with the purpose of realising given land use targets. The integrated approach presented in this paper may serve as a tool for both planners and policy makers in formulating land use plans.

Keywords: Agent Based Modelling, land use, rural, uplands, Vietnam

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5.1 Introduction

The rural uplands of Vietnam, especially in the Northern Uplands region, face major development problems related to livelihoods and natural resource management. The uplands are commonly characterized as hilly to mountainous regions with rugged features, poor infrastructure and low population density. The Northern Uplands in Vietnam are less urbanized and more dependent on agriculture than any other region (Minot *et al.*, 2006; Clement and Amezaga, 2008).

In the Northern Upland region, the large variation in topography, soil and climate, combined with a broad range of suitable crops, provides a large set of alternatives for land use with a high diversity in crop rotations. Because land use strategies strongly depend on land and capital endowments of households (Castella, 2009), conflicts surrounding land use objectives often arise between farmers and other stakeholders. Despite many adjustments by the government in the last 30 years, causes of the conflicts are not clearly identified and they are not adequately solved. Accordingly, achievements in production are still far below the desired targets and resources are not sustainably used (Clement *et al.*, 2006).

There is agreement that decision making in rural planning should aim at improving the process of negotiation among actors (McDonald, 1989; FAO, 1993). In the last decade, many rural development and resource management studies have focused on decision making processes and their adoption at local administrative units or small community levels (district, commune, watershed, village, etc.), following a bottom-up approach with the participation of various stakeholders (Cramb, 2004; Bousquet *et al.*, 2007; Shucksmith and Rønningen, 2011). Agent Based Modelling (ABM) is a participatory approach that has been widely adopted by the land use modelling community in recent years (Etienne *et al.*, 2003; Bah *et al.*, 2006; Matthews *et al.*, 2007; Schreinemachers and Berger, 2011). It is considered a suitable method for understanding, describing and predicting complex land use systems (Bousquet and Le Page, 2004; Matthews *et al.*, 2007). In land use planning studies, ABM can be used to evaluate the influence of individual decisions of stakeholders and to refine land use scenarios based on stakeholders' responses (Etienne *et al.*, 2003; Castella *et al.*, 2005).

A wide range of tools is often used to facilitate operation of ABM, such as mathematical simulation models (Bah *et al.*, 2006; Schreinemachers and Berger, 2011) or Role Playing Games (RPG) (Vieira Pak and Castillo Brieva, 2010). To support ABM, the tools can be used individually or in combination (Barreteau, 2003; Bousquet *et al.*, 2007) with various ways of integration (Castella and Verburg, 2007; Le *et al.*, 2008; Ruankaew *et al.*, 2010).

This paper presents an integrated approach, in which a land use optimization model and a RPG are combined to facilitate dialogues among various stakeholders in the process of land use decision making. This approach was applied in Suoi Con, a small hilly watershed in the Northern Uplands of Vietnam. In this integrated approach, the land use optimization model was used to determine optimal land use plans based on sets of resource avalabilities, land use objectives, constraints and targets of agricultural production. RPG was used to test the land use plans and evaluate their feasibility with stakeholders. The main aims of this integrated approach were to identify existing constraints in specific biophysical and socio-economic conditions and to gain insight in land use decisions of farmers, and to stimulate discussions among stakeholders for formulation of possible solutions.

5.2 Materials and methods

5.2.1 The study site

The Suoi Con watershed (104° 49' 42" E to 104° 53' 41" E and 21° 16' 1" N to 21° 19' 17" N) is a small hilly watershed in the Northern Uplands of Vietnam with a total area of 1760 ha, of which 80% is upland and 20% is lowland. Agricultural land often has a low soil fertility and various degradation problems. The annual variation in climate conditions creates three main cultivation seasons in a year: (1) spring, S_p (from February to June), (2) summer, S_m (from July to October) and (3) winter, W_t (from November to January). The main annual crops are irrigated rice, rainfed rice, grain maize, groundnut, soybean, vegetables, sweet potato and cassava.

Although Suoi Con is not too far from large economic centres (150 km from Hanoi, the capital of Vietnam), the watershed is characterized by a high poverty rate and low agricultural production and household income (PCC, 2008). In the watershed 3 villages are located, inhabited by Muong and Dao ethnic minorities. Livelihood of the households is dependent upon self-sufficient agricultural production, which accounts for nearly 80% of the total production value. On average, a 5 person household consists of 3 labourers and owns 0.5 ha of agricultural land. Land for annual crops often includes 4 – 6 separate plots with different land characteristics. From the farmers' point of view, limited availabilities of agricultural land, labour, capital and improved technology are major constraints to agricultural production. Problems related to irrigation, crop varieties, pests and marketing were occasionally mentioned.

5.2.2 The Role Playing Game

Because tools are integrated following the ABM approach, three main components of ABM, the environment, the agent and their interaction, are taken into consideration in the integrated approach.

In the rural upland areas of Vietnam, each household typically owns several plots, each situated in a different geomorphologic setting (Clement and Amezaga, 2008) with varying terrain, soil fertility, water supply and crop suitability characteristics. Specifically, households in the study site own four distinctive types of agricultural plots: waterlogged plots (WP), lowland plots (LP), terraced plots (TP) and degraded upland plots (DP). Characteristics of the plots are described in Table 5.1.

Table 5.1. Characteristics of land plots used in the Role Playing Game.

Plots*	Description of land plots	Suitable crops		
		Spring season	Summer season	Winter season
WP	Waterlogged, flat, high soil fertility	rice	rice	fallow
LP	Good drainage and irrigation, flat, high soil fertility	rice, maize, peanut, soybean, sweet potato, vegetables	rice, maize, peanut, soybean, sweet potato, vegetables	maize, peanut, soybean, sweet potato, vegetables
TP	Drought terraces, high relative elevation, high acidity, low soil fertility	maize, peanut, soybean, cassava	rice, maize, peanut, soybean	maize, peanut, soybean
DP	Degraded, high slope, low soil fertility	maize, cassava	maize	maize

* WP= waterlogged, LP= lowland, TP= terraced and DP= degraded upland plots

Farmers were considered as farm-based agents. One hundred representative households in the watershed were classified into 4 farm-type groups using the clustering analysis method (Tan *et al.*, 2006; Salasya and Stoorvogel, 2010). The five most effective variables that clearly describe the characteristics of the farm-type groups were determined using Principal Component Analysis (PCA) (Jolliffe, 2002). They are (1) age and (2) basic education level of the householder, (3) household size, (4) available labourers and (5) total cost invested per hectare of rice (Table 5.2). Three householders from each farm-type group were randomly selected from 3 villages and invited to participate in the game. They were assumed to be members of one in-game household (IGH). Consequently, there were 4 IGHs, identified as A, B, C and D, representing the 4 farm-type groups I, II, II and IV, respectively.

In the game, the conditions of the households were defined as close as possible to their actual situation. Each IGH was assumed to have 2 labourers and 4 land plots (WP, LP, TP and DP). The area of each plot is 1 sao (sao is the local area unit, equivalent to 360 m^2). Land use objectives of an IGH are to produce at least 910 kg of rice and a cash income of US$ 575 per year, to satisfy standard food demand (Kennedy *et al.*, 2002) and a basic income (GOV, 2005) for a 4-person household. An IGH also owns 5 pigs and 2 head of cattle, that produce enough Farm Yard Manure (FYM) for cultivation and requires feed and labour inputs.

Table 5.2. Characteristics of the 4 farm-type groups in the Suoi Con watershed

Group	Characteristics of farm-type groups				
	Average age of householder	Education (level*)	Household size (people)	Number of Laborers ** (people)	Cost for rice cultivation (US$ ha -1)
I	63	4	6	3	175
II	28	6	5	3	256
III	48	6	6	4	219
IV	39	5	5	3	244

* There are 12 years equivalent to 12 levels of basic education in Vietnam, in which 5 years of primary school, 4 years of intermediate school and 3 years of secondary school.

** Number of labourers in actual households is larger than in the in-game households. Family size and farm size in RPG were scaled accordingly.

5.2.3 The land use optimization model

The land use optimization model (LUM) is the core of the Land Use Planning and Analysis System (LUPAS), a modelling methodology that has been developed to support strategic land use planning (Roetter *et al.*, 2005). LUPAS allows analysing land use in various cycles in close collaboration with local stakeholders and has been evaluated in a heterogeneous environment (Castella and Verburg, 2007). LUM was built in the GAMS-IDE environment (Rosenthal, 2007), using the CONOPT solver and theories of the Interactive Multiple Goal Linear Programming (IMGLP). In LUM, a land use scenario is a set of crop rotations that are generated using a combination of land use objectives, constraints and input levels on given plots of land.

In the RPG, LUM was used to generate optimal land use scenarios with sets of inputs decided by IGHs. The feasibility of the scenarios suggested by the model was then analysed by stakeholders in game sessions.

The game included 4 sessions (S):

- Session 1 (S1) involved the participation of 12 players, that played the roles of members in the 4 IGHs A, B, C and D. Members of an IGH used their indigenous knowledge to decide on crop rotation and inputs for each of their plots. Facilitators transferred inputs decided by the IGHs into LUM to generate LUM outputs. At the end of S1, differences in the outputs were discussed with the players.
- In session 2 (S2), the 12 players specified their own actual constraints and potential stakeholders that might assist them to alleviate the constraints. The three most important stakeholders selected by the IGHs were invited to join the next game session as additional players.
- Session 3 (S3) aimed at understanding land use decisions of farmers with the assistance of other stakeholders. The 4 IGHs were encouraged to interact with the 3 additional players and make alternative land use decisions. The new set of inputs selected by the IGHs was introduced into LUM again to generate optimal land use options.
- Session 4 (S4) was implemented as an open dialog, in which existing constraints, optimal land use scenarios and their adoption possibilities were discussed among participants in the game. Feedback from participants was collected to support land use planning and policy making.

5.3 Results

5.3.1 Outputs of session 1(S1)

Land use decisions made by the IGHs and LUM in S1 are shown in Table 5.3. The decisions of the 4 IGHs are mainly different in crop rotation and costs made in cultivation. IGHs A and B used winter crops and achieved a higher income than the other two IGHs. Traditional technology was used for all crops under farmer decision making and plots were mostly left fallow in Wt. Consequently, rice production and income are lower than the target values (910 kg of rice and US$ 575 y^{-1}, respectively) for all IGHs. Using the same land and labour resources and lowest capital (93.09 USD y^{-1}), LUM found an optimal land use scenario, in which both target values were realized.

5.3.2 Outputs of session 2 (S2)

Explaining the land use decisions made in S1, the IGHs drew up a list of their actual constraints and specified possible solutions (Table 5.4). The results show that lack of land area, capital shortage and traditional technology remain the major constraints. In addition, markets, land fragmentation and irrigation were significant concerns for the farmers, although they were rarely mentioned by households before.

Table 5.3. Land use decisions made by IGHs and suggested by LUM in game sessions 1 and 3.

		Outputs of session 1					Outputs of session 3				
IGH	Plot	Crop rotation	Capital (USD y^{-1})	Total cost (USD y^{-1})	Rice (kg y^{-1})	Income (USD y^{-1})	Crop rotation	Capital (USD y^{-1})	Total cost (USD y^{-1})	Rice (kg y^{-1})	Income (USD y^{-1})
A			93.09	68.77	590	428.11		218.09	129.20	820	739.55
	WP	Rice-Rice-Fallow					Rice-Rice-Fallow				
	LP	Maize-Rice-Cabbage					Maize-Rice-Cabbage				
	TP	Maize-Rice-Fallow					Peanut -Rice-Sweet potato				
	DP	Cassava					Cassava				
B			121.50	86.56	660	434.06		309.00	104.13	840	660.56
	WP	Rice-Rice-Fallow					Rice-Rice-Fallow				
	LP	Rice-Rice-Cabbage					Rice-Rice-Soybean				
	TP	Maize-Maize-Fallow					Maize-Peanut-Fallow				
	DP	Cassava					Cassava				
C			121.69	79.51	430	318.93		434.19	166.02	810	490.86
	WP	Rice-Rice-Fallow					Rice-Rice-Fallow				
	LP	Maize-Maize-Fallow					Rice-Rice -Soybean				
	TP	Maize-Rice-Fallow					Maize-Maize-Fallow				
	DP	Maize-Maize-Fallow					Maize-Maize -Fallow				
D			122.81	77.75	610	341.63		247.81	88.81	680	514.94
	WP	Rice-Rice-Fallow					Rice-Rice-Fallow				
	LP	Rice-Rice-Fallow					Rice-Rice-Cabbage				
	TP	Maize-Maize-Fallow					Maize-Maize-Fallow				
	DP	Cassava					Cassava				
LUM			93.09	92.79	910	765.50		218.09	160	910	996.77
	WP	Rice-Rice-Fallow					Rice-Rice-Fallow				
	LP	Rice-Rice-Cabbage					Rice-Rice-Cabbage [c]				
							Rice-Peanut-Cabbage [d]				
	TP	Maize-Rice-Fallow [a]					Maize-Rice-Fallow				
		Fallow-Rice-Fallow [b]									
	DP	Cassava					Maize-Maize-Fallow				

[a] and [b]: applied on 10% and 90% of the area of the TP plot, respectively

[c] and [d]: applied on 5% and 95% of the area of the LP plot, respectively

Table 5.4. Agricultural constraints and expected solutions revised by in-game households in session 2.

Constraints	Expected solutions	Household			
		A	B	C	D
Land area	New policies of the government	x	x	x	x
Land fragmentation	New policies of the government	x			x
Capital	Government subsidies	x			
	Loan from banks	x	x	x	
	Loan from private lenders	x			x
	Loan from women's society foundation				x
Technology	Support from the government	x			
	Support from agricultural extension agents	x	x	x	x
Market	New policies of the local government		x		x
	New policies of the national government		x	x	
Irrigation	Government investment			x	
	Village investment	x		x	

To alleviate capital constraints, getting loans from formal services (government banks) was the preferred choice of most IGHs. Informal services seemed to be less interesting. According to farmers, the loans provided by informal services are often smaller than what is required. In addition, these services have limited capacity and are not always available. Agricultural extension agents were considered the best stakeholders to improve the current agricultural technology. To overcome other constraints, farmers look for advice and support to local governments, more than to other stakeholders.

From the results of S2, the 4 main constraints associated with land, capital, technology and market were clarified. The local government, credit services and agricultural extension agents are most effective stakeholders for influencing agricultural production in the region.

5.3.3 Outputs of the session 3 (S3)

With the involvement of additional players, representing the most effective stakeholders defined in S2, the IGHs were provided with information on land administration policies, the land use strategy of the commune, crop management techniques and the loan policies of credit services.

Outputs of S3 (Table 5.3) indicate that all IGHs were willing to increase investments, if they would have access to credit sources. In comparison to S1, the total cost in S3 increased from 12.50 USD y^{-1} (household D) to 81.30 USD y^{-1} (household C). With a small loan (< 100 USD or 1.6 million VND y^{-1}) and application of the recommended (improved) technology, all IGHs would increase their production values. The improvements are closely associated with changes in cropping systems and inputs. High-value crops (peanut and soybean) and winter crops (cabbage and sweet potato) were grown, in addition to continued production of 4 saos of rice per year. Consequently, although rice production was still lower than the standard food demand (910 kg y^{-1}), the incomes of 50% of the IGHs exceeded the target value.

For the same conditions of the IGHs, including their maximum expenditure (162.5 USD y^{-1}), LUM could generate a more favourable land use scenario. In that scenario, 910 kg of rice is produced and 993.80 USD y^{-1} of income generated, while the total cost is only 156.30 USD y^{-1}.

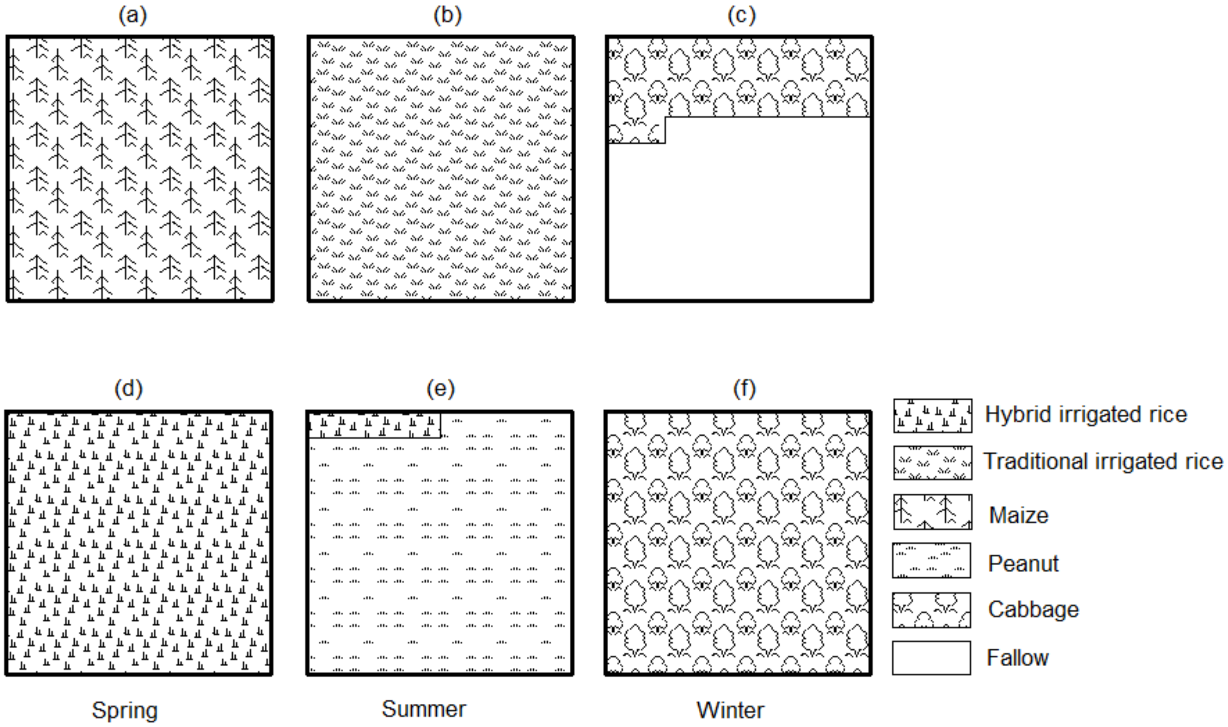

Figure 5.1. Cropping system on the LP plot as decided by household A (a, b and c) and by the land use optimization model (d, e and f) in game session 3.

Figure 5.1 presents the cropping systems on the LP plot of IGH A (a, b and c) and those selected by LUM (d, e and f). The strategy of the IGH was to increase income from maize and cabbage production in the S_p and W_t seasons and to ensure food security by maintaining traditional rice in the S_m season. The IGH explained that they decided for a low plant density in cabbage cultivation (300 plants per sao) to reduce costs. With the same land use objectives, LUM selected hybrid rice in the S_p season, followed by 5% of the plot area for hybrid rice and 95% for peanut in the S_m season, and high density cabbage (900 plants per sao) in the Wt season.

5.3.4 Outputs of session 4 (S4)

In looking at the land use scenarios selected by the IGHs in S1, participants of the game confirmed that current lack of land, capital and improved technology are major constraints for farmers. However, analysing the LUM outputs provided participants with another angle to look at the constraints.

The LUM outputs (Table 5.3) in S1 indicate that households are able to realize the food and income targets with the available land area and the lowest capital availability (93.09 USD y^{-1}), if they adjust their cropping systems and apply the improved technology. Therefore, the traditional technology appears to be the strongest constraint. The outputs of S3 indicate that increased capital investment can lead to higher household food production and income. However, comparing capital availability and total costs shows that IGHs often over-estimate their demand for capital for cultivation. The average capital needed for an IGH is just about 44 USD and for an actual household approximately 150 USD (average farm size in the Northern Uplands of Vietnam is 0.5 ha). IGHs decided to take loans of 125- 312 USD, but this money was not fully invested in cultivation. All participants realized that taking loans exceeding the actual amount needed, may lead to problems for debtors at the end of debt period, if the money is spent on things other than cultivation investments. Therefore, the average loan size of 287.50 USD (from the Vietnam Bank for Social Policies) or 625 USD y^{-1} (from the Vietnam Bank for Agricultural and Rural Development) (Hao, 2005; Takashi, 2009) may be too large for households.

The land use scenarios generated by LUM show optimum solutions for food security and household income. Although the IGHs were very interested in the suggested land use plans, most found that dividing the plots, as in the optimum scenarios, is partly unrealistic. For example, the model in S1 split the TP plot in two parts with different crop rotations: 10% in Maize-Rice-Fallow and 90% in Fallow-Rice-Fallow. Similarly, the LP plot was also split in small proportions (Table 5.3 and Figure 5.1e). In practice, such systems would lead to strong land fragmentation and additional costs and time related to different growing requirements of the crops. Farmers also explained that cultivation habits, perceptions and relationships with neighbours often strongly influence their actual land use decisions. Therefore, changing cropping systems and using improved technologies cannot be implemented by individual households. To deal with these disadvantages of recommended land use scenarios, participants agreed that establishment of household groups could be an appropriate solution. Such a group could comprise households cultivating neighbouring plots, with similar land characteristics. At present, labour exchange groups exist and are working effectively in many rural areas of Vietnam (Vien, 2003). The new form of household group, developed in this open dialog, can help to reduce land fragmentation and optimize the use of available land and capital resources and make use of the current labour sharing scheme.

5.4 Discussion

Ethnicity does not describe the characteristics of farm-type groups in the Suoi Con case study area (Table 5.2). This result is in accordance with the view of other authors that there are no differences between ethnic minorities and others in their livelihood choices (Minot *et al.*, 2006) and their land use decisions do not result from cultural values (Castella and Quang, 2002). However, education level of the householder is clearly associated with land use decisions. Householders at intermediate education level (IGHs B and C) tend to pay more attention to improving agricultural techniques, access to markets and irrigation conditions, while lower educated householders (IGHs A and D) mainly focus on expanding land and household capital (Table 5.4). Although relations between education level on one hand and agricultural development and livelihood improvement on the other were not further analysed in this study, this result implies that education is an important factor in the development of land use strategies at household level.

Land use decisions of farmers shown in the first game session closely reflect the actual agricultural production pattern in the region. Simple maize and rice rotations are associated with successful participatory demonstration trials of maize cultivation techniques recently conducted by the Soils and Fertilizers Research Institute. Although this technical package introduced by SFRI is not new, a significant number of households quickly adopted and applied it in their regular practices. According to Minot *et al.* (2006) and the World Bank (2009), much of the dissemination of agricultural technologies currently occurs indirectly via the village chief or word-of-mouth. This has led to a slow process of shifting cropping systems (from traditional crops to high-value crops) and low adoption rates in rural areas (MARD, 2006). The remarkable change in land use of households in this case study calls for collaboration among local authorities, scientists and agricultural extension services for a wide dissemination of recommended agricultural technologies.

Lack of access to markets is commonly mentioned as a constraint for farmers in rural areas (Sunderlin and Thu Ba, 2005; Folving and Christensen, 2007). However, in this case study, lack of market information is closer to the farmers' situation. Growing maize production in recent years has created challenges for farmers with regard to decisions on planting area and selling products. This implies that market-oriented production is not pre-set in land use objectives of farmers, but the need for market information arises after the target for self-sufficiency has been achieved.

Although access to credit is often mentioned as a major constraint for households in rural Vietnam (Cramb, 2004; Minot *et al.*, 2006; World Bank, 2009), the current analysis has shown that lack of access to credit is mostly related to the capital problem of the poor. Loan packages of formal services (i.e. Vietnam Bank for Social Policies and Vietnam Bank for Agricultural and Rural Development) are hard to access for most households. Therefore, microfinance services offering small loans, that have been successful in Africa, Latin America and some Asian countries (India, Bangladesh and Indonesia) (Pitt *et al.*, 2006; Rosengard *et al.*, 2007; Nagayya and Rao, 2009; Haq *et al.*, 2010) should be considered by the government to alleviate the capital constraint of rural households.

The establishment of household groups as by stakeholders in S4, is a suggestion for the implementation of national programs like the "large-scale rice field" (Ngan, 2011) or the "development of a new countryside" (GOV, 2010) in heterogeneous environments. In addition, this form of land management can reduce the current limitations of serious land fragmentation in rural areas of Vietnam (Barker, 1994; Hung *et al.*, 2007).

Integration of RPG and LUM allowed identification of the actual constraints of farmers and their influence on decision-making. Moreover, this integration represents a participatory approach for land use planning, in which land use plans are developed and revised by stakeholders under their own social and economic conditions. Imperfections in given land use plans and possible solutions proposed by stakeholders provide policy makers with ideas to improve land use planning and to bridge the gaps between land use objectives of the government and of farmers.

5.5 Conclusions

Agricultural development is highly dependent on land use decisions of individual households, hence, understanding the reasoning behind farmers' decisions is needed for effective future land use planning processes. By using a participatory approach, land use plans can be developed and revised based on the responses of multiple stakeholders. Furthermore, such an approach can also take into consideration uncertainties surrounding land use, such as cultivation habit, perceptions and relationships among households that are often ignored in existing land use planning processes. The integration of a Land Use optimization Model and a Role Playing Game provides potentials to address land use problems and to develop feasible plans. Such integration helps in avoiding the negative impacts of top-down approaches in land use planning, which often result in distortion or failure of implementation (Selman, 1988; Hudson, 1991; McPherson, 2012). The integrated approach presented in this paper provides a solution to both planners and policy makers to formulate viable land use plans in the future.

Chapter 6

Synthesis

Synthesis

6.1 Introduction

Economy, environment and society are commonly considered as three interactive drivers of sustainable agricultural development. A small change in one can lead to significant changes in the others. Men play an important role in making such changes and, therefore, men drive direction, success and sustainability of agricultural development. Actors in agricultural development with different opinions often develop different strategies for using common resources which can lead to mismatches in the objectives of stakeholders at different hierarchical levels. In a heterogeneous environment, such as the Northern Uplands of Vietnam (NUV), such a mismatch has created a gap between the objectives of the government, researchers and farmers. Literature shows that many of the government policies have been in conflict with the traditional ways of using resources employed by the local population. The result has been that actual development changes in the region have not followed the long term plans of the government. Consequently, economic development and poverty reduction in the NUV are slower than expected. More than ever before, an integrated and participatory approach is required in order to gain understanding of actual problems and opportunities of the region. This approach will help to bridge the gaps between the objectives of the various stakeholders and identify appropriate interventions for development. Tools are needed to:

- explore characteristics of agro-ecological and socio-economic dynamics,
- stimulate dialogues among various actors on the use of common resources,
- facilitate the emergence of a common agreement on ecologically sustainable, socially equitable and economically viable solutions.

In this thesis, an integrated modelling approach was developed and evaluated with the purpose of exploring limitations and potentials of resources and of analysing optimal land use options and their adoption possibilities. The study was carried out in Suoi Con, a representative agro-forestry watershed in the NUV. This chapter presents main findings associated with the availability of agricultural resources, common constraints of the region and technical issues of the integrated modelling approach. Furthermore, the main contributions, limitations and policy implications of this study are described in this synthesis. This information can be used as additional background information for agricultural development and further modelling in and beyond the NUV.

6.2 Tools for integrated modelling used in the Suoi Con watershed study

The present land use is the result of household decisions that take into account the balance between household endowments and availability of resources. Accordingly, land use planning needs to take into account both socio-economic and bio-physical aspects of land use. Computerized tools can be used to provide better understanding of the aspects of sustainable development. However, an individual tool is often developed for a specific use with its own function. There is general agreement that integrated approaches, in which various tools are linked, can provide a broader and less biased view of land use systems, especially in heterogeneous environments. This thesis project made major new steps forward in this area. In this section, we briefly comment on the individual tools that were used in this thesis to support our integrated approach in land use planning and policy development at watershed scale.

6.2.1 Land evaluation (LE)

FAO’s framework for Land Evaluation (LE) (FAO, 2007) was adapted to assess limitations and potentials of land in the NUV. The original land evaluation framework (FAO, 1976) has been criticized because of its bias toward physical attributes and applicable scales. The scientific community has suggested that concepts of biophysical limitations and potentials of land should be embedded within social, economic considerations and a balance between land use and land conservation needs be taken into account. Therefore, the 1976 framework was extended with socio-economic procedures added (FAO, 2007). Despite the limitations of FAO's LE, it is considered useful and appropriate for resource management studies, especially in developing countries.

For this research, the new framework of the FAO's LE was modified with some novel additions to increase suitability for the Suoi Con case study. Land units (LU) were delineated using a grid map at the resolution of 30x30m to adequately represent the heterogeneity in physical characteristics (i.e. soil, slope, climate), land fragmentation and the average farm size in the watershed (about 0.5 ha). By using this approach, the loss of spatial information and temporal variability could be reduced (Kam et al., 2000). In addition, village boundaries were included in LU properties to allow inclusion of possible cultural and social aspects of land use planning. We adopted a new definition of the Land Use Type (LUT) in this application of the FAO's LE. Accordingly, a LUT was defined as a crop-season combination (e.g. spring rice) instead of a more general term of land use (e.g. paddy land). Because the growth cycle of annual crops is often short (4 months or less), multiple crops can be grown in more than one season on an individual land unit. Combined with the diversity in crops, there are a number of crop-season combinations, each with its own management practice and input-output relation. The process for making such modifications is a contribution that can be used to adapt the FAO LE to any location.

LE output showed that most of the agricultural land in Suoi Con is characterized by low soil fertility, high acidity, steep slope, several degradation problems and low suitability for annual crops. These constraints result in low crop yields and low agricultural income of households. However, the heterogeneities of soils, topography and climate conditions create opportunities for farmers to diversify agricultural products and to make flexible land use decisions.

6.2.2 Household survey (HHS)

The use of a HHS added a good overview of the social and economic prospects in relation to agricultural development in the watershed. The sample size was based on a proportion of the target population instead of on a particular indicator (DESA, 2008). One hundred households from 3 villages (25% of the total number of households) participated in the survey. In practice it is not realistic to randomly select households. Listed households may not be able to participate in the survey for various reasons (e.g. householders are not at home or sick or not willing to provide information). Therefore, representative households were suggested by chiefs of villages based on three levels of agricultural investment (high, medium and low). The chief made appointments with the households in his village. Although the selection of the chief may be biased, this approach can maintain the diversity of sample while reducing time spent on the survey.

The HHS is an appropriate tool for an explorative study. However, a literature review is also necessary in order to provide an objective overview of land use at the study area. The integration of these two approaches supports the first two components of FAO's LE framework very well: (1) the initial consultation with all stakeholders and (2) the diagnosis of land use problems. Input-output relations, the main output of the HHS, were described per crop-season to match the modified LE and spatially referenced per plot. The HHS provided both quantitative information (i.e. quantities of inputs and outputs under farmers' practices) and qualitative information (i.e. priorities and constraints). In general, the variation in collected HH variables was large due to a high heterogeneity of households' conditions (resources, economy, education and management practices).

Contrary to previously published opinions, the output of our HHS showed that the differences between villages or ethnic minorities in crop management and land use decisions do not fall along clear lines. Data presented in Chapter 5 indicate that the main variables distinguishing household groups in the

Suoi Con catchment are the age and education level of the householder, household size, number of labourers and investment in paddy rice. As noted, this is contrary to opinions of some authors that individual household strategies depend primarily on the resource endowments of their village (Castella, 2009) and that each ethnic group has its own distinctive farming system (Vien, 2003). The current similarities and differences found in the NUV may be the result of long term cultural adaptations of ethnic groups and strong interaction between villages in the watershed. The important point is that our approach identified this difference from the current opinion – which is an important factor for effective development plans.

6.2.3 Soil erosion models (PLER and RUSLE)

In this study, two soil erosion models were applied to evaluate the environmental impact of land use scenarios. The 'Predict and Localize Erosion and Runoff (PLER)' model was used to simulate the dynamics of soil erosion processes at watershed scale (Chapter 3) and the Revised Universal Soil Loss Equation (RUSLE) was used to estimate potential soil loss from crop rotations on individual land units (Chapter 4). The novel approach taken in this work allowed consideration of both macro and micro scales.

PLER integrates three hydrological processes of soil erosion (i.e. detachment, transportation and deposition) and is sensitive for a change in vegetation cover. It provides daily output of e.g. runoff rate and soil loss. Although the dynamics of soil erosion are well predicted at the outlet of the watershed, cell-based prediction is poor. Application of PLER requires a number of field measurements, e.g. measurement of the infiltration rate, sediment density and settling velocity, daily rainfall and the dynamics of vegetation cover. In addition it needs calibration and validation in order to be applied in new environments. The quality of the prediction depends very much on the land cover of upstream and downstream parcels, because these strongly influence hydrological processes along the slope. Accordingly, each change of land cover at a single cell generates a new value of soil loss and thus may be considered as a new land use scenario. To take all cells into account in a watershed, the number of scenarios would become unmanageable. Therefore, this type of simulation model is a more appropriate tool for evaluating long term impact of a given land use scenario than a tool to examine alternative scenarios. These disadvantages made PLER less compatible with other components in the conceptual framework of this study (Chapter 1), which is the reason why RUSLE was brought into the study.

An advantage of RUSLE is that it only requires a simple set of input parameters. In RUSLE, calculations of sediment transport and deposition are not explicitly included. This implies that in our modelling practice, there is the assumption that the predicted soil loss at each location can be transported out of the watershed. Two temporally dynamic factors (crop and rainfall) were split into 4 periods, corresponding to 4 distinct development stages of crops (initial, development, middle and late stage). The total soil loss of a whole growing season is the sum of the 4 individual quantities. Our experience with RUSLE showed that the model can easily estimate soil loss of individual cells under every possible land use. Therefore, RUSLE was used to test the impact of intended crops or crop rotations on a given plot of land. Model output indicated that for a given soil type and slope, potential soil loss in summer is always higher than in other seasons, and that erosion rates are highest under cassava, maize, upland rice and groundnut . Soil erosion still occurs if agricultural land is left fallow. Depending on land characteristics and seasons, soil loss from fallow land was estimated to be higher than under some annual crops (e.g. soybean and sweet potato).

6.2.4 Land use optimization model (LUPAS)

The LUPAS model, which can be applied at watershed scale, was adapted and used. LUPAS generates feasible land use options and, thus, provides understanding of constraint-target relations in agricultural land use. Theoretically, LUPAS can use a wide range of spatial scales, from local (e.g. plot and land unit; the RUSLE scale) to region (e.g. village, district and province; the PLER scale). However, working with high spatial resolution creates a significant challenge for modellers due to the model size. Scaling down leads to a huge increase in computer resource and time requirements. For example in the Suoi Con case study, approximately one half hour is required for a single run with 1809 land units (about 360 ha of agricultural land) on a 3.0 GHz, 2Gb RAM computer. The computing time would increase to over 2 hours for a run using individual grid-cells and would be 12 working days to complete all runs. Furthermore, optimizing land use at grid-cell level will result in unrealistic solutions due to the excessive land fragmentation (see Chapter 5). Therefore, a land unit (LU) as defined in the modified LE was considered to be a more realistic spatial detail both for modelling and policy advice purposes.

Based on these considerations, various land use scenarios were analysed to explore the impact of land use constraints (i.e. lack of land area, land fragmentation, lack of capital, lack of agricultural labour and low level of technology) on food security, income and erosion reduction targets. The output indicated that, under current land use conditions, the continued use of traditional technology is the biggest constraint that is hampering increases in agricultural production. In addition, the output indicated that land fragmentation also has a strong limiting impact on agricultural production, suggesting that, even without adoption of new agricultural technologies, introduction of new crops and increased capital availability, land consolidation could significantly increase income of households. However, as will be addressed later, this is not the whole story.

6.2.5 Role playing game (RPG)

To facilitate emergence of a common agreement on ecological sustainability, social equity and economically sound solutions - and to stimulate dialogues among various stakeholders – the agent based modelling technique Role Playing Game (RPG) was used. Through this, shared responsibility of the common resources (the second and third objectives of this study) was achieved. Experiences show that the RPG approach has promising potential (Barreteau, 2003; Barreteau et al., 2001; Bousquet et al., 2007) to facilitate dialogues among stakeholders. In this study, LUPAS was integrated with RPG. All important characteristics of land use described in Chapters, 2, 3 and 4 (i.e. land suitability, land degradation, actors, constraints in land, capital, labour and agricultural techniques) were used to design the structure of the RPG. This ensures that the game environment is as close as possible to the actual situation in the study site. Representatives of local authorities, the extension service, credit organization and farmers were invited to participate in the game. LUPAS was used to generate actual land use options based on decisions of farmers. Land use options that were explored by LUPAS and suggested by farmers in game sessions were discussed among participants. Through this novel way of fostering communication using integrated tools, some social and economic factors of land use that had not been captured by the individual tools could be identified.

The output of this RPG is not a computer model output but land use plans developed and refined by real stakeholders. In addition, a set of collective solutions to overcome constraints in agricultural production was also found through participants' responses. The output showed that the use of RPG with the integration of multiple tools is highly valuable in the participatory process to address existing land use issues and to develop viable land use plans and policies.

6.3 Potentials and challenges of integrated modelling

Integrated modelling (IM) is a technique that connects models to describe complex systems. Each component model deals with an issue and supports a function of the IM system. Because the components are flexible, IM has a high potential for presenting multiple levels of dynamics or for capturing multiple perspectives for policy development. Technically, IM is based on a balanced analysis of the biophysical, economic, social and institutional aspects of a system (Van Ittersum et al., 2008). In the analysis, computer-based models are used to contribute to improved understanding of the system and, therefore, formulation of better information for policy development.

In agriculture, a number of IM frameworks have been developed over the past years for analysis of biophysical and socio-economic problems (Barreteau et al., 2003; Letcher et al., 2006; Ruankaew et al., 2010) and to support policy makers in agricultural and rural development (Roetter et al., 2005; Van Delden, 2009a; Van Ittersum et al., 2008). According to Van Delden et al. (2010), existing IM approaches can be classified into two groups: comprehensive modelling focusing on specific agricultural sectors and Integrated Decision Support Systems focusing on broader issues of land use and land use change which incorporates to a greater degree the relations between economics and land use. The IM technique used in both groups does not replace existing computerized tools but presents a method for organization of tools to improve their usefulness.

Because IM uses separate tools, there are a number of issues that create challenges with the integration of these tools. The experience of Van Delden (2009a) in integrating socio-economic and bio-physical models to support sustainable development showed that mismatches between spatial and temporal scales of data and component models are two major difficulties. Regarding the spatial scale, bio-physical data and models usually represent the system at watershed scale, while most socio-economic data and models are often available at the scale of an administrative unit. A watershed may belong to more than one administrative region (e.g. province or district). Therefore, downscaling information from regional to cellular level and then aggregating them to the desired spatial scale is required. These issues were resolved in this research.

Bio-physical and socio-economic models may use different temporal scales. Some work with daily data (e.g. hydrology, erosion and plant growth models), while others (e.g. land use change and farmers' decisions on cropping system) use seasonal or annual data. Furthermore, data used in the individual models can be collected at different points in time. Synchronizing scales of processes and data collection is often required in IM frameworks. In discussing functions of IM that support policy development, Van Ittersum et al. (2008) specify four major challenges and requirements of IM: (1) overcoming the gap between micro and macro level analysis, (2) handling the bias in how the different biophysical and socio-economic disciplines look into an aspect (3) the ability of models to be reused and (4) the technique used to link separate models. This thesis has made major contributions to resolving and achieving these issues.

Van Delden (2009b) showed that the success or failure of an IM system depends much on the end-users. The author suggested that assumptions used in computerized models need to be clear for the end-users, who are often not familiar with modelling. The way in which the end-users interact with the IM system is another issue. Individual models use different programming languages and have a different interface that the end-users must use to input data, run models and observe outputs. In order to support planning and policy recommendations that often change quickly over time, the IM system needs to be continuously maintained, upgraded and used. The life of an IM system and its value to assist in planning and policy depend on the way in which the end-users are able to manage and adopt it. Therefore, the end-users should be involved in its development, so that their knowledge will contribute to the improvement of the system. This was, clearly, a major aspect of this research, verifying Van Delden's point and showing that involvement of multiple stakeholders is both possible and productive.

Besides specification of the end-users, definition of data requirements for component models and for their integration also needs to be clarified at the initial stage of an IM system, in order to avoid unexpected problems in later stages (e.g. implementation, update and maintenance). These factors are still significant challenges for modellers in developing an IM system. In order to avoid failures in developing IM systems, Van Delden (2009b) determined eight elements that should be considered: strategic value, availability of appropriate data and models, credibility of the system, domain language of the system, institutional embedment, culture, ease of use and maintenance and support. This thesis has demonstrated steps forward in these areas, although there further development and validation is needed.

6.4 Limitations of individual tools, and use of the tools individually, in describing agro-ecological and socio-economic characteristics

Table 6.1 provides a summary of the single tools used in this thesis, with their main limitations for integration: (1) type of tools, (2) the temporal reference at which land use resources are described, (3) the spatial reference of the tools and (4) the qualitative and quantitative representation of the tools. The way the individual tools (LE, HHS, RUSLE, LUPAS and RPG) were integrated in our IM system is presented in Figure 6.1.

FAO's LE tool mainly describes biophysical characteristics of land. It is based on soil, terrain, climate data and irrigation conditions and determines suitability classes for crops. Management, social and economic factors and environmental impact of land use are marginally included in the evaluation process and are not explicitly described in the LE output. Suitability classes of land are described in terms of constraints that either reduce productivity or increase the input requirement of land use. The suitability classes range from high suitability, S1, with few constraints to not suitable, N, where there are many constraints and include the term "temporarily not suitable" (FAO, 1976, 2007). However, the related constraints of land use are not clearly specified. In addition, because the temporal reference of the LE is seasonal-based, the level of constraints must be identified separately for individual growing seasons. The basic spatial unit of the LE are the land units (LU). Each LU may contain many cells, which may cover more than one plot. Therefore, field-to-field variation of land is not adequately described. Due to the generalizations made in delineating LUs, output of LE can only provide a relative quality of land use. In addition, the LE procedure is based on fixed past or current biophysical characteristics of land, the actual suitability of which can change over time due to possible changes in climate or as a result of changing management practices.

The HHS was included to provide information on management and socioeconomic characteristics of land use such as land tenure and labour, agronomic technologies and capital availability. Output of the HHS can be both qualitative data (e.g. experiencing a certain constraint in agricultural production or not) and quantitative data (e.g. quantity of seed and fertilizer used). In the HHS, we used crop-season and land plot as temporal and spatial scales of data. This is the best way to collect information from households because farmers can precisely describe their land use in a specific season and on a given plot of land. However, these socio-economic descriptions are likely biased, as they were only provided by farmers. Therefore, in addition to the HHS, literature review and policy analysis was needed, and included, in order to attain a broader view of the constraints.

Soil erosion caused by agricultural land use on sloping land was not included in the LE procedure and was also poorly described in the output of the HHS due to technical limitations of the tool and current perceptions of farmers on resource conservation. Therefore RUSLE, which is based on bio-physical data, was used to estimate potential soil erosion. Social and economic factors that may influence the erosion process were not included in RUSLE's equations. Spatially, RUSLE can only estimate potential soil loss for individual land plots. In the application of RUSLE in this study, each cell in the raster GIS map was considered as a single plot and estimation of sheet erosion was based on a cell unit. Instead of estimating annual soil loss, the temporal scale of the tool was adapted to the crop-season. Due to certain assumptions made when applying RUSLE at watershed scale (i.e. a combination of hydrological processes in one calculation and the removal of locally eroded soil) the accuracy of RUSLE's quantitative estimation is low. However, our adaptations, including season-based calculations of temporally dynamic factors (e.g. vegetation cover and rainfall) and potential soil loss, made the tool flexible and enhanced its applicability in integrated tools.

Table 6.1. Descriptions of tools used in the Suoi Con case study.

Tools	Type of tool	Temporal reference	Spatial reference	ql/qt presentation*
LE	Bio-physical	season	land unit	ql
HHS	Socio-economic	season	plot	ql/qt
RUSLE	Physical	season	cell	qt
LUPAS	Integrated	season	land unit	qt
RPG	Social	season	plot	ql

* ql = qualitative; qt = quantitative

The LUPAS tool includes all land use aspects described in LE, HHS and RUSLE in an integrated analysis process. This ensures that the output of LUPAS reflects these aspects in the suggested land use options. Because the spatial and temporal scales of LE, HHS and RUSLE are different, they have been adapted to LU and crop-season, respectively to facilitate the linkage of the tools. However, for application of LUPAS a number of additional external processes need to be realised. For example, inputs and outputs of land uses provided by HHS were classified according to the suitability classes defined in LE and therefore had to be further translated to LUs; similarly soil loss at cell level estimated by RUSLE had to be aggregated to LU level. Therefore, the accuracy of inputs and outputs of LUPAS is relatively low in comparison to that of the individual tools. Another disadvantage is that the land use options suggested by the model are far from reality because of the assumptions on which they are based (e.g. land and capital are shared among households in a village). Therefore, outputs of the system have to be revised and validated by stakeholders to reflect more realistic conditions.

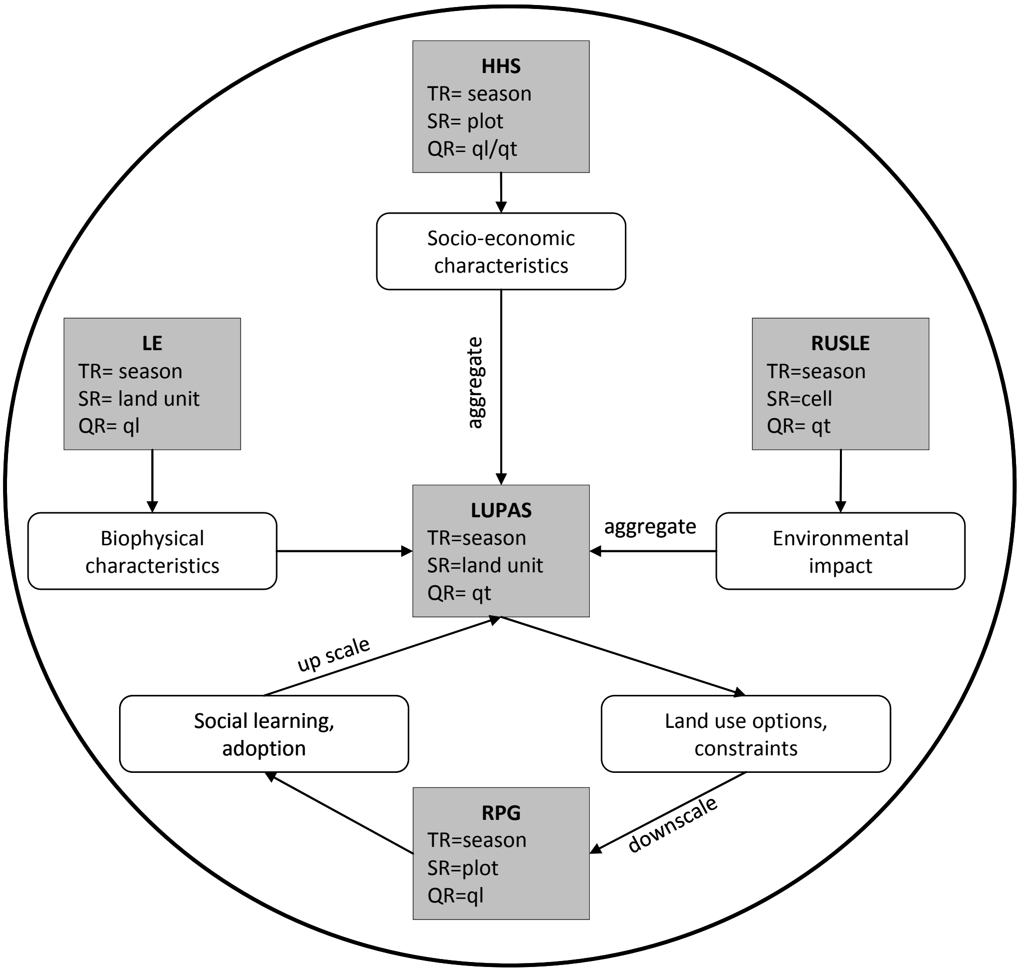

Figure 6.1. Integration of the land use planning tools used in the Suoi Con case study. TR= temporal scale, SR= spatial scale, QR= qualitative (ql) or quantitative (qt) scale. All info from Table 6.1 is also in this figure…

Box 6.1. Views on constraints in agricultural development

HHS:	capital >land area >technique >labour >irrigation >market
Literature review:	technique >land fragmentation >irrigation >market >capital >labour
LUPAS:	technique >land fragmentation >capital >labour >land area >irrigation

RPG and the computerized tools are learning devices that connect the participatory approach to policy development. Castella (2009) stated that these learning devices have three main functions: translation, mediation and visualisation. When using RPG separately, these functions will not be fully realized. For example in the Suoi Con case study, the RPG itself is a translation tool that contributes to identification of common meanings and to mutual understanding. However, it poorly presents the mediation and visualisation functions, because RPG has a limited capacity to generate information and visualize scenarios for debate among stakeholders. These missing functions were incorporated by the inclusion of LUPAS. One of the remaining disadvantages of the RPG in our case is that the number of players participating in the game sessions was limited (12 players in the Suoi Con case study), so that the diversity in decision making was low. In addition, land use decisions in RPG are plot-based. When integrated into RPG, the spatial scale of LUPAS needs to be downscaled to the plot level. Consequently, the land use plans with a downscaled LUPAS result in highly fragmented land.

Bias 'within' individual disciplines not only occurs in the integration of bio-physical and socio-economic characteristics of land use (Van Ittersum et al., 2008) but also happens when the same aspect is described by different disciplines. Comparing output of the HHS with the literature review (Chapter 2) shows that a number of socio-economic issues, such as definitions of land use constraints and formulation of land use objectives and strategies, are still not commonly recognized. Policy makers, local authorities, researchers and farmers often have their own views on land use constraints and they describe these constraints in different ways. Farmers consider lack of capital as the most urgent constraint, while local authorities give priority to agricultural technologies (Box 6.1). Similarly, soil conservation, irrigation and access to markets are emphasized in the development strategy of the central government and the lower administrations (i.e. the People Committees of the province, district and commune) but they are of minor interest to farmers. The different points of view and the limited collaboration among the stakeholders in developing agricultural policies (World Bank, 2009) lead to gaps between the micro and the macro levels of analysis and limit the effectiveness of interventions.

It is obvious that using tools individually leads to various limitations in describing agro-ecological and socio-economic characteristics. In this study, each single tool mainly addresses a specific aspect of land use. (i.e. LE for biophysical factors, HHS and LUPAS for social and economic factors and RUSLE for environmental factors). Each tool only gives us an angle of view on land use based on the specific information that it provides. Therefore, integration of tools is critically required and IM approach is important for land use planning studies in areas like our case study.

6.5 Contribution of integrated modelling (IM)

The IM approach is an appropriate choice to increase insight in the characteristics of agro-ecological and socio-economic dynamics and, therefore, to better support policy development. LUPAS, with an integration of information from the LE, HHS and RUSLE tools, represents a class of IM that belongs more to the first group of IM tools defined by Van Delden et al. (2010) than the second – but not without the perspective of the second group. In the integrated tool presented in this thesis, both agro-ecological and socio-economic characteristics of the region are taken into consideration and the three major aspects of land use (economy, society and environment) are adequately described. At the macro level (e.g. region, province and district), LUPAS is considered as a top-down oriented methodology where the participatory mode of operation mainly involves regional ‘’governing’’ authorities (Castella et al., 2007). The application of LUPAS in this study proved that LUPAS can also provide bottom-up support through its performance at micro levels (i.e. household, village and small watershed). Therefore, the integrated approach using LUPAS can bridge the gap between micro and macro level analysis, which has been specified as a requirement of a good IM system (Van Ittersum et al., 2008) and weakness of previous IM approaches.

Because input requirements of individual tools recommended here (i.e. LE and RUSLE) and LUPAS are often already available or rather simple to be collected, these tools can be reused with new data sets or for new conditions. This addresses another shortcoming of previous IM efforts. Different from the judgement by Castella et al. (2007) that there is no explicit identification of driving forces in LUPAS, our application of LUPAS shows that it can quantitatively highlight the influences of important factors of land use. By integrating various tools into LUPAS, the principal of ‘what is currently realistic and plausible’ (De Ridder et al., 2000) can move towards ‘what is realistic and plausible for the future’. This provides a new perspective on constraints and defines realistic land use targets in a quantitative way.

At another level of integration, LUPAS was integrated with RPG following the ABM approach. Effective interaction of different stakeholders in RPG allowed further consideration of social and economic issues related to land use. Because RPG is a tool to open the black box of ABM (Barreteau et al., 2001), a number of ‘hidden issues’ that were not captured by the earlier described tools came into view and could be taken into account in further discussion. The criticism from the modelling community (Robertson, 2005) on the assumptions of stakeholders in the game approach has now been answered because stakeholders in this game can play their own real-life roles. In the setup of RPG developed and demonstrated in this work, in which both the environmental and stakeholder characteristics are close to reality, the IM system can help to answer real questions like: how do farmers make land use decisions? What is the role of various agents (stakeholders) in agricultural production? And what are feasible solutions to attain livelihood improvement and environmental conservation? The approach presented in this thesis greatly increases the value and effectiveness of IM.

Our integration approach can be used to test given land use plans and evaluate their feasibility. For example, in the Suoi Con case study, the LUPAS-RPG integrated system was used to evaluate the LUPAS output. Results showed that farmers are willing to adopt the recommended cropping systems and technology levels that are selected by the optimization model; but the same farmers refuse to accept the suggested land allocation plans (Chapter 5) due to various social and economic reasons (e.g. relations with neighbours , land and investment fragmentation and costs of management). Computer-based land use scenarios that have been commonly seen as non-validated output (Laborte, 2006; Roetter et al., 2005; Van Ittersum et al., 2004), can now be evaluated by using this integrated approach. Furthermore, social issues identified through HHS and LUPAS (e.g. perceptions on land use constraints or organisation of household groups) (Chapters 2, 4 and 5) can also be validated.

The IM approach developed and presented in this thesis overcomes several of the limitations that have been identified in previous IM systems (Van Delden, 2009a; Van Ittersum et al., 2008). It can make use of individual research tools for describing agro-ecological and socio-economic dynamics and for developing land use policy. The component models in this IM system were adapted to facilitate reuse at new study sites with simple sets of input data. The structure of the IM system is quite flexible, so that end-users can easily setup different scenarios for different purposes. A major contribution is that the approach was proven through application in the Suoi Con watershed with the outcome of insights in land use decision of households and possible solutions proposed by stakeholders that can be used to more effectively achieve the goals of the government and the people. The IM approach presented has the potential to serve planners and policy makers to increase the likelihood of developing plans that will effectively increase farmer livelihood and improve resource conservation.

6.6 Policy recommendations

The world we live in is very complex. A wide range of factors contributes to changes in our environment in various ways. To change the environment in the desired direction, identification of all driving forces is always the most important step. In formulating land use policies, a biased view and missing information often creates unrealistic policies and, therefore, leads to unexpected impacts. With a combination of tools for land evaluation, socio-economic exploration, environmental impact assessment, land use optimization and social learning, the IM approach presented in this thesis made it possible for agricultural policy makers, scientists, extension officers and farmers to look at both the limitations and potentials of the resources. The IM approach developed and advocated here can incorporate different aspects of land use into land use planning and test hypotheses regarding the contributions of intended plans to general development targets. It provides a way to make use of learning devices that were developed for particular purposes, in a decision support system. In analysing trade-offs between land use objectives, this IM approach can also identify imbalances or defects in current policies and suggest possible improvement. From the experiences gained in the development of this IM approach, the following conclusions and policy recommendations have been identified.

The influence of driving factors is site specific. Therefore, large scale implementation of land use policies in the NUV is not appropriate. For example, results obtained from this study indicate various limits associated with the upland environment, which make implementation of land de-fragmentation policies as in the past (GOV, 1998, 2010) rather unrealistic in the uplands. Therefore, land use policies should be tested in different contexts before enforcing them. The RPG of the agent based modelling approach is a good choice for this work.

The way, in which driving factors influence land use decisions, is dynamic. The current 5 year interval is rather long in comparison with the rapid changes in farmers' decision and in cropping systems over time. Intended land use plans may become redundant before they can be implemented. These considerations suggest the need for shorter periods of land use planning for smaller geographical areas.

The current process of land use planning for the NUV often follows a top-down approach, in which the interests of different farmers are not adequately considered. This approach has led to unpredicted changes in land use and created unexpected environmental impacts. The IM approach introduced in this thesis can support bottom-up land use planning as it allows incorporation of different stakeholders in analysing existing problems, proposing solutions and developing land use plans.

This IM system can specify the most important constraints for agricultural development in a specific region. Therefore, it can be used to suggest forceful interventions. For instance, analysing agricultural constraints in this study showed that lack of agricultural technology is more serious than lack of capital or agricultural land in the NUV. And socio-economic analysis showed that de-fragmentation, which has the potential to increase productivity, is not at present an acceptable option. Therefore policy makers should focus on improving agricultural technology adoption at a small scale as the first priority in the development strategy for this region. This does not imply creation of new crop varieties or development of new agricultural techniques but collective actions to increase adoption of existing recommended techniques through collaboration of agricultural scientists and extension agents with farmers.

Policy makers, scientists and agricultural extension officers can be end-users of this IM system. For productive use of the system, however, interaction between end-users during the planning process is required. That is crucial for developing a feasible land use plan or recommending a realistic policy based on common understanding of possible impacts on nature. Adopting the IM approach developed in this work has potentials to evaluate problems and opportunities of land use from different points of view and based on that, to formulate feasible land use plans and recommendations. This IM approach supports the participatory and bottom-up land use planning and thus, it can increase the likelihood of adoption. This in turn will create the chances for achievement of targets of the government, researchers and farmers through effective implementation of the plans.

References

ADB. 2000. Finance for the Poor: Microfinance Development Strategy. Asian Development Bank: Manila, pp. 51.

Akram-Lodhi, A.H. 2002. "All decisions are top-down:" Engendering public expenditure in Vietnam. Feminist Economics 8, pp. 1-19.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. In FAO Irrigation and Drainage Paper 56. FAO, Rome, Italia.

Ananda, J., Herath, G. 2003. Soil erosion in developing countries: A socio-economic appraisal. Journal of Environmental Management 68, pp. 343-353.

Arhonditsis, G.B., Stow, C.A., Steinberg, L.J., Kenney, M.A., Lathrop, R.C., McBride, S.J., Reckhow, K.H. 2005. Exploring ecological patterns with structural equation modelling and Bayesian analysis. Ecological Modelling 192, pp. 385-409.

Azmon, B. 1992. Manning coefficient of roughness - a case-study along soreq stream, 1971-1981. Journal of Hydrology 132, pp. 361-377.

Bah, A., Touré, I., Le Page, C., Ickowicz, A., Diop, A.T. 2006. An agent-based model to understand the multiple uses of land and resources around drillings in Sahel. Mathematical and Computer Modelling 44, pp. 513-534.

Barker, R. (ed). 1994. Agricultural policy analysis for transition to a market-oriented economy in Vietnam. Selected issues. FAO Economic and Social Development Paper. FAO, Rome, Italy.

Barreteau, O. 2003. The joint use of role-playing games and models regarding negotiation processes: Characterization of associations. Journal of Artificial Societies and Social Simulation 6. URL: http://jasss.soc.surrey.ac.uk/6/2/3.html

Barreteau, O., Bousquet, F., Attonaty, J.M. 2001. Role-playing games for opening the black box of multi-agent systems: Method and lessons of its application to Senegal River Valley irrigated systems. Journal of Artificial Societies and Social Simulation 4. URL: http://jasss.soc.surrey.ac.uk/4/2/5.html

Barreteau, O., Le Page, C., D'Aquino, P. 2003. Role-playing games, models and negotiation processes. Journal of Artificial Societies and Social Simulation 6. http://jasss.soc.surrey.ac.uk/6/2/10.html

Bat, L.T. 2001. Soil environmental state of Vietnam. Journal of Vietnam Soil Science 15, pp. 146- 153.

Beven KJ. 2001. Rainfall-Runoff Modelling: the primer. John Wiley & Sons ltd, NY, 360 p.

Bo, N.V., Thi, N.T., Hien, B.H., Chien, N.V. 2003. Fertilizer supply for main crops in Vietnam - from theory to practice. Agricultural Publishing House, Hanoi, Vietnam.

Bousquet, F., Castella, J.C., Trébuil, G., Barnaud, C., Boissau, S., Suan, P.K. 2007. Using multi-agent systems in a companion modelling approach for agro-ecosystem management in South-east Asia. Outlook on Agriculture 36, pp. 57-62.

Bousquet, F., Le Page, C. 2004. Multi-agent simulations and ecosystem management: A review. Ecological Modelling 176, pp. 313-332.

Bousquet, F., Trebuil, G. 2005. Companion modelling and multi-agent systems for collective learning and resource management in Asian rice ecosystems. In Rice is life: scientific perspectives for the 21st century. International Rice Research Institute (IRRI). Los Banos, Philippines.

Bousquet, F., Trébuil, G., Hardy, E. 2005. Companion Modeling and Multi-Agent Systems for Integrated Natural Resource Management in Asia. CIRAD & International Rice Research Institute, Los Baños, Philippines.

Bresson, L.M., Valentin, C. 1994. Soil surface crust formation: contribution of micromorphology. Soil micromorphology, pp. 737-762.

Breuer, L., Huisman, J.A., Willems, P., Bormann, H., Bronstert, A., Croke, B.F.W., Frede, H.G., Graff, T., Hubrechts, L., Jakeman, A.J., Kite, G., Lanini, J., Leavesley, G., Lettenmaier, D.P., Lindstrom, G., Seibert, J., Sivapalan, M., Viney, N.R. 2009. Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM). I: Model intercomparison with current land use. Advances in Water Resources 32, pp. 129-146.

Buda, A.R., Kleinman, P.J.A., Srinivasan, M.S., Bryant, R.B., Feyereisen, G.W. 2009. Factors influencing surface runoff generation from two agricultural hillslopes in central Pennsylvania. Hydrological Processes 23, pp. 1295-1312.

Can, L.T., My, N.Q. 1982. Observation of soil erosion in Vietnam. Ministry of Agriculture, Hanoi, Vietnam.

Castella, J.C. 2009. Assessing the role of learning devices and geovisualisation tools for collective action in natural resource management: Experiences from Vietnam. Journal of Environmental Management 90, pp. 1313-1319.

Castella, J.C., Boissau, S., Thanh, N.H., Novosad, P. 2002. Impact of forestland allocation on agriculture and natural resources management in Bac Kan Province, Viet Nam. In Doi Moi in the Mountains. Land use changes and farmers' livelihood strategies in Bac Kan Province, Vietnam, Castella, J.C., Quang, D.D. (eds). Agricultural Publishing House, Hanoi, Vietnam.

Castella, J.C., Pheng Kam, S., Dinh Quang, D., Verburg, P.H., Thai Hoanh, C. 2007. Combining top-down and bottom-up modelling approaches of land use/cover change to support public policies: Application to sustainable management of natural resources in northern Vietnam. Land Use Policy 24, pp. 531-545.

Castella, J.C., Quang, D.D. 2002. Doi Moi in the Mountains - Land use changes and farmers' livelihood strategies in Bac Kan Province, Vietnam. Agricultural Publishing House, Hanoi, Vietnam.

Castella, J.C., Trung, T.N., Boissau, S. 2005. Participatory simulation of land-use changes in the northern mountains of Vietnam: the combined use of an agent-based model, a role-playing game, and a geographic information system. Ecology and Society 10, pp. 32. URL: http://www.ecologyandsociety.org/vol10/iss1/art27/

Castella, J.C., Verburg, P.H. 2007. Combination of process-oriented and pattern-oriented models of land-use change in a mountain area of Vietnam. Ecological Modelling 202, pp. 410-420.

Chaplot, V., Giboire, G., Marchand, P., Valentin, C. 2005. Dynamic modelling for linear erosion initiation and development under climate and land-use changes in northern Laos. Catena 63, pp. 318-328.

Chen, Y., Li, X., Su, W., Li, Y. 2008. Simulating the optimal land-use pattern in the farming-pastoral transitional zone of Northern China. Computers, Environment and Urban Systems 32, pp. 407-414.

Chieu, T.T., Bat, L.T., Khang, N., Tan, N.V. 1999. Handbook for soil survey and land evaluation. Agricultural Publishing House, Hanoi, Vietnam.

Clark, M.P., Rupp, D.E., Woods, R.A., Tromp-van Meerveld, H.J., Peters, N.E., Freer, J.E. 2009. Consistency between hydrological models and field observations: Linking processes at the hillslope scale to hydrological responses at the watershed scale. Hydrological Processes 23, pp. 311-319.

Clement, F. 2010. Analysing decentralised natural resource governance: Proposition for a "politicised" institutional analysis and development framework. Policy Sciences 43, pp. 129-156.

Clement, F., Amezaga, J.M. 2008. Linking reforestation policies with land use change in northern Vietnam: Why local factors matter. Geoforum 39, pp. 265–277.

Clement, F., Amezaga, J.M. 2009. Afforestation and forestry land allocation in northern Vietnam: Analysing the gap between policy intentions and outcomes. Land Use Policy 26, pp. 458-470.

Clement, F., Amezaga, J.M., Orange, D., Toan, T.D. 2006. The Impact of Government Policies on Land Use in Northern Vietnam: An Institutional Approach for Understanding Farmer Decisions. In Research Report 112. International Water Management Institute, Colombo, Sri Lanka.

Cools, N., De Pauw, E., Deckers, J. 2003. Towards an integration of conventional land evaluation methods and farmers' soil suitability assessment: A case study in northwestern Syria. Agriculture, Ecosystems and Environment 95, pp. 327-342.

Costanza, R., Ruth, M. 1998. Using Dynamic Modelling to Scope Environmental Problems and Build Consensus. Environmental Management 22, pp. 183-195.

Cramb, R.A. 2004. Farmers’ strategies for managing acid upland soils in Southeast Asia: an evolutionary perspective. Agriculture, Ecosystems and Environment 106, pp. 69-87.

Dang, T.H., Coynel, A., Orange, D., Blanc, G., Etcheber, H., Schafer, J., Le, L.A. 2009. Erosion and impact of human disturbance on sediment transport in the Red River, Vietnam. Geochimica Et Cosmochimica Acta 73, pp. A260-A260.

De La Rosa, D., Cardona, F., Almorza, J. 1981. Crop yield predictions based on properties of soils in Sevilla, Spain. Geoderma 25, pp. 267-274.

De Ridder, N., Ittersum, M.K.V., Keulen, H.V. 2000. Four explorative land use studies in South and Southeast Asia at the ecoregional scale: How future-oriented are they? In Systems research for optimizing future land use in South and Southeast Asia, Roetter, R.P., Keulen, H.V., Laborte, A.g., Hoanh, C.T., Laar, H.H.V. (eds). International Rice Research Institute, Los Baños, Philippines.

De Roo, A.P.J., Offermans, R.J.E., Cremers, N.H.D.T. 1996. Lisem: A single-event, physically based hydrological and soil erosion model for drainage basins. II: Sensitivity analysis, validation and application. Hydrological Processes 10, pp. 1119-1126.

De Vente, J., Poesen, J. 2005. Predicting soil erosion and sediment yield at the basin scale: Scale issues and semi-quantitative models. Earth-Science Reviews 71, pp. 95-125.

De Wit, C.T. 1965. Photosynthesis of leaf canopies. In: Agricultural Resources Report No. 663, Pudoc, Wageningen.

DESA. 2008. Designing Household Survey Samples: Practical Guidelines. Department of Economic and Social Affairs, Statistics Division of the United Nations: New York.

Dower, M. 2004. Manuals for training and information on integrated rural development. Agricultural Publishing House, Hanoi, Vietnam.

Dunne, T., Zhang, W.H., Aubry, B.F. 1991. Effects of rainfall, vegetation, and microtopography on infiltration and runoff. Water Resources Research 27, pp. 2271-2285.

ERSDAC. 2009. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM). Earth Remote Sensing Data Analysis Center (ERSDAC): Japan.

Etienne, M., Le Page, C., Cohen, M. 2003. A step-by-step approach to building land management scenarios based on multiple viewpoints on multi-agent system simulations. Journal of Artificial Societies and Social Simulation 6. URL: http://jasss.soc.surrey.ac.uk/6/2/2.html

FAO. 1976. A framework for land evaluation. FAO Soils bulletin 32. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 1990. Guidelines for Distinguishing Soil Subunits in the FAO-UNESCO-ISRIC Revised Legend: Including Amendments to the System. In FAO World Soil Resources Report no. 60, Annex 1. Food and Agriculture Organization of the United Nations, Rome, Italia.

FAO. 1993. Guidelines for land-use planning. FAO Development Series No. 1. FAO, Rome, Italy, Italia.

FAO. 1998. World Reference Base for Soil Resources. In World Soil Resources reports No. 84, Rome, Italia.

FAO. 2007. Land evaluation: Towards a revised framework. Food and Agriculture Organization of the United Nations, Rome, Italia.

FIPI. 2007. Land use map of Thu Cuc commune. Forest Inventory and Planning Institute (FIPI). Ministry of Agriculture and Rural Development: Hanoi, Vietnam.

Flanagan, D.C., Ascough, J.C., Nearing, M.A., Laflen, J.M. 2001. The Water Erosion Prediction Project (WEPP) model. In Landscape erosion and evolution modelling, Harmon, R.S., Doe, W.W. (eds). Kluwer Academic Publishers, New York, USA.

Folving, R., Christensen, H. 2007. Farming system changes in the Vietnamese uplands - Using fallow length and farmers' adoption of Sloping Agricultural Land Technologies as indicators of environmental sustainability. Geografisk Tidsskrift 107, pp. 43-58.

GOV. 1998. Direction No.10/1998/TT-TTg on stepping up and completing the land allotment and the granting of agricultural land tenure certificates. Vietnamese government: Hanoi, Vietnam.

GOV. 2003. The comprehensive poverty reduction and growth strategy. Vietnamese government: Hanoi, Vietnam.

GOV. 2005. National poverty line in period 2006 - 2010. Vietnamese government: Hanoi, Vietnam.

GOV. 2010a. Decision No.800/QĐ-TTg on approving the national target program on building a new countryside during 2010-2020. Vietnamese government: Hanoi, Vietnam.

GOV. 2010b. Decision No. 31/NQ-CP. Government action plan for population and family planning from 2010 to 2015 Vietnamese government: Hanoi, Vietnam.

GOV. 2011. National poverty line in period 2010 - 2011. Vietnamese government: Hanoi, Vietnam.

GSO. 1996. Statistical yearbook of Vietnam. Statistical publishing house, Hanoi, Vietnam.

GSO. 2009. Statistical yearbook of Vietnam. Statistical publishing house, Hanoi, Vietnam.

GSO. 2011. Statistical yearbook of Vietnam. Statistical publishing house, Hanoi, Vietnam.

Ha, N.T. 1996. Determination of soil erosion factors and soil erosion prediction on sloping lands. PhD thesis. Hanoi University of Hydrology, Hanoi, Vietnam.

Hao, Q.M. 2005. Access to finance and poverty reduction. An application to rural Vietnam, PhD thesis. Department of Accounting and Finance. The University of Birmingham, Birmingham, UK.

Haq, M., Skully, M., Pathan, S. 2010. Efficiency of microfinance institutions: A data envelopment analysis. Asia-Pacific Financial Markets 17, pp. 63-97.

Hayami, Y. 1994. Strategiesforthe Reform of Land Policy Relations. In Agricultural Policy Analysisfor Transitionto a Market-Oriented Economy in Vietnam, Barker, R. (ed). FAO, Rome, Italia.

Hergarten, S., Neugebauer, H.J. 1997. Homogenization of Manning's formula for modeling surface runoff. Geophysical Research Letters 24, pp. 877-880.

Hessel, R., Jetten, V., Guanghui, Z. 2003. Estimating Manning's n for steep slopes. Catena 54, pp. 77-91.

Hoanh, C.T., Roetter, R. 1998. Towards decision support systems for land use planning. In A systems approach to analyzing land use options for sustainable rural development in South and Southeast Asia. SysNet special project report, Roetter, R., Hoanh, C.T. and Teng, P.S. (ed). International Rice Research Institute, Manila, Philippines.

Hoanh, C.T., Roetter, R.P., Agganval, P.K., Bakar, I.A., Tawang, A., Lansigan, F.P., Francisco, S., Lai, N.X., Laborte, A.G. 2000. LUPAS: An operational system for land use scenario analysis In Systems research for optimizing future land use in South and Southeast Asia, Roetter, R.P., Keulen, H.V., Laborte, A.G., Hoanh, C.T., Laar, H.H.V. (eds). International Rice Research Institute, International Rice Research Institute, Los Baños, Philippines.

Horton, R.E. 1993. The role of infiltration in the hydrologic cycle. In Transactions, American Geophysical Union, 446-460.

Hudson, N.W. 1991. A study of the reasons for success or failure of soil conservation projects. In FAO soils bulletin. FAO: Rome, Italia.

Hung, P.V., Macaulay, T.G., Marsh, S.P. 2007. The economics of land fragmentation in the north of Vietnam. Australian Journal of Agricultural and Resource Economics 51, pp. 195-211.

IMHEN. 2008. Monthly climate data. The Vietnam Institute of Meteorology, Hydrology and Environment: Hanoi, Vietnam

Janeau, J.L., Bricquet, J.P., Planchon, O., Valentin, C. 2003. Soil crusting and infiltration on steep slopes in northern Thailand. European Journal of Soil Science 54, pp. 543-553.

Janssen, B.H., Guiking, F.C.T., van der Eijk, D., Smaling, E.M.A., Wolf, J., van Reuler, H. 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46, pp. 299-318.

Jetten, V.G., De Roo, A.P.J., Favis-Mortlock, D. 1999. Evaluation of field-scale and catchment-scale soil erosion models. Catena 37, pp. 521-541.

Jetten, V.G., De Roo, A.P.J., Guerif, J. 1998. Sensitivity of the model LISEM to variables related to agriculture. In Modelling Soil Erosion by Water, Boardman, J., Favis-Mortlock, D. (eds). Springer, Berlin.

Jin, N., Termansen, M., Hubacek, K. 2008. Genetic Algorithms for dynamic land-use optimization. In 2008 IEEE Congress on Evolutionary Computation, CEC 2008. Hong Kong, 3816-3821.

Jolliffe, I.T. 2002. Principle Component Analysis, Second edition. Springer, New York.

Kam, S.P., Castella, J.C., Hoanh, C.T., Trebuil, G., Bousquet, F. 2002. Methodological integration for sustainable natural resources management beyond field/farm level: Lessons from the Ecoregional Initiative for the Humid and Sub-Humid Tropics of Asia. International Journal of Sustainable Development & World Ecology 9, pp. 383-395.

Kam, S.P., Yen, B.T., Hoanh, C.T. 2000. Land evaluation for optimizing land and resource use for agricultural production in a heterogeneous mountainous environment - a case study of Bac Kan province, Vietnam. In 6th Seminar on GIS and Developing Countries. International Rice Research Institute (IRRI). Los Banos, Philippines.

Karssenberg, D.J. 2001. The PCRaster Environmental Modelling language. PC-Raster Version 2 manual. Department of Physical Geography, Faculty of Geosciences, Utrecht University. Utrecht, the Netherlands.

Kennedy, G., Burlingame, B., Nguyen, N. 2002. Nutrient impact assessment of rice in major rice-consuming countries. In International Rice Commission Newsletter Vol. 51, Tran, D.V. (ed). Food and Agriculture Organization of the United Nations, Rome.

Krause, P., Boyle, D.P., Base, F. 2005. Comparison of different efficiency criteria for hydrological model assessment. Advances in Geosciences 5, pp. 89-97.

Laborte, A. 2006. Multi-scale land use analysis for agricultural policy assessment: A model-based study in Ilocos Norte province, Philippines. Plant Production System. Wageningen University, Wageningen.

Lan, L.M. 2001. Land fragmentation-a constraint for Vietnam's agriculture. Vietnam's Socio-Economic Development 26, pp. 73-80.

Le, Q.B., Park, S.J., Vlek, P.L.G., Cremers, A.B. 2008. Land-Use Dynamic Simulator (LUDAS): A multi-agent system model for simulating spatio-temporal dynamics of coupled human-landscape system. I. Structure and theoretical specification. Ecological Informatics 3, pp. 135-153.

Letcher, R.A., Croke, B.F.W., Jakeman, A.J., Merritt, W.S. 2006. An integrated modelling toolbox for water resources assessment and management in highland catchments: Model description. Agricultural Systems 89, pp. 106-131.

Littleboy, M., Smith, D.M., Bryant, M.J. 1996. Simulation modelling to determine suitability of agricultural land. Ecological Modelling 86, pp. 219-225.

Maglinao, A.R. 2000. Indicators of sustainable land management for slopeland farms. Food & Fertilizer Technology Center: Taipei, Taiwan.

Maglinao, A.R., Valentin, C. 2003. Catchment Approach to Managing Soil Erosion in Asia. In Research Towards Integrated Natural Resources Management - Examples of Research Problems, Approaches and Partnerships in Action in the CGIAR, Harwood, R.R., Kassam, A.H. (eds). Food and Agriculture Organization, Rome, Italia.

Mandal, D.K., Mandal, C., Venugopalan, M.V. 2005. Suitability of cotton cultivation in shrink-swell soils in central India. Agricultural Systems 84, pp. 55-75.

Manna, P., Basile, A., Bonfante, A., De Mascellis, R., Terribile, F. 2009. Comparative Land Evaluation approaches: An itinerary from FAO framework to simulation modelling. Geoderma 150, pp. 367-378.

MARD. 2006. Results of survey and land use planning for transition of agriculture and forestry systems in the Northern Uplands of Vietnam towards 2010 and vision for 2020. Ministry of Agriculture and Rural Development, Hanoi, Vietnam.

Markussen, T., Tarp, F., Thiep, D.H., Tuan, N.D.A. 2012. Intra- and Inter-farm land fragmentation in Vietnam. Policy brief 06 of 2012. Central institute for economic management 6.

Marsh, S.P., Anh, L.H., Macaulay, T.G. 2006. Credit use in farm households in Vietnam: implications for rural credit policy. In Agricultural development and land policy in Vietnam, Marsh, S.P., MacAulay, T.G., Hung, P.V. (eds). Australian Centre for International Agricultural Research, Canberra, Australia.

Matthews, R.B., Gilbert, N.G., Roach, A., Polhill, J.G., Gotts, N.M. 2007. Agent-based land-use models: A review of applications. Landscape Ecology 22, pp. 1447-1459.

McDonald, G.T. 1989. Rural land use planning decisions by bargaining. Journal of Rural Studies 5, pp. 325-335.

McElwee, P.D. 2010. Resource use among rural agricultural households near protected areas in Vietnam: The social costs of conservation and implications for enforcement. Environmental Management 45, pp. 113-131.

McGlynn, B.L., McDonnell, J.J. 2003. Quantifying the relative contributions of riparian and hillslope zones to catchment runoff. Water Resources Research 39.

McPherson, M.F. 2012. Land Policy in Vietnam: Challenges and Prospects for Constructive Change. Journal of Macromarketing 32, pp. 137-146.

Minot, N., Epprecht, M., Anh, T.T.T., Trung, L.Q. 2006. Income diversification and poverty in the Northern Uplands of Vietnam. Research Report of the International Food Policy Research Institute. Washington, DC

Misra, R.K., Rose, C.W. 1996. Application and sensitivity analysis of process-based erosion model GUEST. European Journal of Soil Science 47, pp. 593-604.

Misra, R.K., Teixeira, P.C. 2001. The sensitivity of erosion and erodibility of forest soils to structure and strength. Soil and Tillage Research 59, pp. 81-93.

Morduch, J., Haley, B. 2002. Analysis of the Effects of Microfinance on Poverty Reduction. NYU Wagner Working Paper No. 1014, pp. 163.

Morgan, R.P.C. 2005. Soil Erosion and Conservation. Blackwell, Oxford, UK.

Morgan, R.P.C., Quinton, J.N., Smith, R.E., Govers, G., Poesen, J.W.A., Auerswald, K., Chisci, G., Torri, D., Styczen, M.E. 1998. The European soil erosion model (EUROSEM): a dynamic approach for predicting sediment transport from felds and small catchments. Earth Surface Processes and Landforms 23, pp. 527-544.

Mulengera, M.K., Payton, R.W. 1999. Estimating the USLE-soil erodibility factor in developing tropical countries. Tropical Agriculture 76, pp. 17-22.

Müller, D., Zeller, M. 2002. Land use dynamics in the central highlands of Vietnam: a spatial model combining village survey data with satellite imagery interpretation. Agricultural Economics 27, pp. 333-354.

Nagayya, D., Rao, D.K. 2009. Micro finance and support organisations in the southern states of India. Journal of Rural Development 28, pp. 285-301.

Nash, J.E., Sutcliffe, J.V. 1970. River flow forecasting through conceptual models part I - A discussion of principles. Journal of Hydrology 10, pp. 282-290.

Nearing, M.A., Jetten, V., Baffaut, C., Cerdan, O., Couturier, A., Hernandez, M., Le Bissonnais, Y., Nichols, M.H., Nunes, J.P., Renschler, C.S., Souchere, V., van Oost, K. 2005. Modeling response of soil erosion and runoff to changes in precipitation and cover. Catena 61, pp. 131-154.

Ngan, P.H. 2011. Vietnamese initiative for food and agricultural policy. Weekly report. Center for Agricultural Policy (Ipsard), Ministry of Agricultural and Rural Development. Hanoi, Vietnam.

Nhapi, I., Holch, W., Mazvimavi, D.A., Jewitt, G., Mudege, N., Swatuk, L.A., Beukman, R. 2005. Integrated water resources management (IWRM) and the millennium development goals: Managing water for peace and prosperity. Physics and Chemistry of the Earth 30, pp. 623-624.

NIAPP. 2006. Soil map of Phu Tho provice at scale 1/50.000. National Institute of Agricultural Planning and Projection. Hanoi, Vietnam.

Niroula, G.S., Thapa, G.B. 2005. Impacts and causes of land fragmentation, and lessons learned from land consolidation in South Asia. Land Use Policy 22, pp. 358-372.

Noble, A.D., Bossio, D.A., Penning de Vries, F.W.T., Pretty, J., Thiyagarajan, T.M. 2006. Intensifying agricultural sustainability: An analysis of impacts and drivers in the development of “Bright spots”. In Comprehensive Assessment Research Report. 13. IWMI, Colombo, Sri Lanka.

Olson, K.R., Olson, G.W. 1985. A soil-climate index to predict corn yield. Agricultural Systems 18, pp. 227-237.

Orange, D., Arfi, R., Kuper, M., Morand, P. 2002. Gestion intégrée des ressources naturelles en zones inondables tropicales. In Colloques et séminaires, Poncet, Y. (ed). IRD. Paris, Actes du colloque Girnzit, Bamako, 20-23 juin 2000, 1000.

Orange, D., Lequeux, B., Henry des Tureaux, T., Rinh, P.V., Toan, T.D. 2007. Charges de fond et suspensions transportées par les eaux d’écoulement dans un petit bassin versant agricole sur pentes dans le Nord Vietnam. In Actes des Premières Journées Scientifiques Inter-Réseaux: Gestion intégrée des eaux et des sols : ressources, aménagements et risques en milieux ruraux et urbains, Orange, D., Roose, E., Vermande, P., Gastellu, J.P., Ha, P.Q. (eds). AUF and IRD. Hanoi, Vietnam.

Orange, D., Noble, A. 2010. Technical methods and tools for integrated land and water management, to deal with issues related to conservation and utilization of land and water resources and systems. In e-Conference on “Integrated Land and Water Resources Management in Rural Watersheds”, 2 Nov.- 4 Dec. 2009. FAO Regional Office for Asia and the Pacific (UNESCAP, APWF, IWMI, GWP).

Orange, D., Toan, T.D., Phuong, N.D., Thiet, N., Salgado, P., Clement, F., Binh, L.H. 2008a. Different interests,common concerns and shared benefits. LEISA magazine 24, pp. 12-13.

Orange, D., Toan, T.D., Phuong, N.D., Thiet, N.V., P.Salgado, Clement, F., Binh, L.H. 2008b. Different interests, common concerns and shared benefits. In LEISA, pp. 12-13.

Paningbatan, E.P., Ciesiolka, C.A., Coughlan, K.J., Rose, C.W. 1995. Alley cropping for managing soil erosion of hilly lands in the Philippines. Soil Technology 8, pp. 193-204.

Parker, C.D., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P. 2002. Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review. Annals of the Association of American Geographers 93, pp. 314-337.

PCC. 2008. Evaluation of the obtained economic and social development in 2008 and development plan in 2009. Annual report of the People's Committee of Thu Cuc commune: Phu Tho, Vietnam.

Phai, D.D., Orange, D., Migraine, J.B., Toan, T.D., Vinh, N.C. 2007. Applying GIS-assisted modelling to predict soil erosion for a small agricultural watershed within sloping lands in Northern Vietnam. In the 2nd International Conference on Sustainable Sloping Lands and Watershed Management: Linking research to strengthen upland policies and practices, Gebbie, L., Glendinning, A., Lefroy-Braun, R., Victor, M. (eds). NAFRI. Luang Phrabang, Lao PDR, 212-228.

Phien, T., Tien, T.M., Thong, T.Q., Siem, N.T., Toan, T.D. 1998. Notes from the models of Cassava cultivation on sloping lands in Phuong Linh site, Thanh Ba, Phu Tho province. In Sustainable Farming on Sloping Lands in Vietnam (research results 1990-1997), Phien, T., Siem, N.T. (eds). Soils and Fertilizers Research Institute. Agricultural publishing house, Hanoi, Vietnam.

Pitt, M.M., Khandker, S.R., Cartwright, J. 2006. Empowering women with micro finance: Evidence from Bangladesh. Economic Development and Cultural Change 54, pp. 791-831.

Podwojewski, P. 2003. Soil mapping of the Dong Cao catchment. In NAFRI-IWMI-IRD workshop on Land and Water Management Research in the Uplands of South-East Asia: Improving land and water management in Vietnam and Thailand. Ventiane, Laos.

Podwojewski, P., Orange, D., Jouquet, P., Valentin, C., Nguyen, V.T., Janeau, J.L., Tran, D.T. 2008. Land-use impacts on surface runoff and soil detachment within agricultural sloping lands in Northern Vietnam. Catena 74, pp. 109-118.

Poesen, J. 1986. Surface sealing as influenced by slope angle and position of simulated stones in the top layer of loose sediments. Earth Surface Processes and Landforms 11, pp. 1-10.

RDCT. 2008. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Recatalá Boix, L., Zinck, J.A. 2008. Land-use planning in the chaco plain (Burruyacú, Argentina). Part 1: Evaluating land-use options to support crop diversification in an agricultural frontier area using physical land evaluation. Environmental Management 42, pp. 1043-1063.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C. 1997. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). US Department of Agriculture, Washington DC, US.

Rerkasem, B., Rerkasem, K. 1998. Influence of demographic, socio-economic and cultural factors on sustainable land use. In Towards sustainable land use: Furthering cooperation between people and institutions, Blume, H.P., Eger, H., Fleischhauer, E., Hebel, A., Reij, C., Steiner, K.G. (eds). Catena Verlag, Reiskirchen, Germany.

Robertson, D.A. 2005. Using Agent-Based Models to Manage the Complex. In Managing the Complex: Philosophy, Theory, and Application, Richardson, K. (ed). Information Age Publishing, Greenwich CT.

Roetter, R.P., Aggarwal, P.K., Ismail, A.B., Lai, N.X., Lansigan, F.P., Hoanh, C.T., Keulen, H.V. 2000. SysNet methodology development for agricultural land use planning: 1996-99 In Systems research for optimizing future land use in South and Southeast Asia, Roetter, R.P., Keulen, H.V., Laborte, A.G., Hoanh, C.T., Laar, H.H.V. (eds). International Rice Research Institute, International Rice Research Institute, Los Baños, Philippines.

Roetter, R.P., Hoanh, C.T., Laborte, A.G., Van Keulen, H., Van Ittersum, M.K., Dreiser, C., Van Diepen, C.A., De Ridder, N., Van Laar, H.H. 2005. Integration of Systems Network (SysNet) tools for regional land use scenario analysis in Asia. Environmental Modelling and Software 20, pp. 291-307.

Roetter, R.P., Laborte, A.G., Hoanh, C.T., Keulen, H.V., Diepen, C.A.V. 2001. Options for future agricultural land use in South and Southeast Asia: cross-site experiences at sub-national scale. In Integrated Management for Sustainable Agriculture, Forestry and Fisheries workshop. International Center for Tropical Agriculture. Cali, Colombia.

Rose, C.V., Williams, J.R., Sander, G.C., Barry, D.A. 1983. A mathematical model of soil erosion and deposition process. I. Theory for a plane element. Soil Science Society of America Journal 47, pp. 991-995.

Rosengard, J., Patten, R., Johnston, D.E., Koesoemo, W. 2007. The promise and he peril of Microfinance institutions Indonesia. Bulletin of Indonesian Economic Studies 43, pp. 87-112.

Rosenthal, R.E. 2007. GAMS - a user's guide (Release 22.5). GAMS Development Corporation, Washington DC.

Rossiter, D.G. 1996. A theoretical framework for land evaluation. Geoderma 72, pp. 165-190.

Ruankaew, N., Le Page, C., Dumrongrojwattana, P., Barnaud, C., Gajaseni, N., Van Paassen, A., Trébuil, G. 2010. Companion modelling for integrated renewable resource management: A new collaborative approach to create common values for sustainable development. International Journal of Sustainable Development and World Ecology 17, pp. 15-23.

Salasya, B., Stoorvogel, J. 2010. Fuzzy classification for farm household characterization. Outlook on Agriculture 39, pp. 57-63.

Sanchez, P.A., Couto, W., Buol, S.W. 1982. The fertility capability soil classification system: Interpretation, applicability and modification. Geoderma 27, pp. 283-309.

Schreinemachers, P., Berger, T. 2011. An agent-based simulation model of human-environment interactions in agricultural systems. Environmental Modelling and Software 26, pp. 845-859.

Sekhar, N.U. 2007. Traditional versus improved agroforestry systems in Vietnam: A comparison. Land Degradation & Development 18, pp. 89-97.

Selman, P.H. 1988. Rural land use planning - Resolving the British paradox? Journal of Rural Studies 4, pp. 277-294.

Shucksmith, M., Rønningen, K. 2011. The Uplands after neoliberalism? - The role of the small farm in rural sustainability. Journal of Rural Studies 27, pp. 275-287.

Sicat, R.S., Carranza, E.J.M., Nidumolu, U.B. 2004. Fuzzy modelling of farmers' knowledge for land suitability classification. Agricultural Systems 83, pp. 49-75.

Sidorchuk, A. 2009. A third generation erosion model: The combination of probabilistic and deterministic components. Geomorphology 110, pp. 2-10.

Siem, N.T., Phien, T. 1999. Upland soils in Vietnam: degradation and rehabilitation. Agricultural publishing house, Hanoi, Vietnam.

Sikor, T. 1998. Forest policy reform: from state to household forestry. In Stewards of Vietnam's upland forests. Research Network Report 10, Poffenberger, M. (ed). Asia Forest Network, United States.

Sonneveld, M.P.W., Hack-ten Broeke, M.J.D., van Diepen, C.A., Boogaard, H.L. 2010. Thirty years of systematic land evaluation in the Netherlands. Geoderma 156, pp. 84-92.

Stoorvogel, J.J., Antle, J.M., Crissman, C.C., Bowen, W. 2001. The Tradeoff Analysis Model Version 3.1: A Policy Decision Support System for Agriculture. Wageningen University, pp. 93.

Sunderlin, W.D., Thu Ba, H. 2005. Poverty Alleviation and Forests in Vietnam. Center for International Forestry Research (CIFOR), Bogor Barat, Indonesia.

Sys, C., Ranst, E.V., Debaveye, J. 1991a. Land Evaluation. Part I: Principles in land evaluation and crop production calculations. Agricultural publications no. 7. General Administration for Development Cooperation, Belgium.

Sys, C., Ranst, E.V., Debaveye, J. 1991b. Land Evaluation. Part II: Methods in land evaluation. General Administration for Development Cooperation, Belgium.

Sys, C., Ranst, E.V., Debaveye, J., Beernaert, F. 1993. Land Evaluation. Part III: Crop Requirement. General Administration for Development Cooperation, Belgium.

Tablecurve 2D. 2002. Automated Curve Fitting and Equation Discovery (TableCurve 2D Version 5.01 for Windows). User's Manual, 5.0. Systat Software Inc, Richmont, CA.

Takashi, O. 2009. Rural Credit and Community Relationships in a Northern Vietnamese Village. Southeast Asian Studies 47, pp. 30.

Tan, P.-N., Steinbach, M., Kumar, V. 2006. Cluster Analysis: Basic Concepts and Algorithms. In Introduction to Data Mining. Addison-Wesley.

The, B.D., Ha, D.T., Chinh, N.Q. 2004. Rrewarding upland farmers for environmental services. Experience, constraints and potential in Vietnam. World Agroforestry Centre, Bogor, Indonesia.

Toan, T.D., Orange, D., Phien, T., Podwojewski, P., Phai, D.D., Rinh, P.V. 2002. MSEC country report for Vietnam 1999 - 2002, Hanoi, Vietnam.

Toan, T.D., Orange, D., Podwojewski, P., Phai, D.D., Phien, T., Maugin, J., Rinh, P.V. 2003. Soil Erosion and Land Use in the Dong Cao Catchment in Northern Vietnam. In From Soil Research to land and Water Management: Harmonizing People and Nature. IWMI-ADB project Annual Meeting and 7th MSEC Assembly, Maglinao (ed). Thailand, IWMISEA, 165-179.

Trinh, M.V. 2007. Soil erosion and nitrogen leaching in northern Vietnam: Experimentation and modelling. PhD. Plant Science Department. Wageningen University, Wageningen, the Netherlands.

Trung, N.H., Tri, L.Q., Van Mensvoort, M.E.F., Bregt, A.K. 2006. Application of GIS in Land-Use Planning. A Case Study in the Coastal Mekong Delta of Vietnam. In International Symposium on Geoinformatics for Spatial Infrastructure Development in Earth and Allied Sciences. Ho Chi Minh City, Vietnam.

Turkelboom, F., Poesen, J., Ohler, I., Van Keer, K., Ongprasert, S., Vlassak, K. 1997. Assessment of tillage erosion rates on steep slopes in northern Thailand. Catena 29, pp. 29-44.

VAAS. 2008. Vietnamese Rice Knowledge Bank. Vietnam Academy of Agricultural Science: Hanoi, Vietnam.

Valentin, C., Agus, F., Alamban, R., Boosaner, A., Bricquet, J.P., Chaplot, V., de Guzman, T., de Rouw, A., Janeau, J.L., Orange, D., Phachomphonh, K., Do Duy, P., Podwojewski, P., Ribolzi, O., Silvera, N., Subagyono, K., Thiébaux, J.P., Tran Duc, T., Vadari, T. 2008. Runoff and sediment losses from 27 upland catchments in Southeast Asia: Impact of rapid land use changes and conservation practices. Agriculture, Ecosystems and Environment 128, pp. 225-238.

Van Delden, H. 2009a. Integration of socio-economic and bio-physical models to support sustainable development In 18th IMACS World Congress and MODSIM09 International Congress on Modelling and Simulation, Anderssen, R.S., Braddock, R.D., Newham, L.T.H. (eds). The Modelling and Simulation Society of Australia and New Zealand Inc. and the International Association for Mathematics and Computers in Simulation. Cairns, Australia, pp. 2457-2463.

Van Delden, H. 2009b. Lessons learnt in the development, implementation and use of Integrated Spatial Decision Support Systems. In 18th IMACS World Congress and MODSIM09 International Congress on Modelling and Simulation, Anderssen, R.S., Braddock, R.D., Newham, L.T.H. (eds). The Modelling and Simulation Society of Australia and New Zealand Inc. and the International Association for Mathematics and Computers in Simulation. Cairns, Australia, pp. 2922-2928.

Van Delden, H., Stuczynski, T., Ciaian, P., Paracchini, M.L., Hurkens, J., Lopatka, A., Shi, Y., Gomez Prieto, O., Calvo, S., Van Vliet, J., Vanhout, R. 2010. Integrated assessment of agricultural policies with dynamic land use change modelling. Ecological Modelling 221, pp. 2153-2166.

Van der Kwaak, J.E., Loague, K. 2001. Hydrologic-response simulations for the R-5 catchment with a comprehensive physics-based model. Water Resources Research 37, pp. 999-1013.

van Diepen, C.A. 1993. Two alternative methods for evaluating regional crop yield potential in the European Community. Geoderma 60, pp. 359-376.

Van Dijk, A.I.J.M., Bruijnzeel, L.A. 2003. Terrace erosion and sediment transport model: A new tool for soil conservation planning in bench-terraced steeplands. Environmental Modelling and Software 18, pp. 839-850.

Van Dijk, A.I.J.M., Meesters, A.G.C.A., Schellekens, J., Bruijnzeel, L.A. 2005. A two-parameter exponential rainfall depth-intensity distribution applied to runoff and erosion modelling. Journal of Hydrology 300, pp. 155-171.

Van Ittersum, M.K., Ewert, F., Heckelei, T., Wery, J., Olsson, J.A., Andersen, E., Bezlepkina, I., Brouwer, F., Donatelli, M., Flichman, G., Olsson, L., Rizzoli, A.E., Wal, T.v.d., Wien, J.E., Wolf, J. 2008. Integrated assessment of agricultural systems – A component-basedframework for the European Union (SEAMLESS). Agricultural Systems 96, pp. 150-165.

Van Ittersum, M.K., Rabbinge, R. 1997. Concepts in production ecology for analysis and quantification of agricultural inputeoutput combinations. Field Crops Research 52, pp. 197-208.

Van Ittersum, M.K., Roetter, R.P., van Keulen, H., de Ridder, N., Hoanh, C.T., Laborte, A.G., Aggarwal, P.K., Ismail, A.B., Tawang, A. 2004. A systems network (SysNet) approach for interactively evaluating strategic land use options at sub-national scale in South and South-east Asia. Land Use Policy 21, pp. 101-113.

Van Keulen, H. 2007. Quantitative analyses of natural resource management options at different scales. Agricultural Systems 94, pp. 768-783.

Van Paassen, A., Roetter, R.P., Van Keulen, H., Hoanh, C.T. 2007. Can computer models stimulate learning about sustainable land use? Experience with LUPAS in the humid (sub-) tropics of Asia. Agricultural Systems 94, pp. 874-887.

VASS. 2011. Poverty alleviation in Vietnam: achievements and challenges. The Gioi publisher, Hanoi, Vietnam.

Verbist, B.J.P., Noordwijk, M.v., Tameling, A.C., Schmitz, K.C.L., Ranieri, S.B.L. 2002. A Negotiation Support Tool for Assessment of Land Use Change Impacts on Erosion in a Previously Forested Watershed in Lampung; Sumatra; Indonesia. In the Integrated Assessment and Decision Support. Lugano, Switzerland.

Vezina, K., Bonn, F., Van, C.P. 2006. Agricultural land-use patterns and soil erosion vulnerability of watershed units in Vietnam's northern highlands. Landscape Ecology 21, pp. 1311-1325.

Vieira Pak, M., Castillo Brieva, D. 2010. Designing and implementing a Role-Playing Game: A tool to explain factors, decision making and landscape transformation. Environmental Modelling and Software 25, pp. 1322-1333.

Vien, T.D. 2003. Culture, environment, and farming systems in Vietnam's Northern Mountain Region. Southeast Asian Studies 41, pp. 180-205.

Vien, T.D., Nga, N.T.D. 2008. Economic Impact of Hybrid Rice in Vietnam: An Initial Assessment. In Proceedings of the JSPS International Seminar 2008: "Hybrid Rice and Transformation of Farming Systems", Ogata, K., Yasui, H., Kurosawa, K., Miyajima, I., Vien, T.D., Cuong, P.V. (eds). Kyushu University. Fukuoka, JAPAN, 19-35.

Vien, T.D., Quang, N.V., Thanh, M.V. 2005. Classification in forestry resource management and people's livelihood. Agricultural Publishing House, Hanoi, Vietnam.

Visser, S.M., Sterk, G. 2007. Nutrient dynamics - Wind and water erosion at the village scale in the Sahel. Land Degradation and Development 18, pp. 578-588.

VNRSC. 2007. Satellite images. Vietnam Remote Sensing Center (VNRSC), Ministry of Natural Resources and Environment, Vietnam: Hanoi.

Walling, D.E. 1999. Linking land use, erosion and sediment yields in river basins. Hydrobiologia 410, pp. 223-240.

Weill, S., Mouche, E., Patin, J. 2009. A generalized Richards equation for surface/subsurface flow modelling. Journal of Hydrology 366, pp. 9-20.

Wezel, A., Luibrand, A., Thanh, L.Q. 2002. Temporal changes of resource use, soil fertility and economic situation in upland Northwest Vietnam. Land Degradation and Development 13, pp. 33-44.

Wischmeier, W.H., Smith, D.D. 1978. Predict rainfall erosion losses - a guide to conservation planning. U.S. Department Of Agriculture, Agriculture Handbook No. 537, Washington DC, US.

Witt, C., Yen, B.T., Quyet, V.M., Thu, T.M., Pasuquin, J.M., Buresh, R.J., Dobermann, A. 2007. Spatially Variable Soil Fertility in Intensive Cropping Areas of North Vietnam and Its Implications for Fertilizer Needs. Better Crops 91, pp. 28 - 31.

World Bank. 2009. Country Social Analysis: Ethnicity and Development in Vietnam. The World Bank, Washington.

Xie, Z., Su, F., Liang, X., Zeng, Q., Hao, Z., Guo, Y. 2003. Applications of a surface runoff model with Horton and Dunne runoff for VIC. Advances in Atmospheric Sciences 20, pp. 165-172.

Yen, B.T., Kam, S.P., Ha, P.Q., Hoanh, C.T., Hien, B.H., Castella, J.C., Duc, H.Q., Tuan, V.D., Nguyen, V., Son, C.K. 2002. Exploring land use options for agricultural development in Bac Kan province, Vietnam. In 17th World Congress on Soil Sciences 2002 (WCSS). Bangkok, Thailand.

Yen, B.T., Visser, S.M., Hoanh, C.T., Stroosnijdere, L. 2013. Constraints in agricultural production in the Northern Uplands of Vietnam. Paper has been submitted to the Journal of Mountain Research and Development.

Yu, B. 2003. A unified framework for water erosion and deposition equations. Soil Science Society of America Journal 67, pp. 251-257.

Yu, B., Rose, C.W., Ciesiolka, C.A.A., Coughlan, K.J., Fentie, B. 1997. Toward a framework for runoff and soil loss prediction using GUEST technology. Australian Journal of Soil Research 35, pp. 1191-1212.

Summary

Since the 1980s, Vietnam has experienced significant economic growth and an increase in living standard as a result of *"doi moi"* and successive development policies. However, the rural areas of Vietnam, especially the Northern Uplands of Vietnam (NUV), still face major development problems related to livelihood and natural resource management. The household livelihood of the common family-orientated farm depends heavily on agricultural production. Land use decisions of households related to that production often do not follow the long term plans of the government.

This PhD study was conducted in Suoi Con, a small watershed situated in Thu Cuc commune, Tan Son district, Phu Tho province, in the NUV. The total area of the watershed is approximately 1760 ha, of which 80% is upland and 20% is lowland. The agricultural land often has low soil fertility and suffers from various degradation problems. The annual variation in climatic conditions creates three main cultivation seasons: (1) spring, S_p (from February to June), (2) summer, S_m (from July to October) and (3) winter, W_t (from November to January). Main annual crops are irrigated rice, rainfed rice, maize, groundnut, soybean, vegetables, sweet potato and cassava. Although Suoi Con is not too far from large economic centers (150 km from Hanoi, the capital of Vietnam), the watershed is characterized by a high poverty rate and low agricultural production and household income. The watershed has 3 villages, inhabited by Muong and Dao ethnic minorities with a total population of 1845 people. The livelihood of the households is dependent upon self-sufficient agricultural production, which accounts for nearly 80% of the total production value.

The main objective of the study is to integrate modelling of (i) erosion assessment, (ii) land use optimization and (iii) land use decision making. The aim is to improve the effectiveness and adoption of recommendations that contribute to the improved livelihood of farmers and sustainable natural resource management. We hypotheses that this can be achieved through: (1) increasing our understanding of the interactions between agro-ecological and socio-economic dynamics at watershed scale; (2) facilitating the emergence of a common agreement on ecological sustainability, social equity and economically sound solutions; and (3) stimulating dialogue among various stakeholders to achieve a shared responsibility of the common resources.

Chapter 2 describes the biophysical and socioeconomic characteristics of the study area through results obtained from surveys, FAO's land evaluation, literature review and stakeholder meetings conducted in the Suoi Con watershed. Results show that most of the total area of the watershed land has steep slopes, low soil fertility, high acidity and several degradation problems. Most land is moderately or marginally suitable for agricultural crops. The diversity in soils, topography and crop suitability requires lots of flexibility in farmers' land use decisions. Farmers have various alternative cropping systems for adapting to changes in biophysical and socio-economic conditions. On average, a five person household consists of three laborers and owns 0.5 ha of agricultural land suitable for annual crops. This area consist of 4 – 7 separate plots that may have different land characteristics.

Households in the Suoi Con watershed indicate that land degradation, steep slope, low suitability of the land and land fragmentation are not the most urgent concerns. Limited household capital was mentioned by 90% of the interviewed households. This was followed by limited land area and quality (45%), lack of agricultural techniques (40%), labour shortage (38%), not enough irrigation water (18%), low yielding crop varieties (14%), pest and diseases (10%) and lack of market accessibility (8%). The local authorities have a different view. Their order of constraints is: lack of technology > lack of land > lack of irrigation > market failures > capital shortage > need of labour.

Although soil erosion is a serious problem on sloping land in the watershed, no conservation measures have been applied under farmer practice. Chapter 3 presents the development of the Predict and Localize Erosion and Runoff (PLER) model. This model is subsequently used to examine the influence of land use on soil erosion at the watershed scale. Daily weather data, soil type and land use characteristics are

inputs to the model. The main outputs are daily runoff and soil loss calculated using the Manning-Strickler equation and the Griffith University Erosion System Template (GUEST) equation, respectively.

Results show that PLER is very good for predicting daily runoff (Nash–Sutcliffe efficiency, Ef =0.76 and the correlation coefficient, r^2 =0.82) and daily soil loss (Ef =0.99 and r^2 =0.99) at the outlet of watershed. However, local site predictions for these two factors are poor. In addition, application of PLER requires a large number of expensive and time consuming field measurements, e.g. measurements of the infiltration rate, sediment density and settling velocity, daily rainfall and the dynamics of vegetation cover, that are often not available in new study sites. In addition, the quality of the prediction depends very much on the land cover of upstream and downstream parcels, because these strongly influence hydrological processes along the slope. Therefore, the PLER simulation model is a more appropriate tool for evaluating the long term impact of a given land use than for examining the impact of alternative scenarios. In addition it is less compatible with the scale of other components in the conceptual framework of this study. For these reasons the Revised Universal Soil Loss Equation (RUSLE) was brought into the study.

Although there are no explicit calculations of sediment transport and deposition in RUSLE, the equation requires only a simple set of input parameters and allows estimation of soil loss under various alternative land uses. Estimations made by RUSLE showed that for a given soil type and slope, potential soil loss in summer is always higher than in other seasons, and that erosion rates are highest under cassava, maize, upland rice and groundnut. Soil erosion still continues if agricultural land is left fallow. Depending on land characteristics and seasons, soil loss from short fallow land was estimated to be higher than under some annual crops (e.g. soybean and sweet potato).

Defining constraints, intervention measures and land use objectives are links in the development of more profitable and sustainable land use. Therefore, land use planning must be developed with involvement of multiply disciplines. This avoids biased views, either by scientists or by farmers, on the limitations and the potentials of available resources; and takes into account the diversity in biophysical conditions and availability of alternative land use options. Chapter 4 shows how the Land Use Planning and Analysis System (LUPAS) was applied to analyse the feasibility of alternative land use scenarios. In the operation structure of LUPAS, there are 3 main parts: (P1) resource assessment, (P2) scenario construction and (P3) the land use optimization. In our application, P1 and P2 use outputs of land evaluation, the household survey, literature review and soil erosion estimations resulting from Chapter 2 and 3. P3 is the Interactive Multi Goal Linear Programming (IMGLP) core module of the system.

Four common land use constraints that were defined by both farmers and local authorities (Chapter 2) were quantitatively analysed in LUPAS. These are: limited land area, traditional technology, limited household capital and labour shortage. Two options for land management (i.e. the current land fragment and after land consolidation) were used. Also two technology levels (i.e. current, Cr, and recommended, Rm,) were used in analysis processes of LUPAS. Three capital opportunities (i.e. Cap0: current availability, Cap1: addition of 125 USD y^{-1} per household and Cap2: addition of 287.5 USD y^{-1} per household from credit services) were also considered. Based on land use objectives and targets of the local and national governments, three land use objectives were identified: (Obj1) increase rice production, (Obj2) maximize agricultural income and (Obj3) minimize soil erosion.

Nine scenarios (LSR0 to LSR8) were used for land use analysis. LSR0 reflects the current situation, whereby agricultural land is fragmented, land use is decided by individual households and only current capital availability (Cap0) and technology level (Cr) were used. Other scenarios were optimized with different combinations of the constraints and targets. Together with comparisons between achievements of given targets, the cost-to-income ratio (CIR), calculated by dividing the total costs by the attained income, was used to evaluate the efficiency of the different LSRs and influence of constraints.

Results presented in Chapter 4 demonstrate that, under current conditions, traditional technology levels appear to be the largest constraint to greater agricultural production in the region. Land area, capital and labor are also important constraints but they only appear if agricultural technology is improved. Land fragmentation is also an important factor. Even without any new agricultural techniques, crop varieties or external capital, land consolidation (sharing land among households within a village) can significantly improve food production and income. One conclusion of the study is that the order of priority of constraints should be technology > land fragmentation > capital > labour > land area.

Land use options obtained from the application of LUPAS were then evaluated via stakeholder interaction in Suoi Con (Chapter 5). LUPAS was integrated with a Role Playing Game (RPG) following the framework of Agent Based Modelling (ABM). Three main components of ABM, the environment, the agent and their interaction, were taken into account. Farmers were the most important agents. One hundred representative households in the watershed were classified into four farm-type groups using the clustering analysis method. Representatives of each farm-type group were assumed to be members of one in-game household (IGH). In the game, the conditions of the households were defined to be as close as possible to their actual situation. Each IGH was assumed to have 2 labourers and 4 land plots: waterlogged plots (WP), lowland plots (LP), terraced plots (TP) and degraded upland plots (DP). The land use objectives for the IGH were to satisfy standard food demand and generate a basic income for a 4-person household.

In the game, LUPAS was adapted for use at household scale. Optimal land use scenarios that are generated by LUPAS using inputs decided by IGHs were analysed and discussed by stakeholders in game sessions. As in the modelling only exercise, outputs of the game also showed that traditional technology is the strongest constraint to greater productivity. Capital shortage also emerged as a major problem of households in upland regions. In addition, cultivation habits, perceptions and relationships with neighbours strongly influence land use decisions of farmers. Therefore, recommended land use plans and improved technologies cannot simply be implemented by individual households. In this context, land fragmentation that causes additional costs and time spent may limit farmers' adoption of alternative practices. Through the process stakeholders identified that establishment of household groups could be an appropriate solution for sustainable agriculture development in the region. This novel form of cooperation between households could help to reduce land fragmentation. In addition it would optimize the use of available land and capital resources and make use of a labour sharing scheme.

Some additional interesting information was generated through the RPG exercises. Lack of access to markets is commonly mentioned by many authors as a constraint for farmers in rural areas. However, this research suggests that lack of market information is the real underlying constraint, at least in this case study. Also, regarding the capital constraint, our analysis shows that lack of access to credit is mostly related to the individual situation of households. These are additional clarifications that resulted from finding a convention for involvement of various local stakeholders.

Integration of LUPAS and RPG represents a participatory approach for land use planning. Problems in land use are explicitly defined and land use plans are developed and revised by stakeholders under their own social and economic conditions. Imperfections in existing land use plans and possible solutions proposed by stakeholders provide policy makers with ideas to improve land use planning. The information resulting from such a participatory approach can contribute greatly to bridging the gap between land use objectives of the government and those of farmers.

The final chapter (Chapter 6) discusses methodological issues of the integrated modelling approach presented in this thesis and summarizes important findings from this study. Potentials of the integrated modelling for land use planning are clearly identified.

It is concluded that the integrated modelling approach developed and presented in this thesis can make use of individual research tools for describing agro-ecological and socio-economic dynamics and for developing effective land use policy. It incorporates different aspects of land use into land use planning, and it can test hypotheses regarding the contributions of intended plans to general development targets. Furthermore, and very importantly, it supports bottom-up land use planning as it allows incorporation of different stakeholders in analysing existing problems and possible solutions. Therefore, it can increase the likelihood of adoption of recommendations which in turn will improve the chances for achievement of targets of the government, researchers and farmers through effective implementation of the plans. This approach therefore has the potential to serve planners and policy makers, and ultimately the people, by improving the ability to develop plans that can in reality increase farmer livelihood and improve resource conservation.

Samenvatting

Als gevolg van 'doi moi' en een aansluitend ontwikkelingsbeleid, vertoont Vietnam sinds de jaren 80 een aanzienlijke economische groei en een verbetering van de levensstandaard. Echter, het platteland van Vietnam, en met name de Noordelijke Hooglanden (NH), heeft nog steeds belangrijke ontwikkelingsproblemen gerelateerd aan de beschikbaarheid van bestaansmiddelen en het beheer van de natuurlijke hulpbronnen. De middelen voor het levensonderhoud van een gangbare, familie-georiënteerde boerderij zijn sterk afhankelijk van de landbouwproductie. Landgebruiksbeslissingen van huishoudens met betrekking tot deze productie sporen vaak niet met de lange termijn plannen van de regering.

Dit onderzoek werd uitgevoerd in Suoi Con, een klein stroomgebied in het Tan Son district, in provincie van Phu Tho, in de NH. De totale oppervlakte van het stroomgebied is ongeveer 1.760 ha, waarvan 20% kan worden omschreven als vlak, laagland en de andere 80 % hoogland is. De landbouwgrond heeft vaak een lage bodemvruchtbaarheid en is onderhevig aan diverse degradatie processen. Door de jaarlijkse variatie in klimatologische omstandigheden zijn er drie teelt seizoenen: (1) de lente (van februari tot juni), (2) de zomer (van juli tot oktober) en (3) de winter (van november tot januari). De belangrijkste éénjarige gewassen zijn: geïrrigeerd rijst, regenafhankelijke rijst, maïs, aardnoten, soja, groenten, zoete aardappel en cassave. Hoewel Suoi Con niet op grote afstand ligt van grote economische centra (150 km van Hanoi, de hoofdstad van Vietnam), wordt het stroomgebied gekenmerkt door armoede, lage landbouwproductie en een laag inkomen. Het stroomgebied heeft een totale bevolking van 1845 mensen, verdeeld over 3 dorpen. De dorpen zijn bewoond door de Muong en de Dao, etnische minderheden in Vietnam. Het inkomen van de huishoudens is afhankelijk van zelfvoorzienende landbouw, die goed is voor bijna 80% van de totale productiewaarde.

De belangrijkste doelstelling van deze studie is om de modellering van erosie en landgebruik optimalisatie te integreren met besluitvormingsprocessen rondom landgebruik. Dit beoogt de effectiviteit en de adoptie (de aanvaarding) te verbeteren van aanbevelingen die bijdragen aan de verbetering van levensonderhoud van de boeren en het duurzame beheer van natuurlijke hulpbronnen. We gaan er vanuit dat dit kan worden bereikt door: (1) het vergroten van ons begrip van de interacties tussen agro-ecologische en sociaal-economische dynamiek op stroomgebiedsniveau, (2) het ontstaan van een gemeenschappelijk akkoord over ecologische duurzaamheid, sociale rechtvaardigheid en economisch verantwoorde oplossingen, en (3) het stimuleren van de dialoog tussen de verschillende belanghebbenden over een gedeelde verantwoordelijkheid van de gemeenschappelijke middelen.

Hoofdstuk 2 beschrijft, aan de hand van resultaten uit enquêtes, een FAO landevaluatie, een literatuurstudie en bijeenkomsten met belanghebbenden uit het Suoi Con stroomgebied, de biofysische en sociaal-economische kenmerken van het studiegebied. Uit de resultaten blijkt dat het merendeel van het stroomgebied steile hellingen heeft, een lage bodemvruchtbaarheid, een hoge zuurgraad en een aantal degradatie problemen kent. Hierdoor is de meeste grond matig of marginaal geschikt voor landbouwgewassen. De grote diversiteit in de bodemkarakteristieken en de topografie en daardoor de grote diversiteit in geschiktheid voor landbouwkundige productie, vereist veel flexibiliteit van boeren bij het maken van landgebruiksbeslissingen. Boeren hebben verschillende alternatieve teeltsystemen waarmee zij zich kunnen aanpassen aan veranderingen in biofysische en socio-economische omstandigheden.

Een gemiddeld vijfpersoonshuishouden bestaat uit drie arbeiders en bezit 0,5 ha landbouwgrond geschikt voor éénjarige gewassen. Deze 0,5 ha bestaat uit 4 - 7 afzonderlijke percelen die allen diverse biofysische eigenschappen kunnen hebben. Huishoudens in het Suoi Con stroomgebied geven aan dat landdegradatie, steile hellingen, de lage geschiktheid van het land en de versnippering niet de meest urgente problemen zijn. Beperkte beschikbaarheid van kapitaal werd door 90% van de ondervraagde huishoudens genoemd als meest urgent probleem; gevolgd door een beperkt land oppervlakte en beperkte kwaliteit van het land (45%), het ontbreken van geschikte agrarische technieken (40%), tekort aan

arbeidskrachten (38%), onvoldoende irrigatiewater (18%), laag renderende gewassen (14%), ongedierte en aandoeningen (10%) en het ontbreken van een toegankelijke markt (8%). De lokale autoriteiten hebben een andere mening. Volgens hen is de rangorde van de beperkingen: gebrek aan technologie> gebrek aan grond> gebrek aan irrigatie> marktfalen> kapitaaltekort> behoefte aan arbeidskrachten.

Hoewel bodemerosie een serieus probleem is op de hellingen in het stroomgebied, passen de boeren in praktijk geen beschermingsmaatregelen toe. Hoofdstuk 3 beschrijft de ontwikkeling van het Predict and Localize of Erosion and Runoff (PLER) model. Dit model wordt gebruikt om de invloed van landgebruik op bodemerosie op de stroomgebiedsschaal te onderzoeken. Dagelijkse gegevens van het weer, bodemtype en landgebruik kenmerken zijn input voor het model. De belangrijkste resultaten zijn dagelijkse afvoer en bodemverlies berekend met respectievelijk de Manning-Strickler vergelijking en de Griffith University Erosie System Template (GAST) vergelijking. Resultaten tonen aan dat PLER de dagelijkse afvoer (Nash-Sutcliffe efficiëntie, Ef = 0,76 en de correlatiecoëfficiënt, r^2 = 0.82) en het dagelijks bodemverlies (Ef = 0,99 en r^2 = 0.99) bij de uitlaat van het stroomgebied kan voorspellen. Echter, voorspellingen voor deze twee factoren op andere locaties in het stroomgebied zijn slecht. Bovendien, vereist de toepassing van PLER een groot aantal dure en tijdrovende veldmetingen. Bijvoorbeeld metingen van de infiltratie, sediment dichtheid en valsnelheid, dagelijkse neerslag en de dynamiek van vegetatie, zijn vaak niet beschikbaar in nieuwe studie gebieden. Daarnaast is de kwaliteit van de voorspelling sterk afhankelijk van de bodembedekking van de boven- en benedenstroomse pixels omdat deze sterke invloed hebben op de hydrologische processen langs de helling. Daarom is PLER meer een geschikt instrument voor de evaluatie van de lange termijn impact van een bepaald landgebruik dan voor het onderzoeken van de invloed van alternatieve scenario's. Om deze redenen is de Revised Universal Soil Loss Equation (RUSLE) verder gebruikt in deze studie.

De RUSLE vereist slechts een eenvoudige set van input parameters en maakt daarmee een schatting van bodemverlies onder verschillende alternatieve vormen van landgebruik eenvoudig. Uit de schattingen van de RUSLE bleek dat voor een bepaald bodemtype en helling, het potentiële bodemverlies in de zomer altijd hoger is dan in andere seizoenen, en dat erosie het hoogst is onder cassave, maïs, regenafhankelijke rijst en aardnoten. Ook als de landbouwgrond braak ligt treedt er nog bodemerosie op. Afhankelijk van de eigenschappen van het land en de seizoenen, werd het bodemverlies op land dat korte tijd braak lag hoger geschat dan onder éénjarige teelten zoals soja en zoete aardappel.

Het definiëren van beperkingen, interventiemaatregelen en doelstellingen voor landgebruik zijn schakels in de ontwikkeling van meer winstgevende en duurzame landgebruiksplannen. Daarom moeten landgebruiksplannen worden ontwikkeld met betrokkenheid van diverse disciplines. Dit voorkomt vooringenomen standpunten, hetzij door wetenschappers of door boeren, op de beperkingen en de mogelijkheden van de beschikbare middelen, en houdt rekening met de diversiteit in de biofysische omstandigheden en de beschikbaarheid van alternatieve landgebruik opties.

Hoofdstuk 4 laat zien hoe het Land Use Planning and Anlysis System (LUPAS) werd toegepast om de haalbaarheid van alternatieve landgebruik scenario's te analyseren. In de structuur van LUPAS, zijn drie belangrijke onderdelen: (P1) het vaststellen van de beschikbare middelen, (P2) scenario ontwikkeling en (P3) landgebruik optimalisatie. In onze toepassing worden voor P1 en P2 de resultaten van de land evaluatie, de enquête onder huishoudens, de literatuurstudie en de bodemerosie schattingen gebruikt die voortvloeien uit hoofdstukken 2 en 3. P3 is de Interactive Multi Goal Linear Programming (IMGLP), de centrale module van het systeem. Vier gemeenschappelijke landgebruik beperkingen die werden vastgesteld door zowel boeren en lokale overheden (hoofdstuk 2) werden kwantitatief geanalyseerd m.b.v. LUPAS. Deze zijn: beperkte land oppervlakte, de traditionele agro-technologie, beperkte huishoudelijke arbeid en kapitaal tekort. Twee opties voor landbeheer (d.w.z. het huidige gefragmenteerde landgebruik en na ruilverkaveling) werden gebruikt. Daarnaast werden twee technologie niveaus (huidig en aanbevolen) gebruikt in de analyse met LUPAS. Drie scenario’s voor beschikbaarheid van financiële middelen werden geanalyseerd: actuele beschikbaarheid, toevoeging van 125 USD y^{-1} per huishouden en toevoeging van 285

USD y^{-1} per huishouden. Bij deze scenario's werd er vanuit gegaan dat de middelen via krediet-diensten beschikbaar kwamen. Op basis van streefdoelen van de lokale en nationale overheden werden drie landgebruik doelstellingen geïdentificeerd: (1) verhoging rijstproductie, (2) maximaliseren van het landbouwinkomen en (3) te minimaliseren bodemerosie. Negen scenario's (LSR0 naar LSR8) werden gebruikt voor de analyse van het landgebruik. LSR0 weerspiegelt de huidige situatie, waarbij landbouwgrond is gefragmenteerd, landgebruik wordt beslist door individuele huishoudens met de huidige beschikbaarheid van kapitaal en het huidige technologie-niveau wordt gebruikt. Andere scenario's werden geoptimaliseerd met verschillende combinaties van de beperkingen en doelstellingen. De vergelijkingen tussen verschillende scenario's en de kosten-baten ratio (CIR), berekend door de totale kosten te delen door het bereikte resultaat, werden gebruikt om de efficiëntie van de verschillende LSRs en invloed van beperkingen evalueren.

Resultaten in hoofdstuk 4 tonen aan dat, onder de huidige omstandigheden, de traditionele technologie de grootste belemmering voor een grotere landbouwproductie in de regio lijkt te zijn. Het beschikbare landoppervlak, kapitaal en arbeid zijn ook belangrijke beperkingen, maar ze worden alleen beperkend als de landbouwtechnologie is verbeterd. Versnippering is ook een belangrijke factor. Zelfs zonder nieuwe landbouwtechnieken, gewassen of extern kapitaal, kan ruilverkaveling (herverdelen van land binnen een dorp) een aanzienlijke verbetering van de productie en het inkomen opleveren. Een conclusie van de studie is dat de rangorde van beperkingen: “technologie> versnippering> kapitaal> arbeid> landoppervlak” zou moeten zijn.

Landgebruik opties verkregen uit de toepassing van LUPAS werden vervolgens geëvalueerd via interactie met belanghebbenden in Suoi Con (hoofdstuk 5). LUPAS werd geïntegreerd met een Role Playing Game (RPG) in het kader van Agent Based Modelling (ABM). Er is rekening gehouden met drie hoofdcomponenten van ABM, de omgeving, de agenten (belanghebbenden) en hun interactie. Boeren waren de belangrijkste agenten. Honderd representatieve huishoudens in het stroomgebied werden ingedeeld in vier boerderij typen met behulp van de clustering analysemethode. Van vertegenwoordigers van elk boerderij type werd aangenomen dat ze lid waren van één in-game huishouden (IGH). In het spel werden de randvoorwaarden van de huishoudens zo dicht mogelijk bij de feitelijke situatie gedefinieerd. Elke IGH werd verondersteld te bestaan uit 2 arbeiders in het bezit van 4 kavels: een drassig perceel (WP), een laaggelegen perceel (LP), een terrasvormige perceel (TP) en een gedegradeerd hooggelegen perceel (DP). De landgebruik doelstellingen voor het IGH waren te voldoen aan de standaard vraag naar voedsel en het genereren van een basisinkomen voor een 4-persoons huishouden.

In het spel, werd LUPAS aangepast voor gebruik op huishoudelijke schaal. Optimale landgebruik scenario's die werden gegenereerd door LUPAS op basis van informatie aangeleverd door IGHs werden geanalyseerd en besproken door de belanghebbenden in het spel. Net als in de modellering, bleek uit de resultaten van het spel dat de traditionele technologie de sterkste beperking tot een grotere productiviteit is. Kapitaaltekort kwam ook naar voren als een groot probleem van de huishoudens in de berggebieden. Daarnaast hebben teelt gewoonten, percepties en relaties met de buren een grote invloed op de landgebruik beslissingen van de boeren. Daarom kunnen bestemmingsplannen en verbeterde technologieën niet eenvoudig worden geïmplementeerd door individuele huishoudens. In deze context, kunnen de extra tijd en kosten veroorzaakt door land fragmentatie de acceptatie en invoering van alternatieve praktijken beperken.

Dankzij het genoemde proces identificeerden de betrokken partijen dat het instellen van huishoudensgroepen een passende oplossing zou kunnen zijn voor een duurzame landbouw ontwikkeling in de regio. Deze nieuwe vorm van samenwerking tussen huishoudens zou kunnen helpen om versnippering te verminderen. Daarnaast zou deze samenwerking het gebruik van de beschikbare grond en kapitaalmiddelen optimaliseren en gebruik maken van een arbeids-uitwisselingsschema.

De RPG heeft aanvullende interessante informatie gegenereerd. Het gebrek aan toegang tot de markten wordt door vele auteurs genoemd als een belemmering voor de boeren op het platteland. Echter, dit onderzoek suggereert dat een gebrek aan marktinformatie de echte onderliggende beperking is, althans in deze case studie. Ook ten aanzien van de beperking van beschikbaar kapitaal, blijkt uit onze analyse dat het gebrek aan toegang tot krediet meestal gerelateerd is aan de individuele situatie van de huishoudens.

Integratie van LUPAS en RPG staat voor een participatieve aanpak voor het plannen van landgebruik. Problemen in landgebruik zijn expliciet gedefinieerd en landgebruiksplannen worden ontwikkeld en herzien door belanghebbenden onder hun eigen specifiek sociale en economische omstandigheden. Onvolkomenheden in de bestaande landgebruiksplannen en mogelijke oplossingen, door belanghebbenden voorgesteld, brengen beleidsmakers op ideeën om het beleid omtrent agrarisch landgebruik te verbeteren. De informatie die voortvloeit uit een dergelijke participatieve benadering kan een belangrijke bijdrage leveren aan het overbruggen van de kloof tussen doelstellingen in landgebruik van de overheid en die van de boeren.

Het laatste hoofdstuk (hoofdstuk 6) bespreekt methodologische vraagstukken van de geïntegreerde modellen in dit proefschrift en vat belangrijke bevindingen van deze studie samen. De potenties van de geïntegreerde model benadering voor land gebruiksplanning zijn duidelijk herkenbaar. Geconcludeerd wordt dat de geïntegreerde model benadering, zoals ontwikkeld en gepresenteerd in dit proefschrift gebruik kan maken van individuele onderzoeksinstrumenten voor het beschrijven van agro-ecologische en sociaal-economische dynamiek en voor het ontwikkelen van een effectief beleid inzake land gebruiksplanning. De benadering bevat verschillende aspecten van het landgebruik in de planning, en kan hypothesen over de bijdragen van de voorgenomen plannen aan de algemene doelen testen. Bovendien ondersteunt de geïntegreerde benadering bottom-up landgebruiksplanning door middel van betrokkenheid van diverse belanghebbenden bij de analyse van de bestaande problemen en mogelijke oplossingen. Dit verhoogt de adoptie kans van de aanbevelingen wat vervolgens de kans op realisatie van doelstellingen van de overheid, onderzoekers en boeren door middel van effectieve uitvoering van de plannen zal verhogen. Deze aanpak heeft dus nut voor planners en beleidsmakers, en uiteindelijk voor de boeren, door middel van het verbeteren van het vermogen om plannen te ontwikkelen. Deze plannen beogen een werkelijke verbetering van de levensstandaard van boeren in NH en het duurzaam gebruik van natuurlijke hulpbronnen.

PE&RC PhD Training Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.2 ECTS)
- Exploring situation of agro-forestry land use in the Northern Upland of Vietnam (2008)

Writing of project proposal (1 ECTS)
- Integrated modelling for land use planning and policy recommendation in the Northern Uplands of Vietnam

Post-graduate courses (7.5 ECTS)
- GStat/PCRaster; PCRaster online, Utrecht (2008)
- Advanced statistics: linear models (PE&RC (2009)
- Research methodology: from topic to proposal: Mansholt Graduate School of Social Sciences, CERES Graduate School (2009)
- Scaling and governance; PE&RC, Mansholt Graduate School of Social Sciences (2009)
- Information literacy, include endnote introduction; Wageningen UR Library (2009)
- Economic and technological information for senior researcher; Ministry of science and technology (MOST), Vietnam, Science and Technology Management Institute (2010)
- Introduction to participatory socio-environmental games and simulations; PERC (2011)

Laboratory training and working visits (3.3 ECTS)
- COMMOD: companion modeling for integrated renewable resource management (ComMod for IRRM); CIRAD, Chulalongkorn University, Thailand (2009)

Deficiency, refresh, brush-up courses (3 ECTS)
- Quantitative analysis of land use systems, QUALUS (2008)
- Impact assessment of land and water management (2008)

Competence strengthening / skills courses (2.3 ECTS)
- Competence assessment; PE&RC (2008)
- Academic writing (2010)
- Improve IELTS skills; LDD group (2011)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)
- PE&RC Days (2008, 2011)
- PE&RC Introduction weekend (2011)

Discussion groups / local seminars / other scientific meetings (3.9 ECTS)

- Spatial Methods, SPAM; PE&RC (2009)
- Regular scientific seminars at Soils and Fertilizer research Institute, Vietnam (2010, 2012)
- Seminar on “managing land and soil resources in Vietnam: application of GIS and modelling” (2013)

International symposia, workshops and conferences (3.0 ECTS)

- Workshop on Science and Technology application in Red River Delta; Vietnam (2009)
- Rice congres; Hanoi (2010)
- Workshop on Decision Support Systems (2011)

Supervision of 2 MSc students (6 ECTS)

- Development of a GIS web interface for PromUp model, a dynamic erosion model
- Land use optimization in the Thu Cuc Catchment in Northern Vietnam, application of LUPAS

Curriculum vitae and author's publications

Bui Tan Yen was born on May 9, 1973 in Hung Yen, Vietnam. He graduated secondary education from Hanoi-Amsterdam High School, Hanoi in 1990. He studied at the Hanoi University of Agriculture for 4.5 years and got his BSc degree in Soil and Fertilizer Science in 1996. From September 1996 he started his career in the Soil Genesis and Classification Research Department of the Soils and Fertilizers Research Institute of Vietnam (SFRI). From 1996 to 1999, he has participated in various special trainings and projects on applications of Geographic Information System (GIS) and modelling in agricultural science. From November 1999 to December 2001 he followed the postgraduate program in Vietnam and got an MSc degree in Soil Science with a specialisation in the application of Geographic Information System in land evaluation and land use planning. In October 2002 he got a one year contract with the International Rice Research Institute (IRRI), Philippines to work on development of GIS tools and modelling. He contributed to a number of publications in fields of soil science, land use planning and modelling.

After being awarded a Sandwich PhD fellowship from the Wageningen University in August 2007, Bui Tan Yen studied at the Plant Production System Group and Land Degradation and Development Group. His study focused on integrated modelling for land use planning and policy recommendation in the Northern Uplands of Vietnam. His email addresses: yenbt.sfri@mard.gov.vn; buitanyen@gmail.com.

Publications

Journal articles

Bui Tan Yen, D. Orange, S. M. Visser, C. T. Hoanh, M. Laissus, A. Poortinga, T. D Toan, L. Stroosnijder. 2013. Lumped surface and sub-surface runoff for erosion modeling within a small hilly watershed in northern Vietnam. Hydrological Processes, in press.

Christian Witt, **Bui Tan Yen**, Vu Manh Quyet, Tran Minh Thu, Julie Mae Pasuquin, Roland Buresh, Achim Dobermann. 2007. Spatially variable soil fertility in intensive cropping areas of North Vietnam and its implications for fertilizer needs. Better Crops 91. pp 28 - 31.

Le Thi My Hao, **Bui Tan Yen**, Ho Quang Duc, Tran Quoc Vuong. 2013. Phosphorus content in grey degraded soils in the North of Vietnam. Science and Technology journal of Agriculture and Rural Development, pp 24- 30.

Book

Ho Quang Duc, Nguyen Van Dao, Truong Xuan Cuong, Le Thi My Hao, Nguyen Quang Hai, Hoang Trong Quy, **Bui Tan Yen**, Luong Duc Toan. 2010. Saline soil and sulphat soil in Vietnam. Agricultural Publishing House. Hanoi, Vietnam.

Edited publications

Kam Suan-Pheng, Chu Thai Hoanh, Thavone Inthavong, **Bui Tan Yen**, Abeed H. Chowdhury. 2005. Land evaluation – IRRI's approaches, experiences and contribution in SE Asia. In: Agro-ecological zoning and GIS applications in Asia with special emphasis on land degradation assessment in dry lands (LADA). FAO, Rome, Italy. pp 31-42.

Bui Tan Yen, Ho Quang Duc. 1999. Research and application of land evaluation methods for sustainable agro-forestry land use in Vietnam. In: Nguyen Van Bo, Thai Phien, Bui Dinh Dinh, Tran Thuc Son, Doan Van Cung, Nguyen Minh Hanh (eds). Soil and fertilizer research results. Volume 3. Agriculture Publishing House. Hanoi, Vietnam. pp 53-63.

Bui Tan Yen, Tran Minh Thu, Nguyen Van Dao, Nguyen Thanh Long. 2005. Spatial analysis of soil properties for soil quality management. In: Bui Huy Hien, Bui Quang Xuan, Tran Thuc Son, Tran Thi Tam, Ho Quang Duc, Pham Quang Ha (eds). Soil and fertilizer research results. Volume 4. Agriculture Publishing House. Hanoi, Vietnam. pp 80-87.

Proceedings

Bui Tan Yen, Kam Suan Pheng, Pham Quang Ha, Chu Thai Hoanh, Bui Huy Hien, Jean-Christophe Castella, Ho Quang Duc. 2002. Exploring land use options for agricultural development in Bac Kan province, Vietnam. Proceedings of the 17th World Congress of Soil Sciences, 14–21 August 2002. Bangkok, Thailand, Paper no. 1217, pp 1–10.

Ho Quang Duc, **Bui Tan Yen**, 2001. GIS in Land Resource Management in Vietnam. Proceedings of the workshop on GIS in Land Resource Management. Food and Fertilizer Technology Center for the Asian and Pacific Region. Los Banos, Philippines.

Kam Suan Pheng, **Bui Tan Yen** and Chu Thai Hoanh, 2000. Land Evaluation for Optimizing Land and Resource Use for Agricultural Production in a Heterogeneous Mountainous Environment - a Case Study of Bac Kan Province, Vietnam. Proceedings of the Fifth Seminar on GIS and Developing Countries (GISDECO 2000), November 2000. International Rice Research Institute. Los Banos, Philippines. pp 1-18