MODÉLISATION DE L'ÉROSION ET DU TRANSPORT SÉDIMENTAIRE SUR LES BASSINS VERSANTS SOUMIS À UN RÉGIME DE MOUSSON DANS UN CONTEXTE DE GESTION INTÉGRÉE DES RESSOURCES EN EAU

(MODELING OF EROSION AND TRANSPORTATION OF SEDIMENT ON THE BASINS INFLUENCED BY THE MONSOON REGIME, IN A CONTEXT OF INTEGRATED MANAGEMENT OF WATER RESOURCES)

par
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AGNPS	AGricultural Non-Point Source pollution model
ANSWERS	Areal Non-point Source Watershed Environment Response Simulation
CREAMS	Chemicals, Runoff and Erosion from Agricultural Management Systems
DEM	Digital Elevation Model
EPIC	Erosion/Productivity Impact Calculator
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GIS	Geographical Information System
GIBSI	Gestion Intégrée des Bassins versants à l'aide d'un Système Informatisé
HYDROTEL	HYDROlogie TELédétection
HWSD	Harmonized World Soil Database
MoNRE	Ministry of Natural Resources and Environment, Vietnam
NRCS	Natural Resources Conservation Service
QUAL2E	Enhanced Stream Water QUALity Model
ROTO	Routing Ouputs To the Outlet model
RUSLE	Revised Universal Soil Loss Equation
SS	Suspended Sediment
SWAT	Soil and Water Assessment Tool
SWRRB	Simulator for Water Resources in Rural Basins
TDS	Total Dissolved Solids
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
VAST	Vietnamese Academy of Science and Technology
WEPP	Water Erosion Prediction Project

I. RÉSUMÉ EN FRANÇAIS DE LA THÈSE

Le bassin versant de la rivière Cau, caractérisé par des conditions climatiques de type mousson et par le manque de données, a été choisi comme cas d'étude pour l'application du système de gestion intégrée par bassin versant GIBSI. L'objectif principal de cette étude est de développer des méthodologies pour l'application des modèles d'érosion des sols et du transport de sédiments à l'échelle du bassin versant et de proposer des modifications à ces modèles afin qu'ils soient applicables au bassin versant à l'étude dont (1) les conditions topographiques et climatiques sont largement différentes de celles du bassin versant pour lequel les modèles ont été conçus à l'origine, et (2) le manque de données d'observation rend difficile l'étalonnage des paramètres et la validation des modèles.

Les contributions de cette étude sont axées sur:

(1) l'analyse et l'identification des problèmes posés par l'application des modèles d'érosion des sols et de transport de sédiments dans le bassin de la rivière Cau;

(2) les solutions à apporter pour l'obtention des paramètres d'entrée, dont les valeurs ne sont pas disponibles dans le bassin versant, afin de calculer l'érosion des sols;

(3) la mise en œuvre de méthodes pour adapter, modifier et réécrire les codes pour le calcul de facteurs associés au modèle d'érosion des sols (MODEROSS) et à celui du transport de sédiments (ROTO);

(4) l'apport de solutions pour améliorer la sensibilité des quantités de sédiments simulés et transportés aux conditions climatiques de type mousson, en général, et du bassin versant de la rivière Cau, en particulier;

(5) l'analyse de sensibilité et l'analyse de performance des paramètres qui permettront de mettre en place des procédures et des lignes directrices pour réaliser un étalonnage efficace des modèles adaptés;

(6) le souci de s'assurer que le système GIBSI est applicable aux régions climatiques tropicales, telles que le bassin versant de la rivière Cau, dans un contexte de limitation de données grâce notamment aux adaptations et modifications apportées.

Les résultats de cette étude ont confirmé l'applicabilité des modèles hydrologique, de l'érosion des sols et du transport de sédiments dans un contexte de climat tropical de type mousson où les données sont rares. Ce travail de recherche est une contribution importante à la mise en place d'un outil pratique de gestion intégrée du bassin versant de la rivière Cau. Il offre ainsi des possibilités pour modéliser la qualité de l'eau afin de mieux planifier l'utilisation du territoire et d'analyser l'impact de divers scénarios d'intervention.

S-1 Introduction

S-1.1 Problématique et contexte de recherche

Les bassins fluviaux et les plaines deltaïques du Vietnam sont en proie à un développement socio-économique, à une industrialisation et à une urbanisation accélérés ainsi qu'à un changement rapide de l'utilisation du sol. L'étude et la mise en application des outils récents de gestion des bassins versants, de même que l'adaptation de ces outils au contexte local du Vietnam, peuvent contribuer au développement durable. Le bassin versant de la rivière Câù, situé dans la partie nord-ouest du delta du fleuve Rouge au Vietnam, a été choisi pour faire l'objet d'un projet-pilote en raison de la dégradation de la qualité de son eau, de l'érosion du sol, du transport des sédiments, des crues en saison des pluies et de son manque d'eau en saison sèche. Le système GIBSI (Villeneuve *et al.*, 1998a), un outil de modélisation intégrée développé par l'Institut national de la recherche scientifique – Centre Eau Terre Environnement (INRS-ETE) de Québec (Canada), démontre un grand potentiel d'application pratique pour la gestion intégrée par bassin versant.

Dans GIBSI, les modèles d'érosion des sols (MODEROSS) et de transport de sédiments en rivière (ROTO) jouent un rôle important. Ils constituent des modules de traitement intermédiaires qui fournissent des données quantitatives provenant d'autres modèles (*p. ex.* modèle hydrologique) pour produire des sorties relatives à la quantité de sédiments en suspension et à la qualité de l'eau en rivière. Ainsi, ces modèles estiment diverses concentrations à partir desquelles il est possible d'établir des scénarios de gestion du bassin versant, puis de refléter les changements apportés une fois les scénarios mis en pratique. Pour ce faire, il est primordial de développer des méthodes pour adapter et caler les modèles d'érosion et de transport des sédiments dans un contexte de bassin versant où les données observées sur le terrain sont restreintes et dans diverses conditions climatiques. L'utilisation d'un système intégré de gestion des bassins versants comme GIBSI dans une région comme le Vietnam deviendrait alors possible. En outre, les modèles MODEROSS et ROTO ont à l'origine été intégrés à GIBSI sur la base d'études réalisées sur des bassins versants de la province de Québec, où le climat est tempéré et les données (*p. ex.* pluviométrie, topographie, etc.) sont facilement accessibles. Ces modèles doivent donc être adaptés et des méthodes de calage particulières doivent être développées en vue de la mise en œuvre du système GIBSI dans une région tropicale où les données sont restreintes.

Le bassin versant de la rivière Câù constitue une étude de cas intéressante en raison des conditions climatiques de la région et de la faible quantité de données d'observation qui y sont disponibles, ce qui complique la mise en application d'un système de gestion intégrée par bassin versant. Ainsi, la mise en œuvre d'un tel système dans un bassin versant de ce genre permettrait d'évaluer les possibilités et les limites d'un tel outil en vue d'applications ultérieures sur d'autres bassins versants qui présentent le même problème d'accessibilité aux données.

S-1.2 Objectifs de recherche

Le principal objectif de la présente recherche consiste à mettre au point une méthodologie d'adaptation, de calage et d'application des modèles d'érosion et de transport de sédiments à l'échelle du bassin versant dans une région tropicale où les données sont restreintes. En outre, la présente étude vise à atteindre les objectifs spécifiques suivants :

- Proposer des changements à apporter aux modèles (MODEROSS, ROTO) afin qu'ils s'appliquent davantage à un climat tropical et dans des bassins versants où peu de données d'observation sont accessibles.
- Mettre au point une méthode d'estimation de la variation journalière de l'érodabilité dans un climat de mousson, comme celui du bassin versant de la rivière Câù, où un tel climat rend impossible la mise en application des méthodes existantes.
- Instaurer des lignes directrices et établir une procédure efficace relativement au calage des modèles, et ce, à partir de l'analyse de sensibilité. Cela permet de s'assurer de la justesse des résultats de simulation dans un contexte comme celui du bassin versant de la rivière Câù.
- Évaluer l'applicabilité de modèles hydrologique, d'érosion et de transport des sédiments comme support à la gestion intégrée par bassin versant au Vietnam, où l'accès aux données d'observation est restreint et où les conditions climatiques sont différentes de celles de la région où les modèles ont été initialement développés. Ces modèles pourront par la suite être utilisés pour évaluer l'impact sur la qualité de l'eau de divers scénarios d'intervention, comme par exemple des scénarios d'utilisation du territoire, en vue d'appuyer les décideurs politiques dans leur prise de décision.

S-1.3 Originalité du sujet

La présente étude vise à s'assurer qu'il est possible d'appliquer des modèles de gestion intégrée par bassin versant basés sur les processus physiques dans une région où : (1) les conditions topographiques et climatiques sont fort différentes de celles qui prévalent dans les régions où les modèles ont été développés; et (2) la qualité et la quantité des données d'observation disponibles sont restreintes.

Ainsi, les points forts de la présente thèse résident dans : (1) le développement d'une méthodologie d'estimation des paramètres d'entrée en vue de répondre aux exigences des modèles utilisés ; (2) l'adaptation des modèles aux conditions observées sur le bassin versant de la rivière Câù en tenant compte des limites que présente le milieu; et (3) le calage des modèles. Finalement, l'élaboration d'une méthode qui permet d'estimer l'érodabilité à l'échelle journalière constitue, à notre connaissance, la première tentative de quantification de la variation journalière de cette variable dans une région soumise à un climat tropical de type mousson.

Également, l'apport de la présente étude est axé sur les points suivants :

- Trouver des solutions en vue d'obtenir la valeur des variables d'entrée pour lesquelles il est impossible d'avoir accès à des données observées, de manière à pouvoir calculer l'érosion du sol.
- Mettre au point des méthodes qui permettront d'adapter le calcul de certains facteurs liés à l'érosion du sol et au transport de sédiments dans le bassin versant de la rivière Câù, où il est difficile de recueillir des données.
- Trouver des solutions en vue d'améliorer les résultats de simulation relativement au caractère saisonnier des processus dans les régions sujettes au climat de mousson, et particulièrement dans le bassin de la rivière Câù.
- Mettre au point une procédure et établir des lignes directrices, par l'analyse de sensibilité, en vue de parvenir à un calage adéquat des modèles utilisés.
- S'assurer que le modèle d'érosion s'applique aux régions tropicales, notamment au bassin de la rivière Câù, où l'accessibilité des données est restreinte.

S-2 Revue de littérature

Par le passé, diverses études ont été menées dans le but d'analyser les caractéristiques et d'évaluer le rendement des modèles de bassin versant, notamment quant à la qualité de l'eau (Patrick *et al.*, 1999), aux composantes hydrologiques (Migliaccio *et al.*, 2007), et aux bases mathématiques (Borah et Bera, 2003). La plupart des modèles par bassins versants ont été conçus dans les années 1970 et 1980. En outre, depuis le début des années 1990, la majeure partie des recherches de modélisation a porté sur les systèmes d'information géographique (SIG) et la télédétection. Si des progrès significatifs ont été accomplis dans la création et la mise au point des interfaces, il s'avère maintenant nécessaire de nous concentrer sur la formulation et l'élaboration de modèles d'évaluation avancée des bassins versants (CWM, 1999; Chen, 2001).

Les modèles hydrologiques et ceux axés sur les sources diffuses de pollution à l'échelle du bassin versant se divisent en deux catégories : les modèles événementiels et les modèles continus. Les modèles présentés dans la revue de littérature de cette thèse sont parmi les plus couramment utilisés. Ils s'appliquent dans un contexte de gestion par bassin versant et font intervenir des modèles portant sur l'érosion et le transport de sédiments. Le calage des modèles constitue une étape cruciale de la modélisation. Il nécessite la comparaison des valeurs prédites et des valeurs mesurées, l'objectif étant de réduire la disparité des résultats en apportant les correctifs nécessaires aux valeurs des paramètres. L'étape de validation suit celle du calage. Elle consiste à comparer les valeurs simulées aux valeurs mesurées, pour une série de données autre que celle utilisée pour le calage, et ce, sans ajustement supplémentaire des paramètres (Migliaccio *et al.,* 2007).

Plusieurs études portant sur l'application de modèles d'érosion ont déjà été menées dans des conditions tropicales particulières. Cependant, les problèmes liés à l'adaptation des modèles aux régions tropicales, de même qu'à l'adaptation des coefficients d'érosion, nuisent à l'avancement de ces études. L'équation universelle des pertes en terre est l'un des modèles d'érosion les plus connus. Au Viêtnam, elle a été proposée et mise en application pour la première fois dans le cadre d'études scientifiques menées dans les années 1980 (Nguyen, 2005). En outre, depuis la fin des années 1990, ce modèle est de plus en plus utilisé. Cependant, la plupart des études portant sur l'érosion spatiale et quantitative n'analysent ni les répercussions de l'agriculture, ni la diversité de l'utilisation des sols, particulièrement à l'échelle du bassin versant, ni les répercussions de la variation saisonnière des facteurs de l'érosion. Par conséquent, c'est dire que ces études n'analysent pas non plus la dynamique des paysages et leur impact sur l'érosion (Vézina *et al.*, 2006).

S-3 Outil de modélisation et zone d'étude

S-3.1 GIBSI

GIBSI (*Gestion intégrée des bassins versants à l'aide d'un système informatique*), l'outil qui fait l'objet d'une adaptation dans la présente étude, constitue un logiciel de gestion intégrée de l'eau de surface dans les bassins versants. Cet outil présente quatre principaux modèles de simulation : un modèle hydrologique, un modèle portant sur l'érosion, un modèle de transport de nutriments et de pesticides (produits agrochimiques), ainsi qu'un modèle de simulation de la qualité de l'eau des rivières (Figure S-3.1).

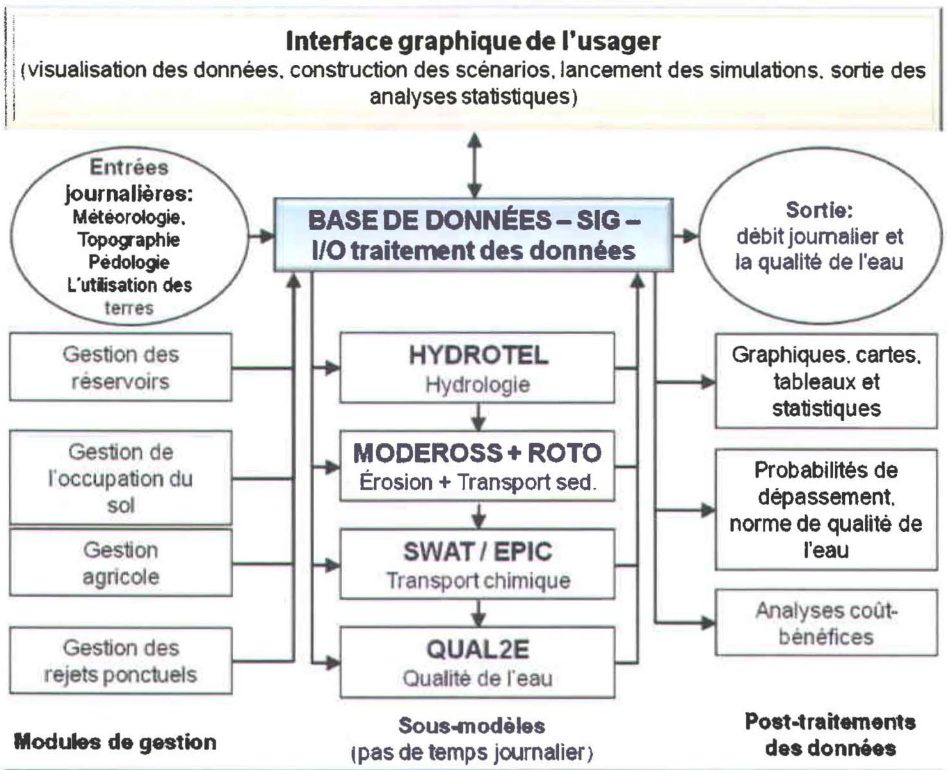


Figure S-3.1: Composantes et structure de GIBSI (d'après Rousseau et al., 2000).

S-3.2 Le modèle d'érosion MODEROSS et le modèle de transport des sédiments ROTO

La dernière version de GIBSI a recours au modèle MODEROSS en vue d'estimer l'érosion du sol et le transport des sédiments (Duchemin, 2000). Ce modèle se base sur la production et le transport des sédiments par l'eau de ruissellement (Figure S-3.2).

Quant au modèle ROTO (Arnold *et al.*, 1995a), il a été choisi pour simuler le transport des sédiments en rivière. Dans ce modèle, le processus de sédimentation est principalement représenté par la vitesse de sédimentation des particules en suspension, telle qu'élaboré par Bhargava et Rajagopal (1992). Cette pratique permet ainsi d'estimer la vitesse de sédimentation des particules en suspension pour un diamètre représentatif.

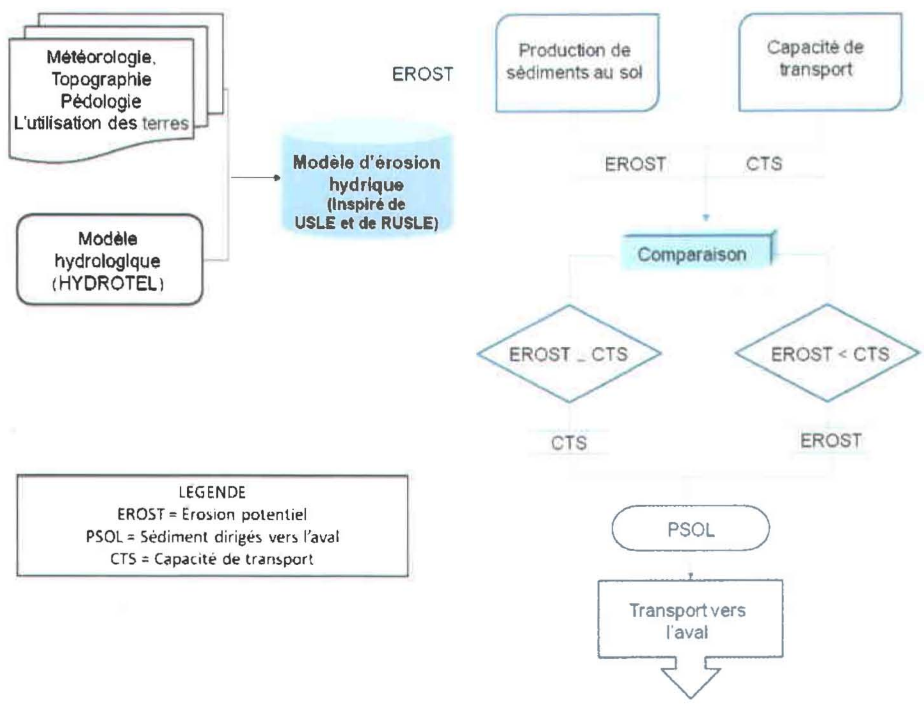


Figure S-3.2: Structure des modèles d'érosion des sols et de transport des sédiments en rivière (adapté de Duchemin, 2000).

S-3.3 Le bassin versant de la rivière Câù

La zone d'étude (figure 3.3) s'étend sur près de 4 500 km^2. Le bassin versant se situe dans le nord du Viêtnam, dans une région au climat de type mousson. En été, les conditions météorologiques y sont chaudes, humides et ponctuées de fortes précipitations. En hiver, le climat y est relativement froid et sec. La température annuelle moyenne varie de 21°C à 23°C. Dans cette région, la période estivale s'étend de mai à septembre alors que l'hiver commence au mois de novembre pour se terminer en mars. Ainsi, les mois d'avril et d'octobre correspondent à une période de transition entre les deux principales saisons.

La topographie du bassin versant est relativement diversifiée. Elle présente trois types de milieux : les terrains montagneux, les vallées et les plaines. Les précipitations annuelles sur le bassin versant se situent entre 1 500 et 2 700 mm. La saison des pluies coïncide avec la période ensoleillée, soit d'avril à octobre. Au cours de cette période, la région reçoit des précipitations qui représentent 85 à 90 % des précipitations annuelles totales. Le régime hydrologique de la région est clairement divisé en deux saisons. En outre, le débit des rivières au cours de la saison des pluies, soit de juin à octobre, représente 75 à 85 % du débit total annuel.

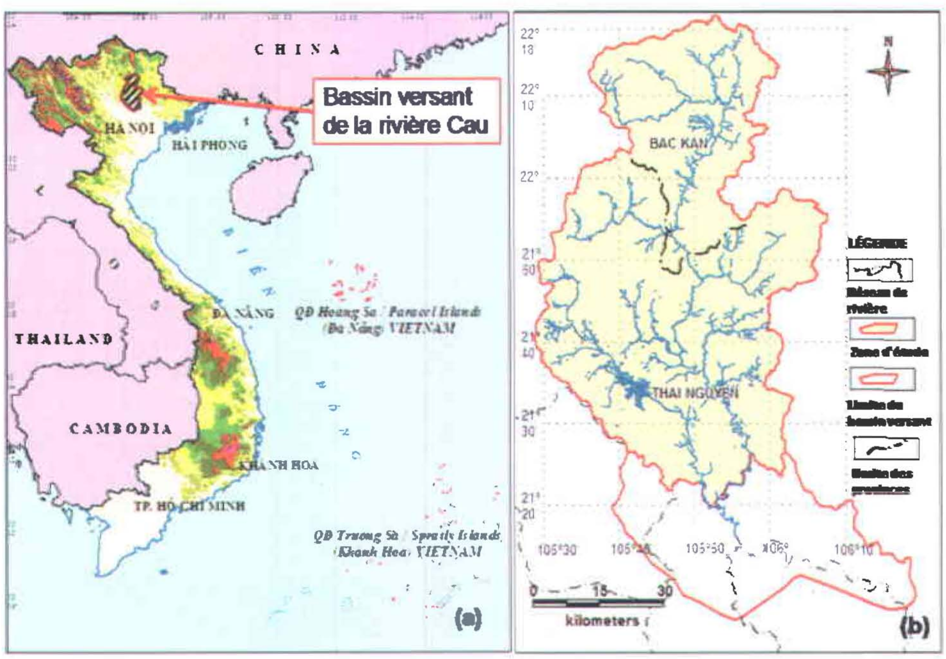


Figure S-3.3: Localisation du bassin versant de la rivière Câù (a) Vietnam; (b) Zone d'étude.

S-3.4 Accessibilité des données, exigences techniques et orientation de la mise en application

Le manque de données dans le bassin versant de la rivière Câù constitue l'un des plus grands obstacles, de façon générale, à l'utilisation de GIBSI sur ce bassin versant, et plus particulièrement à l'utilisation de modèles d'érosion et de transport des sédiments. Les contraintes relatives à l'accessibilité des données sont liées au nombre de variables évaluées, à l'échelle de temps des données, à la continuité de la cueillette de données, à la qualité des données recueillies ainsi qu'au nombre de stations d'observation.

Pour arriver à mettre en pratique la gestion intégrée dans le bassin versant de la rivière Câù dans un contexte où les données sont limitées, où les conditions climatiques sont variables et où l'utilisation du sol est particulière, il s'avère nécessaire de tenir compte des trois principaux points suivants :

- *Le choix de la base de données et la préparation des données* : les entrées doivent être préparées de manière à ce qu'elles soient en tous points uniformes. En outre, les données cartographiques doivent être modifiées afin de corriger les erreurs spatiales, d'y ajouter des attributs nécessaires et de les convertir en un format compatible en entrée aux modèles de simulation.
- *L'adaptation du modèle et des équations en raison des différences relatives au climat et au terrain* : pour adapter les modèles utilisés aux conditions observées dans le bassin versant de la rivière Câù, il sera nécessaire de tenir compte : (1) des différences de température et de leur périodicité; (2) de l'intensité des précipitations; (3) des variables qui sont inaccessibles ou inadéquates pour la mise en application du modèle dans le bassin versant de la rivière Câù. Ainsi, l'adaptation, la modification ou même le remplacement de certaines variables ou équations sont des pistes de solution;
- *L'adaptation du modèle et des équations en raison des différences relatives à l'utilisation du sol* : sur le plan local, les différences d'utilisation du sol peuvent avoir une incidence sur l'adaptation du modèle utilisé, et ce, non seulement en raison des habitudes locales d'utilisation du sol, mais également en ce qui a trait aux divers types de végétation. Si les habitudes d'utilisation du sol nous aident à comprendre à quoi ressemble la gestion du terrain, la végétation locale nous fournit une foule d'indices quant à la périodicité et aux cycles d'utilisation du sol durant toute l'année. Ainsi, une estimation juste de ces facteurs, basée sur l'utilisation locale du sol, s'avère essentielle pour que les simulations effectuées par la suite soient concluantes.

S-4 Adaptation et calage des modèles de GIBSI dans le bassin versant de la rivière Câù

S-4.1 Modifications et adaptations

Les modifications et adaptations apportées à GIBSI pour qu'il convienne au bassin versant de la rivière Câù touchent les deux modèles suivants, et leurs groupes de paramètres sous-jacents : (1) le modèle d'érosion (MODEROSS), et (2) le modèle de transport des sédiments (ROTO), lesquels correspondent respectivement aux processus de surface et à ceux rencontrés dans les cours d'eau du bassin versant.

Le tableau S-4.1 présente les modifications ou les adaptations effectuées pour chacun des facteurs ainsi que les paramètres et composantes qui leur sont associés. Ces modifications et adaptations ont été réalisées soit pour définir les conditions locales avant d'entreprendre les simulations, soit pour adapter les modèles aux conditions locales. Les tâches ont été classées selon quatre considérations principales : (1) les bases théoriques; (2) l'utilisation des données locales; (3) les équations; et (4) le code informatique. Chacun des paramètres peut toucher une de ces considérations ou plus. En outre, chaque considération est qualifiée de modification ou d'adaptation selon la nature du travail effectué. La « modification » signifie que la méthode, les équations ou le code informatique a été remplacé. D'un autre côté, « l'adaptation » signifie qu'une correction ou qu'un ajustement a été apporté à la méthode, aux équations ou au code informatique déjà existant.

Tableau S-4.1: Résumé des tâches exécutées comme adaptations/modifications des modèles d'érosion et de transport des sédiments dans GIBSI pour le bassin versant de la rivière Câù.

Modèle	Facteurs	Paramètres / composantes	Définition des paramètres / des composantes	Tâches effectuées						Objectif	
				(1) dans les bases théoriques	(2) dans l'utilisation des données locales	(3) dans les équations		(4) dans le code de calcul		Définition des conditions locales avant simulations	Ajustement des équations aux conditions locales
				Révision de la théorie de base/ méthodologie pour obtenir le paramètre	Localisation des paramètres avec la base de données disponible (adaptation)	Nouveau calcul/formule (modification)	Ajustement de formule (adaptation)	Réécriture du code informatique (modification)	Ajustement du code informatique (adaptation)		
MODEROSS	R_{tji} *érosivité totale journalière*	R_{pji}	*Érosivité des précipitations*	•	•		•		•		•
		R_{pji} *contrainte*	*Limite inférieure des précipitations*	•			•		•		•
	K_{asi} *érodabilité annuelle moyenne du sol*	*cs*	*Code de structure du sol*	•	•	•			•	•	
		cp	*Code de perméabilité du sol*	•	•	•			•	•	
		MO	*Matière organique (%)*	•	•	•			•	•	
		SL	*Sable et limon très fins(%)*		•		•		•	•	
		SF	*Sable très fin(%)*		•		•		•	•	
	K_{ji} *érodabilité quotidienne moyenne du sol*	R_{an}	*Érosivité annuelle moyenne des précipitations*	•	•	•		•		•	
		t_{min}	*Jour où K est minimum*	•	•	•		•		•	
		t_{max}	*Jour où K est maximum*	•	•	•		•		•	

Tableau S-4.1 (suite).

		Δt	*Période sans gel du sol*	•	•	•		•		•	
		K_{min}	*Minimum d'érodabilité annuelle du sol*		•		•			•	
		K_{max}	*Maximum d'érodabilité annuelle du sol*		•		•			•	
	LS *facteur de pente*	*m*	*Exposant dans différents cas d'érosion (en rigole/inter-rigole)*	•	•			•		•	
	C_{ji} *gestion quotidienne du sol*	*Utilisation des terres 1(*)*	*Groupe constant*		•		•		•	•	
		Utilisation des terres 2(**)	*Groupe variable*	•	•	•		•		•	
	P *pratiques de conservation du sol*	*Utilisation des terres 1(*)*	*Groupe constant*		•					•	
		Utilisation des terres 2(**)	*Groupe variable*	•	•	•		•		•	
ROTO	CTS_{ji} *capacité de transport journalière*	T_{ji}	*Capacité de transport*	•			•		•		•
	$PERO_{ti}$ *réentraînement*	*IAS*	*Indice d'apport sédimentaire*	•			•		•		•
	SED	SED_i	*Quantité de sédiments déposée*	•			•		•		•

NOTE :

(*) *Utilisation des terres 1*: Groupe constant d'utilisation des terres, y compris: *urbain*, *forêt*, *eau* et *sol nu.*

(**) *Utilisation des terres 2*: Groupe variable d'utilisation des terres, incluant : *Agricole*, *arbustes* et *mélange*.

S-4.2 Calage et validation

S-4.2.1 Analyse de sensibilité

L'analyse de sensibilité a été réalisée à deux échelles spatiales : l'unité spatiale de simulation (USS) et le bassin versant. A l'échelle de l'USS, afin de déceler les différences, s'il y a lieu, entre l'impact prévu (théorique) des paramètres et leur impact réel, nous avons procédé aux deux analyses suivantes : l'analyse de sensibilité théorique, basée sur des fonctions analytiques, et l'analyse de sensibilité numérique, basée sur la variation de la valeur des paramètres et les résultats de simulations avec le modèle.

L'analyse a été effectuée pour les paramètres de calage des modèles d'érosion et de transport des sédiments (tableau S-4.2). À l'échelle de l'USS, les dates représentatives du 5 février 1998 (en saison sèche) et du 7 juillet 1998 (en saison des pluies) ont été utilisées. Cette analyse a été réalisée pour les paramètres *a, b, c* (pour l'érodabilité du sol [*R*]), $K_t n$ et *o* (pour la capacité de transport [*CTS*]) et D_r (pour la vitesse de sédimentation des particules [V_c]). À l'échelle du bassin versant entier, la quantité de matières en suspension à la sortie du bassin versant (exutoire) a été analysée par rapport aux variations des paramètres de calage du modèle.

Les résultats obtenus ont démontré que : (1) le facteur *R* est beaucoup plus sensible au paramètre *b* en saison des pluies qu'en saison sèche. En saison sèche, le paramètre *a* est celui auquel le facteur *R* est le plus sensible, alors qu'il est très peu sensible aux paramètres *b* et *c*. (2) Quant à la *CTS*, elle est particulièrement sensible aux paramètres $K_t n$ et *o* en saison des pluies. En outre, si la *CTS* augmente de façon linéaire en réponse à une variation du $K_t n$, elle diminue cependant lorsque le paramètre *o* augmente. (3) Pour ce qui est de la vitesse de sédimentation des particules (V_c), il s'avère qu'elle est très sensible à *Dr*, tout comme la charge solide en suspension dans la rivière. Une synthèse des résultats de l'influence saisonnière de chaque paramètre est présentée au tableau S-4.2a.

S-4.2.2 Lignes directrices et procédure de calage

À partir de l'examen des résultats de l'analyse de sensibilité, d'importants points peuvent être mis en relief et des lignes directrices de calage des modèles ont été émises pour l'utilisation des modèles dans des conditions semblables à celles du bassin versant de la rivière Câù :

- Un grand contraste est prévu entre les valeurs quotidiennes des sédiments en suspension (SS) selon la période de l'année (faibles ou fortes précipitations).
- Le paramètre *Dr* est celui auquel les résultats du modèle sont le plus sensibles. En effet, il pourrait avoir une incidence directe sur la quantité totale journalière, mensuelle ou annuelle de sédiments en rivière. L'impact de *Dr* est encore plus marqué lors des périodes où la quantité de sédiments en suspension est élevée, soit au cours de la saison des pluies. Ainsi, l'ajustement du paramètre *Dr* peut servir à contrôler les pointes de *SS* ainsi que la charge totale sur de longues périodes. La production de sédiments et le transport en surface sont sensibles aux paramètres *a*, *b*, $K_t n$ et *o*. Finalement, si l'influence des paramètres *b* et *o* est élevée en saison des pluies, celle des paramètres *a* et $K_t n$, quant à elle, ne varie pas selon les saisons.
- L'élaboration de lignes directrices basée sur les résultats de l'analyse de sensibilité peut contribuer à rendre le calage des modèles plus simple et plus rapide. L'ajustement combiné de certains paramètres pourrait aussi permettre d'améliorer les résultats du calage. Par exemple, la combinaison d'une *augmentation* du paramètre *b* et d'une diminution du paramètre *a* pourrait contribuer à l'augmentation de la production de *SS* pendant la saison sèche tout en la gardant stable en saison des pluies. Quant aux paramètres $K_t n$ et *o*, ils n'ont qu'une incidence mineure sur le transport des sédiments. Toutefois, une diminution de $K_t n$ à sa valeur minimum combinée à une augmentation du paramètre *o* à sa valeur maximum pourrait contribuer à une réduction plus efficace de la valeur des *SS* pendant la saison des pluies.
- Le tableau S-4.2 présente un résumé des éléments suivants : a) l'influence dans chaque saison des paramètres de calage utilisés dans la région du bassin versant de la rivière Câù; et b) des suggestions quant aux choix de combinaisons possibles en vue d'obtenir le calage le plus juste en saison sèche et en saison des pluies.

- Sur la base des résultats obtenus, la procédure de calage devrait être la suivante : (1) ajuster d'abord la valeur de *Dr* afin d'obtenir la charge totale mensuelle ou annuelle de *SS* en fonction des données observées, ce qui servira de base pour le calage plus fin subséquent; (2) ajuster ensuite les autres paramètres de façon méthodique pour obtenir la charge totale saisonnière observée, notamment quant aux valeurs maximales et au temps d'arrivée de ces valeurs maximales; (3) les *SS* devraient être considérés dans l'ordre, de leur production à leur transport en rivière. Dans le cas présent, la production de sédiments en surface (dont les paramètres clés sont *a* et *b*) devrait constituer le processus à bien représenter de façon prioritaire, suivie du transport de surface (dont les paramètres clés sont $K_t n$ et *o*); (4) ainsi, des lignes directrices relatives au calage des paramètres (tableaux S-4.2a et S-4.2b) peuvent dorénavant être énoncées. En outre, la combinaison des valeurs des paramètres devrait varier selon les conditions observées et les besoins particuliers du modélisateur.

Tableau S-4.2: (a) Résumé de l'influence des paramètres dans chaque saison et (b) directives pour le choix des combinaisons saisonnières.

(a) Influence dans la saison des paramètres de calage

Paramètres	Saison pluvieuse	Saison sèche	Signification
a	•	•	*Non saisonnier*
b	•	*Non*	*Augmente en saison des pluies*
c	*Non*	*Non*	*Faible influence*
$K_t n$	•	•	*Non saisonnier*
o	•	*Non*	*Influence en saison des pluies*
Dr	•	•	*Forte influence en saison des pluies*

(b) Meilleurs choix des combinaisons par saison pour le calage

Facteur	Si l'on souhaite augmenter les valeurs de *SS* en saison des pluies et les abaisser en saison sèche	Si l'on souhaite abaisser les valeurs de *SS* en saison des pluies et les augmenter en saison sèches	Si l'on souhaite augmenter les valeurs de *SS* dans les deux saisons	Si l'on souhaite abaisser les valeurs de *SS* dans les deux saisons
R	*b*↑(pour pluvieux ↑, sèche→) *a*↓ (pour sèche↓)	*a*↑(pour sèche↑) *b*↓(pour pluvieux↓, sèche→)	*a*↑(pour sèche↑) *b*↑(pour pluvieux ↑, sèche→)	*a*↓ (pour sèche↓) *b*↓(pour pluvieux↓, sèche→)
CTS	*n*↑ (pour pluvieux ↑) *o*↑ (pour sèche↓)	*o*↓ (pour sèche↑) *n*↓ (pour pluvieux↓)	*n*↑ (pour pluvieux ↑) *o*↓ (pour sèche↑)	*n*↓ (pour pluvieux↓) *o*↑ (pour sèche↓)
Vc	*Dr*→	*Dr*→	*Dr*↑	*Dr*↓

Note : ↑= *augmentation;*↓= *diminution;*→= *aucun changement.*

S-4.2.3 Analyse des données observées de SS

Cette section porte principalement sur la vérification des valeurs de sédiments en suspension (*SS*) observées à la station située à l'exutoire du bassin versant, soit la station de Gia Bay. Ces données ont servi au calage des modèles et à la vérification des modifications apportées à GIBSI pour le bassin versant de la rivière Câù. L'analyse effectuée a permis de : (1) confirmer que la méthode employée pour la mesure des concentrations de sédiments en rivière est une méthode reconnue et couramment utilisée; (2) confirmer que les données relatives à la charge en sédiments sont réalistes, et qu'elles peuvent donc être utilisées pour le calage des modèles dans la présente étude; (3) confirmer le comportement réaliste des données à long terme (moyennes mensuelles); (4) déceler une variation anormale des valeurs quotidiennes de *SS* qui ne reflèterait pas le régime d'écoulement de la rivière Câù pendant la saison sèche; (5) conclure que l'activité humaine constitue le principal facteur d'augmentation de la concentration des sédiments en suspension au cours de la saison sèche. Cela peut s'avérer un obstacle à la modélisation et au calage des modèles utilisés dans le bassin de la rivière Câù.

S-4.2.3 Calage du modèle

Le calage du modèle a été effectué après que ce dernier ait été modifié, puis adapté aux conditions locales. Le choix des paramètres a été basé sur les modifications et les analyses de sensibilité dont il a été question précédemment, de même que sur les équations utilisées dans GIBSI qui interviennent dans tous les processus d'érosion, de sédimentation et de transport des sédiments. Le tableau S-4.4 présente les paramètres dont la valeur a été estimée lors du calage. En outre, seules des données quotidiennes de *SS* de 1998 à 2006 enregistrées à la station de la station de Gia Bay (exutoire) sont disponibles pour le bassin versant de la rivière Câù. Par conséquent, ce sont ces données qui ont été choisies pour effectuer le calage et la validation des modèles d'érosion et de transport des sédiments. Les paramètres de ces deux modèles ont été calés manuellement de manière à réduire les écarts entre les valeurs de *SS* observées et simulées. Pour ce faire, les données de la période de 1998 à 2002 ont été utilisées pour le calage alors que celles de 2003 à 2006 ont servi à la validation des modèles.

S-4.3 Résultats

Le tableau S-4.4 résume les valeurs sélectionnées lors du calage des modèles. La figure S-4.1 compare les valeurs de *SS* simulées et observées à la station Gia Bay. Les résultats des modèles ont été analysés selon quatre échelles de temps, soit journalière, totale mensuelle, moyenne mensuelle et annuelle, et ce, tant pour le calage que pour la validation. Les analyses effectuées ont conduit aux conclusions suivantes : (1) Sur une base journalière (figures S-4.1 a et b), les résultats ont démontré une reproduction jugée acceptable des observations dans leur ensemble; (2) Sur une base mensuelle (figure S-4.1c), les résultats obtenus concordent bien avec les observations, surtout pour les pics en saison de pluies (les valeurs de *SS* les plus élevées ont été notées au mois de juillet 2001). Également, le modèle calé s'est montré plus performant les années où les *SS* totaux étaient les plus élevés aux mois de juin, juillet et août. Toutefois, le modèle apparait comme étant moins performant pendant les années où les valeurs de pics étaient observées aux mois de mars, d'avril, de septembre ou d'octobre, soit les mois du début et de la fin de la saison des pluies. Durant ces mois, les valeurs de *SS* simulées étaient souvent inférieures à celles observées; (3) En ce qui concerne les moyennes mensuelles (figure S-4.1 d), les mois d'avril à juin et de septembre à octobre correspondent aux mois où les écarts sont les plus élevés. Cela pourrait en partie s'expliquer par des erreurs de simulation dues à un manque d'informations sur la dynamique saisonnière de l'utilisation du territoire et par la qualité des données observées de *SS*; (4) Les résultats, selon les analyses des critères de Nash, de R^2, et de RMSE (tableau S-4.3) confirment que les modifications apportées aux deux modèles ont permis de bien les adapter au contexte particulier du bassin versant de la rivière Câù.

Tableau S-4.3: Critères de performance des modèles

Période	Critères			
	Nash	R^2	RMSE	Variation relative (%)
1998	0,11	0,82	1,30	-24,6
1999	0,13	0,45	1,20	-19,6
2000	0,25	0,63	1,17	-21,5
2001	0,45	0,88	1,20	-17,4
2002	0,21	0,83	1,20	-21,7
2003	0,22	0,86	1,15	-14,2
2004	0,20	0,91	1,21	-11,1
2005	0,35	0,62	1,16	12,4
2006	0,32	0,20	1,17	1,7
Période de calage 1998-2002	0,35	0,71	1,02	-21,0
Période de validation 2003 - 2006	0,30	0,56	1,09	-4,0

De façon générale, les modèles adaptés au contexte du bassin versant de la rivière Câù ont montré de bons résultats en matière de variations journalières des variables de l'érosion. Pour ce qui est de la production de sédiments, les résultats sont meilleurs aux échelles mensuelle et saisonnière. En outre, les résultats sont meilleurs les années où une seule valeur de pointe est apparue au cours des mois de fortes précipitations, soit les mois de juin, de juillet et d'août (cas de l'année 2001). Les modèles n'ont pas présenté d'aussi bons résultats les années où la valeur de pointe a été notée plus tôt ou plus tard dans la saison des pluies, ni lorsque plusieurs pointes de *SS* sont apparues entre avril et septembre. Cela pourrait être attribuable à plusieurs raisons, comme la qualité des données observées de *SS*, la dynamique saisonnière de l'utilisation du territoire non prise en compte dans le modèle hydrologique, des informations manquantes pour la modélisation hydrologique, l'impact des activités humaines dans le bassin vu le niveau d'anthropisation du bassin versant, etc.

Tableau S-4.4: Valeurs par défaut et valeurs ajustées des paramètres des modèles pour le bassin versant de la rivière Câù.

	Processus ou sous-modèle	Paramètre	Valeur par défaut initiale utilisée	Valeur ajustée
Érosion du sol				
1	R_{tji} érodabilité totale quotidienne sur USS *i*	***a***	0,181	0,2
2		***b***	1,5	1,4
3		***c***	0,1	0,025
Transport des sédiments érodés sur la surface du sol				
4	T Capacité de transport des sédiments	K_t	0,5	0,45
5	W_{ri} Largeur d'écoulement sur la section *i*	***n***	15,42	15,42
6		***o***	0,51	2,2
Transport des sédiments sur les tronçons de rivière				
7	V_c Vitesse de chute (diamètre représentatif des particules en suspension)	D_r	0,3 mm	0, 11 mm

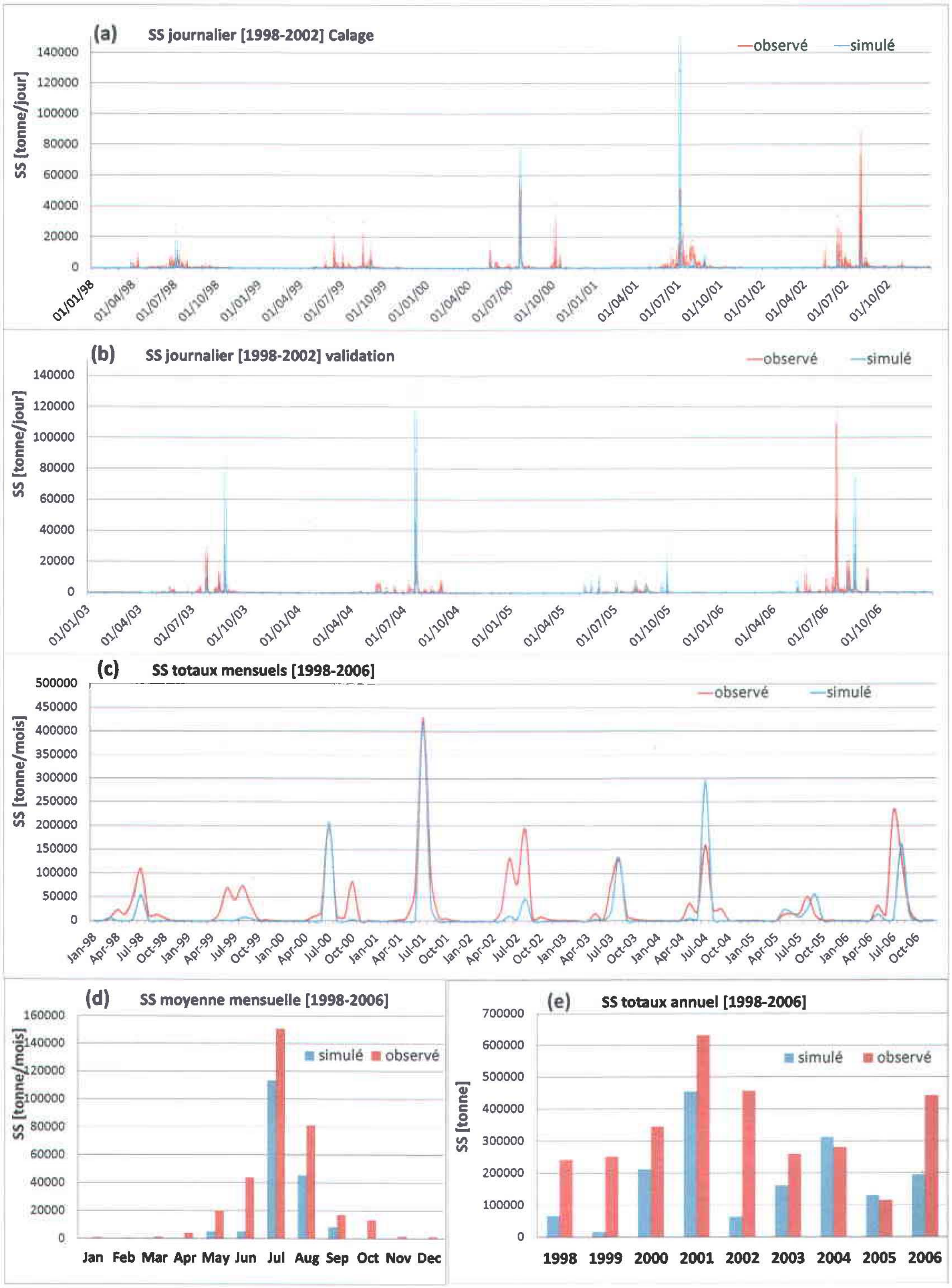


Figure S-4.1: Valeurs de *SS* simulées et observées: (a, b) Journalières; (c) Total mensuel; (d) Moyenne mensuelle; et (e) Total annuel.

S-5 Vérifications et applications du modèle

L'objectif de cette section est d'évaluer la performance des modèles adaptés et calibrés. Pour cela on se base sur les aspects suivants. D'abord, on vérifie la tendance des SS simulés par rapport aux SS observés. Ensuite, on évalue la variation de plusieurs variables simulées de qualité de l'eau telles que le phosphore organique et l'azote organique par rapport à leurs données observées respectives. Enfin, on évalue les réponses des S et des SS utilisant différents scénarios d'utilisation du territoire. La vérification pourrait aider à s'assurer que le modèle adapté peut être considéré comme un outil efficace de gestion intégrée de l'eau par bassin versant utilisable par les experts. Le cas échéant, le modèle adapté permettra de faire des prédictions quantitatives qui aideront les décideurs à améliorer leurs politiques.

S-5.1 Vérification de la tendance des sédiments en suspension (SS)

Dans la partie qui suit, la variation saisonnière des *SS* a été comparée à la variation du débit (*Q*) à l'exutoire du bassin versant en vue d'évaluer le réalisme des résultats et d'obtenir un aperçu du comportement du bassin versant quant à la variation des *SS* par rapport à celle des conditions hydrologiques locales. Sur l'ensemble des mois de l'année, la comparaison des variations des moyennes de totaux mensuels de *SS* et de débits à la station Gia Bay (figure S-5.1) démontre une relation entre les *SS* et les débits moyens mensuels à l'exutoire du bassin versant de la rivière Câù. Cependant, durant le mois de juin, les charges de *SS* apparaissent comme étant plus faibles que prévu par rapport au débit de ce mois.

Durant l'année, près de 95 % des charges annuelles de *SS* arrivent au cours des mois de la saison des pluies, soit d'avril à octobre, période qui correspond à 85 à 90 % du débit total annuel de la rivière. En juillet, la quantité de sédiments en suspension augmente rapidement à la station de Gia Bay pour atteindre près de 50 % de sa valeur annuelle totale. C'est également en juillet que le débit est le plus élevé.

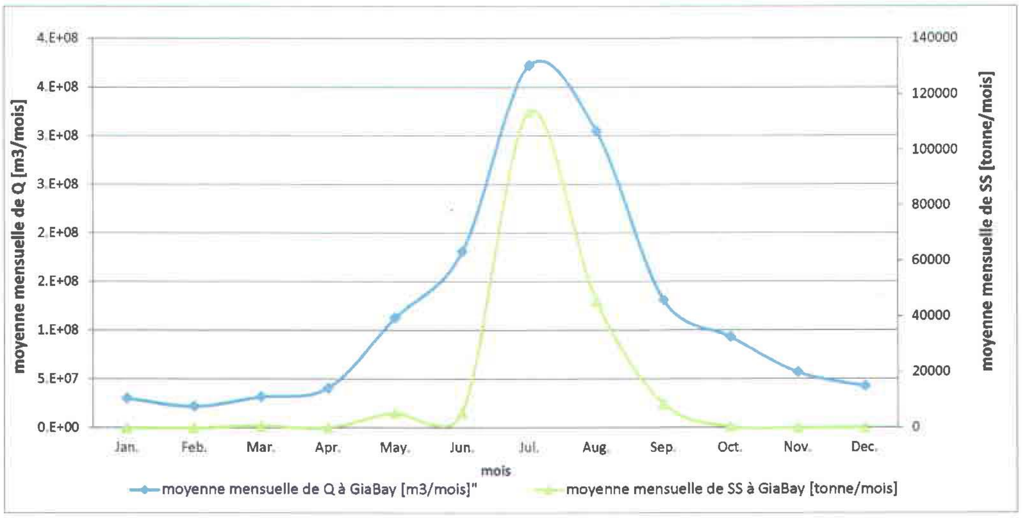


Figure S-5.1: Comparaison des moyennes mensuelles de *SS* et de débit en rivière (Q) à la station Gia Bay (1998-2006).

S-5.2 Réponse du phosphore et de l'azote organiques aux modifications apportées au modèle d'érosion

Dans la présente partie de l'étude, les concentrations de phosphore organique (P_{org}) et d'azote organique (N_{org}) dans la rivière Câù ont été utilisées pour évaluer le réalisme des modifications et de l'adaptation des modèles d'érosion et de transport des sédiments. Cette partie a également pour autre objectif d'évaluer la relation entre la variation des *SS* en rivière et celle des variables de la qualité de l'eau comme P_{org} et N_{org}. Cette approche permet également de vérifier dans quelle mesure il est nécessaire d'adapter le modèle de qualité de l'eau utilisé dans le bassin versant de la rivière Câù.

La comparaison entre les données journalières simulées à long terme (N_{org} et P_{org}) et les données observées a démontré que les valeurs obtenues, les jours où des données observées existent, se rapprochent bien des valeurs simulées pour les deux saisons (Figures S-5.2 et S-5.3).

Ces figures montrent une bonne adéquation entre les variables simulées (Porg et SS d'une part et Norg et SS d'autre part). En effet, les modèles parviennent à représenter adéquatement les résultats des variables de qualité de l'eau étudiées. Ainsi, ceci démontre que le fait de modifier et d'adapter les modèles permet d'obtenir des résultats plausibles relativement aux sédiments en suspension, ce qui n'aurait pas été nécessairement le cas sans l'adaptation des modèles d'érosion et de transport, étant donné que les contaminants P_{org} et N_{org} sont liés aux particules érodées sur la surface du sol. Ces modifications apportées au modèle d'érosion pourront donc être bénéfiques pour l'application d'une gestion intégrée de la qualité de l'eau dans le bassin versant de la rivière Câù, au-delà de l'objectif initial de modélisation de l'érosion et du transport de sédiments.

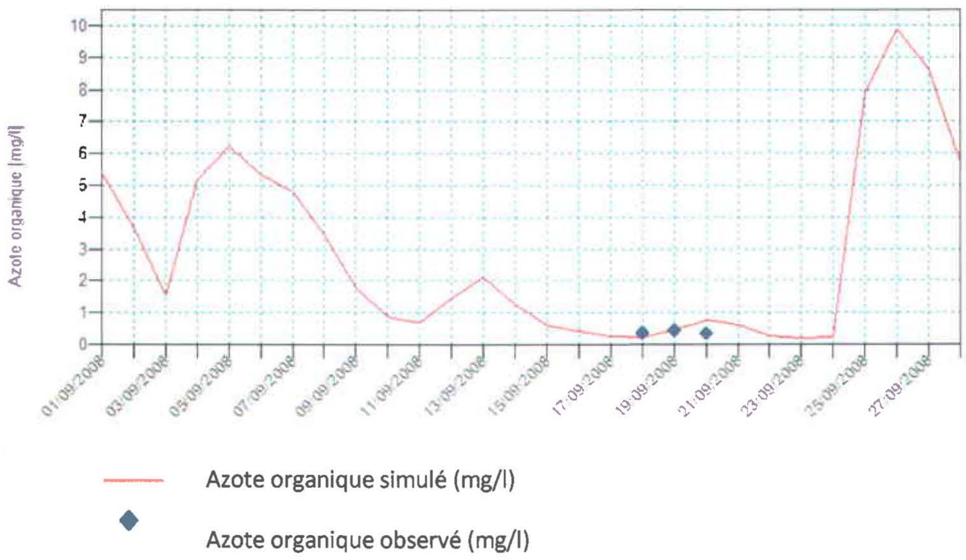


Figure S-5.2: Comparaison de l'azote organique simulé et observé en 2008.

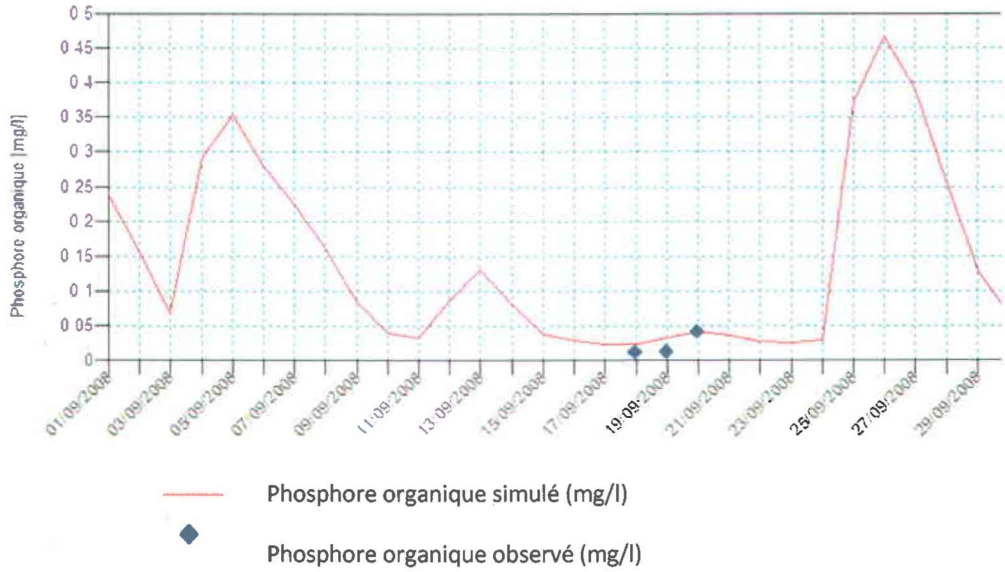
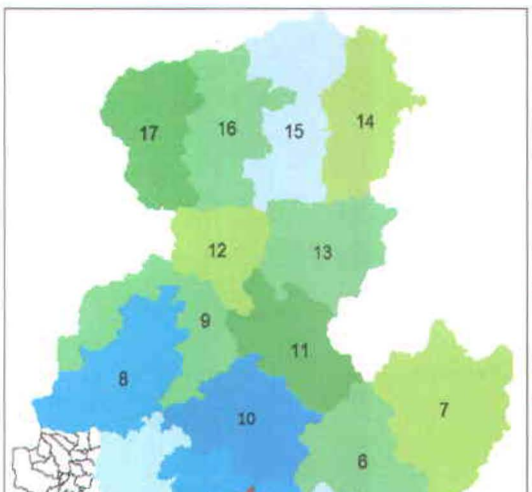


Figure S-5.3: Comparaison du phosphore organique simulé et observé en 2008.

S-5.3 Réponse de l'érosion (S) et des sédiments en suspension (SS) aux changements d'occupation du territoire

La présente partie vise principalement à : (1) analyser les variations des particules érodées (S) et des sédiments en suspension (SS) en fonction de divers scénarios de changement d'occupation du territoire dans le bassin versant; (2) analyser l'incidence de l'occupation du territoire sur les S en tenant compte de divers contextes topographiques; et (3) analyser, pour quelques zones, l'incidence du changement d'occupation du territoire sur les *SS* à l'exutoire en fonction de la distance qui sépare la zone de l'exutoire.

Pour les besoins des simulations, la zone d'étude a été subdivisée en dix-sept zones dont l'occupation est la plus homogène possible (Figure S-5.4). L'objectif est de disposer de zones considérées comme soit non convertibles (*p.ex.* urbain), soit entièrement convertibles d'une classe d'occupation en une autre (*p. ex.* forêt en agricole).



Zone	Type
1	Urbain et AgriHabPlant *
2	Mélange **
3	AgriHabPlant
4	Mélange
5	Mélange
6	Forêt
7	Forêt
8	Mélange
9	Forêt
10	Mélange
11	Forêt
12	Forêt
13	Forêt
14	Forêt
15	Mélange
16	Forêt
17	Forêt

Figure S-5.4: Les 17 zones d'utilisation du sol dans le bassin versant de la rivière Câù.

(*) AgriHabPlant : mélange de champs, de petits villages et de plantations.

(**) : Mélange des classes forestière et AgriHabPlant.

En ce qui concerne l'influence du changement d'occupation du territoire sur l'érosion, les résultats obtenus ont démontré que : (1) la déforestation peut entraîner un changement quelques fois extrême de la résistance du sol à l'érosion et au transport de sédiments; (2) à l'opposé, la reforestation contribue à réduire les pertes en sol et le transport de sédiments; (3) les résultats de calage des modèles peuvent être considérés comme suffisants pour évaluer les impacts de changements d'occupation du territoire sur l'érosion; et (4) le modèle peut être utilisé, dans un contexte de gestion du territoire, en vue de comprendre la réponse du bassin à différents changements, ce qui peut s'avérer utile pour les gestionnaires du bassin versant (Figure S-5.5).

En ce qui concerne l'érosion (S) en fonction du contexte topographique, les résultats obtenus (Figure S-5.6) ont permis de confirmer un fonctionnement adéquat du modèle, que la pente soit élevée (*p. ex.* en zone de montagne) ou douce. Les surfaces situées en zone de forte pente s'érodent plus que celles situées en zone de faible pente, comme le montre l'exemple des zones 4, 8 et 15 (Figure S-5.6).

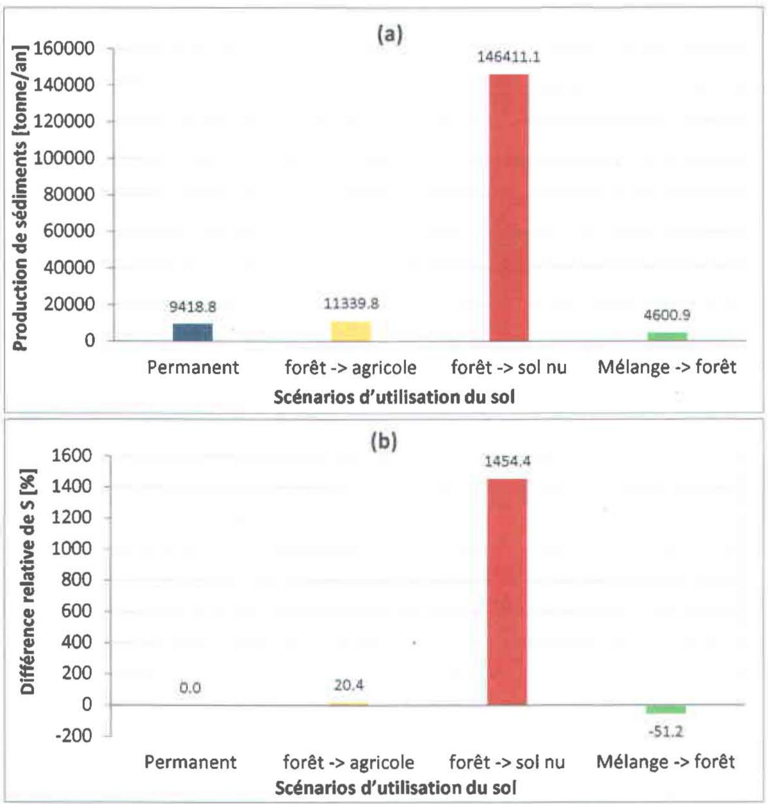


Figure S-5.5: Comparaison (a) de la production de sédiments et (b) de la différence relative de sédiments produits pour les scénarios de reforestation et de déboisement.

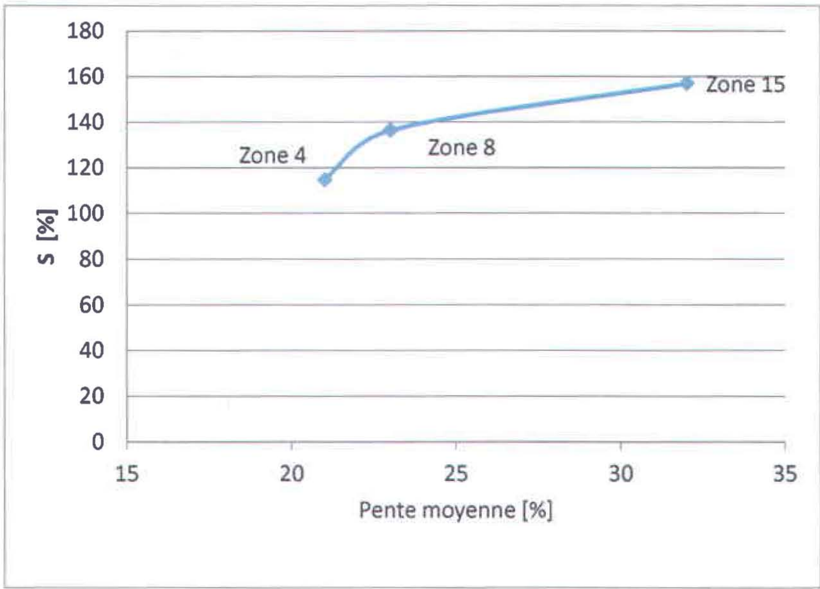


Figure S-5.6: Variation relative de sédiments produits (%) par rapport à la pente moyenne (%) des zones (exemple des zones 4, 8 et 15).

Compte tenu de la variation de la charge des *SS* observées dans divers scénarios d'utilisation du territoire (Figure S-5.7), il est possible de conclure que la transformation des terres agricoles et des terres mixtes en forêt permettrait de réduire la quantité de *SS* produite sur le bassin versant de près de 27 %. En revanche, la déforestation pourrait augmenter la charge sédimentaire jusqu'à 72 %. De façon générale, la comparaison des divers scénarios a permis de démontrer le bon fonctionnement des modèles dans l'exemple d'utilisation analysé dans cette thèse. Cela montre que ces modèles peuvent être utilisés dans un contexte d'aménagement, de planification et de prise de décisions stratégiques concernant l'utilisation des ressources en eau ainsi que l'aménagement du territoire.

Pour ce qui est de l'évaluation de la variation de la charge de *SS* en fonction de la distance à l'exutoire comme autre variable potentiellement explicative, les résultats ont révélé une augmentation de la quantité de *SS* à mesure que les zones où les modifications effectuées se rapprochent de l'exutoire (Figure S-5.8). Ainsi, en raison du processus de sédimentation dans les cours d'eau, les zones les plus rapprochées de l'exutoire (ou du point d'observation) auraient une plus grande incidence sur les quantités de sédiments en suspension que les zones les plus éloignées, et ce, lorsque les changements du territoire appliqués sont les mêmes. Même si cela n'a pas été analysé dans cette étude, on pourrait supposer que les zones éloignées de l'exutoire devraient avoir une incidence plus marquée dans des tronçons de rivière plus proches de ces zones.

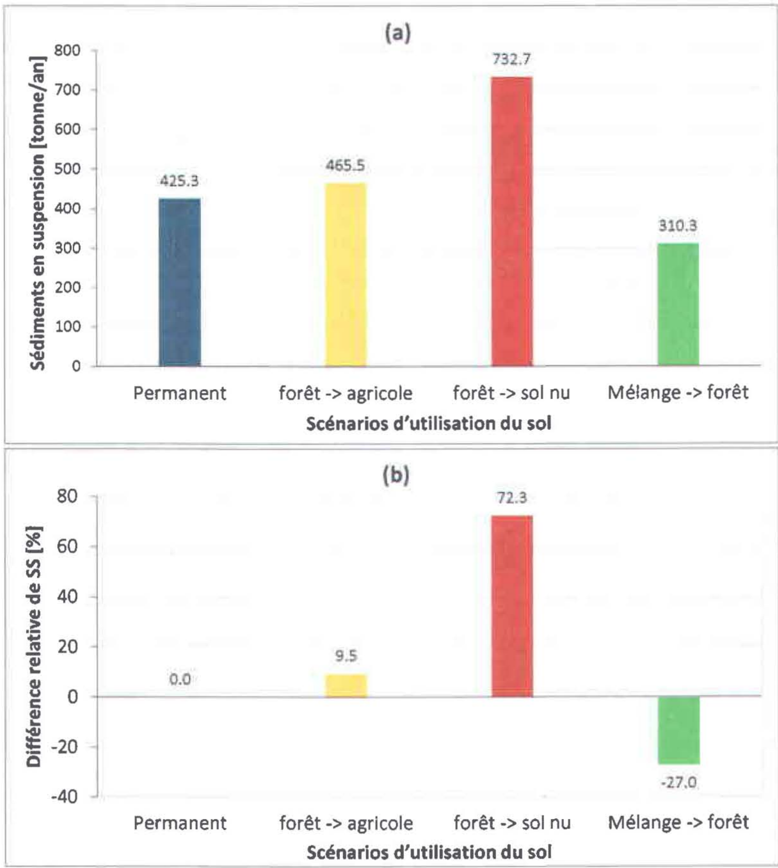


Figure S-5.7: Comparaison (a) des *SS* en rivière et (b) de la différence relative des sédiments en suspension pour différents scénarios de modification de l'utilisation du sol par rapport au scénario de référence.

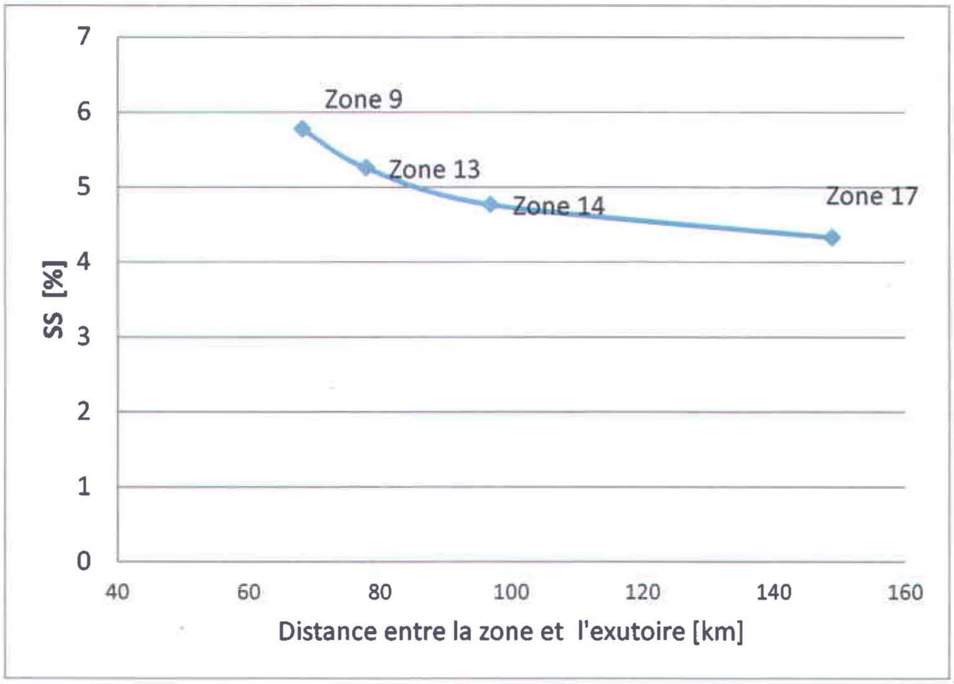


Figure S-5.8: Variation relative des *SS* par rapport à la distance de transport dans le réseau hydrographique.

De façon générale, les vérifications effectuées ont permis de confirmer la pertinence des modifications et des adaptations apportées aux modèles d'érosion et de transport des sédiments pour le bassin versant de la rivière Câù, dans un contexte de données limitées et de conditions climatiques de type mousson. La vérification a tenu compte des quatre points énoncés précédemment : (1) en assurant un fonctionnement fiable des modèles d'érosion et de transport des sédiments de GIBSI sur le bassin versant de la rivière Câù par l'ajustement des paramètres des modèles en fonction des conditions climatiques et des autres caractéristiques (sol, topographie, calendrier de cultures, etc.) de la région et de l'accessibilité des données; (2) en démontrant une réponse intéressante de la quantité de sédiments en suspension en rivière, qui concorde avec les données d'observation hydrologiques et météorologiques recueillies; (3) en représentant une variation quantitative du phosphore et de l'azote organiques qui correspond à la variation de la quantité de *SS* dans le bassin versant, permettant ainsi la modélisation de divers scénarios de gestion de la qualité de l'eau; (4) en confirmant la nécessité d'apporter des modifications au modèle GIBSI et d'adapter ce dernier de manière à ce qu'il devienne un outil utile pour la gestion intégrée du bassin versant de la rivière Câù; et (5) en vérifiant comment les modèles modifiés permettent d'analyser l'impact sur la réponse du bassin, de variations dans l'activité humaine, par l'analyse de variation de la quantité de *SS* simulée en fonction de changements dans l'utilisation du territoire.

S-6 Conclusions, recommandations et perspectives

Conclusions

La présente thèse a permis d'adapter, de modifier, de caler et de mettre en pratique des modèles d'érosion et de transport de sédiments à l'échelle du bassin versant. Pour ce faire, les problèmes liés aux conditions locales ont été soulevés, puis résolus systématiquement. L'analyse exhaustive des exigences relatives aux données et de leur accessibilité a contribué à l'adoption de solutions adéquates pour estimer la valeur des paramètres des modèles. Ces étapes ont constitué le premier pas vers l'adaptation de GIBSI au bassin versant de la rivière Câù.

Les résultats de l'étude ont confirmé que ces modèles adaptés et calés peuvent être utilisés sur le bassin versant de la rivière Câù et qu'il est possible de mettre en œuvre un système de gestion intégrée de l'eau par bassin versant dans un milieu où les données observées sont rares et où les conditions climatiques sont différentes de celles du milieu dans lequel les modèles ont été initialement conçus. En outre, les modèles relatifs à l'érosion et au transport de sédiments sont parmi ceux qui présentent un grand potentiel d'application. Ainsi, l'adaptation de ces deux modèles permettra aux modélisateurs et spécialistes de l'environnement du Vietnam de disposer d'un outil approprié pour simuler, entre autres, des variables liées à la qualité de l'eau et à l'utilisation du territoire. Cet outil permettra également d'élaborer des scénarios de changements du ciimat, des activités humaines, de la topographie et d'autres formes de changements dans l'utilisation du territoire. Ces résultats pourraient alors aider les planificateurs de l'utilisation du territoire et les décideurs politiques à améliorer leurs stratégies d'intervention.

En plus de la contribution de cette étude en matière de gestion des eaux et des sols dans le bassin versant, la présente thèse a permis :

- de comprendre l'importance des paramètres et des composantes des modèles en vue d'apporter les modifications et les adaptations nécessaires en tenant compte des données disponibles et des conditions locales.
- de fournir des pistes de solution en vue d'obtenir les données d'entrée difficilement accessibles ou inexistantes dans ce bassin afin de pouvoir calculer des caractéristiques du sol qui interviennent dans le calcul de l'érosion (structure du sol, perméabilité du sol, teneur en matière organique).

- d'adapter certains codes ou de les réécrire de manière à ajuster le calcul des facteurs d'érosion *LS*, *C* et *P* dans le bassin versant, où la seule carte disponible est celle de l'utilisation du territoire.
- de tenir compte pour la première fois, dans ce cas d'application dans le bassin versant de la rivière Câù, de deux groupes d'occupation du territoire : un groupe d'occupation du territoire avec une couverture constante du sol dans l'année (eau, forêts, urbain) et un groupe d'utilisation du territoire avec une couverture du sol variable dans l'année (agricole, mélange, arbustes et sol nu). La séparation en deux groupes est nécessaire pour une meilleure adaptation des facteurs d'occupation des terres (*C*) et de pratique de conservation (*P*).
- d'effectuer une analyse de sensibilité des modèles afin d'identifier les paramètres auxquels les résultats des modèles sont les plus sensibles et d'établir des lignes directrices et des procédures de calage des modèles d'érosion et de transport des sédiments. Cela a permis d'améliorer le calage des modèles et la qualité des résultats de simulation. Ces directives de calage se présentent comme un outil efficace pouvant permettre de savoir comment améliorer le calage pour obtenir des résultats visant d'autres objectifs (*p. ex.* étude en saison des pluies des problématiques des sédiments en suspension et de la contamination d'origine agricole).
- d'assurer le réalisme des résultats de GIBSI dans une région tropicale telle que celle du bassin versant de la rivière Câù, dans un contexte où les données sont restreintes, et ce, tout en s'assurant d'effectuer les adaptations et les modifications requises.
- d'analyser, sur la base d'une étude de cas, les impacts sur l'érosion et les sédiments en suspension, des changements de l'occupation du territoire, en plus de fournir un moyen d'évaluer divers scénarios d'aménagement sur le plan quantitatif.
- de contribuer aux études portant sur la modélisation de la qualité de l'eau et sur les scénarios de gestion intégrée dans le bassin versant de la rivière Câù.

Recommandations et perspectives

Sur la base des résultats obtenus, des recommandations peuvent être formulées. Des perspectives d'études futures peuvent aussi être proposées à partir des principaux enjeux soulevés tout au long de la présente étude.

- *Données restreintes :* le manque de données pourrait être réglé : (1) en ayant recours à d'autres sources d'information pour obtenir ou estimer les données requises; et (2) en modifiant les données d'entrée requises après modification des équations.
- *Différences de topographie et de climat :* cette question exige la révision ou la modification des équations et de la théorie inhérente aux calculs. Cela doit être fait en tenant compte des particularités des conditions locales.

- *Le concept des cycles de cultures* dans la version initiale de GIBSI pourrait être remplacé par un concept basé sur le *cycle annuel d'occupation et d'utilisation du territoire.* Ce concept permettrait d'évaluer avec plus de précision la valeur journalière de *C* pour un bassin versant dans lequel certaines classes d'occupation n'existent qu'une partie de l'année. Cela est aussi important pour améliorer davantage les résultats de simulation de l'érosion dans un bassin versant dont l'utilisation du territoire change rapidement dans l'année.

- *Données d'observation :* par souci de réalisme et pour réduire les incertitudes, elles doivent être vérifiées (méthodes de mesures, corrélation avec d'autres variables, etc.) avant les étapes de calage et de validation. Cette vérification pourrait contribuer à une amélioration des résultats de calage. Dans certains cas, cela pourrait même aider à expliquer certains résultats *a priori* surprenants.

- *Analyse de sensibilité :* cette analyse, axée sur la variation des valeurs des paramètres de calage, constitue une étape importante précédant celle du calage. Les résultats de cette analyse sont à l'origine de propositions quant au choix des valeurs des paramètres lors du calage, aux attentes par rapport aux résultats, ainsi qu'à l'économie de temps réalisée en mettant un accent sur les valeurs des paramètres qui ont le plus d'impact sur les résultats.

- *Choix des valeurs des paramètres de calage :* les paramètres de calage ont des impacts différents sur les résultats de simulation. Un ajustement basé sur une combinaison adéquate de paramètres peut entraîner de meilleurs résultats pour les saisons de fortes ou de faibles précipitations.

- *Lignes directrices relativement au choix des paramètres et des procédures de calage :* elles se sont avérées très utiles pour proposer une orientation ainsi que des suggestions quant aux paramètres à caler en priorité (tableau S-4.2) en fonction des objectifs de l'utilisateur.

- *Résultats liés aux SS :* tel qu'attendu, les résultats sont meilleurs sur une base mensuelle que sur une base journalière. Pour ce qui est des valeurs journalières, les écarts observés pourraient être une combinaison d'erreurs provenant du modèle hydrologique, de la forte variabilité dans la pluviométrie entre les deux saisons, des données observées, du changement rapide dans l'utilisation du territoire, etc.

  La priorité dans le calage, pour une zone d'étude sous climat tropical de type mousson, devrait être accordée aux pluies extrêmes ayant lieu en saison pluvieuse et qui représentent une large contribution dans l'apport total annuel en sédiments dans le bassin versant. Le choix d'un autre jeu de paramètres de calage pourrait être recommandé dans le cadre d'une étude de l'érosion sur une période spécifique et pour d'autres objectifs autres que celui de la gestion intégrée par bassin versant. Dans de pareilles situations, il est important de s'appuyer sur les directives de calage suggérées.

- *Le changement rapide de l'occupation du territoire* devrait être pris en compte. De nombreux travaux dans la littérature ont démontré l'impact du changement d'occupation du territoire sur l'érosion et le transport de sédiments. Cela a également été démontré par l'étude de cas effectuée dans la présente thèse (chapitre 5). La carte d'occupation du territoire utilisée est celle de 2003 et elle ne tient donc pas compte des changements possibles avant et après 2003, soit respectivement entre 1998-2002 et 2004-2006. L'analyse de la dynamique d'occupation du territoire et sa prise en compte dans les simulations, dans le cas de modifications majeures, contribuerait à améliorer le calage et la validation du modèle.

- *Dans le cadre de la présente étude,* nous avons réussi à surmonter les obstacles liés à l'accessibilité restreinte des données afin de mettre en pratique les modèles d'érosion et de transport des sédiments de GIBSI dans le bassin versant de la rivière Câù. Il s'agit là d'une étape importante qui donnera lieu à des études de suivi portant sur la qualité de l'eau basées sur divers scénarios d'aménagement du bassin versant de la rivière Câù. Il s'agit en outre d'une référence pertinente pour des applications similaires.
- *L'application de la présente étude* à des bassins versants similaires au Vietnam ou dans la région de l'Asie du Sud-Est demeure possible en portant une attention particulière aux points suivants : (1) Disponibilité des données d'entrée et méthodes d'estimation des données manquantes; (2) Vérification de la qualité des données observées de sédiments en suspension à partir de l'adéquation entre des variables comme la pluviométrie, le débit en rivière, les sédiments en suspension, etc.; (3) Calage du modèle à partir des directives énoncées dans cette thèse. Les valeurs des paramètres de calage du modèle pour le bassin versant de la rivière Câù peuvent servir de référence. Une application du présent modèle est finalement possible dans d'autres bassins versants, moyennant des adaptations, pour des objectifs de gestion intégrée par bassin versant (*p. ex.* gestion de la qualité de l'eau, analyse de différents scénarios d'occupation du territoire ou d'interventions).

II. THÈSE

SUMMARY

The Cau River watershed, with monsoon climate conditions and constrains of data availability was selected as a case study for the application of the integrated watershed management system GIBSI. The principle objective of this study is to develop methodologies for the application of erosion and sediment transport models at the catchment scale and suggest modifications to the models for watershed where (1) topographic and climatic conditions are largely different from the watersheds where the models were originally designed, and (2) there is a limitation of observation data which makes difficulties for calibration of parameters and validation of the models.

The contributions of this study are focussed on: (1) Analyse and identify problems posed by the application of soil erosion and sediment transportation models into the Cau River watershed. (2) Provide solutions to obtain input parameters which values are not available in the watershed, in order to calculate soil erosion. (3) Provide methods to adapt, modify, and re-write codes for calculations of factors in the soil erosion model MODEROSS and the transportation model ROTO, in Cau River basin. (4) Provide solutions to improve the sensitivity of simulated sedimentation and transportation quantities to the specific seasonal behaviour of sediment processes in monsoon climatic areas, particularly for the Cau River basin. (5) Through analyses of sensitivity and performances of parameters, set up procedures and provide guidelines to achieve an effective calibration the applied models. (6) Ensure that the GIBSI system is applicable to tropical climate regions, such as the Cau River basin, in a context of data limitation while keeping certainty of the applied adaption and modifications.

Results of this study have confirmed the applicability of the models, with the proposed adaptations and modifications, enabling the applicability of hydrological models, erosion and sediment transport as a support for integrated watershed management in an area where observation data are scarce and where climatic conditions are different from those of the watershed where the models were first developed. This research work is a significant step towards providing a practical tool to users, setting up possibilities for quantitative studies of water quality modeling, land use planning and integrated management scenarios in the Cau River watershed.

1. Introduction

1.1 Rationale

Vietnam is a developing country in South-East Asia, where river basins and plain deltas have increasingly become areas with a high concentration of economic development, industrialization and urbanization activities. These activities, however, have been creating great pressure on environmental quality and natural resources.

The confliction between economic development and environmental protection is becoming a more complex issue. It challenges efforts of the government to maintain economic development rate as well as to protect natural environment and human health. It is recognized that the management of river watersheds will play an important role in the sustainable development of the economy. With acknowledgement of this importance, the Vietnamese government has been recently paying more attention to implementing the integrated management of river watersheds which are bearing key factors for a sustainable development achievement. A study to apply the advantage of recently developed watershed management tools and adapt them to local conditions would be a feasible solution to achieve the target.

Located in the North-Western part of the Red River delta, Cau River watershed was selected as the pilot study for an integrated watershed management. The study area has a total area of 4500 km^2, with population of 1.3 million. It lies within coordinates 21°16'N ÷ 22°19'N and 105°29'E ÷ 105°07'E. Within this watershed, there are over 400 industrial sites and thousands of small-scale handcraft workshops. Accordingly, the environmental situation of the watershed was reported to become worse, with the degradation of river water quality, irregular flooding in rainy season and shortage of water in dry season. It is caused by agriculture and deforestation activities, the discharge of wastewater from industrial sites to the river system, and improper policies for water management.

The good management of this river watershed requires the comprehensive, systematic preservation of natural environment, maintenance soil and water quality, and prediction of possible changes. Tools are thus needed to understand the current state of the watershed and be able to predict the impacts on water quality of different measures, such as controlling water quality by the implementation of water treatment plants, reforestation, etc.

The GIBSI system (Villeneuve *et. al.,* 1998a), an integrated modeling system for watershed management developed by INRS-ETE, shows its potential for practical application on the Cau River watershed. GIBSI is designed to help stakeholders make decisions in water management at the watershed scale. It can either be used as a data management system or as an impact assessment tool to study the effect of management scenarios on surface water quality using mathematical models (Rousseau *et al.,* 2000).

1.2 Problematic and context of the research

In an integrated watershed management system, soil erosion (MODEROSS) and transportation (ROTO) models play an important role. They are intermediate-processing modules, which contribute to inputs to other models and give outputs to estimate water quality in a watershed. Thus, they can provide means to setup the management scenarios and reflect the quantitative changes when the scenarios are applied. Consequently, having a solution to adapt soil erosion and transportation models to a watershed which has limited field information would be an important key, opening the applicability of an integrated watershed management system such as GIBSI in that kind of area.

Water soil erosion and transportation models were originally designed for small scale or single slope estimates. They were developed on farmland topography and for temperate climatic regions rather than for monsoon tropical conditions. Their mathematic formulas to estimate involved parameters could result in errors when being applied to a large scale estimate such as watershed scale. This therefore requires adjustment in formulas as well as a lot of observation data for the calibration and validation of the models.

Cau River watershed presents itself as a good case study with limitations in observation data and capacity to carry out field study campaigns, challenging the application of integrated watershed management systems. Success in the implementation of these systems on this type of watershed would bring us good experience and make possible its application to other watersheds which have the same constraints of data availability.

1.3 Position of the thesis research in the application of GIBSI to the Cau River watershed

The soil erosion model takes an important position as an intermediate-processing module connecting, processing, and contributing to quantitative inputs from and to other models. It also provides a means to setup the management scenarios and, in turn, reflects the quantitative changes in sediments when the scenarios are applied. The present thesis is part of a broader project that aims at applying GIBSI to the Cau River Basin. This project is a partnership between INRS-ETE and VAST. This thesis uses hydrological results from the adaption and calibration of the HYDROTEL model for the Cau River Basin (Nguyen, 2012). In turn, results of this thesis will provide means to calibrate the river water quality model, and finally enable the evaluation of management scenarios for the Cau River Basin.

1.4 Objectives of the research

The principal objective of the study is to develop methodologies for the application of erosion and sediment transport models at catchment scale and suggest modifications to the models for their application in tropical climates where few data are available, in order to reduce the uncertainties associated with model results in such conditions. More specifically, the study will pursue the following objectives:

- To propose changes to MODEROSS and ROTO models, that will be adapted to the tropical climatic conditions and to the lack of data encountered in most tropical countries.
- To develop a method to estimate the variation at daily time-scale of soil erodibility (*K* factor) in monsoon tropical conditions, such as those encountered in the Cau River basin, where existing methods to estimate daily the *K*-factor cannot be applied due to the climate particularities.
- To introduce guidelines and setup a procedure for the effective calibration of the models from the sensitivity analysis. This helps to ensure the accuracy of the simulation results in a context such as the watershed of the Cau River.
- To assess the applicability of hydrological models, erosion and sediment transport as a support for integrated watershed management in Vietnam, where access to observational data is limited and where the climatic conditions are different from those of the region where the models were originally developed. These models can then be used to assess the impact on water quality of various intervention scenarios, such scenarios of land use, in order to support policy makers in their decisions.

1.5 Originality of the thesis

The most important target and also the biggest goal of this study is to ensure the applicability of a process-based model onto a watershed where (1) topographic and climatic conditions are largely different from the watersheds where the models were originally designed, and (2) there is a limitation, in both the quality and quantity of observation data, which makes the calibration of parameters and validation of the models difficult.

Within the context of these limitations, the development of methodologies to estimate input parameters to meet the requirements of the models while ensuring their certainty will be the principal contribution of this thesis.

To adapt and modify the methods to obtain the input parameters, this study is based on a comprehensive analysis of local conditions and data availability, recognizing the difficulties and differences posed by the application of a small scale, single-slope-based soil erosion model onto a large scale, integrated management watershed.

Finally, developing a method to estimate the daily soil erodibility is, to our knowledge, the first attempt to quantify the variation of this parameter in a region subject to tropical monsoon.

The contributions of this study are focussed on analyzing and identifying the problems posed by the application of soil erosion and sediment transportation models to the Cau River watershed toward:

- providing solutions to obtain input parameters for which values are not available in the watershed, in order to calculate soil erosion;
- providing methods to adapt, modify, and re-write codes to calculate factors in the soil erosion model MODEROSS and the transportation model ROTO, in the Cau River basin, where little information is available;
- providing solutions to improve the sensitivity of simulated sedimentation and transportation quantities to the specific seasonal behaviour of sediment processes in monsoon climatic areas, particularly for the Cau River basin;
- analysing the sensitivity and performance of parameters, setting up procedures and providing guidelines to achieve an effective calibration of the applied models;
- ensuring that the GIBSI system is applicable to tropical climate regions, such as the Cau River basin, in a context of data limitation.

1.6 Plan of the report

This report contains six main sections including: (1) *Introduction*. (2) *Literature review*: This chapter aims at assessing the problems encountered in previous studies related to the objectives of the thesis. (3) *Modeling tool and study area*: Within this section, the GIBSI system and its componential models will be discussed with an emphasis on soil erosion and sediment transport models. This chapter also presents an overview of the Cau River watershed to analyze its specific natural and social conditions, which are challenging the application of a watershed management system. (4) *Adaptations, modifications, and calibrations:* This chapter discusses the modifications and adaptations made to the models, a sensitivity analysis and calibration methods, in a context of limited observational data and climatic differences. Parameters involved in soil erosion and transportation simulations, a method to prepare input datasets and parameter behaviour, and adjustments through simulations are briefly explained together with an introduction of procedures and guidelines for the effective calibration of the models. (5) *Application and validations*: This section summarizes the tasks carried out for adaptations / modifications made so far for the application of GIBSI to the Cau River watershed. The validation of adaptations and modifications made for the soil erosion and transportation models on Cau River basin condition is also carried out by 1) analyzing the responses of suspended sediments, organic phosphorus and organic nitrogen with limited available observations; 2) verifying responses of the modified models to some land use change scenarios to confirm the effectiveness of the applications on the Cau River watershed. (6) *Conclusion and recommendations*: This section summarizes the tasks, achievements and conclusions, and it highlights some limitations and expectations for further studies.

2. Literature review

2.1 USLE and RUSLE models

USLE (Wischmeier and Smith, 1978) is an empirically based model for soil erosion assessment and soil conservation planning. It was developed from erosion plots and rainfall simulator experiments. It is composed of five factors used to predict the long-term average soil loss (Equation. 2.1):

- The climate factor *R* accounts for the potential of falling raindrops and flowing water in a particular area prone to erosion. The cumulative effects of all yearly storms above a certain intensity and duration make up this numerical value. As the energy of a storm increases, the potential for more soil particles to detach also increases. Runoff also increases with the intensity and duration of storms, thereby increasing erosion potential.

- The soil erodibility factor *K* considers soil properties that influence both the detachment and transport of soil particles. These include soil organic matter content, texture, structure, size, shape, and stability of aggregates, and the permeability of the soil to water. Soil erodibility tends to increase with greater silt content and decrease with greater sand and clay contents. Organic matter binds individual particles together thus increasing aggregate strength, hence the resistance to detachment. Permeability of the soil to water, resulting from soil particle size, can affect erosion because of its capacity to infiltrate rainfall and minimize surface runoff (James, 1995).

- Soil erosion by water is affected by slope length, *L*, and slope steepness, *S*, which jointly determine the amount and velocity of runoff.

For a given tract of land, an operator has little direct control over rainfall characteristics, soil properties, topography, or slope. However, the effects these factors have on soil erosion can be limited by using management techniques represented by factors *C* and *P*.

- The soil and crop management factor *C* includes crop sequences, residue management, soil fertility management, time of tillage, intensity of tillage, and row spacing of row crops.

- Factor *P* represents soil conservation practices that essentially slow the runoff water and thus reduce the amount of soil it can carry. The most important of these supporting practices are contour tillage, strip cropping, and terracing.

The Revised Universal Soil Loss Equation (RUSLE) is based extensively on the USLE model and its data. It offers several major improvements to USLE users. Each factor value has been updated, expanded and improved (Renard *et al.,* 1994):

- The *R* factor contains expanded and more precise information for locations across the United States. It takes into consideration total rainfall, intensity and seasonal distribution of the rain. *R* is generally the same in USLE and RUSLE. However, RUSLE computes a correction to *R* to reflect, for flat land, the effects of raindrop impact on water ponded on the surface.
- *K* in RUSLE was adjusted to account for seasonal changes in the soil such as freezing, thawing, soil moisture, and soil consolidation. The *K* factor in RUSLE contains more significant erodibility data from around the world such as soil type, the diameter of soil particles, and the presence of rock fragments.
- The *LS* factor in RUSLE is refined by assigning new equations based on the ratio of rill to interill erosion and accommodates complex slopes.
- *C* is the ratio of soil loss under the conditions in question to that which would occur under continuously bare soil. *C* uses the sub-factors: prior land use, canopy cover, surface cover and roughness, and soil moisture. RUSLE divides each year into 15-day intervals, calculating the soil loss ratio for each time period. It also recalculates a new soil-loss ratio every time a tillage operation changes one of the sub-factors.
- The *P* factor determines the effect of strip cropping based on the transport capacity of flow in dense strips related to the amount of sediment reaching the strip, the contour cultivation, and also the conservation practices applied to rangeland.

2.2 Watershed scale modeling

The watershed-scale models are increasingly used because of their ability to produce comprehensive assessments, to estimate how the natural systems that are driven by hydrological processes are impacted by anthropogenic disturbances (Migliaccio *et al.,* 2007). Previously, several studies had been conducted to analyze characteristics and evaluate performance of watershed-scale models through their main aspects such as water quality modeling (Patrick *et al.*, 1999), hydrological components (Migliaccio *et al.,* 2007), and mathematical bases (Borah and Bera, 2003). Most of the commonly used watershed models were formulated in the 1970s and 1980s, and since the early 1990s, most modeling research has focused on the development of graphical user interfaces (GUI) and integration with geographic information systems (GIS) and remote sensing data. While enormous progress has been made in developing and refining interfaces, greater efforts are now needed to focus on the formulation and development of advanced models for watershed assessment (Chen, 2001; CWM, 1999).

Certain watershed models are based on simple empirical relationships, while others use physically based equations, solved numerically. Simple models are sometimes unable to provide detailed results, while detailed models can sometimes be prohibitive for large basins and require a lot of input data, which are not always available. Therefore, finding an appropriate model for an application and for a certain watershed is quite a challenging task (Borah *et al.*, 2003). Watershed-scale hydrologic and nonpoint-source (NPS) pollution models can be divided into two groups: (1) single-event models, and (2) continuous models. There are several models that have been developed for assessments at the watershed scale; it is impossible to list them all in this report. The models that will be presented here are those which, first, are among the most commonly used and, secondly and more importantly, have three major components (hydrology, sediment and chemical) applicable to the watershed scale, and/or use models of soil erosion and sediment transport, which this study is focussed on.

2.2.1 Single-event models

- The model AGNPS (Young *et al.*, 1987, 1989) was developed by the USDA-ARS. It simulates runoff, sediment, and transport of nitrogen (N), phosphorous (P) and chemical oxygen demand (COD) resulting from single rainfall events.
- The model ANSWERS (Beasley *et al.*, 1980) uses a distributed parameter concept to model the spatially varying processes of runoff, infiltration, subsurface drainage, and erosion for single-event storms. The model has two major components: hydrology and upland erosion responses. The conceptual basis for the hydrologic model was taken from Huggins and Monke (1966), and for the erosion simulation, from Foster and Meyer (1972).
- The model CASC2D (Ogden and Julien, 2002) was initially developed by Julien and Saghafian (1991) and Julien *et al.* (1995), and further modified by Ogden (1998) and Ogden and Julien (2002). This model is physically based. It simulates water and sediment in two-dimensional overland grids and one-dimensional channels and has both single-event and long-term continuous simulation capabilities.
- The model DWSM (Borah *et al.*, 2002) simulates distributed surface and subsurface storm water runoff, propagation of flood waves, upland soil and streambed erosion, sediment transport, and agrochemical transport in agricultural and rural watersheds during single rainfall events.

2.2.2 Continuous models

- The model AnnAGNPS (Bingner and Theurer, 2001), is an upgraded version of AGNPS for continuous simulations of hydrology, soil erosion, and transport of sediment, nutrients, and pesticides. It is designed to analyze the impact on the environment of nonpoint-source pollutants from predominantly agricultural watersheds. The model simulates hydrology, sediment, nutrient, and pesticide transport. AnnAGNPS allows the user to select either a grid (or cell) spatial representation or a hydrologic response unit spatial representation, with the selected unit being characterized by homogeneous land and soil properties. AnnAGNPS applications are predominantly for sites in the U.S. (e.g., Yuan *et al.*, 2001; Yuan *et al.*, 2002; Polyakov *et al.*, 2007); however, applications in other countries have also been published, e.g., Australia (Baginska *et al.*, 2003), Canada (Das *et al.*, 2006) and China (Hong *et al.*, 2005).

- The model ANSWERS-Continuous (Bouraoui *et al.*, 2002) was developed from ANSWERS as a continuous model. The model was expanded with upland nutrient transport and losses based on GLEAMS (Leonard *et al.*, 1987), EPIC (Williams *et al.*, 1984) and others. The primary purpose of the model is to qualitatively evaluate alternative management practices with respect to runoff, sediment losses, and nitrogen and phosphorus from agricultural watersheds. This model is only appropriate for watersheds with overland flow dominated hydrology, since deep percolation, groundwater flow, interflow, and stream base flow are currently not well developed in the model (Bouraoui and Dillaha, 2000). Land and soil characteristics are designated using a grid matrix or square cell system in which they are homogenous. The model has predominantly been applied to U.S. watersheds (e.g., Bouraoui and Dillaha, 1996, 2000); other application areas include Argentina (Braud *et al.*, 1999) and the U.K. (Bradford *et al.*, 2002).

- HSPF (Bicknell *et al.*, 2001) is a continuous watershed simulation model that produces a time history of water quantity and quality at any point in a watershed. HSPF includes components that predict pesticides, conservative components, fecal coliforms, sediment, nitrogen, phosphorus, phytoplankton and zooplankton. This model has typically been used for assessing land use changes, reservoir operations and point and NPS pollution abatement (Migliaccio *et al.,* 2007). HSPF is based on the original *Stanford Watershed Model IV* (Crawford and Linsley, 1966). In addition, HSPF is a combination of the model *Agricultural Runoff Management* (ARM) (Donigian and Davis, 1978), the model *Nonpoint-Source Runoff Model* (NPSM) (Donigian and Crawford, 1976) and the *Hydrologic Simulation Program* (HSP, Hydrocomp, 1977; Donigian and Huber, 1991; Donigian *et al.*, 1995). There are many published applications of HSPF in the U.S. (e.g., Johnson *et al.*, 2003; Saleh and Du, 2004) and throughout the world, for example, in China (Chen *et al.*, 2004), Ireland (Nasr *et al.*, 2007) and Turkey (Albek *et al.*, 2004). Also in the U.S., HSPF has been incorporated as a NPSM into the *USEPA's Better Assessment Science Integrating Point and Nonpoint Sources* (BASINS), (Lahlou *et al.*, 1998).

- The model SWAT (Arnold *et al.*, 1998) was developed at the USDA-ARS. It emerged mainly from SWRRB (Arnold *et al.*, 1990) and features from CREAMS (Knisel, 1980), GLEAMS (Leonard *et al.*, 1987), EPIC (Williams *et al.*, 1984) and ROTO (Arnold *et al.*, 1995a). It was developed to assist water resources managers in predicting and assessing the impact of management on water, sediment, and agricultural chemical yields in large un-gauged watersheds or river basins. The model is intended for long-term yield predictions and is not capable of detailed single-event flood routing. It is an operational or conceptual model that operates on a daily time step (Borah *et al.*, 2003). The model has eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management. Although most of the applications of SWAT have been on a daily time step, recent additions to the model are the Green and Ampt (1911) infiltration equation using rainfall input at any time increment, and channel routing at an hourly time step (Arnold, 2002). Applications of the SWAT model are numerous and were previously identified by White and Chaubey (2005). In addition, SWAT has been implemented internationally, e.g., in Greece (Gikas *et al.*, 2006), Ireland (Nasr *et al.*, 2007), and Switzerland (Abbaspour *et al.*, 2007).

- GIBSI (Villeneuve *et al.*, 1998a) was developed at INRS-ETE (Mailhot *et al.*, 1997; Villeneuve *et al.*, 1998b; Rousseau *et al.*, 2000). GIBSI is designed to help stakeholders to make decisions in water management at the watershed scale. It can either be used as a data management system or as an impact assessment tool to study the effects of management scenarios on surface water quality using mathematical models (Quilbé and Rousseau, 2007). The model simulates continuous hydrology, erosion, pollutant transport and surface water quality at a daily time-scale. In addition to the modification of soil erosion and transportation components of sediment in GIBSI, Duchemin (2000) has developed a model named MODÉROSS. This model addresses the three main components of the tear-off, transportation and sedimentation of eroded materials. As compared to the abovementioned models, while the AGNPS (USDA, 1998) and EPIC (Williams, 1995) use, in part, the algorithms of USLE/RUSLE in their water erosion module, the model MODÉROSS was developed on the basis of these models and by adding some special notes from other models (*e.g.* transport capacity) (Duchemin, 2001). A detailed description of the model will be given in Chapter 3.

Borah *et al.* (2003) admits that single storm event models, such as AGNPS, ANSWERS or DWSM, are needed for analyzing severe actual or design single-event storms and evaluating watershed management practices, especially structural practices. It is recognized that the conceptual design and mathematical formulations of these models use one time step (storm duration) and generate a single value for each of the output variables (such as runoff volume, peak flow, sediment yield, and average concentrations of nutrients). These models can be used to study the overall response from a single severe or design storm, but they are not suitable for analyzing a storm during which the flow and constituent concentrations and loads vary drastically.

The continuous simulation models are considered useful for analyzing long-term effects of hydrological changes and watershed management practices, especially agricultural practices. The models AnnAGNPS, ANSWERS-continuous, HSPF, SWAT and GIBSI are in this group. These models, however, are not adequate for simulating intense single-event storms due to: the use of daily time steps (SWAT, GIBSI), the conceptualization of the overland (sub-basin) areas as leveled detention storage and the use of the storage-based or nonlinear flow equations in routings (HSPF, AnnAGNPS and ANSWERS-continuous) (Borah *et al.*, 2003).

2.3 Model calibration and validation

2.3.1 General

Calibration involves comparing predicted values to measured values and assessing the difference between the two, with the objective of minimizing the differences through the appropriate adjustment of parameters or inputs. Validation is carried out after calibration and consists in comparing the simulated values to measured values for a new set of data (not used for this calibration) without adjusting parameters or data entry (Migliaccio *et al.,* 2007).

Watershed model boundaries are defined by hydrologic considerations, and the model structure is generally designed for representing the components of the hydrologic cycle (Migliaccio *et al.,* 2007). The most historically common component included in hydrologic calibration-validation is the comparison of predicted and measured downstream flows. A more comprehensive flow calibration-validation is presented in modeling applications that include base flow, surface runoff flow, and total flow (e.g., White and Chaubey, 2005; Srivastava *et al.*, 2006). The inclusion of multiple variables in the calibration process has also led to further development of global sensitivity analyses (Van Griensven *et al.*, 2006) and automated multi-objective calibration methods (Bekele and Niklow, 2007; Confesor and Whittaker, 2007). Predicting and calibrating multiple outputs from a watershed model leads to the identification of a multi-objective function for watershed modeling applications. Multi-objective functions provide optimization criteria for multiple-modeling objectives in a mathematical form (Yan and Haan, 1991; Gupta *et al.*, 1998; Yapo *et al.*, 1998).

Concerning the calibration of soil erosion models, several comparisons and evaluations of soil erosion and sediment transport models have been made at both field-scale and catchment-scale. Victor (1999) has conducted a study on the evaluation of field-scale and catchment-scale comparing 14 models to determine the suitability of modeling approaches for the estimation of soil erosion under global change. His study has led to some suggestions and recommendations as summarized bellow:

- In referring methods for model calibration, especially for catchment-scale models, the dataset was divided into training (with calibration) and validating (without calibration) sets. Calibrations were done focussing on the hydrological part of the model, mostly by the visual fitting of the hydrograph when possible and otherwise on the discharge total.
- For the model comparison, the study applies a simple method to compare only the main output variables such as total discharge (m^3), peak discharge, and total sediment (ton) with a relatively coarse time step (1hour-1day) for continuous simulation models, and a small time step (< 1 min) for single event models.
- Concerning the model errors at a daily time scale, simulated and measured daily values of runoff and soil loss show a wider scatter than monthly results, and a poorer fit for soil loss compared with runoff.
- Data quality has a strong impact on results. Results for testing datasets were generally poorer than results from the training sets: calibration thus appears to have improved results noticeably (cf. Favis-Mortlock *et al.*, 1996).
- The term "soft information" (qualitative information) was also emphasized as an important factor in carrying out calibration. Knowledge related to the agricultural activities, degree of soil structure change in the given climatic context and a general feel for the soils and relief are imperative to improve the results.
- Concerning temporal error accumulation, models generally do better at estimating long term (*i.e.* multi-year) averages. Findings are less clear when the estimation of results for a particular time period (*e.g.*, a year, month or day) is considered.
- Concerning the spatial error, erosion modeling is very error prone. The total discharge often constitutes only a small percentage of the rainfall. Given that the spatial variability of the rainfall is largely ignored, and that the spatial variability of infiltration-related variables is difficult to handle on the scale of observation, the resulting runoff always has a high degree of error. As this error may accumulate in certain places or level out in others inside the catchment, the net water and sediment output also have a high degree of uncertainty. There is room for some improvement if observed runoff patterns could be compared to predicted runoff maps, so that at least the runoff contributing areas can be checked.

- The un-calibrated use of catchment models is not advisable. Calibration is imperative for small- and medium-scale catchment applications (10–1000 ha), where the spatial variability of the runoff and erosion processes strongly influences the simulation.
- Even in a catchment for which the model is calibrated, it is not sure that the model will have a good predictive quality if the event lies outside the range of calibration events.
- Results improve if more data are available about agricultural activity (including runoff routing aspects) and the interaction between climate and soil surface. These data can be descriptive in nature, as it helps the modeller construct the database.
- Finally, modellers tend to emphasize the successful part of the simulation only, while much more can be learned from the difficulties encountered.

2.3.2 Applications of the calibration and evaluation of distributed watershed models

Various approaches have been applied by modeling experts for the sensitivity and uncertainty analysis (Beck, 1987; Haan et al., 1998), the evaluation and the calibration of distributed watershed model. This section provides a brief review of studies related to models that contain both processes of sedimentation and sediment transport in river.

Regarding the calibration of watershed models, several methods have been applied in different studies with applications on different watershed models. These methods are:

- Multi-objective global optimization method. The method provides a set of solutions that can match the important characteristics of the observed data at a single site (Yapo *et al.*, 1998). This method was applied by Li Xuyong *et al.* (2010) for the calibration of the General Watershed Loading Function (GWLF) at the Rhode River Basin, in Maryland, United States. In this study, the method is applied for multi-sites in which the model parameters for stream flow and the loads of sediments were first estimated using multi-objective optimization at each calibration site, and then finalized by weighted averaging the parameter values across sites. The weight for each site was calculated from the prediction error at that site.
- Non-dominated Sorting Genetic Algorithm (NSGA) and NSGA II (Srinivas and Deb, 1994), is a multi-objective optimization algorithm used to develop an automatic calibration routine. NSGA-II is one of the contemporary multi-objective evolutionary algorithms that exhibit the highest performance and it has been widely applied in various disciplines. Some of the recent applications include optimal design of water distribution networks, long-term groundwater monitoring design and watershed water quality management (Bekele and Niklow, 2007). The NSGA-II was applied for the automatic calibration of daily stream flow and sediment concentration in the SWAT model (Bekele and Niklow, 2007).

- Genetic Algorithms (GA) are stochastic search procedures inspired by the evolutionary biology of natural selection and genetics, such as inheritance, mutation, selection and crossover. GAs have been successfully applied to solve complex nonlinear programming problems in many science and engineering branches (Reca and Martínez, 2006).
- Shuffled Complex Evolution Algorithm (SCEA) (Duan *et al.*, 1992) belongs to the family of genetic algorithms. This method was applied to test the possibility of an automatic calibration of the SWAT model. The model was calibrated against measured daily runoff data.
- Bayesian Model Averaging (BMA) is a standard approach to infer in the presence of multiple competing models (Raftery and Zheng, 2003). This approach has been used to infer probabilistic predictions that possess more reliability than the original ensemble members produced by several competing models (Duan *et al.*, 2007). In BMA, the probabilistic distribution of a hydrologic prediction is the weighted average of the posterior distribution of each model under consideration. For the calibration and uncertainty analysis of the SWAT model, Zhang *et al.* (2009) first selected several SWAT models with different structures. Next, GAs were used to calibrate each model using observed stream flow data. Finally, BMA was applied to combine the ensemble predictions and provide uncertainty interval estimations.

Concerning the sensitivity of a distributed watershed simulation model to spatial scale, Muleta *et al.* (2007) have conducted a detailed sensitivity analysis of the SWAT model in the Big Creek watershed, Southern Illinois, United States. Concentrated on both overland sedimentation and channel transportation processes, this study extracted and compared simulated data of stream flow and sediment concentrations at different spatial scales. Its key findings include two aspects. First, stream flow and its components such as surface runoff, lateral flow, and ground water flow are relatively insensitive to spatial scale. Second, parameters derived from topography, soil, and land use are equally responsible for the model's sediment generation behaviour, whereas channel properties (*e.g.* slope and length) along with topography, soil, and land use properties are responsible for sedimentation processes in the channel.

2.4 Adaption, calibration and evaluation of erosive parameters in the USLE soil erosion model

The USLE model is an empirical model for the assessment of soil erosion, mainly used to plan the control of soil erosion. The USLE model was created from erosion plots and rainfall simulation experiments. It is composed of six factors to predict the average soil erosion in the long term (Wischmeier and Smith, 1978). The model equation was simplified as follows:

$$A = R\,K\,LS\,C\,P \qquad (2.1)$$

Where: A: soil erosion rate (t/ha);

R: climate factor (erosivity) (MJ mm / ha h);

K: soil factor (erodibility) (t h / MJ / mm);

LS: topographic factor (slope length and slope angle) (no unit);

C: vegetation factor (no unit);

P: soil management practice factor (no unit).

Methods for estimating the value of each of these parameters will be described briefly in the following sections.

2.4.1 Erosivity

The R factor, introduced by Wischmeier and Smith (1958), was the product of rainfall energy and the maximum 30-min intensity divided by 100, known as the EI_{30} index. The soil erosion index concept is used in the USLE as a numerical description of the potential of rainfall to erode soil (Wischmeier, 1959). On an annual basis, R is the sum of values over the storms in an individual year (Haan *et al.*, 1994):

$$R = \Sigma\, EI_{30}/100 \qquad (2.2)$$

Foster *et al.* (1977) proposed to replace the factor of rain erosivity (R) with a governing factor (R_t), which also reflects the runoff erosivity by taking into account the two components of erosivity (rainfall erosivity and overland flow). Richardson *et al.* (1983) developed a method to estimate the erosion index from daily rainfall data considering seasonal and spatial relationships between daily soil erosivity R_{ji} and daily precipitation P_{ji}, (Equation 2.3). Daily rainfall data collected from 22 locations in the U.S. were used to evaluate the following relationship:

$$R_{ji} = aP_{ji}^{b} + \varepsilon \qquad (2.3)$$

where a and b are adjustment parameters, aP_{ji}^{b} is the deterministic component and ε is the random component of the relationship.

The random component ε for a given observation is the difference between the observed R for a given event and the predicted R using the deterministic portion of Equation 2.3. Parameter a was used to determine the seasonal relationship and b was used to represent the spatial relationship for each month of the year for 11 locations in the U.S. Obtained results showed that there is no spatial pattern detected in the variation of b. Consequently, b is assumed as a constant for all locations with an average value of 1.81. The results also showed that a varies with seasons. Its value is higher in summer months and lower in winter months.

Several other studies have been done in different geographic locations to estimate a and b values. The exponent b can take the mean value of 1.81 from studies in different regions with long recorded daily rainfall data such as: a) 11 locations in the United States (Richardson *et al.,* 1983), b) 23 locations in the Eastern and central U.S. (Haith and Merrill, 1987; Sheridan *et al.*, 1989; Bullock *et al.*, 1990); Elsenbeer *et al.,* 1993); c) 8 stations in Finland (Posch and Rekolainen 1993); and d) 32 stations in Sicily, Italy (Bagarello and D'Asaro 1994). This value can however be adjusted within a range from 1.50 to 2.20 (after Richardson *et al.,* 1983; Haith and Merril, 1987; Posch and Rekolainen, 1993; Bagarello and D'Asaro, 1994).

Seilker *et al.* (1990) state that coefficient a presents more important spatial and temporal variations than b. Their procedure for calibrating the model for rainfall erosivity, based on long recording daily rainfall in 33 sites in Eastern and central locations in the U.S., has suggested the use of two different a values: one for the cold period (a_f), and the other for the warm period (a_c). Studies on a_f and a_c calibration were also made for different locations in the U.S., Canada, North and South Europe. Within locations in the U.S., a_f and a_c respectively vary between 0.06 - 0.33 and 0.13 - 0.79 (Richardson *et al.,* 1983); within locations in central U.S. they vary, respectively, between 0.09 - 0.36 and 0.24 - 0.56 (Haith and Merril, 1987). In the Quebec region, where GIBSI and its MODEROSS model were applied, a_f and a_c values for different stations were evaluated to vary respectively from 0.099 to 0.107 and from 0.184 to 0.191 (Duchemin, 2000). For locations in Finland, estimated a values vary within 0.67 - 4.66

for the frost free period only (April to October). For locations in Sicily, Italy (Mediterranean area), *a* values were reported to vary only slightly between seasons. Its seasonal variation was therefore neglected. The mean *a* value estimated for this area is 0.332 (Bagarello and D'Asaro, 1994).

It is worth noting that the abovementioned studies on the estimation and calibration of the daily rainfall erosivity, with a_f and a_c seasonal variations, are all based on the use of long recordied data of 30-min maximum rainfall intensity. Applying these methods to watershed which do not have this type of recorded data, like the Cau River Basin, would be a big challenge.

2.4.2 Soil erodibility

In the USLE model, *K* is assumed to be constant throughout the year. Its values are also tabulated in the more recent soil survey manual (Hann *et al.*, 1994). The following relationship, proposed by Wischmeier *et al.* (1971), is often used to predict soil erodibility:

$$K = \frac{2.1\times10^{-4}(12-OM)M^{1.14}+3.25(S_1-2)+2.5(P_1-3)}{100} \times 0.1317 \qquad (2.4)$$

Where K = mean annual soil erodibility (ton h/MJ/mm), OM = % organic matter, P_1 = permeability index, S_1 = structure index and M = function of the primary particle size fractions. The values of these parameters depend upon soil texture of the area where K was estimated.

To meet the requirement for daily time scale estimates in several soil erosion models, seasonal variations of *K* values were taken into account. Mutchler and Carter (1983) have shown in their study that soil erodibility varies with antecedent moisture and freezing/thawing. When averaged over a number of years, freezing/thawing and high antecedent moisture conditions tend to occur on a predictable basis (Hann *et al.*, 1994). In the RUSLE model, a procedure was developed to account for this variability based on the correlations between annual soil erosivity (*R* factor) and the ratio K_{max}/K_{min} on the one hand, and the correlation between the frost-free period Δ_t and t_{max} (time of maximum erodibility) and t_{min} (time of minimum erodibility) on the other hand. Detailed explanations of daily *K* estimation are given in chapter 3.

Several efforts have been made to estimate the seasonal and regional variations of soil erodibility in different geographic conditions. One of the studies has acknowledged the evidence of a strong climate effect on seasonal variation of soil erodibility (Sanchis *et al.*, 2008). This last study used monthly K values in different climate zones extracted from literature and regression models to analyze climate effects on the susceptibility of soils to water erosion. However, it failed to explain the K variation in tropical climates where the mean monthly temperature does not vary significantly during the year, as in the Cau River Basin.

2.4.3 Topographic factor

Both the length and steepness of the land substantially affect the rate of soil erosion by water. The two effects have often been evaluated separately and are represented in the soil loss equation by L and S. In applications, however, considering the topographic factor, LS, is more convenient (Wischmeier and Smith, 1978):

$$LS = \left(\frac{\lambda}{72.6}\right)^m (65.41\, sin^2\theta + 4.56\, sin\theta + 0.065) \qquad (2.5)$$

where λ is slope length in feet, θ is angle of slope and m = 0.5 if slope is 5% or more, 0.4 on slope of 3.5 - 4.5%, 0.3 if slope is 1 - 3%, and 0.2 on gradients of less than 1%.

For slope lengths greater than 15 ft, the S factor from USLE was modified significantly in RUSLE by McCool *et al.* (1987, 1993). It was modified as the result of an extensive re-evaluation of the original database, the addition of the factor for short slope lengths and new values for thawing soils.

The slope length factor was developed by McCool *et al.* (1989, 1993), from the original USLE database and enhanced with theoretical considerations. McCool *et al.* (1987, 1989) have introduced three cases to estimate the slope length exponent for three levels of rill / interill relations (weak, moderate and high) in association with typical soil types in each level. Additional explanations can be seen in chapter 3.

2.4.4 Soil cover management

Cover management effects cannot be independently evaluated because their combined effect is influenced by many significant interrelations (Wischmeier and Smith 1978). It accounts for the effect on soil erosion of (1) cover above ground, (2) ground cover, (3) root mass, (4) incorporated residue, (5) surface roughness, and (6) soil moisture (Haan *et al.*, 1994).

The values of C can generally be divided into two main groups, namely (1) for agricultural land and (2) for non-agricultural land. The simplest approach to define factor C is to use values calculated by Haan *et al.* (1994). For non-agricultural land, such as construction sites, mines and urban areas, the values of C can be obtained from tabulated values (Wischmeier and Smith, 1978; Transportation Research Board, 1980; McKendry *et al.,* 1992; Haan *et al.*, 1994).

Quantitative assessments of the effects of cultivation and management areas were introduced in the USLE model by Wischmeier and Smith (1978) for agricultural conditions in the United States. This sub-factor approach was fully developed and used in the RUSLE model to account for prior land use, canopy, surface cover, surface roughness, and soil moisture (Equation 2.6). Similarly, the procedure of the RUSLE model allows for estimating systematic interactions between soil and plant properties that affect soil erosion. However, the procedure is computationally intensive and requires the use of a computer for running applications (Haan *et al.*, 1994). In RUSLE, the C factor is computed using the following equation:

$$C=C_{plu}C_{cc}C_{sc}C_{sr}C_{sm} \tag{2.6}$$

where C_{plu} is the prior land use factor, C_{cc} is the canopy cover sub-factor C_{sc} is the surface cover sub-factor, C_{sr} is the surface roughness sub-factor and C_{sm} is the soil moisture sub-factor.

The importance of factor C, its effects on erosion calculations (Pierce *et al.*, 1986), and adaptations for different geographical conditions have received abundant attractions from scientists (Komas *et al.*, 1997; García-Ruiz *et al.*, 1995; Martinez-Mena *et al.*, 1999; Tiwari *et al.*, 2000). A certain number of studies have been done to adapt C values to other local crop rotation conditions (Lagacé, 1980; Villeneuve *et al.*, 1998a) and to local specific plant types (Mckendry *et al.*, 1992; Li, 2002).

Employing USLE into watershed models has raised an issue of uncertainty in parameters characterizing erosive factors. For example, uncertainty in parameters characterizing different land covers can lead to uncertainty in model predictions of land use change effects (Eckhardt *et al.*, 2002). The study of Eckhardt *et al.* (2002) has ensured that even in a context of uncertain parameters, we can significantly detect different soil covers according to their effect on simulation results. For this last study, an artificial basin of two square kilometres was built in Germany and the model SWAT-G was applied. The model of the artificial basin was calibrated by comparing the calculated flow output with monthly observations over a period of six years.

2.4.5 Soil conservation support practice

The conservation practice factor is typically used only for agriculture land and rangelands, but could be used with some caution for construction and disturbed lands (Haan *et al.,* 1994). As for the *C* factor, a first approximation of the *P* factor can be determined using tabulated tables from the USLE database. This can be used for first or rough estimates. For estimates allowing for a more detailed consideration of a variety of combined practices, a sub-factor approach from the RUSLE can be applied.

Tabulated values for *P* from the USLE database are available for agriculture practices of contouring, strip cropping and contour terracing (Wischmeier and Smith, 1978; Haan *et al.*, 1994). The RUSLE model is an alternative to the tabulations of USLE with the use of a sub-factor analogy:

$$P = P_c P_{st} P_{ter} \qquad (2.7)$$

where P_c is the contour sub-factor, P_{st} is the strip cropping sub-factor and P_{ter} is the terracing sub-factor.

The use of this sub-factor analogy, according to Haan *et al.* (1994), allows for a more detailed evaluation of factors affecting *P*, particularly when considering a combination of practices.

The contour *sub-factor accounts* for the impact on soil erosion of tillage on the contour. Foster *et al.* (1983) developed sub-*P* factors, which include parameters quantifying the effectiveness of contour cultivation (size of ridge-furrow storage system, slope, degree of cross-contour component of the tillage marks, runoff amount and peak runoff rate). *P* values for contouring are given in terms of slope, depending on whether it exceeds or not the critical slope length (Foster *et al.*, 1983; Haan *et al.*, 1994).

Concerning the cropping conservation support factor P_{st} (the use of alternating strips), the effectiveness of the strip depends on the strip width and slope, and on the type of tillage. Using CREAMS equations, Foster *et al.* (1983) developed a computational procedure that is included in the RUSLE program. They also published typical sub-factor values for selected strip crops and buffer and filter strips (Haan *et al.*, 1994).

Terracing support (factor P_{ter}) corresponds to the making of terraces to collect flows from slopes and divert them to a stabilized waterway or to closed outlet, thus preventing them from having excessive slope lengths and, thereby, reducing soil erosion.

Terraces reduce sediment yield in two ways: by decreasing the slope length and by allowing deposition in the terrace channels. Foster and Highfill (1983) developed factors to account for the effects of terraces on soil loss and also for deposition in channels. In the RUSLE model, the two factors are considered separately. The impact of slope length is included in the *LS* factor. The effects of deposition are included in the terracing factor. The impact of terraces on the loss of soil from the slope is reflected in the slope length factor calculation based on the terrace spacing (Haan *et al.*, 1994).

2.5 Studies on the application of soil erosion models into specific climatic regions

Several studies on the characterization of factors affecting soil erosion in tropical climate have been done in different regions. They are focussed on several aspects such as: soil properties, including the stability of soil aggregation in South West of Mexico (Cotler *et al.*, 2006), land use and land cover in Vietnam (Vézina *et al.*, 2006; Podwojewski *et al.*, 2008), seasonal soil erodibility in Indonesia (Sanchis *et al.*, 2008), variability of organic carbon on steep tropical slopes in Laos (Chaplot *et al.*, 2009), under the overall hot and humid climatic conditions encountered in tropical regions.

A single study, to our knowledge, attempted to empirically reformulate the USLE model to estimate the risk of soil erosion in a tropical watershed (Cohen *et al.*, 2005). The study used 420 geo-referenced observations of soil erosion. It analyzed the relationship between the risk predicted by the USLE model and observed erosion using logistic regression. The results of the study, performed on a portion of the drainage basin of Lake Victoria in Kenya, only demonstrated that un-validated applications of the USLE model may fail to adequately identify regions with the highest needs for intervention, suggesting that USLE should not be applied in its standard form without an explicit ground survey based local calibration.

Generally, some studies concerning the application of soil erosion models have already been conducted under specific tropical conditions. Models of soil erosion and watershed management, including components of the USLE model, have also been used in studies on soil erosion under tropical conditions. However, although some of these studies have acknowledged the uncertainty associated with the models when applied in such circumstances, this uncertainty has not yet been formally studied. The "tropicalization" of models, as well as the adaptation of the coefficients of erosion, therefore remain issues for further studies.

2.6 Studies on soil erosion modeling and watershed scale management in Vietnam

The USLE model was first introduced and applied in scientific researches in Vietnam in the 1980s (Nguyen, 2005). Since the late 1990s, when software for remote sensing and geographic information systems (GIS) became common, the use of the USLE model has been extended.

Over the last decade, Vietnamese literature has focussed on the calculation of soil erosion over large areas. Most of the studies on spatial and quantitative erosion do not reflect the impact of agriculture or the diversity of land use, particularly at the catchment scale, or the impact of the annual variability of seasonal factors on the vulnerability to soil erosion and, by extension, the dynamics of landscapes (Vezina *et al.*, 2006).

A limited number of watershed models have been applied on Vietnam's watersheds, for example the model MIKE for the Central region (Ngo *et al.*, 2009). Some of the previous studies concerning the application of the USLE model in Vietnam tend to avoid considering factors *C* and *P*. They only use available databases (e.g., DEM), GIS tools and remote sensing and interpolation methods to estimate factor maps such as *K*, *LS* and *R* maps to produce, ultimately, a so-called "potential" map of soil erosion for the whole country (Tran *et al.*, 1998) and for the Chay River Basin (Nguyen, 2009). Additionally, studies for componential maps of erosive parameters from USLE have been done so far for the *K* factor (Nguyen, 2011a) and for the *R* factor (Nguyen, 2011b) in the Cau River Basin.

Tran *et al.* (1998) introduced a country map of the potential soil loss volume based on USLE but excluded the calculation of factors *C* and *P*. This study specified nine classes of potential soil loss volumes which vary correspondingly from less than 50 to over 4500 ton/ha/year. According to this result, the potential soil loss volume for the Cau River Basin varies mainly within classes 1 to 5 (< 50 to 800 ton/ha/year), decreasing from North to South, and from East and West to the center of the basin, following its elevation pattern. In some small areas along the Tam Dao mountain (SW of the basin), the estimated soil loss volume can reach class 6 (up to 3,200 ton/ha/year). A summary of this study is presented in Appendix 2.1.

More recently, Le *et al.* (2011) have introduced a study on the estimation of soil erosion in a watershed, on the highland area of Vietnam. The study uses available spatial analysis modules in the GIS software and the USLE algorithm to estimate and compare the potential and practical soil loss in the basin. The study emphasizes the role of surface land cover on the reduction of soil loss rate. Its result shows an average potential soil loss of 133 ton/ha/year, compared with the practical soil loss rate estimated based on existing land use of 18 ton/ha/year.

In general, the limitations in the application of soil erosion and water management models in Vietnam indicate some of the following main aspects:

First, there is a lack of data, which probably prevents the studies from yielding results that can give a complete picture of soil erosion, as requested in the USLE model.

Second, local scientists tend to apply models the simplest way with the data they have in hand, using GIS computer tools, while neglecting the importance of parameters that require essential local information to use a model. As an example, the exclusion of human-related factors in the calculation of soil erosion (*e.g.* *C* and *P* in USLE) has limited a lot the practical use of modeling works.

Third, the application of models is still at a raw stage. Simulations are made without any adaption and calibration, and without considering spatial and temporal variability.

Finally, the need for a systematic study on the application of models of soil erosion in integrated management modeling systems has not been properly emphasized by local scientists or decision makers. Recent international cooperation projects, such as the projects in 1) evaluation of the potential risks caused by the degradation of surface water in urbanized zones on Nhue-Day River with the *Centre national de la Recherche Scientifique - -CNRS - France* (CNRS, 2001), and 2) Intergrated managerment of the Cau River watershed with the *Institut National de la Recherche Scientifique* (INRS) Quebec, Canada (INRS, 2010), seem to promise the opening of a new millennium for studies on soil erosion and watershed management in Vietnam.

3. Review of modeling tool and study area

This section concentrates on a detailed review of the two main parts that are considered as the basic conditions for this thesis work. They are: 1) the existing models of soil erosion and sediment transportation on river of the GIBSI system (section 3.1), and 2) the local conditions and data availability of the Cau river watershed where the models are intended to be applied (sections 3.2 and 3.3). Finally, from analyses of the existing conditions, imagination of technical requirements and orientations for application, adaption and modifications of the existing models to meet local conditions of the Cau river watershed will be discussed in the section 3.4.

3.1 Modeling tool: the GIBSI system

3.1.1 General structure of GIBSI

GIBSI (*Gestion intégrée des bassins versants à l'aide d'un système informatique*) is a watershed-based software system for the integrated management of surface water. The effects of agricultural, industrial and municipal management scenarios can be analyzed with GIBSI (Rousseau *et al.*, 2000). As a decision support system, GIBSI has been designed to assist two types of users: water resources managers (decision makers) and technical experts. GIBSI is composed of a watershed database, daily time step physically-based simulation models for several physical processes and a geographical information system GIS (Eastman et McKendry, 1991). Typical data stored in the database include spatial and attribute data (digital elevation model, soil characteristics, meteorological data, gauge locations, crop management, livestock production, etc.). GIBSI is a modular model, which means that the system allows, if necessary, for the integration of new system components or the replacement of existing ones (Rousseau *et al.,* 2000).

GIBSI can be used to assess the effects of different management scenarios (reservoirs, land use, waste water treatment plants, diffuse pollution, etc.) on watershed hydrology, erosion and water quality (Quilbé *et al.*, 2007). It provides a means to identify the river segments which may be suitable for specific water uses, allows comparing intervention scenarios in terms of their impacts on hydrology and water quality and thus provides a rigorous basis for decision making. Additionally, if an *in situ* assessment of the ecological integrity of several river segments is known, the simulated variables from GIBSI may be used to complement the ecological assessment of a watercourse. If more data regarding the physical characteristics of a stream segment (riparian vegetation, land use, sinuosity, etc.) are available, GIBSI can also be used to study the impact of human-induced stresses and their consequences on stream habitat (Rousseau *et al.*, 2000). GIBSI simulation models and their short descriptions are summarized in Appendix 3.1.

3.1.2 Componential models in the GIBSI system

GIBSI was built with four main componential simulation models. They are: (1) hydrology; (2) soil erosion; (3) nutrients and pesticides transport (agricultural chemicals); and (4) water quality in rivers (Figure 3.1).

The hydrological model HYDROTEL is a distributed and physically-based model (Fortin *et al.*, 1995, 2001).

The soil erosion model was initially RUSLE, the revised version of USLE (Universal Soil Loss Equation) (Wischmeier and Smith, 1978). RUSLE was coupled with Yalin's (1963) sediment transport model to estimate soil erosion by water and the inherent sediment transport by runoff. Later, Duchemin (2000) introduced MODÉROSS, a soil erosion model coupled with ROTO, an algorithm of sediment transport in rivers (Arnold *et al.* 1995a).

The transport and transformations of agricultural chemicals are based on the modeling of nitrogen, phosphorus and pesticides. The chemical transport model uses algorithms from the SWAT (Arnold *et al.*, 1995b) and EPIC (Williams, 1995) models. Finally, QUAL2E (Brown & Barnwell, 1987), a standard water quality model, was adapted for water quality modeling. Appendix 3.1 shows a table presenting the componential models and features included in GIBSI.

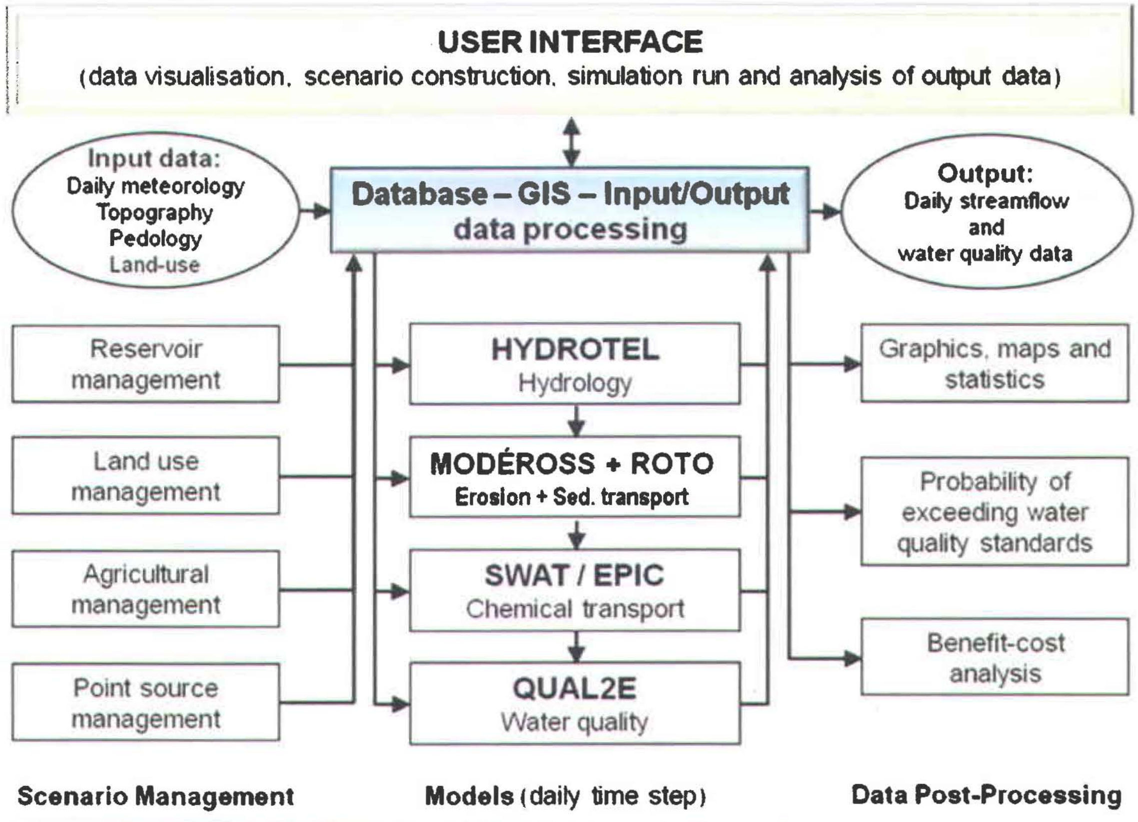


Figure 3.1: GIBSI components and structure (after Rousseau *et al.*, 2000).

3.1.3 Scenarios

In GIBSI, the current state of the studied watershed is defined as the reference state / scenario. Management scenarios are defined by a set of variables and parameters characterizing a specific state (hypothetical or real) of the studied watershed. Management scenarios can be defined by modifying the values of variables and parameters of the reference scenario. The simulation models in GIBSI (with modified values) can therefore help assessing the impacts of different activities or management on river discharge, suspended solids and water quality. The interpretation of results is based on the comparison of different management scenarios and meteorological series with the reference state or other management scenarios (Mailhot *et al.*, 1997).

Management scenarios for the watershed can be obtained by changing parameters in any of the following elements:

- Point sources: wastewater treatment plants, industrial and municipal discharge points
- Agricultural production systems: number and types of livestock, crop management practices, application of fertilizers and pesticides, etc.
- Land use: different land use classes
- Hydraulics: addition or removal of reservoirs, hydraulic characteristics of dams, etc.

The possible management scenarios are inherently linked to the capabilities of the selected models. Appendix 3.2 presents a list of typical sets of scenario parameters that could be modified to create new management scenarios. For example, a possible land use management scenario would involve the specification of a modified distribution of watershed fractions of agricultural land and forested areas.

3.1.4 Soil erosion model and criteria for the selection of the soil erosion model in GIBSI

In GIBSI, the soil erosion model first constitutes an intermediate module which contributes to quantitative inputs from and to other models. For example, this model takes inputs from HYDROTEL (precipitation, runoff, etc.) and can give outputs to the chemical transport and water quality models (*i.e.* quantity of sediments). The soil erosion model also provides a means to setup the management scenarios and, in turn, reflects the quantitative changes when scenarios are applied.

Concerning the first aspect, the soil erosion model employs input data (meteorology, topography, pedology, land use) and hydrological data (river network, runoff) to present the current state of *in-situ* soil erosion and its capacity to transport it downstream. Simulated results from the model can then be exported as inputs to other models (chemical transport and river water quality models).

As for the second aspect, the model allows for the direct application of management scenarios concerning agriculture and land use (two of the four main considerations to set management scenarios) (Appendix 3.2), by adjusting the erosive parameters such as soil and crop management factors, and soil supporting practice factor.

The selection of the soil water erosion model for the GIBSI system was conducted in two stages (Villeneuve *et al.,* 1998a). First, a comprehensive set of criteria was considered, which led to the retention of only a limited number of specialized models among the vast quantity of existing erosion models. These criteria were: (1) appropriate documentation and code availability, (2) modeling of the processes involved, (3) simplicity of models, (4) mechanistic modeling approach. Second, three crucial points were considered in the selection process of the erosion model to be integrated to the GIBSI system: (1) compatibility of the model with other GIBSI models, (2) compatibility of the model for the establishment of agricultural scenarios; (3) availability of input data.

The base soil erosion model USLE (Wischmeier and Smith, 1978) was targeted to act as the soil erosion module of the GIBSI system. It was then brought into practice by the introduction of MODEROSS + ROTO (Duchemin, 2000). This choice allows for a better adaptation to the constraints imposed by other simulation models in GIBSI.

3.1.5 Soil water erosion model MODEROSS in GIBSI

The updated GIBSI uses the MODEROSS model (Duchemin, 2000, Villeneuve *et al.,* 2003) for soil erosion and transportation estimates. This model is based on the concept of production and transportation of sediments by runoff (Figure 3.2) (Villeneuve *et al.,* 1998a). Runoff is simulated from the hydrological model HYDROTEL (Fortin *et al.,* 1995) for each spatial unit (USS). The calibration of the HYDROTEL model with daily runoff data have been done for the Cau river watershed by Nguyen (2012). The soil erosion simulation, afterwards, allows evaluating the quantity of sediments that is produced on each USS as well as the quantity of sediments that can be transported to the river system from each soil spatial unit in the watershed. This simulation, moreover, works with the help of a soil water erosion model for which the main concept is based on the modified factors for daily time step of the RUSLE model. Sedimentation on the soil is taken into consideration based on a factor of stress-related transport capacity of overland flow and availability of eroded sediments. Introduction of the structure, processes and algorithms of the runoff model of HYDROTEL in GIBSI is shown in Appendixes 3.3 a, b and c.. The sample of simulated and calibrated result of HYDROTEL model for river discharge Q at Gia Bay station (1998-2006) is shown in Appendix 3.3 d

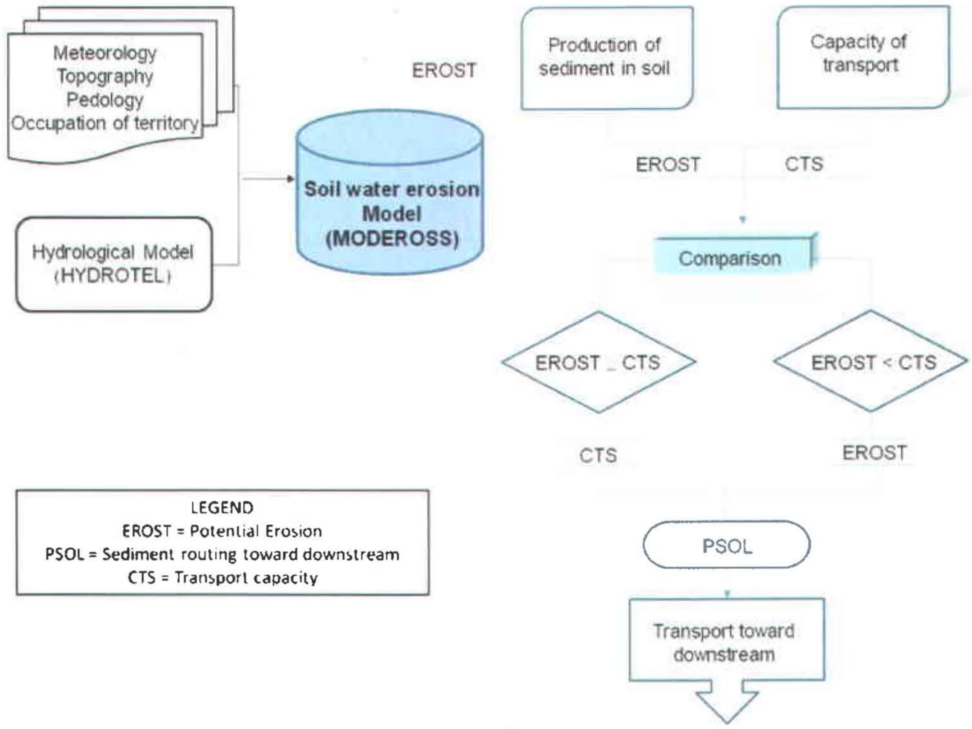


Figure 3.2: Structure of the soil water erosion model adapted by Duchemin (2000).

3.1.5.1 Soil erosivity factor R

Foster *et al.* (1977) proposed to replace the factor of rainfall erosivity (*R*) by a governing factor (R_t), which can take into account the two components of erosivity (rainfall erosivity *Rp* and resulting runoff *Rr*).

$$R_{tji} = R_{pji} + R_{rji} \tag{3.1}$$

$$R_{tji} = 0.646\, R_{pji} + 0.45\, c\, Q_{ji} {q_{pji}}^{0.333} \tag{3.2}$$

Where:

R_{tji} = total daily soil erosivity on element *i* (MJ mm/ha h).

R_{pji} = daily soil erosivity of precipitation on element *i* (MJ mm/ha h).

Q_{ji} = height of daily water flow on element *i* (mm).

q_{pji} = daily flow rate for element *i* (mm/h).

c = adjustment coefficient (MJ /mm ha).

The value of parameter R_{tji} can be obtained daily through the following relation (Lombardi, 1979; Bingner, 1990; Richardson *et al.,* 1983):

$$R_{pji} = a\, P_{ji}{}^{b} \tag{3.3}$$

Where:

R_{pji} = daily soil erosivity of precipitation on the element *i* (MJ mm/ha h).

P_{ji} = daily precipitation on the element *i* (mm).

a = adjustment coefficient (MJ / ha h).

b = adjustment coefficient.

Limits are imposed to R_{pji} as following:

$$R_{pji}(min) = P_{ji}{}^{2}(0.00364\ \log P_{ji} - 0.000062) \tag{3.4}$$

$$if\ P_{qi} \leq 38mm;\ P_{qi}(max) = P_{ji}{}^{2}(0.0291 + 0.1746\ \log P_{ji}) \tag{3.5}$$

$$if\ P_{qi} > 38mm;\ P_{qi}(max) = 0.566\ P_{ji}{}^{2} \tag{3.6}$$

Exponent ***b*** can take the mean value of 1.81, but can be adjusted from 1.5 to 2.2, according to Richardson *et al.* (1983), Haith and Merrill (1987), Bullock *et al.* (1990) and Posch and Rekolainen (1993). Coefficient ***a*** shows more important spatial and temporal variations. Seilker *et al.* (1990) proposed a method to estimate coefficient ***a*** under normal climate conditions. They suggested two values for *a*, in the year, one for the cold period (a_f for October to March) and one for the warm period (a_c for April to September). With the necessary meteorological data, it is possible to evaluate this seasonal coefficient for different meteorological stations (Villeneuve *et al.,* 1998a). In the Quebec region, where GIBSI was firstly applied, a_f and a_c values for different stations were also evaluated (Duchemin, 2000).

3.1.5.2 Formula of factor K

In GIBSI, the factor of mean annual erodibility (K_{asi}) was first evaluated by using pedological databases for soil series in the river basin, based on the equation below (Wischmeier and Smith, 1978; Foster *et al.*, 1981):

$$K_{asi} = \frac{\{[2.1[SL(100-AR)]^{1.14} * 10^{-4} * (12-MO) + 3.25(cs-2) + 2.5(cp-3)]\}}{100} * 0.1317 \quad (3.7)$$

where:

K_{asi} = mean annual soil erodibility on each unit *i* (ton h/ MJ mm).

SL = percentage (%) of very fine sand and silt (0.002 to 0.1 mm) = (SF + IL).

SF = % very fine sand or $[(\%SA)^{0.576} * (\%AR)^{0.06}]$ (Bernard, 1990).

IL = % silt (0.002 to 0.050 mm).

SA = % sand (0.050 to 2.000 mm).

AR = % clay (0.000 to 0.002 mm).

MO = % organic matter.

cs = soil structure code.

cp = soil permeability code.

When having only information for organic carbon content (% CO), MO can be approximated as follows:

$$MO = (\%\ CO)*1.72 \quad (3.8)$$

(the maximum MO for this approximation is 4%).

Equation 3.7 is valid only when the SL content (silt and very fine sand content) is inferior to 70%.

According to Vold *et al.* (1985), depending on the concentration of SL in the soil texture, the mean annual soil erodibility in each specified condition ($K_{asi\,mod}$) can be adjusted as:

$$\text{if } 70\% < SL < 80\% : \quad K_{asi\,mod} = K_{asi}\left[1 - 0.2\frac{(SL-70)}{10}\right] \quad (3.9)$$

$$\text{if } SL \geq 80\% : \quad K_{asi\,mod} = 0.08 * K_{asi} \quad (3.10)$$

In the presence of coarse fragments (> 2 mm) in soil, an adjustment is needed using the following equation:

$$K_{asi\,mod} = K_{asi}(0.983 - 0.0189\,X + 0.0000973\,X^2) \qquad (3.11)$$

Where:

X = ratio of coarse fragments > 2 mm (% / volume).

The variation of soil erodibility over a year due to climatic conditions was taken into account to meet the requirement for a daily time step in GIBSI. Young's procedure (1990) is therefore used to calculate the variation of the daily soil erodibility (K_{ji}) in GIBSI for each element / soil occupation (USS/occupation) (i) for each day (j) of the year (Figure 3.3):

$$K_{ji} = K_{max} \text{ when } K_{ji} > K_{max} \qquad (3.12)$$

$$K_{ji} = K_{min} \text{ when } K_{ji} < K_{min} \qquad (3.13)$$

if $t_i < t_{max}$, then $K_{ji} = K_{min} * e^{[0.0009\,(ti - tmin + 365);\; Kji \leq Kmax]}$

if $t_{min} \leq t_i \leq t_{max}$, then $K_{ji} = (K_{min}/K_{max})^{[(ti - tmax/\Delta t]}$

if $t_i \geq t_{min}$, then $K_{ji} = K_{min} * e^{[0.0009\,(ti - tmin)]}$

if $T_{moy} \leq -3^{\circ}C$, then $K_{ji} = K_{min}$

where:

$K_{max} = K_{asi}(3.0 - 0.003\,R_{an})$;

$K_{min} = K_{max}(3.0 - 0.003\,R_{an})$;

K_{max} = maximum annual soil erodibility.

K_{min} = minimum annual soil erodibility.

K_{asi} = mean annual soil erodibility.

R_{an} = mean annual rainfall erosivity.

t_i = day i of the year.

$t_{max} = 154 - 0.026\,R_{an}$

$t_{min} = t_{max} + \Delta_t$

T_{moy} = mean daily temperature.

Δ_t = frost free period of the soil.

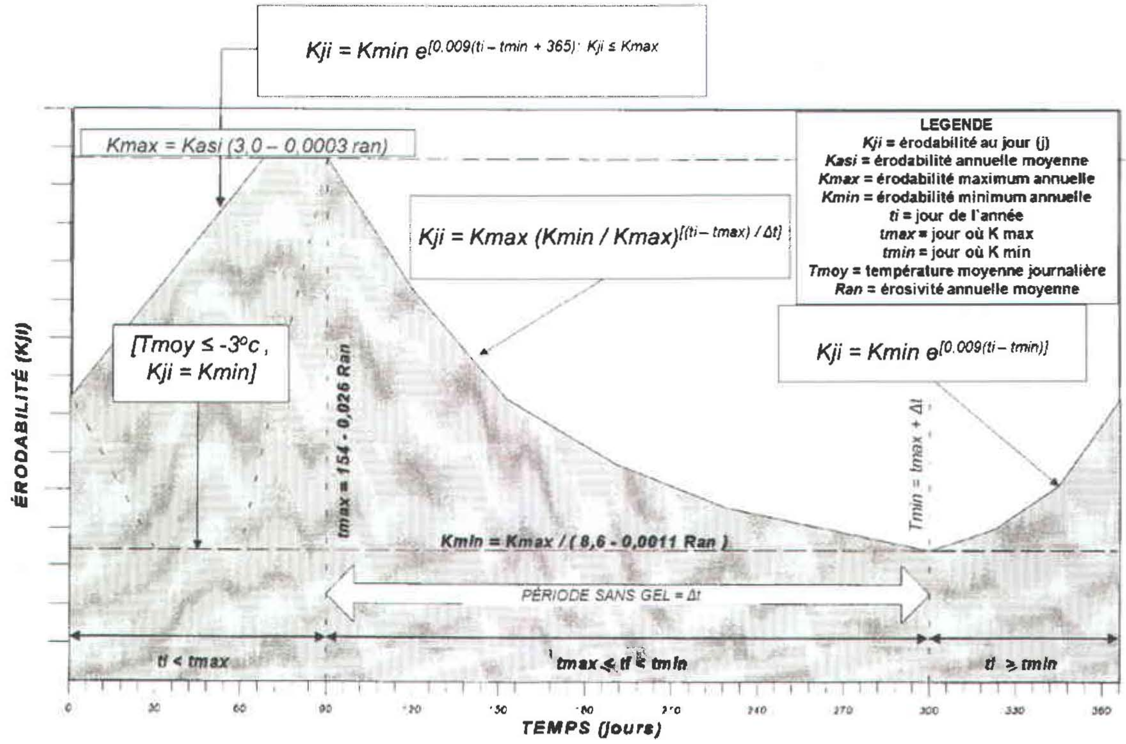


Figure 3.3: Procedure for evaluation of the seasonal erodibility originally applied in GIBSI (from Villeneuve *et al.*, 1998a).

In this procedure, the average annual erosivity (R_{an}) in the watershed is estimated using the following relationship (Ateshian, 1974; Madramooto, 1988):

$$R_{an} = R_p + R_h \tag{3.14}$$

Where:

$$R_p = 0.417(P_{2\text{-}6})^{2.17} \tag{3.15}$$

$$R_h = R_p\left(\frac{P_h}{P_a}\right) \tag{3.16}$$

R_p = annual erosivity of precipitations (MJ mm / ha h).

R_h = "winter" erosivity (MJ mm / ha h).

$P_{2\text{-}6}$ = 6 hour precipitation for a 2 year return period (mm) (Ateshian, 1974).

P_h = Total precipitation of months from December to March (mm).

P_a = total annual precipitation (mm).

When applying GIBSI in the region of Southern Quebec, the precipitation for a period of 6 h for a 2-year recurrence was obtained from Hogg and Carr (1985) and Ferland and Gagnon (1974). Data for P_h and P_a must correspond to the climate values averaged over a period of at least 30 years. In Canada, these precipitation data can be taken from the *Normales Climatiques au Canada 1961-1991* (Environment Canada, 1993). Therefore, Equations 3.12 to 3.16 allow obtaining, for each element (i), a value of K_{ji} for each day (j) of the year.

3.1.5.3 Formula of factor LS

Slope length and slope steepness influence the intensity of erosion by water. The *LS* factor is a function of slope length L_i (m) and slope angle θ (degree). For each element (i), LS_i is calculated based on the McCool *et al*, (1987; 1989) relations:

for $\theta_i \leq 9\%$ ($< 5.1428^\circ$):

$$LS_i = (l / 22.13)^m \, (10.8 \sin\theta_i + 0.03); \qquad (3.17)$$

for $\theta_i \geq 9\%$ ($\geq 5.1428^\circ$):

$$LS_i = (l / 22.13)^m \, (16.8 \sin\theta_i - 0.5) \qquad (3.18)$$

Where:

LS_i = topographic factor on element *i*.

l = length of slope on the element *i*.

θ_i = mean slope angle on element *i* (degree).

m = exponential evaluated depending on the rill/interill erosion relation.

There are three cases which can be applied for the *m* value:

- If (rill/interill) is weak (consolidated soil; pasture):

$$m = \frac{\beta}{2(1+\beta/2)} \qquad (3.19)$$

- If (rill/interill) is moderate (cultured agriculture soil):

$$m = \frac{\beta}{(1+\beta)} \qquad (3.20)$$

- If (rill/interill) is high (soil recently disturbed, construction sites):

$$m = \frac{2\beta}{(1+2\beta)} \qquad (3.21)$$

With $\beta = \frac{\sin\theta_i}{0.0896(3\sin^{0.8}\theta_i + 0.56)}$ (3.22)

3.1.5.4 Formula of soil management factor C

Factor C represents the resistance of ground surface to the transport of water-soil mixture. The C factor is used to reflect the effect of cropping and management practices on erosion rates. It is the factor most often used to compare the relative impacts of management options on conservation plans. The C factor indicates how the conservation plan will affect the average soil loss and how that soil-loss potential will be distributed in time during construction activities, crop rotations or other management plans.

The land cover factor C depends on the types of land use and soil occupation on each USS, for different agriculture management systems (rotations) and for different periods of crop growing (crop stages) during the year.

Wischmeier and Smith (1978) provide tables that show the corresponding values (Cp) for certain agricultural periods. However, these tables were however prepared for the United States' conditions and it must be adapted to local conditions. GIBSI uses the same table of C_p values for certain agricultural periods (Wischmeier and Smith, 1978) and with adaptations for Quebec conditions (Lagacé, 1980).

The model considers an agricultural calendar comprising five periods of vegetation. The determination of the calendar dates associated with these agricultural activities should be carried out jointly with the model of pollutant transport. Daily values of factor C (C_{ji}) are estimated based on interpolation within periodic values C_{pi}:

$$C_{ji} = C_{pi} + FPOS[C_{p+1} - C_{pi}] \quad (3.23)$$

With periodic factor: $$FPOS = \frac{(JO - TC_p)}{(TC_{p+1} - TC_p)} \quad (3.24)$$

Where:

C_{ji} = daily value of C on element i.

C_{pi} = periodic value of C on element i.

p = period 1 to 5.

JO = Julian day (1 to 365).

TC_p = Starting Julian day of period p.

3.1.5.5 Soil conservation practice factor P

The *P* factor represents the barrier to erosion and reflects the efforts of people to prevent soil erosion. This factor in the RUSLE model is the proportion of soil loss that occurs with a specific practice in relation to the corresponding loss with up-and-down slope tillage. On cultivated land, practice factors include: (1) contour or cross-slope farming, (2) strip cropping and buffer strips, and (3) terraces.

As with the other factors, the *P* factor differentiates cropland and rangeland (or permanent pasture). Both options allow for terracing or contouring, but the cropland option contains a strip-cropping routine whereas the rangeland / permanent-pasture option contains an "other mechanical disturbance" routine. For the purpose of this factor, the rangeland/permanent-pasture option is based on the support operation being performed infrequently, whereas in the cropland option, the support operation is part of the annual management practice.

GIBSI distinguishes, for the Southern Québec region, two types of intervention to determine *P* values (Bernard, 1990) (Table 3.1).

Table 3.1: Two types of intervention to determine the P values in GIBSI.

Agriculture practices	Slope			
Land slope	< 2 %	< 7 %	< 12 %	≥ 12 %
Direction of slope	1	1	1	1
Across the slope	0.75	0.80	0.90	1

It is possible to obtain the *P* factor value in two ways. First, by using the tabulated values from the USLE databases. This approach can be used for planning purposes. Second, by using the sub-factor approach from RUSLE (Equation 2.7). This second use, however, requires comprehensive and data-ready information of crop practice with tillage and slope parameters. This requirement is inadequate for land use and crop practices in the Cau River watershed, because this information is not available.

3.1.6 Sediment transport model

The comparison between the quantity of sediments produced on soil and the transport capacity of runoff helps determine what proportion of eroded sediments should be transferred to the receiving streams.

The calibration of the water erosion model is mainly based on the consistency between observed and calculated concentrations of suspended solids. Observed data, in most cases, only exist for some water quality stations in rivers. Thus, a model of sediment transport in rivers, which simulates the transport of sediments along the drainage system until such measuring stations, towards the outlet of the basin slope, is required (Villeneuve *et al.*, 1998a). In GIBSI, the ROTO model was chosen for the simulation of sediment transport in rivers.

ROTO (*Routing Outputs to the Outlet*) is a physically based continuous water routing model, operating on a daily time step (Arnold *et al.*, 1995a). The model's objective is to predict water and sediment movement in large, ungauged basins of several thousand square kilometres by accepting daily measurements of sub-area inputs and routing them through channel reaches and reservoirs.

The model uses readily available inputs (does not need detailed channel cross-section data). This is important, due to the limitation of channel cross-section data for large basins. It is continuous in time and can accept inputs from any continuous daily water and sediment yield models (e.g. RUSLE, SWRRB, and EPIC). Outputs can also be used as inputs to another ROTO run, making the model capable of handling unlimited drainage areas.

ROTO simulates the processes of erosion, re-suspension and sedimentation in river. The process of sedimentation is mainly based on the concept of falling velocity of suspended particles (Bargava *et al.*, 1992). ROTO was selected for the GIBSI system because it is composed of simple algorithms that allow the simulation of the daily hydraulic behaviour of sediments in rivers (Villeneuve *et al.*, 1998a). This model can easily be adapted to the structure of discretization in sections adopted by the water quality model in GIBSI.

3.1.6.1. Sediment transport capacity

The quantity of sediment likely to be transported downstream depends on the characteristics of the surface flow and of the eroded materials. When an amount of sediment produced on the ground ($EROST_{ji}$) exceeds a certain threshold (*e.g.* the transport capacity of the flow), there will be deposition of a portion of the eroded materials. The carrying capacity of the flow is compared to the quantity of sediment produced by erosion to determine whether there will be transport or sedimentation (Figure 3.2). The simple method proposed by Flinker *et al.* (1989), modified from the transport equation of Yalin (1963), is applied to evaluate sediment transport in the GIBSI model. This equation uses the concept of shear stress force applied by the surface flow on eroded materials. The sediment transport capacity is expressed as:

$$T = K_t T_s^{1.5} \qquad (3.25)$$

Where $T_s = \rho gHS$;

T = sediment transport capacity (kg/m s).

K_t = transport coefficient.

T_s = shear stress (N/m^2).

ρ = water density (kg/m^3) [999,1 at 15°C].

g = acceleration by gravity (9,81 m/s^2).

H = water height (m).

S = slope (m/m) = tan(θ_i).

Thus, on each element *i*, for day *j* (kg/m s):

$$T_{ji} = K_t \left[\frac{\rho\ g\ H_{ji}\ tan\theta_i}{1000}\right]^{1.5} \qquad (3.26)$$

The K_t value varies as a function of surface flow and pedology. Coefficient K_t will be calibrated in this study. Once the value of T_{ji} is obtained for each element (*i*), the mass of sediment that the flow can transport each day is:

$$CTS_{ji} = (T_{ji})(W_{ri})\frac{(86400sec/jour)}{(1000kg/tonne)} = (T_{ji})(W_{ri})(86.4) \qquad (3.27)$$

Where: CTS_{ji} = sediment transport on element *i* (ton/day).

T_{ji} = sediment transport capacity on element *i*.

W_{ri} = width of the flow on element *i* (m).

The width W_{ri} corresponds to the width of a "fictive" river on element (i). This value is given by the relations of fluvial hydraulics (Ferguson, 1986). The base equation to evaluate W_{ri} is:

$$W_{ri} = n(QJO)_i^{\,o} \tag{3.28}$$

Where:

$(QJO)_i$ = mean daily flow rate on element i (m^3/s).

n, o = adjustment coefficients.

Leclerc and Lapointe (1994) determined the relation between the mean annual flow rate (Q_m) and the width (W) from measurements carried out in several locations along rivers in the South of Quebec. This relation is:

$$W = 15{,}42\, Q_m^{\,0{,}51} \tag{3.29}$$

$$(r^2 = 91{,}8\%)$$

The values of coefficients n = 15.42 and o = 0.51 can then serve as starting points for the calibration of the width.

The transport capacity (CTS_{ji}) is subsequently compared to the volume of daily eroded sediments ($EROST_{ji}$) to determine the volume of sediments transported downstream ($PSOL_{ji}$):

$$\text{if } EROST_{ji} \geq CTS_{ji} \text{ then } PSOL_{ji} = CTS_{ji}$$

$$\text{if } EROST_{ji} < CTS_{ji} \text{ then } PSOL_{ji} = EROST_{ji} \tag{3.30}$$

Where:

$EROST_{ji} = A_{ji} * S_i$ = daily soil erosion rate for the element i (t/day).

A_{ji} = soil erosion rate on a specific day on element i (t/ha/day) = $R_{ji}K_{ji}LS_iC_{ji}P_{ji}$.

S_i = surface area of the element i (ha).

The value $PSOL_{ji}$ will therefore be the volume of sediments outgoing to the river reach draining the USS. This variable, which constitutes the main output of the water soil erosion model, serves as an input for the sediment transport in rivers model and also for the agriculture pollutant transport model.

3.1.6.2. Sediment transport in river

The ROTO model was selected in GIBSI to simulate sediment routing in river. In this model, the process of sedimentation is mainly represented by the concept of falling velocity of suspended particles. Bhargava and Rajagopal (1992) proposed a procedure that allows for the estimation of the falling velocity from a representative diameter for the particles in suspension (Figure 3.4).

In GIBSI, a solution to the Bhargava and Rajagopal (1992) equations, for suspended sediments having a specific density of 2.65 at water temperature 25°c, is implemented (Duchemin 2000):

$$Vc = exp[-32{,}9218 + X(40{,}4373 - 12{,}5788\,X)] \quad (3.31)$$

Where:

X = ln [-ln(Dr)].

Vc = fall velocity (m/s).

Dr = representative diameter of suspended particles (m).

The vertical distance (Hc) of the falling particles on a section (i) is determined according to the duration of sediments transport on this section, which is computed with:

$$Dt_i = \frac{Lr_i}{Vr_i} \quad (3.32)$$

Where:

Dt_i = travel time on section i (s).

Lr_i = length of section i (m).

Vr_i = velocity of water on section i (m/s).

The vertical distance in section (i) is given by:

$$Hc_i = Vc_i \, Dt_i \tag{3.33}$$

Where:

Hc_i = vertical distance of particles of diameter Dr on the section i (m).

Vc_i = fall velocity (m/s).

To limit the amount of sediments transported along a section, an index, or sediment delivery ratio, IAS (Indice d'Apport Sédimentaire), was applied in GIBSI:

- if $Hc_i < Hr_i$ then :

$$IAS_i = 1 - \left(0{,}5\frac{Hc_i}{Hr_i}\right) \; and \; 0{,}5 < IAS < 1 \tag{3.34}$$

- if $Hc_i > Hr_i$ then :

$$IAS_i = 0{,}5\frac{Hc_i}{Hr_i} \quad and \; 0 < IAS < 0.5 \tag{3.35}$$

Where:

IAS_i = sediment delivery ratio for section i.

Hr_i = water depth on section i (m).

The model then calculates the total amount of sediments entering section i by summing the mass from the upstream section and the mass from the surface drained to section i:

$$PSED_{ti} = PSOL_i + PSED_{(i-1)} \tag{3.36}$$

Where:

$PSED_{ti}$ = total quantity of sediment that comes in section i (ton).

$PSED_{(i-1)}$ = quantity of sediment from the river upper part (ton).

$PSOL_i$: quantity of sediment from the surface of soil drained by section i (ton).

The portion of *PSED* that is deposited in section *i* is estimated by:

$$SEDr_i = PSED_{ti}(1 - IAS_i) \quad (3.37)$$

Where:

$SEDr_i$ = sediment to be deposited on the section *i* (ton).

The erosion in river integrates the processes of sediments re-entrainment (return to suspension) and sediments extraction. It can be obtained on section *i* with:

$$PEROr_i = \left[\frac{69.44 * SUPBV}{100}\right]^{-0.5} \gamma\, dur\, P_{ri}\, Wr_i^{0.5}[Hr_i Vr_i]^{1.5} \quad (3.38)$$

Where:

$PEROr_i$ = quantity of sediment re-entrainment on section *i* (ton).

γ = water density (= 0,9982 t/m^3 at 20°C);

Pr_i = slope of section *i* (m/m).

Wr_i = width of section *i* (m).

dur = duration of the flow on section *i* = 86400 s for the daily time scale.

SUBBV = area of the USS that drains to the section *i*.

Hr_i = depth of water on section *i* (m).

Vr_i = velocity of water on section *i* (m/s).

The re-entrainment continues until all the sediment materials ($SEDr_i$) are released. When $PEROr_i > SEDr_i$, then the pull-out (extraction) of the materials from the riverbed can begin on section *i*. This component of erosion is assessed by:

$$PEROI_i = K_i C_i (PEROr_i) \quad (3.39)$$

Where:

$PEROI_i$ = extraction of materials on section *i* (ton).

$PEROr_i$ = re-entrainment on section *i* (ton).

K_i = mean soil erodibility factor *K* on the surface area that is drained by section *i*.

C_i = mean vegetation factor *C* on the surface area that is drained by section *i*.

The values of K_i and C_i correspond to mean weighted values (by types of soil or agricultural practices) of these factors calculated on the area drained by river section *i*. These K_i and C_i values are different than the K_{ji} and C_{ji} values used for the soil erosion estimate (for each USS/occupation *i*). K_i and C_i values can be calculated as mean values of K_{ji} and C_{ji}, which are calculated in the soil erosion model, but within the corresponding surface area that is drained by section *i* only.

Estimations of K_i and C_i are presented by Williams and Berndt (1972; 1977). For the *K* factor (soil erodibility), we have:

$$K_i = \sum_{s=1}^{n} \frac{K_s - S_s}{SD_i} \tag{3.40}$$

Where:

K_i = erodibility factor for section *i*.

K_s = erodibility factor for soil type *s*.

S_s = surface covered by soil type *s* (km^2).

SD_i = surface drained by section *i* (km^2).

n = number of series of soil on the surface area drained by section *i*.

For the factor *C* (cover management), we have:

$$C_i = \sum_{u=1}^{m} \frac{C_u - S_u}{SD_i} \tag{3.41}$$

Where:

C_i = vegetation factor for section *i*.

C_u = vegetation factor for soil occupation *u*.

S_u = surface covered by the soil occupation *u* (km^2).

SD_i = surface drained by section *i* (km^2).

m = number of types of soil occupation on the surface area drained by section *i*.

The total soil erosion in river is calculated with:

$$PERO_{ti} = (PEROr_i + PEROI_i)\, IAS_i \tag{3.42}$$

Where:

$PERO_{ti}$ = total amount of sediment eroded and transported on section *i* (ton).

Finally, the amount of sediment that reaches the outlet of section *i* is:

$$PSED_i = PSED_{ti} - SED_r + PERO_{ti} \tag{3.43}$$

Where:

$PSED_i$ = amount of sediment at the exit of section *i* (ton).

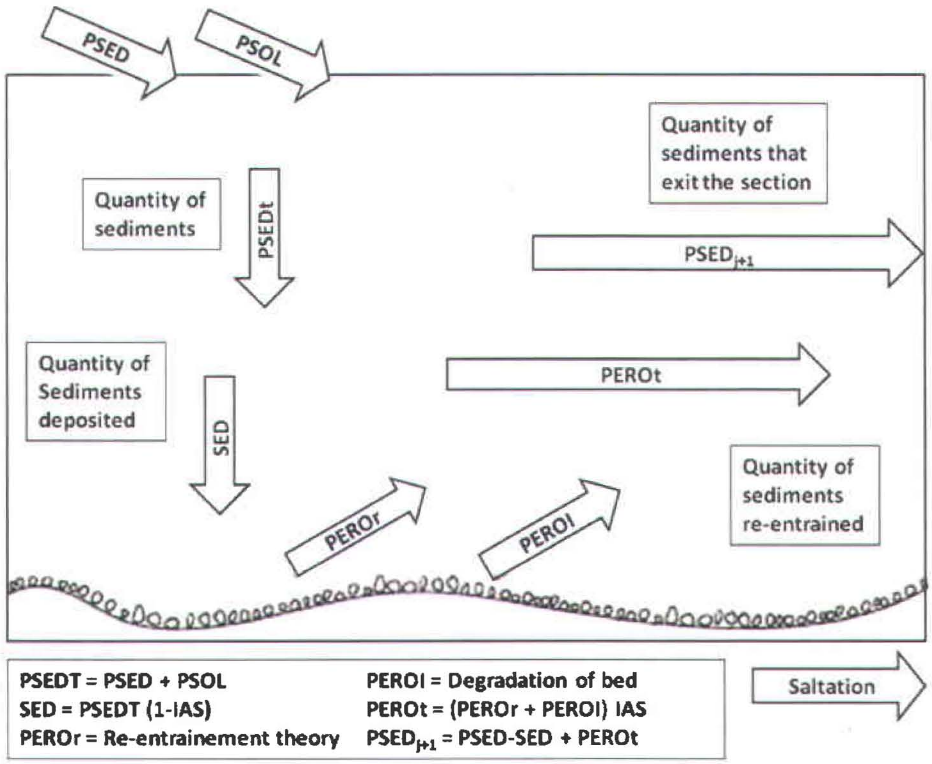


Figure 3.4: Sediment processes in river (from Villeneuve *et al.*, 1998).

3.2 Cau River watershed

3.2.1 Geographical and social-economical characteristics

Located in the North-Eastern part of Vietnam, the watershed area extends to 6,030 km^2, covering (partly or not) six provinces, which are Bac Kan, Thai Nguyen, Bac Ninh, Bac Giang, Vinh Phuc and Ha Noi. This thesis focuses on the upper part of this watershed. This selected area comprises two provinces, Bac Kan and Thai Nguyen, which cover approximately 60% of the territory of the whole basin. In the remainder of the document, the words "study area" or "Cau River watershed" will refer to the area of the basin in these two provinces (Figure 3.5).

The study area covers about 4 500 km^2. Its coordinates vary from 21°20'N to 22°20'N and 105°28'E to 106°08'E. The watershed covers three districts with 43 communes of Bac Kan province, and nine districts with 165 communes of Thai Nguyen province.

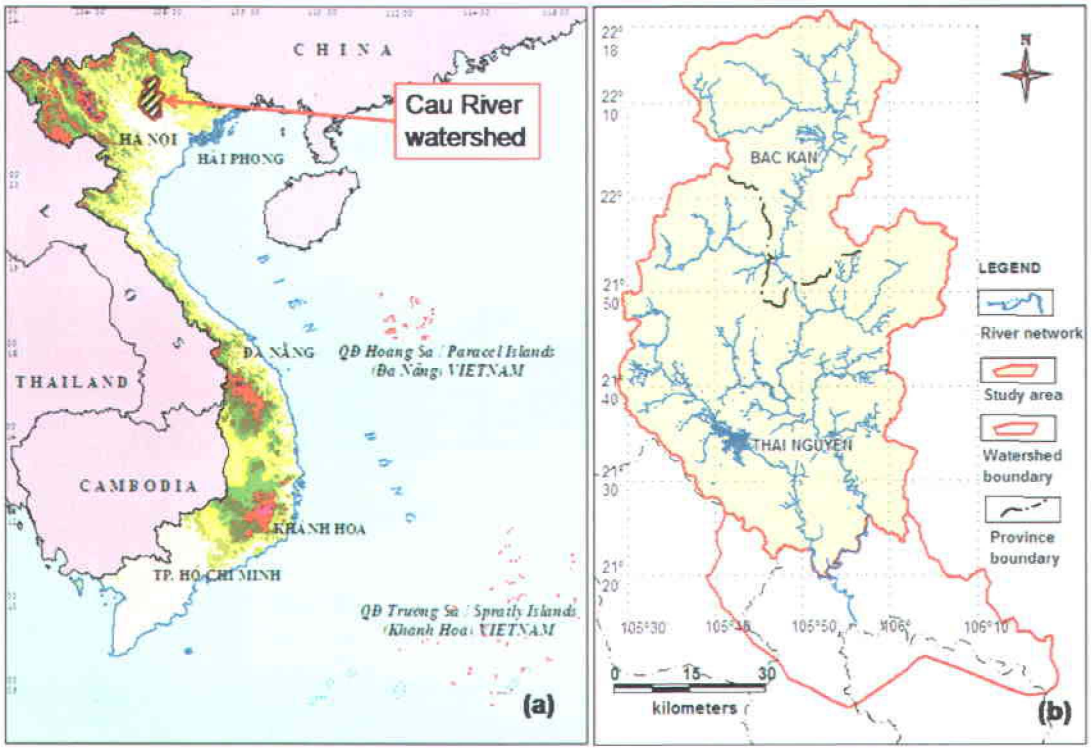


Figure 3.5: Location of the Cau River watershed in Vietnam (a) and the study area (b).

3.2.2 Topography

The elevation is higher in the North and lowers towards the South and Southeast. The elevation varies from over 1000 m in the Northern mountains of Bac Kan to less than 100 m at the outlet in Thai Nguyen province. Generally, the slope direction of the watershed is from the North to the South and from the Northwest to the Southeast. The topography of the Cau River watershed is relatively diverse in formation and complex in structure, comprising three typical types of terrain: mountainous, midland, and flat plains at the outlet. Figure 3.6 presents an overview of the topographical characteristics of the Cau River watershed.

- *The mountainous terrain* is limited by the Tam Dao Mountains (West and Southwest) and the Van On Mountains (North and Northwest). This terrain is complex with high, steep slope mountains dissected by gorges and creeks which create long and narrow valleys. The river system in this area is therefore characterized by narrow width, high slope and V-shaped bare rock bottom. It is rare to see a river section which has flat alluvial banks on this terrain. Thus, areas of this terrain type have very few population and agricultural activities.

- *The transition terrain* in the Cau River watershed is characterized by a combination of high to average hills mixed with long and narrow flat step-back slope terrain. This type of terrain is the continuation of the mountainous terrain in the North and Northwest and is the most represented in area in the watershed.

- *The flat plain terrain* occurs at lower sections, along the two banks of Cau River. From Thai Nguyen City, the terrain elevation is lower with expansion of the flat plains and mixed, although rarely, with low and gentle slope hills. The width of the river in this section is also expanded with a more gentle flow. Sedimentation processes have shown their effects in creating river benches and sand beaches along the last 50 km of the river, just before the outlet.

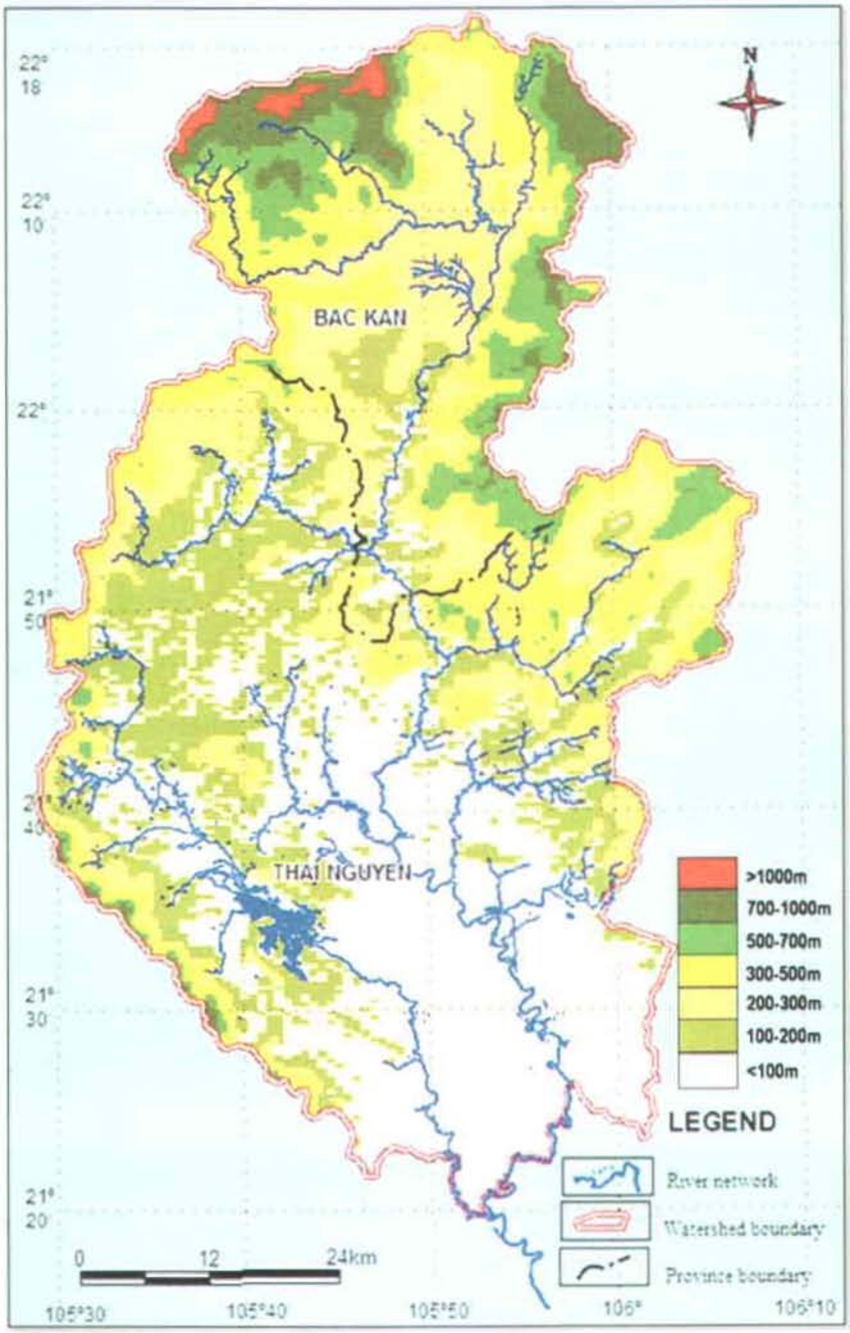


Figure 3.6: Topographical characteristics of the Cau River watershed (from MoNRE, 2001).

3.2.3 Geology and pedology

Geological formations of the mountainous terrain are characterized by:

- Jurassic system (undivided). Formations of red eruptive acidic and base volcanic sediments, sand-stone and Aerolite.
- Triassic system (undivided): Sands-tone, clayish-shale, lime grit-stone, acidic and base eruptive.
- Devonian system with Givetian limestone, clayish-shale and sand-stone.
- Ordovician system: Aerolite and sand-stone, rarely limestone strips.

The pedology in this terrain type is composed of (1) sediments deposed on sand-stone mother rock slopes; (2) red clay on lime-stone and metamorphic rocks; and (3) partly reddish yellow, brownish yellow clay on alluvial cliffs.

The geological formations of the transition terrain are composed of low slope eluvium, dentrital cones and alluvial sediment cliffs. Soil layers in this terrain type are relatively thick. They vary from a few meters to over ten meters on clayish-shale, silt-stone, and coloured in yellowish brown to reddish brown.

Flat plain terrain belongs to the quaternary sediment system with gravel, sand and clay deposits. Soil layers in this terrain type are mainly diluvium, proluvium and alluvium deposed annually following floods. They are mostly coloured in yellowish brown and light brown.

3.2.4 Meteorological and hydrological conditions

The Cau River watershed is located in a region with a typical monsoon tropical climate, in Northern Vietnam. It is hot and humid (with a lot of rain) during the summer and relatively cold and dry in winter.

3.2.4.1 Air temperature regime

The Cau River watershed has a mean annual temperature varying from 21°C to 23°C. This mean temperature, however, is not uniform for the entire watershed. The annual temperature is divided into two seasons in a year and between specific locations within the watershed. Generally, summer occurs from May to September. Winter starts in November and ends in March. April and October are the transition months between the two seasons. As moving to the North of the watershed, winter gets longer and colder. Appendix 3.4 presents the mean monthly temperature of the two provinces in the watershed. Winter in Bac Kan tends to be longer and colder than in Thai Nguyen.

3.2.4.2 Air humidity

Air humidity in the study area is relatively high. Average annual is more than 80%. Humidity varies unequally during the year and even in a season. Months with the highest humidity are March and April (when drizzling rain occurs) and August (when sudden and brief shower rains appear). The lowest humidity in a year often occurs during December and January. The relative humidity during this period may be as low as 70% (Appendix 3.5).

3.2.4.3 Wind regime

Affected by the Southeast Asia monsoon circulation and local topography, the wind direction in the watershed changes during seasons. Most of the winds are from the Northeast or North during winter and from the Southwest or South in summer. The mean wind velocity generally varies around I m/s, except in the Tam Dao Mountains (Appendix 3.6).

3.2.4.4 Rainfall regime

The annual precipitation in the watershed varies from 1,500 mm to 2,700 mm. The area has an extremely high rainfall centre on the Tam Dao Mountains (along the West of the watershed). Annual rainfall in this area may reach 3000 mm. This rainfall area expands to the East, crossing Thai Nguyen city with annual rainfall that exceeds 2000 mm (Figure 3.7), (Appendix 3.7).

The rainfall season is from April to September where April is the month of transition from dry season to wet season, during which 85% to 90% of annual total precipitation falls. During the rainy season, there are some months which have 15 to 20 rainy days (Appendix 4.2). The dry season is from October to the end of March, where October is the month of transition from wet season to dry.

3.2.4.5 River network

Cau River takes its source from the Van On Mountains (105°37'40" – 22°15'40") at an altitude of 1,175 m in Cho Don, in the Northern part of Bac Kan province. The length of the main channel up to the outlet at Cau Vat is about 165 km.

In the upper part of the watershed, within the Bac Kan area, Cau River flows from North to South; the mean elevation of the river in this section varies from 300 m to 400 m. The river bed is typically in V-shape, the river is narrow and slope is high, with a lot of rapids and a high curve coefficient (2.0). The mean channel width varies between 50 to 60 m in the dry season and can expand up to 80 - 100 m in the flooding season. The bed slope angle is estimated to be around 10‰ in this section.

In the lower part of the watershed, the river flows from the Northwest to the Southeast, then changes back to the North-South flow until Thai Nguyen. In this section, the river valley is expanded and the mountains are lower. The mean elevation of the river becomes 100 - 200 m with a bed slope angle of 5‰. The river width in the dry season is about 80 - 100m, with a curve coefficient of 1.90.

3.2.4.6 River flow rate

The Cạu River watershed hydrological regime is clearly divided into two seasons. The flooding season is from June to September, and the dry season is from October to May. In some areas such as the Du River, the Cong River and some main streams nearby the Tam Dao Mountains, the rainy season often occurs later. Thus, the flooding season on these areas is also prolonged (June to October). The river discharge during the flooding season accounts for 75 to 85% of the annual discharge (Appendix 3.8).

Figure 3.7: Mean annual rainfall in Cau River watershed (MoNRE, 1995).

3.2.5 Mineral resources

There are a total of 62 mineral mines which are under exploitation within the Cau River watershed. The minerals with the largest reserves are coal (17 million tons), iron (31 million tons) and titanium (29 million tons). Other minerals are also available with small reserves such as tin, zinc, gold and construction materials (MoNRE, 2007).

3.2.6 Social, economic and environmental conditions

3.2.6.1 Population

The Cau River watershed is the habitat for eight ethnic groups with rich traditional customs and living manners. According to the statistic data of 2007, the population of the two provinces within the study area is nearly 1.3 million, with 77% in rural areas. The population annual growth rate is 1.2% and the rate of population in working ages is about 55%. During recent years, together with the growth of economy, the population and labour structure between urban and rural areas have increased toward urban. This change can be explained not only by the relocation of farmers to cities, but also by the urbanization processes which are now quickly changing small towns into urban and industrial centers.

3.2.6.2 Economy

The gross domestic product (GDP) of the two provinces reflects the economical difference between the upper and lower parts of the watershed. The economy of the upper part (in Bac Kan) is far lower than in the lower part (in Thai Nguyen). In the upper section, agriculture, forestry and aquaculture sectors contribute for a larger part in the total production value compared to industry and services.

3.2.6.3 Land use

Although recent land use statistical data has not been properly updated for the Bac Kan area where agriculture and forestation are most present (Bac Kan, 2004), the land use status in Thai Nguyen (Appendix 3.9) may give an overview for a large part of the watershed.

The categories used for classification (land use groups) in these figures are from statistics of Thai Nguyen (2007). They may be different or more general than those used for the soil erosion estimates.

3.2.6.4 Agriculture

According to agricultural reports at the provinces level in 2008, there are several main types of crop within the watershed, such as rice, corn, bean, fruit, tea and some other vegetables. Apart from tea and fruit, which are perennial cropping plants, the other types are seasonal plants. The timing for the plantation and selection of plant types in the watershed mostly depends on the weather and irrigation capacity. Within the watershed, the crop timing of some main plants is different for the two main regions: (1) *upper region*: upstream from the Thac Huong dam and upstream from the Nui Coc reservoir; (2) *lower region*: downstream from the Thac Huong dam and downstream from the Nui Coc reservoir. This division reflects the availability of irrigation, which is different in the upper and lower parts of the watershed due to the use of dams and reservoirs. The detailed crop timing and crop rotations for the main plant types are shown in tables **A** and **B** in Appendix 3.10, for the upper and lower regions respectively.

3.2.6.5 Forestry

Forest land in the watershed is divided in three main types based on classes of protection and purpose of use:

- The productive forest is planted forest and can be logged for commercial purpose. This type is the most popular in the watershed and constitutes one of the most important incomes for local inhabitants. The planting rotation duration for this forest type varies from 5 to 25 years, depending on types. The most popular plantation in the area is wood for paper industry and construction use, namely *Eucalyptus alba*, with a 5 to 7 year rotation, and *Acacia*, with a 7 to 8 year rotation.
- The protective forest is used to prevent adverse effects from flooding, soil erosion and sedimentation. This type of forest is restricted to any disturbance.
- The specially used forest is used for the preservation of biological systems, wild plants and animal species. As for the protective forest, this type is restricted to any disturbance.

Appendix 3.11 illustrates the current proportion of forest types for the two provinces within the watershed.

3.2.6.6 Industry

Mining and mineral processing industries are highly developed in both Bac Kan and Thai Nguyen provinces. According to the Ministry of Natural Resources and Environment

(MoNRE, 2007), almost all mines and mineral processing factories release their wastewaters to the river system without applying any treatment.

The metallurgy industry is mostly concentrated in Thai Nguyen province with a total estimated wastewater discharge to the river system of about 16,000 m^3/day, in which wastewater from the Thai Nguyen metal processing complex (with an annual wastewater volume of about 1.3 million m^3/year) and the Song Cong industrial zone make the largest contributions.

The paper production industry in the watershed also provides a considerable volume of 3,500 m^3/day of wastewater while food processing factories are responsible for an additional volume of 2,000 m^3/day (MoNRE, 2007).

3.2.6.7 Development strategy and environmental pressures

Following the rapid development of the country, Bac Kan and Thai Nguyen provinces have their own ambitions for economic development. Master plans for the mid-term and long-term development of the two provinces show orientations toward urbanization with an increase in the service sector, a reduction of agriculture and status quo in the industrial sector with a contribution of about 42% (Bac Kan, 2004, 2009; Thai Nguyen, 2009).

The economic development plan has clearly and quantitatively explained its objectives. However, it did not focus much on the means to ensure that the environment can sustain with the expected rate of development or on any strategy for the treatment of recently abandoned solid waste and wastewater from industries which are contaminating the river system in the area.

Several researches have been conducted so far to evaluate the environmental status of the watershed (MoNRE, 2007; Institute of Water Resource Planning, 2008). However, the effect of these studies on the development policies and environmental management of local administrations is limited. In other words, the "weight of science" in the development policies for the watershed is relatively low. This limitation is caused by two main reasons. First, the recent studies focused only on individual scientific aspects. As a result, they can only reflect some parts of a comprehensive picture of the current environmental status. Second, the studies have not yet come to a quantitative prediction of the possible effects of development at the watershed scale and could not connect their results to likely future development scenarios.

Having a decision support system adapted to the Cau River watershed like GIBSI, which can perform systematic analysis and quantitative predictions for different management scenarios at the watershed scale, is far more than a need for scientists. In some means, it is an indispensable tool for scientists, managers, decision makers and local authorities to develop and apply a policy for the sustainable development of the Cau River watershed.

3.3 Data availability for the application of integrated watershed management models on the Cau River watershed

The shortage of data in the Cau River watershed is one of the biggest problems (apart from the specific climatic and topographic differences) when considering the application of the GIBSI model in general, and of the soil erosion and sediment transport models in particular. Data limitations, in terms of number of recorded parameters, time scale of data, continuation of data records and density of monitoring stations, make it difficult to implement and verify these watershed management models, which were designed in other countries where monitoring data are more readily available.

Within the study area, databases including digital maps and monitoring records related to the soil erosion and sediment transportation models are available. In some cases, selection and pre-processing of the raw data are required to synchronize some characteristics such as recording periods, time steps, measuring units, resolution, etc., in order to meet the requirements for input data for the models.

3.3.1 Map data

At the early stages of this study, there were four types of maps available for the Cau River basin. They are: (1) a topographic map (DEM - Digital raster 30 x 30 m grid resolution); (2) a pedological map with attribute data for three layers of soil texture: sand, silt and clay (digital raster 30 x 30 m grid resolution); (3) a land use and land cover map derived from a satellite Landsat-ETM image (digital raster 30 X 30 m grid resolution). The map shows seven classes of land occupations: Urban, Forest, Water bodies, Bare soil, Agriculture, Brush and Mixed land use. Those classes have been selected following hydrological modeling criteria and technical constraints (Hoang, 2008; Hoang *et al.*, 2009); and (4) an organic matter content (MO) map extracted from the Harmonized World Soil Database HWSD (2008) (digital raster, approximately 1 km grid resolution). More details about these maps are given in Appendixes 3.12a and 3.12b.

3.3.2 Monitoring data

This type of data in the Cau River basin comes from different sources and is not uniform both in time scale and location. Also, there are some missing parameters, missing recording periods or even discontinued stations. These problems, unfortunately, sometimes prevent the practical use of the data.

Consequently, the only data that can be used in this study include: daily hydrological recording data (river discharge) for a 9 year period (1998-2006) at three main stations along the main river channel; daily suspended sediment data for a 9 year period (1998-2006) at the Gia Bay station, and some other water quality records for Gia Bay during some short monitoring campaigns within 2005-2009. The Gia Bay station (Appendix 3.13) is the outlet of the study area

Table *a* in Appendix 3.12 presents the availability of the digital spatial databases while Table *b* lists the recording periods of monitoring data which are available for this study. Further discussions and methods for the adaption and/or modification of input data to the models appear in Chapter 4.

3.3.3 Suspended solids data measurement in the Cau River watershed

The measurement of suspended sediments (*SS*) in the Cau River Basin was conducted daily, at the same time scale and station (Gia Bay) with other hydraulic parameters including flow, discharge and water height for a nine-year period (1998-2006). The method applied to obtain this SS data is the Equal-Discharge-Increment (EDI) method (Nguyen *et al.*, 2003).

The EDI method is a daily estimate of SS load per day at a cross section of river. It requires: (1) a complete daily flow measurement, to be carried out across the cross-section of the river. The cross-section is then divided into five (more on large or complex rivers) increments (*e.g.* vertical sections) having equal discharge. The number *n* of increments is based on experience. (2) Suspended sediment concentration sampling (g/m^3) is carried out at one vertical within each of the equal-discharge-increments, usually at a location representing the centroid of flow for that increment.

The method applied for the daily SS estimate at Gia Bay station does not consider a particular sediment particle size classification. In fact, this information is not available in the station. The sediment concentration (g/m^3) for each equal-discharge-increment is measured using a sediment trap. The sampling was taken by gauging of total suspended sediment per water unit at different increments of a river's cross section in a specified time in a year. That averaged total SS concentration (g/m^3) then can be used as the *representative SS concentration* for a period of time in a year. It is used to calculate daily SS by multiplying the observed daily discharge (m^3/day) at the cross section. The representative SS concentration can be measured only several times in a year to make them become most representative for different flow regims of the river section during a year.

In case of the Gia Bay station, the sediment concentration was verified only a few times per year at each increment, in representative periods (dry, flood...). Accordingly, 4 to 10 samples of suspended sediment concentration were taken per year for a monitored cross-section. The exact timing for sampling was not specified but it was mostly concentrated following the flow regime of river, especially during the flood season. More specifically, 90% of samples are taken during the flood season while only 10% of them were taken during dry months. The observed information was used as representative for daily *SS* calculation. The mean discharge-weighted suspended sediment concentration (SS_C, mg/l) is obtained by taking the average of the sediment concentration values C_i (mg/l) for each interval i:

$$SS_C = \frac{\sum_{i=1}^{n} C_i}{n} \qquad (3.44)$$

The discharge-weighted suspended sediment load for the river cross-section (SS_L), in ton per day, is obtained by multiplying the concentration, C_i, in mg/l, by the discharge, Q_i, in m^3/s, of each equal-discharge increment *i*, and summing for all increments:

$$SS_L = \sum_{i=1}^{n}(C_i Q_i) \times 0.0864 \quad (3.45)$$

According to the World Health Organization, this method is the most used by sediment agencies (Bartram and Ballance, 1996).

3.4 Technical requirements and orientations for the application, adaption and modification of the soil erosion and transportation models to local condition

This section highlights some main points that are necessary to consider, in order to properly applying the model to the Cau River watershed in a context of: (1) data limitation, (2) climatic differences, and (3) particularities of land use activities.

3.4.1 Database selection and parameter preparation

For every simulation work, the required input data must be prepared and synchronized to be uniform in all aspects. In this application, there are two types of database that need to be prepared. The first is the observation data, which must be uniform in unit, time scale, length of period, location, and so on. The second type is digital map data (such as land cover, pedology, MO). In the Cau River basin, this data was obtained from different sources, in different digital formats and grid resolutions. Correcting spatial errors, adding attributes and converting them to a system-friendly format is important. Concerning data availability, not all required parameters (in the form of statistic data or digital raster map) are available as inputs for simulations in the Cau River watershed. Some solutions will thus be proposed to: (1) reproduce the needed data from any available means or (2) find out other ways to obtain results without using the missing data.

3.4.2 Adaption of theory and formula due to the climatic and terrain differences

Empirical models such as USLE, its later modifications RUSLE, or even MODEROSS in GIBSI, were initially designed and calibrated to be used in temperate climatic zones. Their parameters and coefficients are, therefore, optimized to meet local conditions of meteorology and hydrological regimes. To adapt the models to the tropical climatic conditions of the Cau River watershed, it will be necessary to consider: (1) temperature differences and timing; (2) precipitation density and intensity, usually higher in the tropics; and (3) variables or parameters that were not be available or suitable for application in a tropical climatic region such as the Cau River watershed. Thus, the adaption, modification or even the replacement of some variables and/or formulas will need to be considered. This, however, should come with a properly theoretical explanation which will be given later in the thesis.

3.4.3 Adaptation of theory and formula due to the local land use differences

Local land use differences could affect the model adaptation in two aspects: (1) local habits in the use of land; and (2) differences in types of local vegetation. These factors are extremely important when intending to reproduce the behaviour and time variation of simulated soil erosion at a daily, monthly or long-term annual time scale. This, in fact, directly affects the estimates of the C and P parameters in soil erosion calculations. While land use habits help understand how the soil is managed, the types of vegetation can provide information about the timing and land use cycles throughout the year. A well-adapted calculation of C and P based on local land use habits is essential to get accurate simulations.

Details about the problematic, solutions and procedures to carry out the adaption and modification of the soil erosion and transportation models applied for the Cau River watershed are discussed throughout Chapter 4, for each model parameter.

4. Adaptation and calibration of models in GIBSI for the Cau River watershed

This chapter presents detailed works and contribitions made to the study. Considering the limitations of previous studies (Sections 2.5 and 2.6, Chapter 2), the existing model (Section 3.1, Chapter 3), local conditions and data availability (Sections 3.2 to 3.4, Chapter 3), the objective of this chapter is to adapt the soil erosion and transportation models in GIBSI to the local conditions of the Cau River watershed. The task of adaptation here has two main requirements. First of all, it is to highlight in details the adaptation methodology for the two models in order to ensure that they can run in a context of monsoon climate conditions with data limitations. Secondly, the calibration and validation of simulation results of the new adaptations will be presented to confirm their realism as well as limitations when applied for conditions such as in the Cau River watershed. For a better follow-up of the analyses and discussions throughout this thesis, definitions of common terms used in modeling, sensitivity analysis and calibration are presented in Section 4.1.

To achieve the first requirement of this chapter, the differences in local conditions of climate, topography, and data availability between the Cau River watershed and the regions where erosion and sediment transport models were initiated and previously applied were analyzed. Modifications were mainly made for variables closely linked to local conditions. This helps identifying the modifications and adaptations needed for the soil erosion model MODEROSS (Section 4.2) and sediment transport model ROTO (Section 4.3) for their application to the Cau River watershed. Sub-sections 4.2.1 to 4.2.5 discuss about modifications and adaptations for input data in the erosion model. Modifications in the sub-sections 4.3.1 to 4.3.3 concern the ROTO model (revision of some concepts, equations and computing codes).

Section 4.4 is meant to satisfy the second requirement, namely the calibration and validation of the modified models. In this section, three main tasks are presented. First, several parameters involved in both the soil erosion model and transportation model were selected for the sensitivity analysis, in order to understand how the models' results react with the adjustment of parameters and to identify the parameters on which the calibration efforts should be focussed (sub-sections 4.4.1). Second, the analysis of observed suspended sediments data was carried out to confirm, to some extent, the realism of the observation data used to calibrate the modified models (sub-sections 4.4.2). This section therefore provides an overview of how the observed data behave at different time scales, finding anomalies and explaining the reasons if any. Third, the calibration of the new modified models was carried out and the results were analyzed and discussed (sub-sections 4.4.3 and 4.4.4).

4.1 Definitions of some expressions

It is necessary to clarify the definitions of some expressions like *models*, *processes*, *factors*, *calibration parameters* and *variables*. This thesis focussed on two models: soil erosion model (MODEROSS) and sediment transport in river model (QUAL2E). The soil erosion model corresponds to two processes which are sediment production (RUSLE) and transport on surface (ROTO) and the sediment transport corresponds to sediment transport in river (QUAL2E). Each model has different contributing *factors* or input variables in their corresponding equations (for example, soil erodibility (K) and slope factor (LS) in the soil erosion model). In some equations, there are some coefficients called *calibration parameters*, which can be adjusted in order to have a good fit between simulations and observations. For example, Equations 3.2 and 3.3 (Chapter 3) for the total daily rainfall erosivity on a spatial unit USS, contains coefficients *a*, *b* and *c* as calibration parameters.

4.2 Modifications and adaptations of the soil erosion model MODEROSS

MODEROSS is a soil erosion model which was introduced by Duchemin (2000) and used for soil water erosion estimations in an updated version of GIBSI. The main factors that affect soil erosion in this model are rainfall erosivity *R*; soil erodibility *K*; slope factor *LS*; land cover *C*; and management practice *P*.

In MODEROSS, the rate of soil erosion *A* (t/ha) is calculated on each spatial element for each land use (USS/occupation) of the river basin. It is strongly influenced by precipitation as well as by the resulting runoff. The erosivity factor *R* gives a quantitative approximation of the energy of these two agents of erosion. In GIBSI, the hydrological model HYDROTEL provides data of precipitation and runoff for each element of calculation of the catchment. The vulnerability of soil to detachment by precipitation is taken into account by the factor of soil erodibility *K*. The *K*-factor is calculated for each series of soil encountered in the watershed using a relationship that involves the texture of soil, its content in organic matter, its structure and permeability (Foster *et al.*, 1981) and the variation of soil erodibility throughout the year (Young *et al.*, 1990).

The influence of topography is represented by the factors of length and the slope angle of the land. MODEROSS calculates, for each element of the watershed, the value of the slope length and angle using equations proposed by McCool *et al.* (1993) and Nearing (1997). The protective effect which is offered by vegetation cover is introduced in the model by the factor *C* whereas the conservation practices are considered by the factor *P*.

This study uses the daily hydrological inputs of the HYDROTEL model which have been adapted and calibrated for the Cau river watershed (Nguyen, 2012). Detail of adaptation and calibration of HYDROTEL model was discussed in detail in the thesis work of Nguyen (2012).The Appendix 3.3 presents: (a) the structure of the model, (b) the algorithms selected for estimations in the Cau River watershed, (c) ilustration of Vertical Balance (BV3C) to evaluate the quantity of water that will run off the surface and which will infiltrate, to store and run into the ground, and (d) an example of simulated daily river discharge at Gia Bay station in the Cau River watershed.

Within this thesis, factors and their corresponding formulas are basically the same as in GIBSI. However, different modifications are introduced in order to comply with the context of data availability and monsoon climate in the Cau River watershed. The following sections will address the different modifications of theory and methods both for input preparation and model equations.

4.2.1 Modifications for erosivity factor (R)

GIBSI employs the method proposed by Foster *et al.* (1977) to calculate rainfall erosivity (*R*). In this method, *R* in USLE (which is calculated as the product of rainfall energy and maximum 30-minutes intensity (Equation 2.2, Chapter 2)) was replaced by another factor R_t with two terms: (1) rainfall erosivity *Rp* and (2) runoff erosivity *Rr* (Equations 3.1, Chapter 3). Rainfall erosivity was however estimated by multiplying *Rp* by 0.646 (Equation 3.2, Chapter 3). In the case of the Cau River basin, the expression of R_t was simplified by taking into account 0.646 in the calibration parameter *a* as follows:

$$R_t = aP^b + 0.45\, c\, Qq_p{}^{0.333} \tag{4.1}$$

Where:

R_t = total daily soil erosivity on USS (MJ mm/ha h);
P = daily precipitation on USS (mm);

Q = Water height on USS (mm);
q = daily discharge at the exit of USS (m^3/s);
a, b, and c = calibration parameters.

4.2.2 Adaptations for soil erodibility factor (K)

4.2.2.1 Estimation and preparation of input data cs and cp

The data needed to estimate the K value come from a soil pedology profile. They include soil texture classes, soil structure codes (*cs*), soil permeability (*cp*), organic matter content (*MO*) as well as information on soil texture (% sand, % silt, and % clay).

The data used to estimate K factor in the Cau River watershed was limited to a single digital map of pedology (Appendix 4.1) providing only information on soil classes (according to the USDA's classification) and soil texture (% sand, %silt, and %clay). Missing data to estimate the K values on the Cau River basin were thus soil structure codes (*cs*), soil permeability codes (*cp*), and organic matter content (*MO*) for each soil polygon.

Soil profile K estimates in the Cau River watershed will be based in this thesis on the USDA's twelve basic soil texture classes (Table 4.1). Values for soil structure codes (*cs*) and soil permeability codes (*cp*) will be obtained using USDA's soil texture classes and grain size ranges key identification.

Table 4.1*: USDA's soil texture classes.*

USDA's soil texture classes	
1. Clay	7.Clay loam
2. Silt	8.Silt loam
3. Sand	9.Sandy Loam
4. Loam	10.Loamy sand
5. Silty clay	11.Silty clay loam
6. Sandy clay	12.Sandy clay loam

According to the classification of Cook *et al.* (1985), the *cs* parameter in GIBSI was determined based on the diameter of soil particles. Diameters of soil particles are divided into four groups with assigned code numbers from 1 to 4, corresponding to grain diameters Φ in the ranges: 0-1; 1-2; 2-10 and > 10 mm. These codes therefore correspond to four groups of structure types (Table 4.2).

Table 4.2: *cs* codes for K estimation in GIBSI (Cook *et al.*, 1985).

Code	Particle diameter Φ (mm)	Structure type
1	< 1	No structure or very fine grain
2	1-2	Fine grain
3	2-10	Medium to coarse grain
4	> 10	Coarse, massive, prismatic

Usually, soil permeability is determined on the basis of soil hydraulic conductivity measures. Like *cs*, the soil permeability parameter (*cp*) in GIBSI was classified and coded from 1 to 6. These codes were assigned orderly from rapid to very low soil permeability, corresponding to their hydraulic conductivity ranges and classes of soil texture (Table 4.3). These soil texture classes are based on the USDA's soil texture classification.

Table 4.3: *cp* codes for K estimation in GIBSI (Cook *et al.*, 1985).

Code	Texture Classes	Hydraulic Conductivity (cm/s)
1 (very rapid)	*Stone, coarse sand*	$> 4.4 \times 10^{-3}$
2 (rapid)	*Loamy sand, sandy loam*	$1.4 - 4.4 \times 10^{-3}$
3 (moderate rapid)	*Fine sandy loam, loam*	$0.4 - 1.4 \times 10^{-3}$
4 (moderate slow)	*Loam, silt loam, clay loam*	$0.14 - 0.4 \times 10^{-3}$
5 (slow)	*clay loam, clay*	$4 - 14 \times 10^{-5}$
6 (very slow)	*Dense structure, compact*	$< 4 \times 10^{-5}$

In the case of the Cau River watershed, the data required to estimate *cs* and *cp* are rare. In addition, a quantitative analysis of the diameters of soil particles and hydraulic conductivity throughout the watershed is impossible to achieve. Therefore, in this study, it is necessary to find a different approach to obtain values for *cs* and *cp*. The methods used to obtain *cs* and *cp* values are presented below.

For the Cau River watershed, only a map of soil texture classes and sand/silt/clay contents can be used to obtain *cs* and *cp* in the watershed. This map uses the same USDA classification system as in GIBSI to identify textural classes in both horizontal (different locations) and vertical (soil depths) directions. Apart from indicating the texture, the map also identifies rocky/urban areas. These areas are not listed in the USDA texture classes. However, they are considered as a class in the present study.

With the available soil texture map, a method of similarity analysis was applied. For the *cp* coding of the entire Cau River watershed, six groups of texture classes, which correspond to six codes of *cp*, are used as key for comparison (Table 4.3). Each class available in the soil map is checked and gathered into groups that are similar to Cook's classification (1985). The soil texture triangle (Figure 4.1) is used to verify textures in the groups. Once all texture classes in the map are grouped, corresponding *cp* codes can be determined. Resulting *cp* codes for the soil texture map of the Cau River watershed are shown in Table 4.4. Figure 4.2 shows the map of *cp* codes adapted for the Cau River watershed.

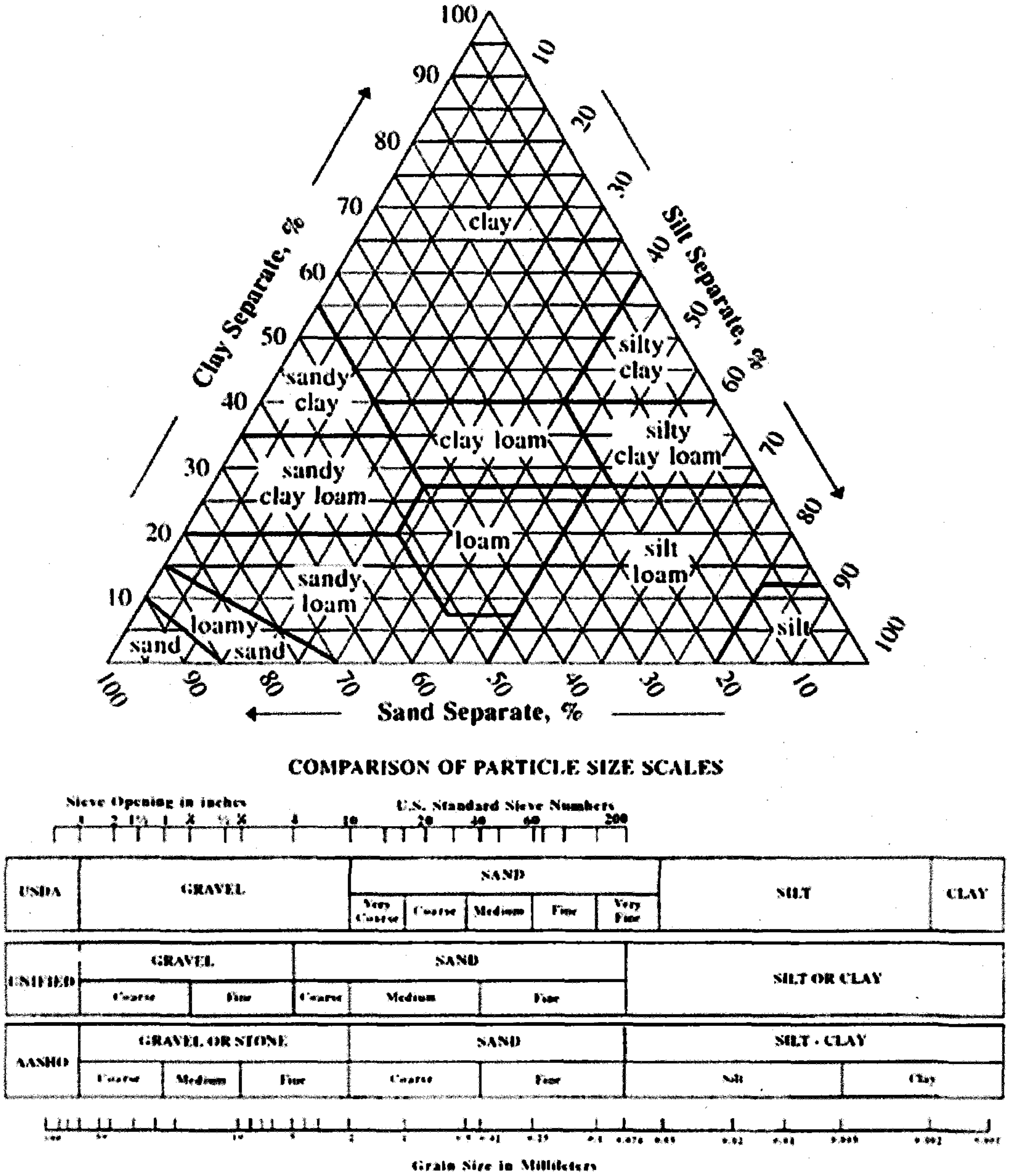


Figure 4.1: Soil texture triangle according to USDA classification system based on grain size.

Table 4.4: *cp* codes determined for the Cau River watershed, based on the USDA's soil texture classes.

Code	Cook's (1985) texture classes	Soil texture for the Cau River basin database
1 (very rapid)	Stone, coarse sand	--
2 (rapid)	Loamy sand, sandy loam	Loamy Sand, Sandy Loam
3 (moderate rapid)	Fine sandy loam, loam	Loam
4 (moderate slow)	Loam, silt loam, clay loam	Silt Loam, Clay Loam
5 (slow)	Clay loam, clay	Silty Clay Loam, Silty Clay, Clay
6 (very slow)	Dense structure, compact	Rocky Urban area

To obtain the *cs* code, structural types (name and definition) are used as key analysis instead of using particle dimension values, which are not available in the Cau River watershed database. It was found that texture classes in the watershed's soil map are mainly of the *cs* codes 1 to 2 and partly of code 3. The *cs* code 4 (coarse, massive, prismatic structures) did not meet the texture class listed in the watershed's soil map. According to field observations in the watershed, due to the relatively thick and well weathered soil layers, coarse or massive structures occurred mostly on rocky, mining or urbanization areas (where mining, construction and landfill activities are more frequent). The *cs* code 4 is, therefore, assigned to the rocky/urban class in the watershed. Results for the *cs* code in relation to the map of soil texture classes in the Cau River watershed are shown in Table 4.5. The map of *cs* codes adapted for the Cau River watershed is shown in Figure 4.3.

Table 4.5: ***cs*** **codes determined for the Cau River watershed, based on the USDA's soil texture classes and grain size scale.**

Code	Particle diameter Φ (mm)	Structure type	Cau River basin database
1	< 1	*No structure or very fine grain*	Silty Loam, Clay Loam, Silty Clay Loam, Silty Clay, Clay
2	1-2	*Fine grain*	Loamy Sand, Sandy Loam, Loam
3	2-10	*Medium grain, Coarse grain*	--
4	> 10	*Coarse, massive, prismatic*	Rocky Urban area

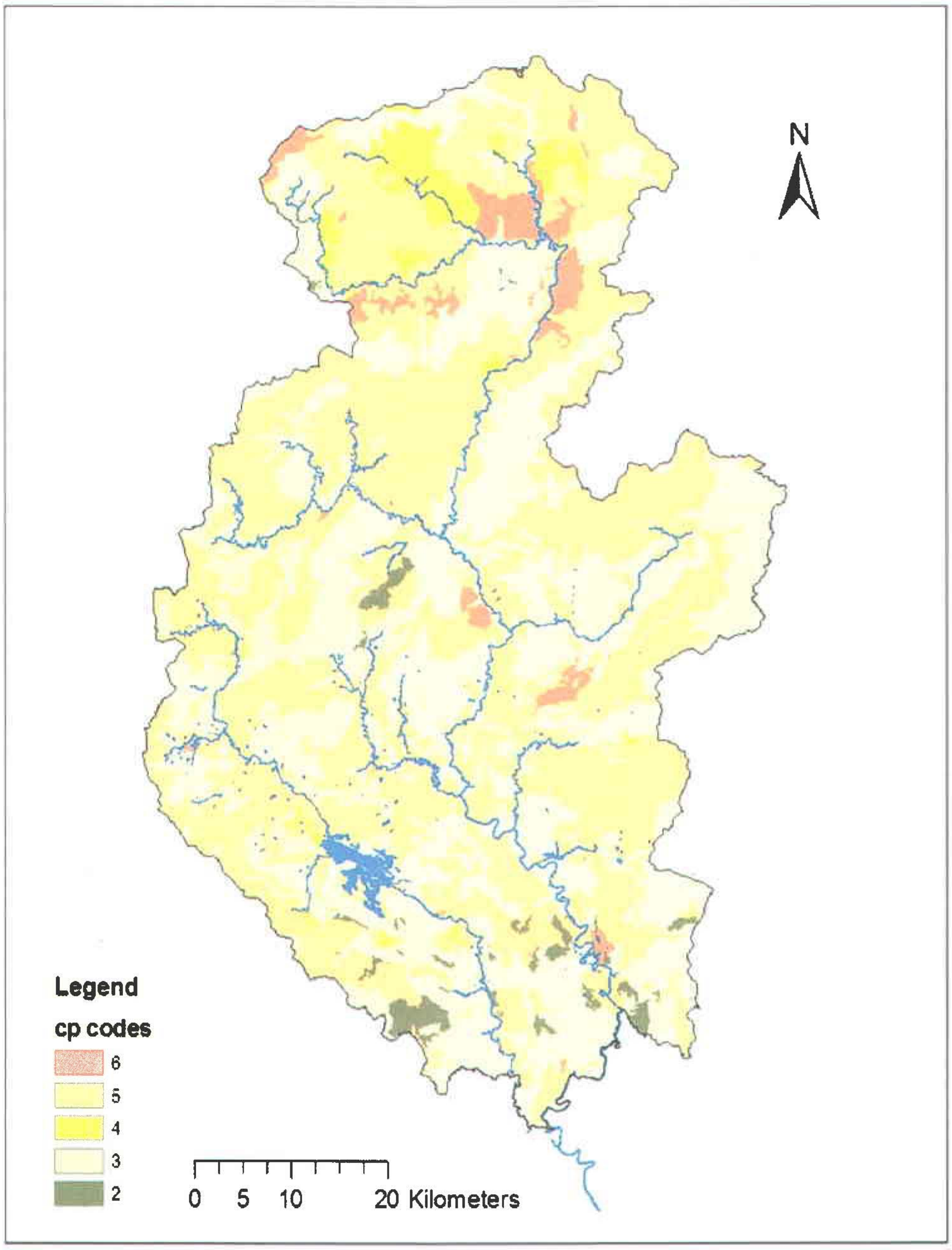


Figure 4.2: Map of *cp* codes for the Cau River watershed, after the proposed method.

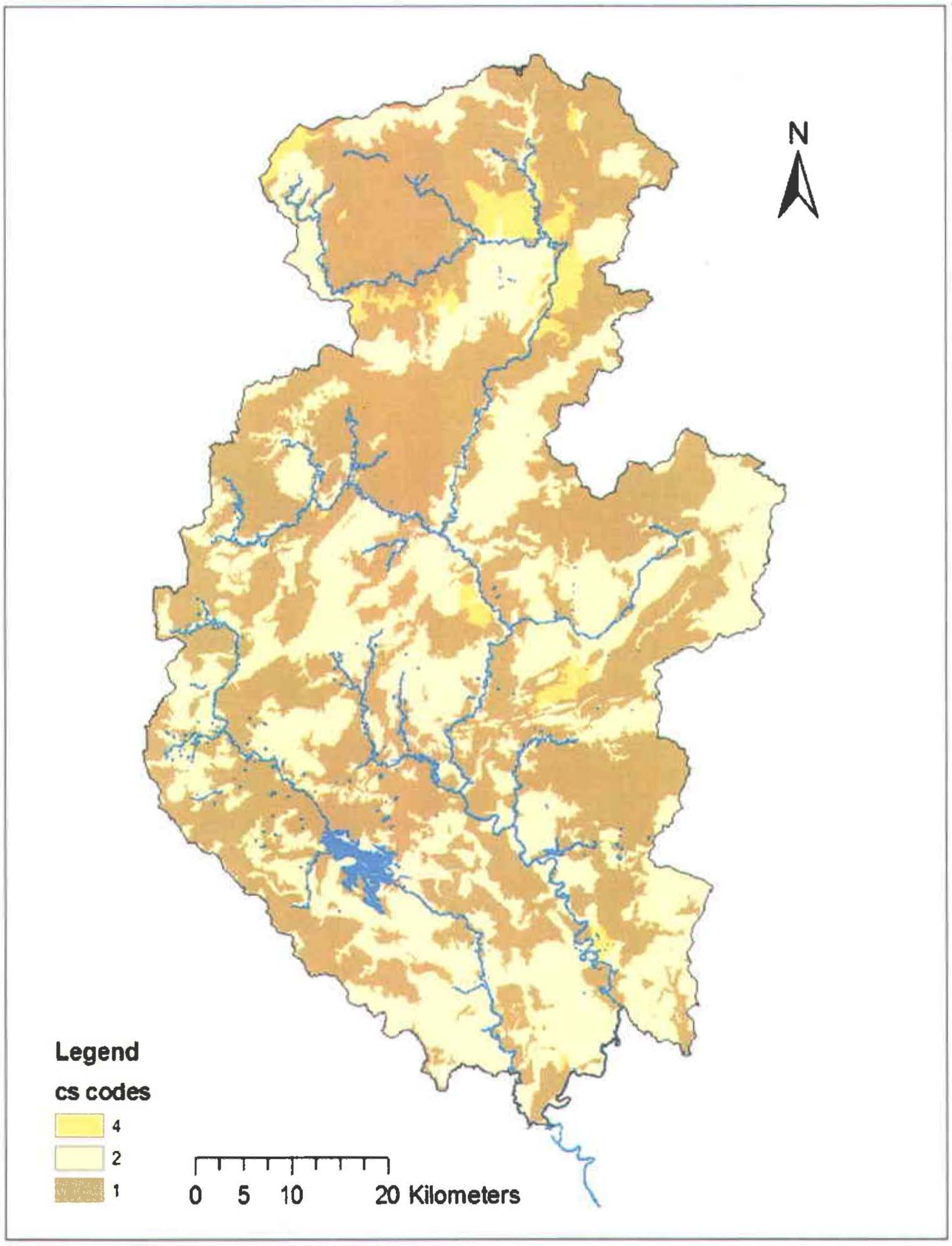


Figure 4.3: Map of *cs* codes for the Cau River watershed, after the proposed method.

4.2.2.2 Estimation and preparation of organic matter data

The organic matter content (*MO*) can be expressed as a function of the organic carbon (*CO*) content (see Equation 3.8, Chapter 3). Since *MO* data are not available at a reasonable scale for the entire area of the Cau River watershed, the *FAO Harmonized World Soil Database* (2008) is used to extract the information of *MO* content in the form of a raster map. The map of the FAO database divides the watershed into four different zones of *MO* content (%) (Figure 4.4).

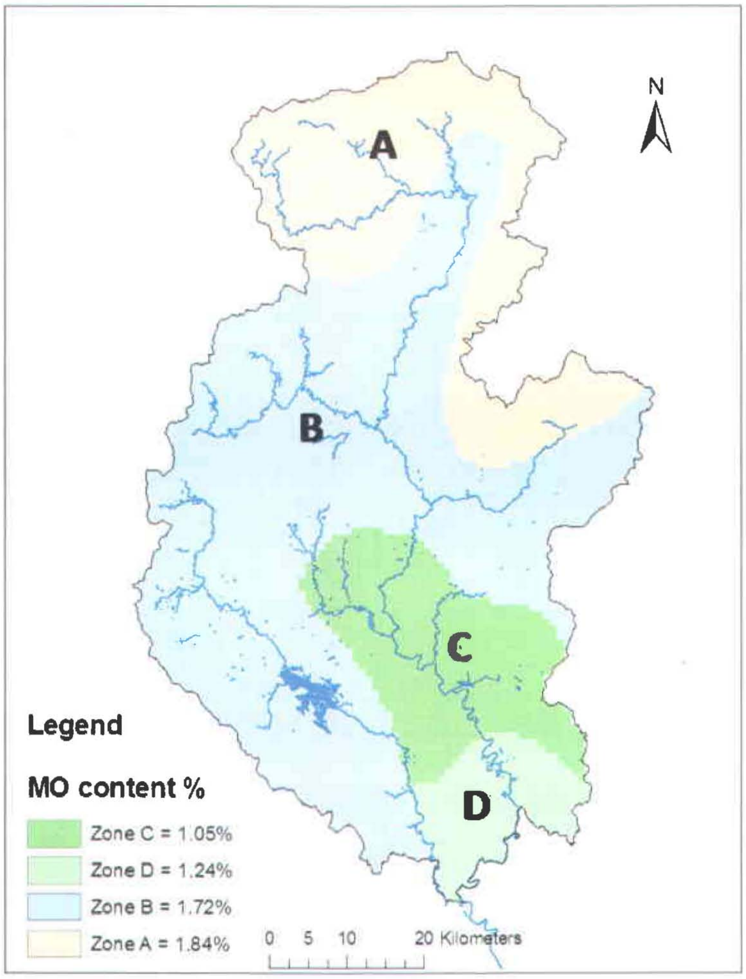


Figure 4.4: Map of the four *MO* zones extracted from the FAO Harmonized World Soil Database (2008).

4.2.2.3 Modifications for K daily calculation

In GIBSI, the soil erodibility factor (K) requires daily values (K_{ji}) calculated from the annual erodibility (K_{asi}). For this purpose, the procedure of Young *et al*, (1990) is used to estimate daily erodibility (K_{ji}). This procedure takes into account the variations of K in:

- the upper and lower boundaries of K value (K_{max} and K_{min}), which are related to annual erodibility K_{asi} (Equation 4.12) and the mean annual erosivity R_{an}
- the time boundaries (t_{max} and t_{min}) which are related to R_{an} and Δ_t, the frost-free time in the study area. The R_{an} value is estimated from Equations 3.14, 3.15 and 3.16 in Chapter 3 (Ateshian, 1974; Madramooto, 1988). In general, we can get K_{ji} based on K_{asi}, R_{an}, and Δ_t (Figure 4.5).

The value of Δ_t is taken into account to calculate the variation of K during the year. This climatic variation was presented in the revised version of USLE for the Eastern regions of the United States (Haan *et al.*, 1998), where the effect of snowy winter is dominant. In the Cau River watershed, under the monsoon climatic condition, adaptation is necessary in order to modify the method to calculate K_{max} and K_{min}. The following procedure was therefore adopted to obtain K_{ji} :

- Estimate the mean annual (R_{an} value) for the Cau River watershed (from existing maps and reports);
- Assign R_{an} value to its corresponding spatial location of each soil occupation;
- Choose values of t_{min}, t_{max} and Δ_t based on the analysis of the mean monthly rainfall database (1997-2006). First, the mean monthly precipitation value was estimated. Then, after the two months with the highest and lowest precipitation were identified, the mean daily values for both months were estimated in order to select the day that had the lowest mean precipitation in the lowest month and the day that had the highest mean precipitation in the highest month (Appendix 4.2). Estimated results show that the highest days fall within the end of June and beginning of July, and that the lowest days are around the end of December and beginning of January. Thus, July 1st and January 1st were selected for t_{max} (day 182) and t_{min} (day 366).

Due to the lack of data, estimations of t_{min}, t_{max} and Δt in the Cau River Basin were based on the assumption that t_{min} and t_{max} coincide with the variation of mean daily precipitation during a year. Thus, t_{max} would occur on the date when precipitation reaches its maximum, and t_{min} would occur on the date when precipitation reaches its minimum. In general, estimations of t_{min}, t_{max} and Δt in the Cau River Basin are based on the availability of mean daily precipitations over 10 years. t_{max} will be the day where the mean value of the precipitation is the highest, and t_{min} will be the day where the mean value of the precipitation is the lowest. Figure 4.6 shows t_{max}, t_{min} and Δ_t corresponding to the annual variation of mean monthly precipitation in the Cau River Basin. The following values are therefore finally considered: t_{min} = January 1st = 366; t_{max} = July 1st = 182; $\Delta t = t_{min} - t_{max}$ = 184.

- Compute K_{asi}, which is the mean annual value (equation 3.7, chapter 3)
- Compute: $K_{max} = (3 - 0.0003R_{an})K_{asi}$ (4.2)
- Compute: $K_{min} = \frac{K_{max}}{8.6-0.0011R_{an}} = \frac{(3-0.0003R_{an})K_{asi}}{8.6-0.0011R_{an}}$ (4.3)
- For 1 < t_i < t_{max}: $K_{ji} = K_{min}e^{coeff(t_i - t_{min})}$ (4.4)
  with: $coeff = \frac{\ln(8.6-0.0011R_{an})}{t_{max}-t_{min}}$
- For $t_{max} \le t_i \le 365$: $K_{ji} = K_{max}\left(\frac{K_{min}}{K_{max}}\right)^{\frac{(t_i - t_{max})}{\Delta t}}$ (4.5)

All variables that appear in these equations are defined in the figure below (Figure 4.5).

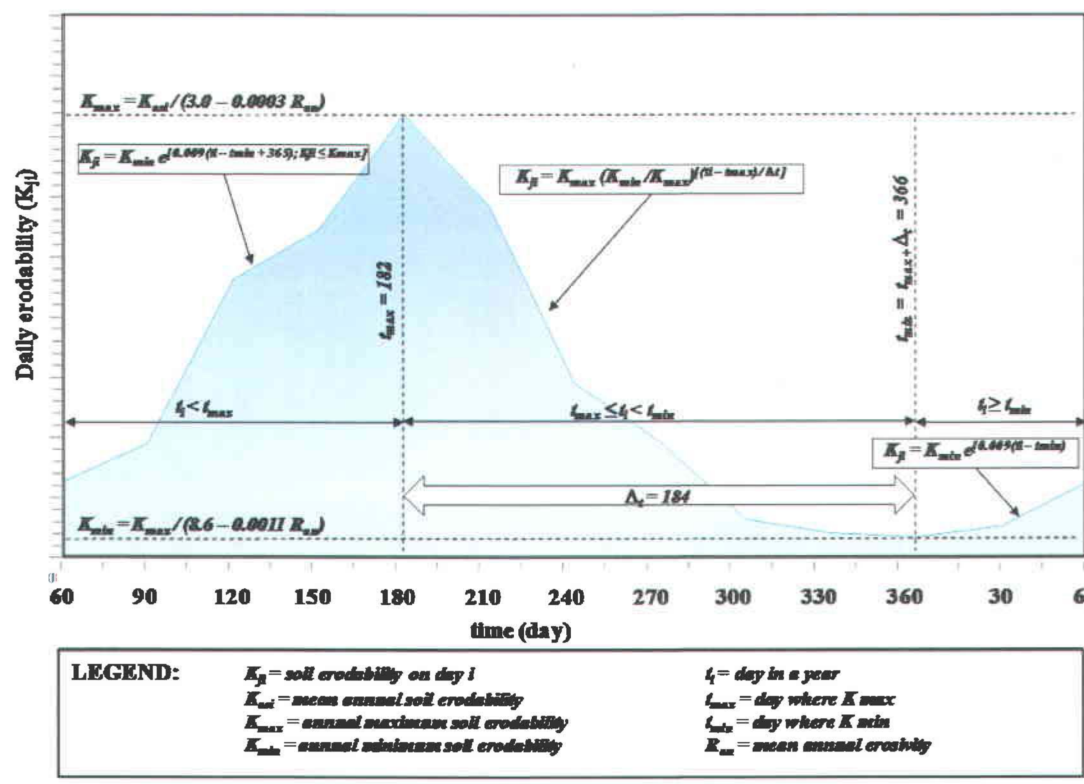


Figure 4.5: Procedure for the evaluation of the seasonal erodibility in the GIBSI model.

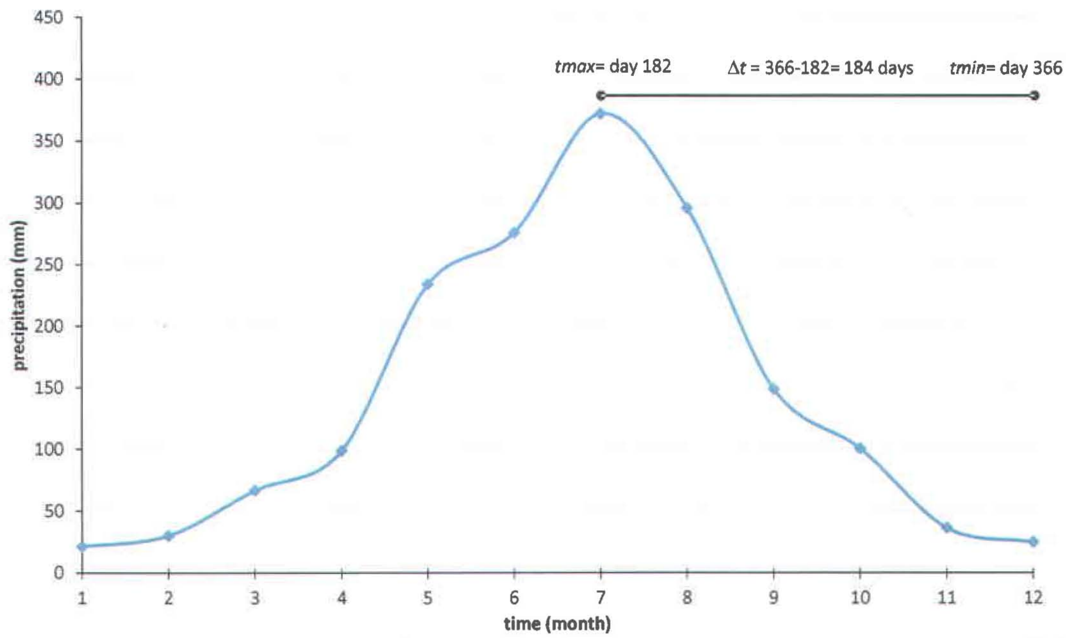


Figure 4.6: t_{max}, t_{min} and Δ_t corresponding to the annual variation of mean monthly precipitation in the Cau River Basin.

4.2.3 Adaptation for topographic factor (LS) calculation

According to Equations 3.17 to 3.22 (Chapter 3), in the conditions of the Cau River watershed, *m* values for cases A, B and C will be applied, depending upon the definition land use and land cover types at each USS/occupation. Land use and land cover maps available for the Cau River Basin (Table 4.6) are re-classified into three main types of land occupation. They are: (1) forest and forestation land; (2) agriculture land; and (3) urban, industrial and land excavation areas. These three groups can, correspondingly, meet the requirements for the A, B and C cases of McCool *et al* (1987 and 1989).

Table 4.6: Attribute information available in the land use map of the Cau River Basin

Identity (OID)	VALUE	Corresponding land use class
1	2	Agriculture
2	3	Forest
3	4	Water
4	5	Urban
5	6	Bare soil
6	7	Mixture
7	8	Brush

To estimate the *m* value, a programming code is rewritten to check which one of the three cases should be used according to land use:

- Apply Case (A), expression: $= \frac{\beta}{2(1+\beta/2)}$, If land use map **VALUE = (1); (3); (8); (4)**.
- Apply Case (B), expression: $= \frac{\beta}{(1+\beta)}$, If land use map **VALUE = (2); (7).**
- Apply Case (C), equation: $m = \frac{2\beta}{(1+2\beta)}$, If land use map **VALUE = (5); (6).**

Where:

m = exponential evaluated depending on the rill/interill erosion relation

$\beta = \frac{sin\theta_i}{0.0896(3sin^{0.8}\theta_i+0.56)}$;

θ_i = mean slope angle on element *i* (degree).

4.2.4 Modifications for the soil management factor (*C*)

The adaptation of the *C* value to local land use conditions in the Cau River watershed is considered very important. The area under consideration is characterized by large variations in landscape features such as high mountains, steep hills, and narrow plain-valleys mixed with moderate hills. These characteristics, along with living habits of local residents, have created a complex mixture of land use types (see Chapter 3, Section 3.2).

4.2.4.1 C factor grouping

Water soil erosion models are designed primarily for agriculture and conservation measures for cropland. USLE and its revised version follow this trend. Certain types of land-occupation units, such as water bodies, urban and industrial areas, were not considered in these models. This may cause problems when we apply the models at the watershed scale, which has multiple categories of land use.

The selection of a method to adapt the values of *C* to the Cau River Basin is performed in several steps:

- Step 1: types of land use and land-occupation in the Cau River watershed (Figure 4.7) are identified and divided into two main groups of occupation: (1) *Stable group* and (2) *Variable group*. Group (1) should be defined as including the classes with stable or relatively stable *C* values. In other words, *C* values of this group will not vary over a long period (*i.e.* months or years) in normal conditions. Group (2) will contain classes for which *C* values may vary with seasons or crop-stages. This separation helps decide to which classes modified values should be applied, after different sources of literatures. According to the available land use map (including seven classes), the classes in group (1) are: *Urban*, *Forest*, *Water bodies*, and *Bare soil*. The second group contains: *Agriculture* land, *Brush*, and *Mixture* (of agricultural, dwellings and other plantations).

- Step 2: *C* values for group 1 are selected and verified based on tabulated values from references. *C* values for group 2 are calculated based on the analysis of sub-*C*-factor values with field experiments of mass residue, the establishment of local crop stages and crop cycles over a year, and from literature reviews. Table 4.7 shows the plan to apply, to adapt or to calculate *C* values for different classes of land-cover.

- Step 3: for *C* values from group 2, in order to represent the actual variation of land cover and human-related land use activities in the Cau River basin, this study uses: (1) Modification of theory to apply crop cycles on the Cau River Basin, (2) Calculation of sub-*C* factors according to Equation 2.6 in Chapter 2 (Haan, 1994) and based on relevant literatures and field examinations.
- Step 4: Rewrite the calculation code to adapt the new modifications into GIBSI.

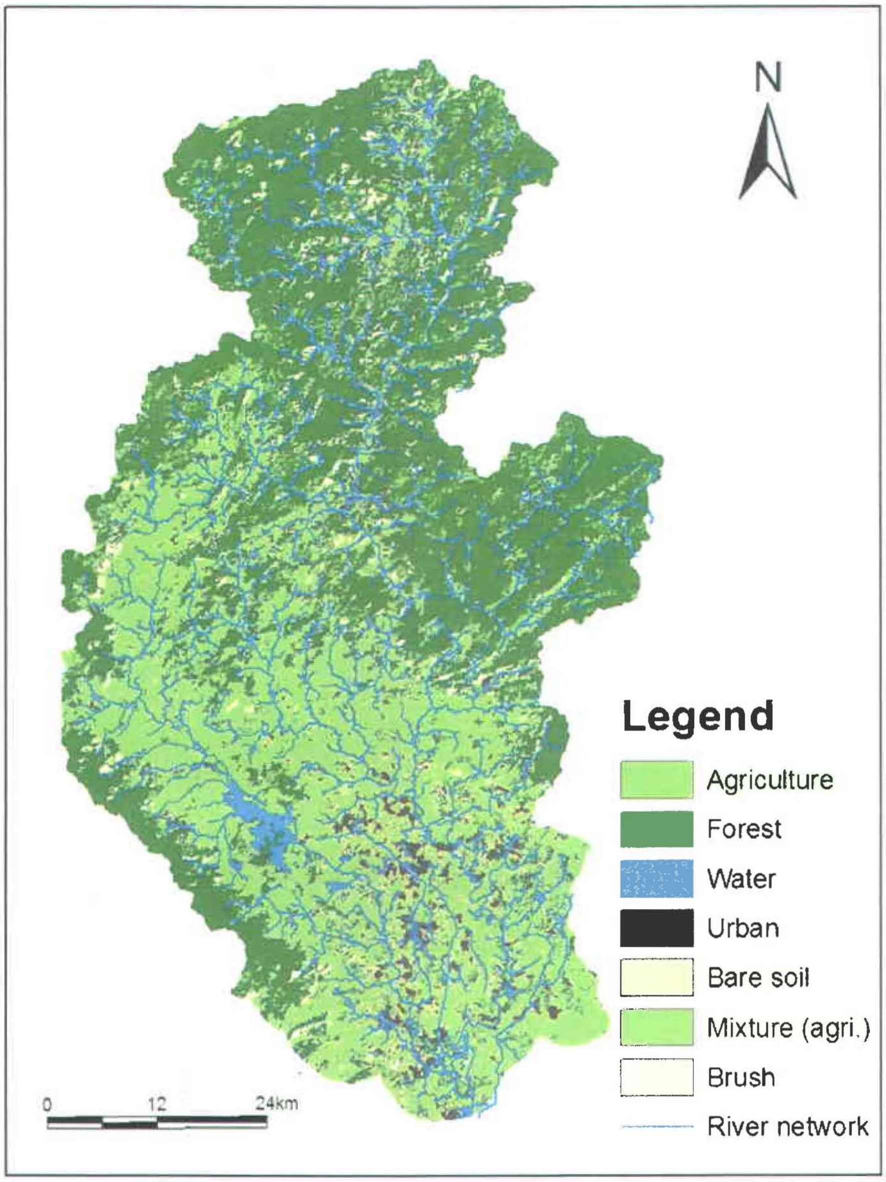


Figure 4.7: Map of land use classes in the Cau River watershed (adapted from Hoang, 2008).

Table 4.7: *C* values adapted from different sources for the classes of land-cover in the Cau River Basin.

Land use classes in the Cau River database	Referred, weighted *C* value	Applicability			Reference sources
		Direct application	With adaptation	Join with crop-steps and seasonal changes	
GROUP 1					
Urban	1.00	•			(1)(2)
Water bodies	0.00	•			(1)
Forest	0.001	•			(1)(2)
Bare soil/pasture	0.28[a]		•		(1)
	0.45[b]		•	•	(2)
GROUP 2					
Agriculture	0.05-0.65			•	(1)(3)(*)
Brush	0.012-0.043			•	(2) (*)
Mixture (vegetation)	0.40-0.60			•	(2) (*)

[a] for dry season
[b] for rainy season
(1) Mckendry *et al.* (1992).
(2) Wischmeier and Smith (1978).
(3) Transport Research Board (1980).
(*) combined with methods to calculate *C* value from sub-*C*-factor estimates

4.2.4.2 Crop timing, crop cycle estimate

Crop timing and crop cycle estimates in the conditions of the Cau River watershed are determined according to the following steps:

- Step 1: Identifying the time difference of crop timing between spatial areas of the watershed: a digital map is created which has four different irrigation zones based on the report of the Institute of Water Resource Planning (2008). The four zones are: (1) Upper Thac Huong dam, (2) Upper Nui Coc reservoir, (3) Lower Thac Huong dam, and (4) Lower Nui Coc (Appendix 4.3).
- Step 2: Dividing the Cau River watershed into two parts that correspond to the given four irrigation zones; the upper part includes the cropping zones (1) and (2) and the lower part includes the cropping zones (3) and (4). Annual agriculture activities in the Cau River watershed mostly depend on water availability. Elevation differences and the existence of the Nui Coc reservoir and Thac Huong dam drive the timing of crop seasons. Dividing the watershed into two zones could improve a lot the results of the crop timing analysis, and finally improve the accuracy of daily *C* variation estimates.
- Step 3: From the above two zones, analyzing crop timing according five main categories: (1) Main types of plants. In the Cau River basin, there are three main plant types. They are *rice*, *corn*, and several kinds of *vegetables*. (2) Timing for cropping seasons (start-end). (3) Growing characteristics (growing stages). (4) Local habits of soil work (soil preparing) and plant feeding. (5) Timing for watering and irrigation availability. This information was obtained from different local reports (Bac Kan, 2007, 2008, 2009; Thai Nguyen, 2007, 2008, 2009 and 2010).
- Step 4: Assigning crop cycles and crop stages to the three main types of plant (rice, corn, and vegetables) into the land use classes of group 2 of the land use map.

4.2.4.3 Land use cycle estimate

In GIBSI, estimates of the daily variation of the *C* factor are based on (1) the calculation of the starting time of periods for plantation in a year and (2) the crop cycle of each plantation. Primarily applied for Quebec, five periods were programmed to start within some days of a period which meet some specific weather conditions. The end of each crop cycle would depend on the type of plant and could even complete one cycle in two or three years (Villeneuve *et al.*, 1998a; Duchemin 2000).

In the Cau River conditions, there are some differences. First, all plant types (land use classes) in group 2 (the *variable group* for which we intend to estimate daily *C*) have short cycles (rice, corn, and vegetables). Second, these plants are usually planted for more than one cycle per year. Third, timing for starting of a cycle mostly depends on (1) water availability, (2) type of plant, and (3) local cultivation habits rather than on weather conditions. Finally, there is one crop cycle, although shorter than one year, which starts near the end of a year and ends early the following year. Thus, integrating these local conditions into the programming theory used in GIBSI, for Quebec crops, would be complex and it might not reflect the accuracy of *C* variations in watersheds such as the Cau River watershed.

To solve this problem, our target for *C* estimates is to represent the variation of land cover management at any given stage of a year. Land cover management is reflected by what people do on the soil that changes land cover. Thus, using crop cycles in the case of the Cau River Basin to interpret the time variation of *C* could be less significant than specifying what land use actions are done on a spatial soil unit, its timing, and its related land cover indications. So in the Cau River, we can use the sum of all stages in a crop cycle and all cycles that occur in one year as a complete global year-cycle for each class of land use. It is then possible to identify the changing points of land use stages to estimate the daily variation of the land cover management *C* factor for a land use class.

The theory for the modification of *C* daily variation estimates is based on several steps.

- Step 1: we assume that cultivation cycles on a land use class (*e.g.* agriculture) in Vietnam are in a complete one-year cycle. Each cycle begins at day one (Julian day) and is completed on the last day of each year, and then it continues with a new cycle from the 1st day of the next year. Doing this, we skip the term *crop cycle* and use the concept of *one-year land use and land cover cycle*. Therefore, we will not consider individual crop cycles but rather combine them together into a continuous chain of stages of land uses. This land use cycle is based on indications of land cover through the timing of different stages of crop cycles in a year.

- Step 2: we divide and set the beginning and end of each year-cycle into different stages based on the local agriculture calendar. Categories for stage identification include: timing for soil preparation (*soil work*), irrigation (*watering*, *drying*, and *submerging*), and plant growth and covering rates (*seedling*, *growth 1*, *growth 2*, *growth 3*, and *harvesting*) for each crop-cycle in a one-year-cycle in the Cau River Basin. This one-year-cycle is set to fit a complete Julian year for easier programming and application in GIBSI.

In general, it is not necessary to be concerned about each crop-cycle but rather to estimate how many stages there are in total per each one-year-cycle and to identify when a crop stage starts. The ending of a stage will be the beginning of next stage. Once we know the C value at the beginning of each stage, an interpolation between them can be made to estimate the daily variation of C during a year. A more detailed crop stage division could result in more accurate C variations.

In the Cau River watershed, 18, 16 and 8 crop stages respectively have been identified for the land use classes corresponding to *agriculture*, *mixture*, and *brush*. There is a delay in the starting of each stage between the upper and lower parts of the watershed for the agriculture class. Appendix 4.4 shows the stages specified for different land use classes in the upper and lower parts of the study area.

4.2.4.4 Sub-C factors calculations

The calculation of the sub-C factor is carried out on each of the sub-C factor parameters and coefficients adapted for the Cau River conditions depending on: type of plant, crop timing and crop rotations for rice and vegetables, methods for soil work (Thai Nguyen, 2010), seasonal variation of temperature and precipitation, as well as referring information on the canopy carbon/nitrogen ratio of several vegetation types and rice straws in Vietnam (Luu *et al.*, 2006).

According to Equation 2.6 (Chapter 2), sub-C factors include prior land use (C_{plu}), canopy cover (C_{cc}) surface cover (C_{sc}) , surface roughness (C_{sr}) , and soil moisture (C_{sm}). They are calculated as follows:

- $C_{plu} = D_{en} * e^{-C1*Rs}$ (Haan *et al.*, 1994) (4.6)

Where:

D_{en} = density variable related to tillage practices (D_{en} = 1 for rice and mixture of freshly tilled soils and D_{en} = 0.94 for brush);
Rs = amount of live roots and buried residue (pounds per acre);
$C1$ = 0.00088 was selected for the Cau River basin as for the "*typical cropland erosion*".

- C_{cc}: Canopy cover sub-factors from the literature for corn, vegetable, brush (Wischmeier et Smith, 1978; Terrence *et al.*, 1998) and rice (Nguyen *et al.*, 2004) are used.

- C_{sc} was estimated by employing tabulated values and calculations of: (1) the relationship between the percentage of residue cover and surface cover, (2) *C* factor values for mulch under disturbed-land conditions (Terrence *et al.*, 1998), and (3) mulch factor and length limits for construction slopes (Wischmeier and Smith, 1978). For the rice class in the Cau River Basin, the C_{sc} value was based on field estimates of root mass and mass residue of rice straws in different rice seeding and harvesting methods applied in the basin.

- From Haan *et al.* (1994) : $C_{sr} = e^{-0.14R_G}$ (4.7)
  where:
  $R_G = (25.4R_R - 6)(1 - e^{-0.0015R_s})e^{-0.14P_T}$ with $R_G \geq 0.0$;
  R_R = total random roughness (inches) after a field operation. The value of this coefficient depends on tools and methods applied for soil work (Haan *et al.*, 1994);
  P_T = total rainfall (inches) after last field operation;
  Rs = total root and buried residue (Haan *et al.*, 1994).
- C_{sm}: was defined as a function of specific conditions on different plan types and soil work methods (Haan *et al.*, 1994).

Appendix 4.5 shows the estimated results for: a) the seasonal variation of vegetation covering rate (%); b) the daily variation of *C* and sub-*C* values for the mixture class; c) the daily variation of *C* and sub-*C* values for the agriculture class in the upper part of the watershed; d) the daily variation of *C* and sub-*C* values for the agriculture class in the lower part of the watershed; and e) the comparison of *C* daily variation for the mixture, agriculture, and brush classes.

4.2.5 The modification of factor *P*

4.2.5.1 P factor grouping

Like *C* values estimate, *P* values for the Cau River watershed are also based on the existing land use map (Figure 4.7). The two land use groups in Table 4.7 can be reused. For the classes *Urban*, *Water bodies*, and *Bare soil* in group 1, given values extracted from Mckendry *et al.* (1992) can be applied. For the other classes, the tabulated values given in Table 4.9, specified below, can be applied. At the first stage of this study, and with the current available land use classes, *P* values extracted from Mckendry *et al.* (1992) will be employed where the values in Table 4.9 cannot be applied.

4.2.5.2 Analysis of the land use map for P value assignment

Tabulated *P* values from Wischmeier and Smith (1978) (Appendix 4.6) are employed in the Cau River watershed instead of the RUSLE sub-factor approach.

Considering the terrain and agricultural system of the Cau River Basin, the design of the fields of rice, corn and other vegetables correspond to the group of *contour-farmed terraced fields* where *slope length is the horizontal terrace interval*, with *broadbase, steep backslope* and *level terraces* (column V in Table c of Appendix 4.6). Paddy fields correspond to *graded channels sod outlets* (column IV). Other vegetation types correspond to *strip-crop* (column III). Appendix 4.7 shows sample pictures of rice and vegetation field designs which are popular in the study area.

It is notable that areas of the *Brush* class are often used by local farmers for agriculture with *contouring* type in a few months during a year, when water is sufficient. Thus, it suggests the possibility to use *P* values from Table a (Appendix 4.6) during the rainy season. Table 4.8 presents the land use classes and *P* values applied in the Cau River watershed.

Table 4.8: Land use classes and *P* values applied in the Cau River watershed.

Land use classes in the Cau River database	*P* value applicability		
	From Mckendry *et al.*, (1992)	Adapted from Mckendry *et al.*, (1992)	Tabulated tables from Wischmeier and Smith (1978)
GROUP 1			
Urban	1.0		
Water bodies	1.0		
Forest	1.0		
Bare soil/pasture	1.0		
GROUP 2			
Agriculture	0.5		Appendix 4.6 (table c IV)
Brush	0.5		Appendix 4.6 (table a, for rainy season)
Mixture (vegetation)		0.5	Appendix 4.6 (table c III)

4.2.5.3 Code preparation for the new assigned values of P

Based on the available land use map, a new code for the calculation of *P* values was prepared in conjunction with the two conditions of slope angle (%) and the date of estimate (Julian day). For the land use classes of group 1, *P* values are employed directly from

Mckendry *et al.* (1992). For group 2, values extracted from Appendix 4.8 with consideration for slope variation (Wischmeier and Smith, 1978) are applied. Details about the computing code writing conditions are listed in Appendix 4.8.

4.3 Modifications and adaptations of the sediment transportation model ROTO

Modifications and adaptations involve the sub-routine ROTO (Arnold *et al.,* 1995a) for the improvement of the simulation results for the catchment area of the Cau River. The modifications in this thesis work are made by following a thorough analysis of the ROTO algorithm implemented in GIBSI (Villeneuve *et al.,* 1998a) and the work of Arnold *et al.* (1995a) for the simulation of the transport, deposit and re-entrainment of sediments on a river section.

In practice, this study focussed on the revision of concepts and the correction of equations and computing codes for the sediment transportation processes. Factors involved in the modifications include: $PERO_{ri}$ (total amount of sediments re-entrained on each river section *i*), $PERO_{ti}$ (total amount of sediments eroded and transported on each river section *i*); and SED*ri* (sediment deposition on river section *i*).

4.3.1 Sediment re-entrainment

First, the equation for sediments re-entrainment (Equation 3.38) was reviewed. Units for the calculation of *PEROri* (tons) and for the drainage surface (km^2) were corrected. Equation 3.38 thus becomes:

$$PEROr_i = 10^{-3}\left[\frac{69.44*SUPBV}{100}\right]^{-0.5} \gamma\, dur\, P_{ri}\, Wr_i{}^{0.5}[Hr_iVr_i]^{1.5} \qquad (4.8)$$

The variables and parameters of this equation are defined in Chapter 3 (Equation 3.38).

Second, the equation for $PERO_{ti}$, the total amount of sediments eroded and transported on river section *i* (Equation 3.42) was corrected based on a review of the paper by Arnold *et al.* (1995a). By definition, for a small watershed, the sediment delivery ratio (*IAS*) is the rate of sediment load delivered at the exit of a river section per total quantity of sediments produced on its associated surface. Equation 3.42 thus becomes:

$$PERO_{ti} = (1 - IAS_i)(PEROr_i + PEROI_i): \quad (4.9)$$

4.3.2 Deposition of sediments

The amount of deposited sediments, SED_{ri}, in each river section i is estimated using Equation 3.37 in GIBSI. In this work, the equation was corrected by adjusting the re-entrainment delivery rate in the calculation of the total amount of sediment eroded and transported on section i ($PERO_{ti}$):

$$SEDr_i = PSED_{ti} - IAS * PERO_r + (1 - IAS_i) * PEROI \quad (4.10)$$

The variables and parameters of this equation are defined in Chapter 3 (Equations 3.39 to 3.43).

4.4 Calibration and validation

4.4.1 Sensitivity analysis, guidelines and procedure for calibration

In this study, to ensure a correct orientation in the adjustment of the calibration parameters of the models, which were adapted to the local conditions of the Cau River Basin, it is necessary to understand how the models behave in response to changes in the values of the calibration parameters. Sensitivity analysis can be defined as the study that quantifies the effects of variations in the calibration parameters values on the model calculated results (Cacuci, 2003). In other words, the understanding of the influence of the variation of the calibration parameters values on the output variables is of fundamental importance. The sensitivity analysis can also be useful to guide the calibration of a model. Parameters of the soil erosion and transportation models were set to be adjustable during calibration, in order to achieve the best fit to observation data.

The sensitivity analysis was performed using (1) both theoretical and numerical methods at the USS scale and (2) a numerical method at the whole watershed scale. The USS scale was considered in order to conduct a sensitivity analysis on a small unit of the river basin with analytical functions prior to analyzing the whole watershed. The watershed scale was to analyze the response of the entire watershed (in variation of *SS*) due to changes in the values of the calibration parameters

The analysis at the USS scale was conducted for each of the three processes of the two models (erosion on soil surface, sediment transportation on soil surface and sediment transport in river). Based on the derivatives of the mathematical equations which govern the processes, the analysis at the USS scale was performed to verify, in general, the theoretical influence of some calibration parameters on the variables involved in the processes. The theoretical sensitivity analysis of individual calibration parameters of the two models was performed according to their direct involvement in an equation for the calculation of a factor or a process taking part in sedimentation or transportation of sediments.

Specifically, this analysis will help highlighting useful information for the adjustment of some calibration parameters. The analysis at the scale of the whole watershed was also considered in order to: (1) take into consideration the whole study area for which it might be difficult to perform a sensitivity analysis based on analytical functions; (2) confirm some results and information obtained at the USS scale. Methodology and parameters applied in the analyses are discussed in detail in sections 4.4.1.1 and 4.4.1.2. Detailed derivations and analysed results for each parameter are descripted through sections 4.4.1.3 to 4.4.1.7.

4.4.1.1 Methodology and parameters for sensitivity analyses at USS scale

This sensitivity analysis at the USS scale was conducted based on the following main considerations:

- Calibration parameters for the sensitivity analysis are associated with three main processes or models, orderly, sediment production on surface, sediment transportation capacity on surface and then suspended sediments transportation in river.
- In GIBSI, output (result) of the earlier model is an input data for the latter. Each model itself has different mechanisms including different parameters. Some parameters are directly in the function of the model's output while some others play the role of a condition to decide which methods or formulas should be applied for the calculation of that model's output (see Figure 3.2, Chapter 3). Thus, it is impossible to determine,

theoretically, a general analytical function for all calibration parameters for the sensitivity analysis.

- Parameters analyzed during the sensitivity analysis are those that will be used for calibration. They are selected according to the requirements of the models and their associated parameters and factors (Table 4.11). This aims at verifying the sensitivity of a result to variations in the value of a parameter from the mathematical formula.
- A specific location on the watershed was selected for the analysis (a spatial simulation unit, USS, with its corresponding river section) based on the location of the available data required. Even if the whole watershed was not considered at this step of the sensitivity analysis, the results obtained at the USS scale may help to understand the influence of some parameters prior to the calibration of the models at the river basin scale.
- Where applicable, the selection of two representative periods (date) which reflect the seasonal differences for the analysis of one parameter was performed. This is to verify the behaviour of a parameter when there are changes in hydrological or meteorological conditions (seasonal changes). Seasonal changes may have impacts on surface erosion and sediments transport.

To verify the difference, if any, in the influence of parameters at the USS scale, this work applied two types of analyses: (1) theoretical variations of parameters in the mathematical formulas, for a sensitivity analysis based on analytical functions; and (2) practical variation of values of the parameters, using actual local input data and performing simulations with the model. These are considered, respectively, as "theoretical" and "numerical" sensitivity analyses.

The theoretical sensitivity analysis was carried out based on the derivative function with respect to each parameter: $\frac{\partial f}{\partial x_i}$ where x_i is a calibration parameter. The analyzed functions are respectively: *R* in surface erosion (see Equation 4.1); *CTS* in surface transportation (Equation 3.27); and V_c in suspended sediment transport in river (Equation 3.31). These functions were chosen because they are the ones which include one or several calibration parameters in their expressions: *R* for parameters *a, b* and *c*; *CTS* for parameters *Kt, n* and *o*; *Vr* for parameter *Dr*.

For the purpose of the numerical sensitivity analyses, the values of suspended solids on the river section located at the outlet of the watershed with the corresponding USS are simulated using the computer model. The chosen USS and its associated river section at Gia Bay station were selected (Appendix 4.9). The station is located at the outlet of the river basin and is selected based on the following reasons: (1) Gia Bay is the station that has the most available daily observation data for hydrological (discharge), meteorological (rainfall) and suspended solids data; (2) this river section is, therefore, selected for the calibration of the models in GIBSI (modified for the Cau River Basin conditions); (3) sensitivity analysis of the modified models at the same location where they are calibrated could help understanding the behaviour of the models, as well as give an overview of the necessity and effectiveness of adjustment decisions when calibrating the models.

This section addresses the sensitivity analysis of three groups of calibration parameters that relate to the yield of sediment production and transportation on surface before getting into a river section, and one parameter that takes part in the transportation of suspended solids in a river section (see Table 4.11 Section 4.4.3). They are: (1) parameters which are responsible for the production of sediment (*a, b* and *c* in subsection 4.4.1.3); (2) parameters that are related to the transportation of eroded sediment to the output of an USS (*k, n* and *o* in subsection 4.4.1.4); (3) a parameter representative of the particle size of sediment that defines the rate of *SS* to be transported to the exit of a river section (*Dr* in subsection 4.4.1.5).

With regard to the sensitivity analysis during different seasons, it was recognized that precipitation is the main input variable that defines the seasonal changes. Thus, for all selected functions for the calculation of which variables related to precipitation (such as rainfall, soil surface discharge, surface water flow height, etc.) are used, different sets of values were applied for the "wet" and "dry" seasons. These sets of values are selected from hydrometeorological simulation results from HYDROTEL. For the purpose of this analysis, the following representative dates are selected: February 5, 1998 for the *dry* season and July 7, 1998 for the *wet* season. This distinction was applied for the *a, b, c, k, n,* and *o* parameters (sub sections 4.4.1.3 and 4.3.1.4).

4.4.1.2 Methodology and parameters for sensitivity analyses at watershed scale

In addition to the sensitivity analysis at a selected USS, a broader view of sensitivity analysis at the scale of the whole watershed was also carried out (sub section 4.4.1.6). The objective of this task was to analyze the variation of the output variable *SS* at the exit of the watershed (Gia Bay station) according to changes in the values of the calibration parameters. The analysis performed at this scale is different from the one done at the USS scale in the way that it helps, based on simulations, determining the influence of the variation of each calibration parameter on the estimated *SS* load in rivers as the final output variable. On the other side, the USS scale analysis was found to be helpful to understand how the changes in calibration parameters values can influence each of the processes in which they are involved.

4.4.1.3 Expression and results obtained for erosivity factor R with variations of a, b, and c on a selected USS

From Equations 3.1 to 3.3 about erosivity (sub section 3.1.5.1), partial derivatives of erosivity was determined with respect to each parameter *a*, *b* and *c* (see Table 4.9a). These theoretical derivations, first, were used to compute the theoretical relative variations. Then, we compared the theoretical and the numerical relative variations as a function of *a*, *b* and *c* parameters. The corresponding formulas for relative variations of *R* with respects to *a*, *b*, and *c* are given in Appendix 4.10 a.

Since derivations depend on input data for rainfall (*P*), water height (Q) and discharge (*q*) at the outlet of a USS, two days of input data were considered as representative for the wet and dry periods on the USS located at the outlet (USS 60) of the watershed (Table 4.9b). The values of *a, b* and *c* are set to values suggested in the literature as default values for calibration. The result presented is for the soil erosivity (*R*) on USS 60 only. However, at any other USS in the watershed, the values of variables *P*, *Q* and *q* could sometimes be similar to the ones at USS 60. Thus, in some limits, the results of the analysis on the USS 60 are probably representative of the whole watershed. The sensitivity analysis of erosivity *R* based on USS 60, therefore, may be useful for calibration.

Table 4.9: (a) Derivatives and (b) Reference values and selected dates for the sensitivity analysis of erosivity with respect to parameters *a*, *b* and *c*.

(a) Derivations with respect to parameters *a*, *b* and *c*

Root equation: $R = a\,P^b + 0.45\,c\,Q\,q^{0.333} = a\,P^b + a_2 c$ [1]

Where: R: total daily soil erosivity on USS (MJ mm/ha h)

P : daily precipitation on USS (mm/day),

Q : Water height on USS (mm/day),

q : daily discharge at the exit of USS (m^3/s)

a: calibration parameter coefficient [range: 0.18-0.19]

b: calibration parameter [range: 1.5-2.2]

c: calibration parameter [range: 0.1-0.6]

$a_2 = 0.45Qq^{0.333}$

With respect to a: $\frac{\partial R}{\partial a} = P^b$ [2]

With respect to b: $\frac{\partial R}{\partial b} = a * ln(P) * P^b$ [3]

With respect to c: $\frac{\partial R}{\partial c} = a2$ [4]

Table 4.9 (continuing).

(b) Default values and seasonal selections

Default values according to literatures	**Calibration parameter or input variable**	**Value**	**Note**
	a	0.185	Calibration parameter
	b	1.81	Calibration parameter
	c	0.6	Calibration parameter
Selected wet season day:			
07/07/1998	Q	31.3	Water height on USS (mm)
	q	0.2	(daily) discharge at the exit of the USS (m^3/s)
	P	34.9	daily precipitation on the USS (mm)
	a_2	8.12	.
Selected dry season day:			
05/02/1998	Q	0.03	Water height on USS (mm)
	q	0.0008	(daily) discharge at the exit of the USS (m^3/s)
	P	1.01	(daily) precipitation on the USS (mm)
	a_2	0.0005	Component of R_{rji} calculated in the selected day of dry season.

Figure 4.8 shows the theoretical and numerical variations of *R* (%) with respect to the variation of *a*, *b*, and *c* parameters during the wet and dry seasons at USS 60. It was found that:

- Except for parameter *b* during the wet season, the trends of variation of *R*, for the two seasons, are almost the same in both theoretical and numerical analyses.
- Parameter *b* is the one to which *R* is the most sensitive in wet season while having almost no effect in dry season. In the wet season, variations of *b* can lead to an important increase of *R* (*e.g.* a 14 % increase in *b* can conduct to a 220 % increase in *R*, see curve of *RwB% theoretical* in Figure 4.8.a). This trend of variation of *R* with respect to *b* during the wet season can be explained by the fact that *b* is an exponent of precipitation *P*. This may dramatically increase erosivity during the rainy season. Furthermore, with the default value of 1.81, an increase of *b* results in a rapid rise of *R*. But a decrease of *b* results in a smooth gradual decrease of erosivity (-14% of

variation of *b* results in around -30% of variation of *R*, see curve *RwB% theoretical* in Figure 4.8.a).

- In dry season, due to the low precipitation, variations of parameters *b* and *c* have almost no effects on *R*. In Figure 4.8.b, the curve of *RdB%* is overlapped by the curve of *RdC%,* and the corresponding *R* variations are negligible, regardless of the parameter variations. In wet season, variation of *R* with respect to *c* remains negligible (see curve *RwC%*, Figure 4.8.a).
- Parameter *a* is not affected by seasonal differences. *R* keeps almost the same rate of variation linearly to changes of *a* in both seasons (see curves *of RwA%* and *RdA%* in Figures 4.8.a and 4.8.b).
- Variations of *R* with respect to parameter *c* are negligible for both seasons (see *RwC%* and *RdC%* in Figures 4.8.a and 4.8.b).

Finally only parameters *a* and *b* were found to have impacts on *R*. While *b* is the dominant parameter in wet season, *a* becomes the factor with the most effects on *R* during the dry season.

It is important to emphasize that, when we consider the sensitivity to parameters used for calibration, the final target is to verify how they affect the total value of sediment production. Thus, the relative variation (%) of a parameter may not be sufficient to reflect the real impact of this parameter on the simulated values. Due to the large differences in sediment production between seasons, a small change (in percentage) of sediment in wet season could result in a bigger change of sediment volume rather than a big change (in percentage) on a small amount of sediment in dry season. Thus, having an additional comparison of absolute values affected by the changes is important.

Figure 4.9 show the absolute variations of *R* values. Results show a big contrast of *R* values between the two seasons: *b* is the parameter to which the *R* value is the most sensitive in wet season, due to precipitation, and *a* becomes the parameter to which *R* is the most sensitive in dry season. Thus, for purpose of numerical control of soil erosivity in wet season, *b* should be the most attentive parameter.

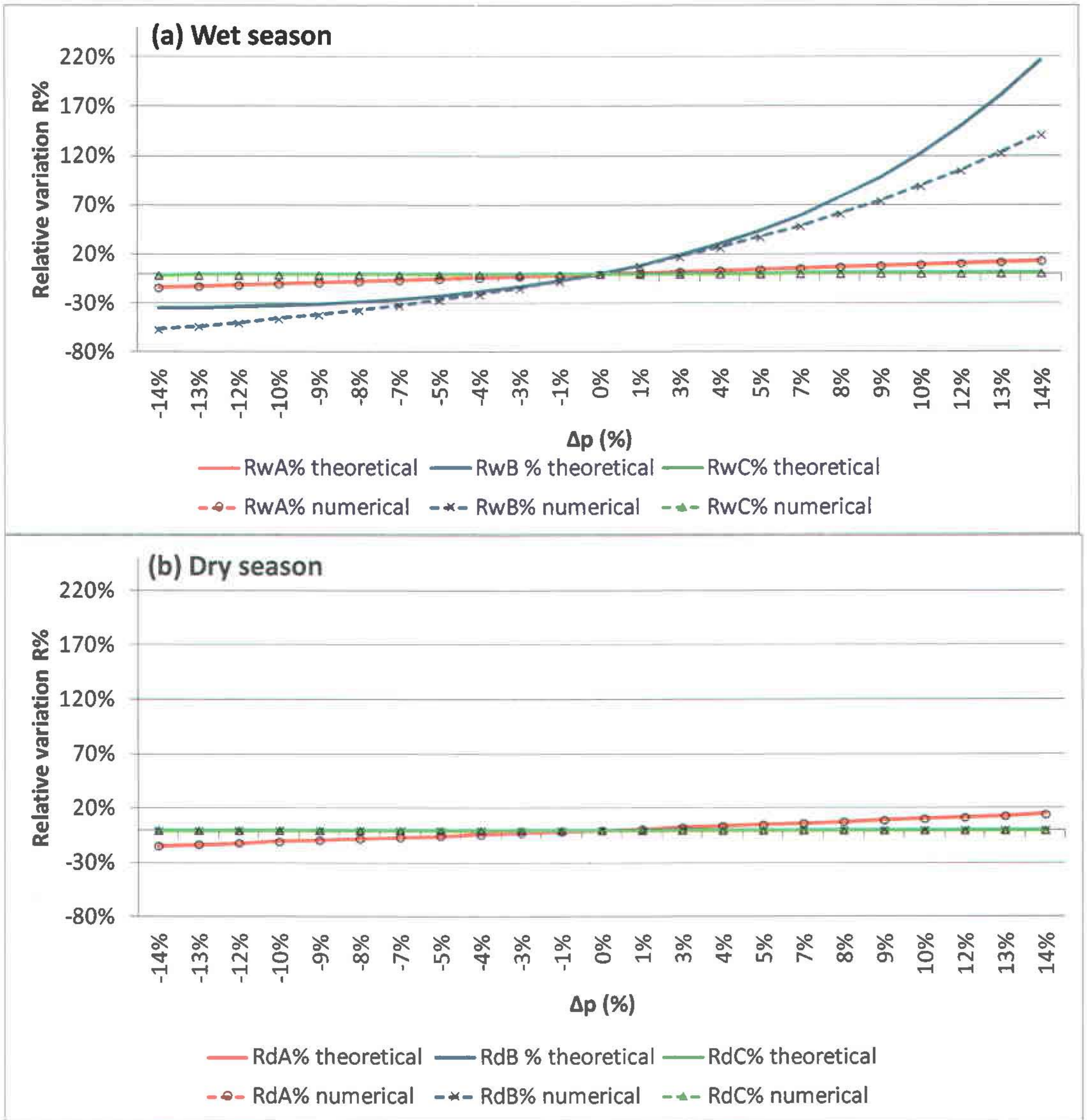
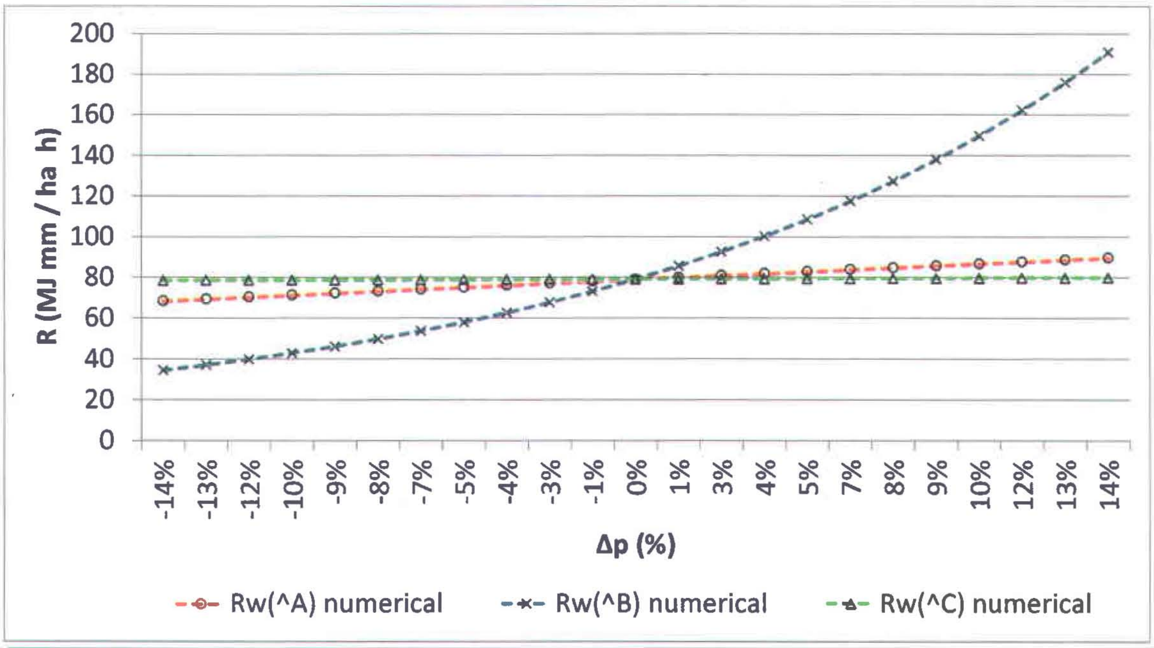


Figure 4.8: Relative variation of *R* with respect to *a*, *b*, and *c* parameters on USS 60.

Where *RwA%; RwB%; RwC% and RdA%; RdB%; RdC%* = Ratio of *R* factor as a function of parameters *a, b,* and *c* in wet (*w*) and dry (*d*) seasons. In dry season, *RdB%* is overlapped by *RdC%;* Δp% = assumed range of parameter variation (0 ± 14%).



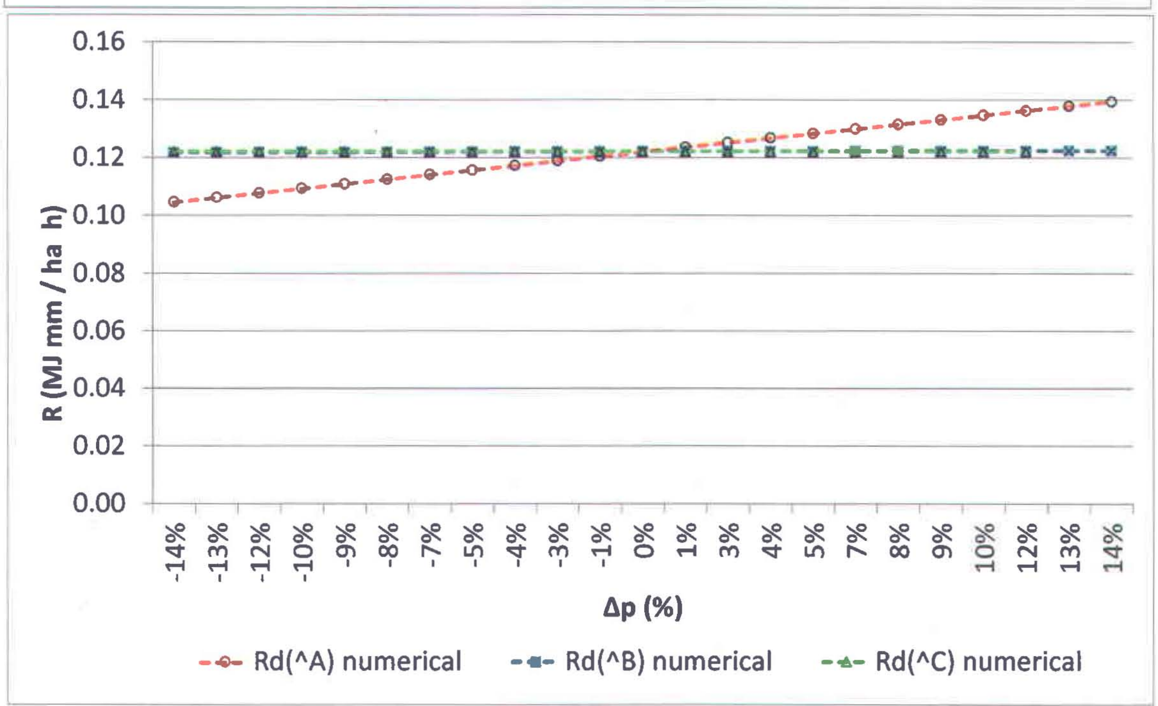


Figure 4.9: Values of *R* with respect to *a, b* and *c* parameters on USS 60.

Where *Rw(^A); Rw(^B); Rw(^C) and Rd(^A); Rd(^B); Rd(^C)* = Values of *R* factor as a function of parameters *a, b,* and *c* in wet (*w*) and dry (*d*) seasons. In dry season, *Rd(^B)* is overlapped by *Rd(^C)*; Δp% = assumed range of parameter variation (0 ± 14%).

4.4.1.4 Surface transport parameters K_t, n and o on a selected USS

The transport capacity *CTS* (ton/day) defines the capacity of the surface water flow to transport eroded sediments on a USS to reach a river section. As mentioned above, due to the mechanic of switching between equations according to the value of some parameters, (Equation 3.30), it is impossible to determine an analytical function of *SS* at the outlet for all calibration parameters. In this case, it is only possible to analyze the sensitivity of *CTS* itself for a specific location and at a selected time.

CTS is expressed as:

$$CTS = K_t\,(0.001\,\rho\,g\,q\,\tan\theta)^{1.5}\,[n(QJO)^{o}] * 86.4 \quad (4.11)$$

$$= K_t\,n\,(QJO)^{o}\,(0.001\,\rho\,g\,q\,\tan\theta)^{1.5} * 86.4 \quad (4.12)$$

Where

K_t = transport coefficient;

q = daily discharge at the exit of USS (m^3/s);

n and o = calibration parameters;

ρ = water density (kg/m^3) [= 999.1 at 15°C];

g = acceleration gravity (9.81 m/s^2);

QJO = Q/(86400*1000)*(S*10000) = mean daily flow rate on USS (m^3/day);

S = surface area at each USS = 57.5 km^2 at the selected USS 60;

Q = water height on USS (mm/day);

θ = mean slope of the USS (m/m).

Variations of *CTS* with respect to *K* (with $K = K_t n$) and *o* are expressed in terms of the relative variation for the theoretical sensitivity analysis (Figure 4.10) and the numerical sensitivity analysis (Figure 4.11) for both wet and dry seasons.

CTS can be simply re-written as follows:

$$CTS = K_t * b_1 * n * b_2^{o} = K * b_1 * b_2^{o} \quad (4.13)$$

Where $\mathbf{b_1}$= $(0.001\,\rho\,g\,q\,\tan\theta)^{1.5} * 86.4$, $\mathbf{b_2}$= *QJO* and $\mathbf{K}$= $K_t * n$

Derivations with respect to parameters K is $\frac{\partial CTS}{\partial K} = b_1 * b_2^o$,

and with respect to parameters o is $\frac{\partial CTS}{\partial o} = K * b_1 * ln(b_2) * b_2^o$

For the theoretical and numerical relative variations, the same approach as for parameters *a*, *b* and *c* was employed. The corresponding formulas for *CTS* with respects to parameters *K* and *o* can be found in Appendix 4.10 b.

The sensitivity analysis of *CTS* was carried out on the same USS 60 with the same input data of water height *Q* and daily discharge *q* of the two selected days shown in Table 4.9b. In addition, the surface area of USS 60 was estimated at 57.5 km^2.

While the hydrometeorological inputs of an USS can be similar to those of other USSs, it is recognized that there are two parameters that could be the keys to decide the difference of *CTS* between an USS to the others. They are the mean slope θ of USS (in b_1) and the area *S* of USS (in b_2). In other words, inputs of weather conditions may be the same over a number of USS in a watershed but since the key input variables that influence the *CTS* result on a specific USS are the mean slope and the area, then erosion could be highly different from one USS to the other. This fact suggests an additional examination of the effect of topography on sediment production of the USS. This will be examined and discussed in Chapter 5.

It was found that:

- As for the sensitivity analysis of erosivity *R*, the results of the theoritical and numerical sensitivity analyses of the transport capacity are similar, in both wet and dry seasons (Figures 4.10 and 4.11).
- Although there is a variation found when changing the values of $K_t n$ and *o* in different seasons, their effects on *CTS* changes are minor.
- In both seasons, *CTS* increases with a rise of $K_t n$ but decreases with a rise of *o*. While the *CTS* changes in percentage with respect to *o* differ from one season to the other, the *CTS* variations in percentage were exactly the same as a function of $K_t n$ in both seasons. This means that the CTS variations as a function of $K_t n$ are not affected by the seasonal changes.
- In wet season, parameter *o* shows less effect (by percentage) on *CTS* than in the dry season (Figure 4.10).

- When considering the *CTS* variations in absolute values (Figure 4.11), results show exactly the trends that were found in figure 4.10. The changes in absolute values are small, especially in dry season. Thus, it can be concluded that the effect of $K_t n$ and o on the calibration results will be limited. However, in wet season, *CTS* parameters would have a greater impact.

- As an extension to this discussion, the role of the mean slope parameter (θ) of the selected USS takes an important part in the *CTS* calculation of that USS. This parameter can be considered as a key parameter influencing the *CTS* value in each USS. Thus we would recommend carrying out additional verifications of the effect of slope on sediment production at different locations of the watershed; this will be discussed in Chapter 5.

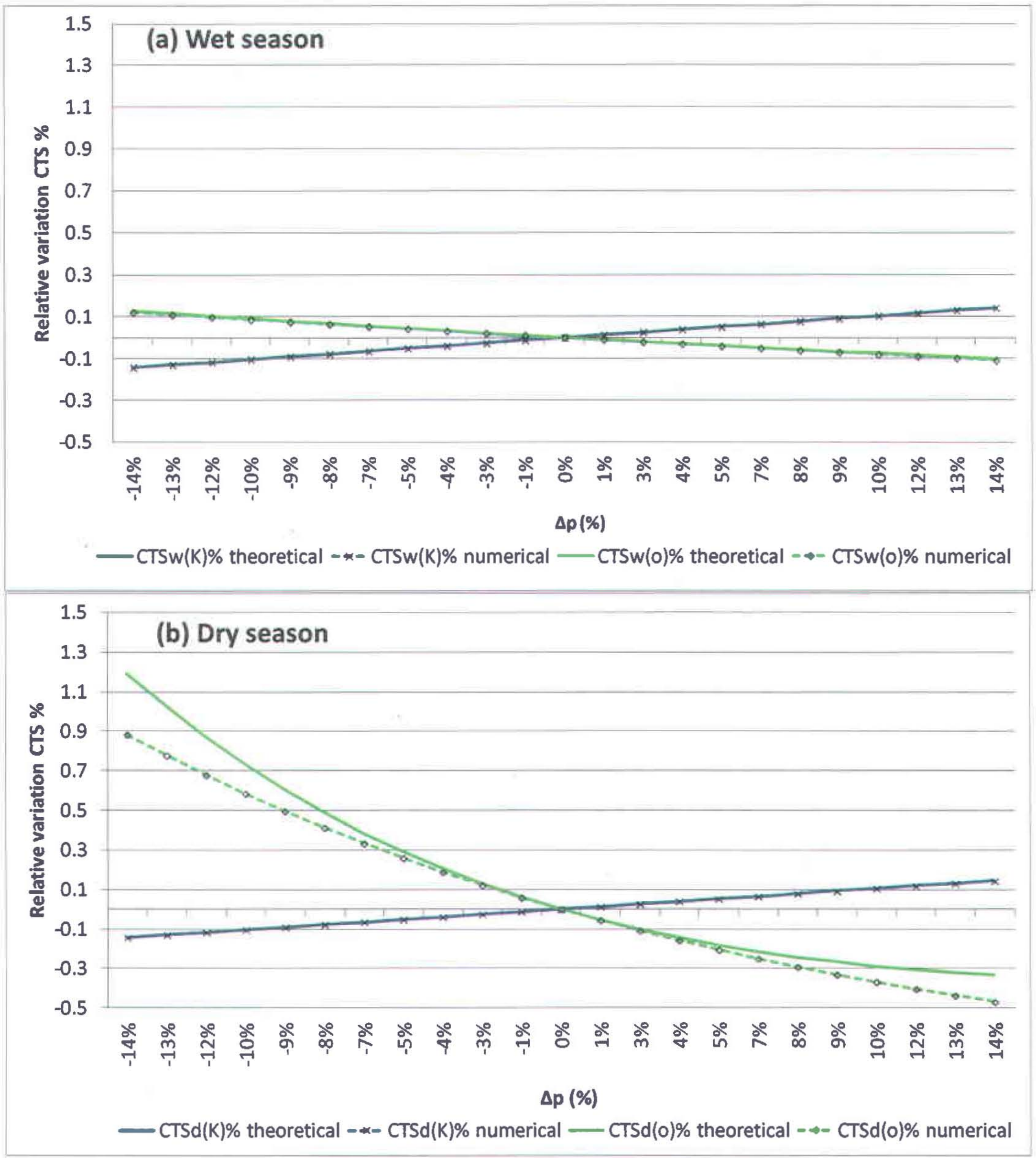


Figure 4.10: Variation of *CTS* with respect to *K* and *o*.

where *CTSw(K)%; CTSw(o)%; and CTSd(K)%; CTSd(o)%* = Ratio of *CTS* factor as a function of parameters *K* and *o* in wet (*w*) and dry (*d*) seasons; Δp% = assumed range of parameter variation (0 ± 14%).

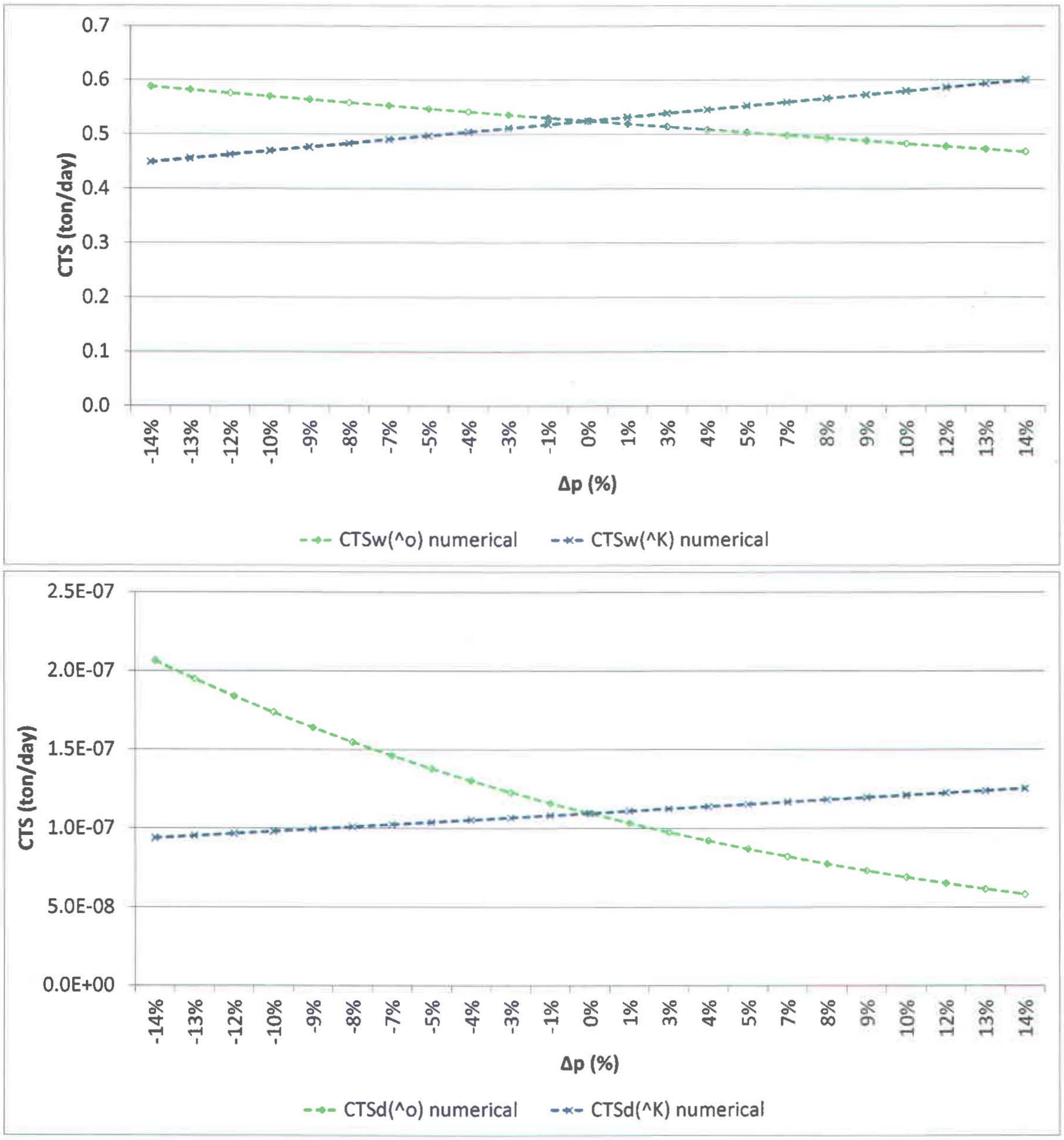


Figure 4.11: Value of *CTS* with respect to *K* and *o*.

where *CTSw(^K); CTSw(^o); and CTSd(^K); CTSd(^o)* = Value of *CTS* factor as a function of parameters *K* and *o* in wet (*w*) and dry (*d*) seasons; Δp% = assumed range of parameter variation (0 ± 14%).

4.4.1.5Parameter for sediment transport (Dr) on a selected river reach

Fall velocity (V_c) of suspended particles in a river reach plays an important role, involving the calculation of vertical distance (*Hc*) for deposit of suspended particles in a river reach (Equation 3.33, sub section 3.1.6.2). The value of *Hc* decides which equation is used to calculate the delivery rate of sediments in a river reach, *IAS* (Equations 3.34 and 3.35, sub section 3.1.6.2). This then directly affects the calculation of the proportions of suspended solids *SS* to be deposited or transported towards the output of a river section. In the application of GIBSI to the Cau River watershed, the fall velocity of particles on a section of river is expressed as:

$$V_c = exp\ (-12.57\ X^2 + 40.44\ X - 32.92) \qquad (4.14)$$

with $X = ln\ (-ln\ D_r)$

where D_r = representative diameter of particles (m)

Thus, *Dr* was supposed to be an adjustable parameter with a high potential to change *Vc* and therefore the *SS* load at the output of river sections. In this analysis, variations of *Vc* were also examined based on both theoretical and numerical sensitivity analyses.

The theoretical analysis was conducted through partial derivative of the analytical function of *Vc* with respect to *Dr* as:

$$\frac{\partial Vc}{\partial Dr} = \frac{(2*c_1*X+c_2)}{D_r*ln(D_r)} * V_c \qquad (4.15)$$

where:

$X = \ln\ (-\ln D_r)$
$Vc = e^{P(X)}$
$P(X) = C_1X^2 + C_2X + C_3$
$C_1 = -12.57$
$C_2 = 40.44$
$C_3 = -32.92$.

Theoretical and numerical variations were compared and the corresponding formulas for the relative variation of *Vc* with respect to *Dr* can be found in Appendix 4.10 c.

The numerical sensitivity analysis was performed trough the analysis of the impacts of ±14% variations of *Dr* with respect to two different default values of 0.15 mm and 0.3 mm.

The results can be summarized as follows:

- The results obtained in both theoretical and numerical sensitivity analyses are similar, *Vc* increases linearly to the changes in *Dr* values (Figure 4.12).
- The higher is the value of *Dr*, the faster the deposition of particles in a river reach. Therefore, the lower *Dr* could be the higher ratio of particles that may be delivered to the next river reach. This is mainly due to the weight of particles which may increase when there is an increase of the diameter.
- The effects of the variation of *Dr* on the falling velocity of particles can help to control the deposition and the final results of *SS* at the outlet. Depending on flow velocity *Vr* and water depth *Hr* of the river section, *Vc* can change through calibration parameter *Dr* in order to control the rate of sediment that remains suspended and transported to the exit of the river reach.

By reviewing the mechanism that allows *IAS* to be higher when water depth is higher (Equations 3.34 and 3.35, sub section 3.1.6.2), the effects of *Dr* could be expected as: (1) there would be a big contrast of daily *SS* between the periods of low and high rainfall because of the switch of equation to compute the delivery ratio index (*IAS)* in the algorithm (figure 3.2, Section 3.1.5); (2) controlling the *Dr* value means controlling the switching point for the equation used to compute *IAS*; (3) the rate of *Dr* changes is not driven by seasonal differences. Thus, the changes in *Dr* may affect *SS* broadly over the periods of a year. However, they could have more impacts during the periods of high *SS* like rainy periods. Thus, the adjustment of *Dr* could be the key to control peaks of *SS* as well as their total mass on a long period.

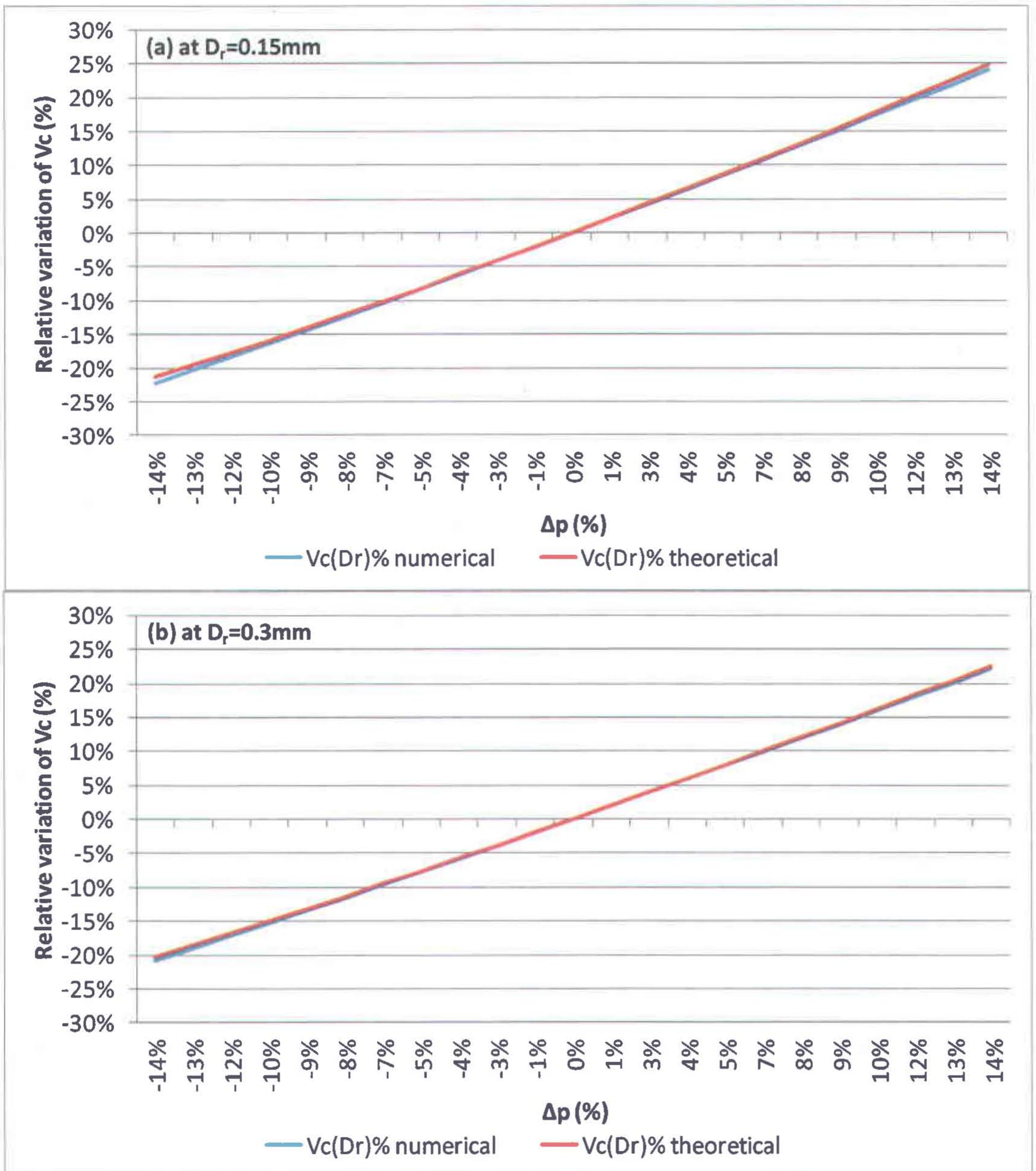


Figure 4.12: Theoretical sensitivity for fall velocity (*Vc*) with respect to two reference values of *Dr*.

Δp% = assumed range of parameter variation (0 ± 14%).

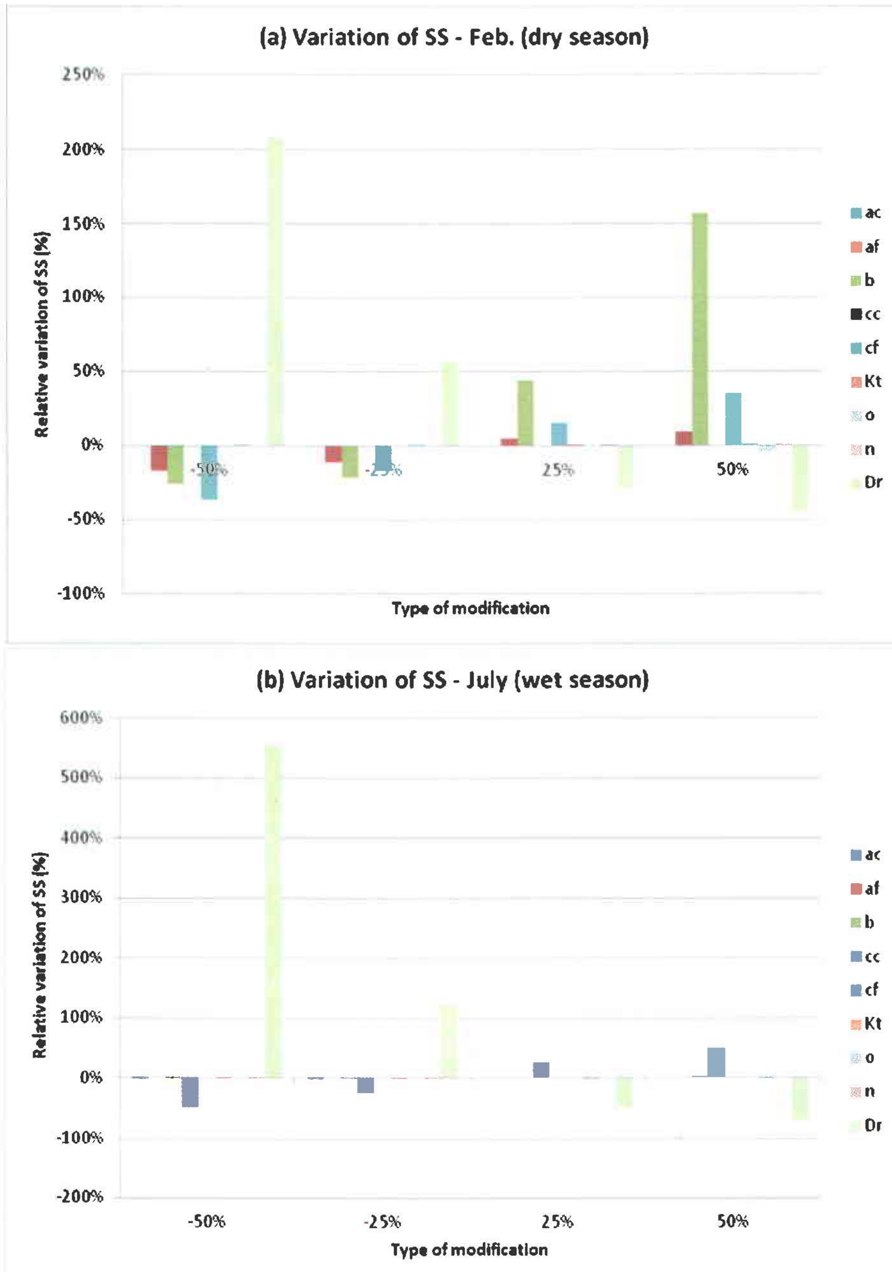
4.4.1.6 Sensitivity analysis at the watershed scale

The sensitivity analysis of suspended solids with respect to variations in the value of some calibration parameters at the watershed scale is carried out in this section. The analysis is based on the relative variations of simulated total suspended sediments at the outlet of the watershed. Calibration parameters are set to vary one at a time by ±25% and ±50% with respect to their default values. Two different months corresponding to the wet period (July) and dry period (February) were chosen as simulation periods. As mentioned before, results of *SS* at the outlet of the watershed is the result of a combination of different processes, linked to the parameters of the soil erosion and transportation models. Due to the succession of models in GIBSI, it is impossible to express *SS* analytically as a function of the calibration parameters. This sensitivity analysis performed at the scale of the whole river basin can help to confirm the trend found at the USS scale. Both results can be used as reference for calibration.

Results of the analyses are shown in Figure 4.13 and can be summarized as follows:

- During the dry season (Figure 4.13 a): The most relevant parameters are the representative diameter of particles (*Dr*) and the exponent of rainfall (*b*), with the impact of *Dr* being the highest for almost all types of variations. Parameter *cf* (value of calibration parameter *c* in dry season) can be considered as the third important parameter.
- During the wet season (Figure 4.13 b): *Dr* appears as the most important parameter for all types of variations of calibration parameters, followed by *cc* (value of *c* in wet season). A negligible impact was found for all other parameters.
- During both seasons, an increase of *Dr* has less impact on *SS* than a decrease. In dry period, there are few days of precipitation so the exponent of the rainfall (*b*) may have a major impact on *SS* when an increase occurs (see 25% and 50% increase of *b*, Figure 4.13 b). The *SS* is broadly sensitive to *Dr* (by percentage) in both wet and dry seasons and the impact of *Dr* is more significant for negative variations. Thus, the independence of *Dr* to seasonal changes is confirmed. Although the trends of sensitivity of *SS* to *Dr* in the two seasons are similar, the rate of *SS* changes in wet season is more than two times higher than during the dry season (more than 500% and 200% of variations respectively, Figure 4.13). During the wet season, together with the already high *SS* load, higher changes in *Dr* could result in a dramatic change of *SS* load. This fact agrees with the sensitivity analysis result of *Dr* at the USS scale, discussed in sub-section 4.4.1.5.

At the scale of the river basin, *SS* at the outlet is influenced in different ways by the sediment production parameters (*a, b, c*) and the fall velocity parameter *Dr*. Although parameters *a*, *b*, and *c* have more influence on sediment production on surface in wet season at the USS scale (Figure 4.8), their imprints on *SS* changes at the exit of the watershed were more visible in dry season than in wet season. Overall, relative variations of *SS* at the outlet of the watershed are mostly influenced by *Dr* changes. Other parameters could modify the variation, depending on seasons.



ac and *af* = calibration parameter for *R* in wet and dry seasons (MJ/ha h);
cc and *cf* = calibration parameter for *R* in wet and dry seasons (MJ/mm ha);
Kt = calibration parameter for sediment transport on surface;
n and *o* = calibration parameters for sediment transport on surface;
Dr = representative diameter of particles (m) for sediment fall velocity in river segments.

Figure 4.13: Relative variation of *SS* to the changes of the parameters values in February and July.

4.4.1.7 Guidelines and procedure for calibration of the models

This section provides attentive notes towards the calibration of the models. Through the analyses of the parameters and their impact on the results of the models, a general procedure for calibration is proposed. This could help the calibration process to be more effective and less time consuming:

- Through studying the models' formulas, calculation mechanisms and characteristics (climate, soil characteristics, topography, etc.) of the study area, it is expected that there should be a big contrast in daily *SS* results between the periods of low and high rainfall.

- Parameter *Dr* is the one to which the simulated *SS* is the most sensitive, among all parameters. Impacts of *Dr* changes are much more significant during the periods of high *SS* (during wet season). Thus, *Dr* could be used to control peaks of *SS* as well as their total mass in a long period because variations in this parameter can reduce or increase deposition in the river reaches. Parameters *a*, *b*, *n* and *o* have influence on sediment production and transportation on surface, before delivery to river segments. While the model results are sensitive to *b* and *o* in wet season, the sensitivity to parameters *a* and *n* is not affected by seasonal differences.

- Although the level of impact of the parameters is different, their combined adjustments could provide best results in a complex calibration process, like the calibration of erosion models. For example, a decrease in *b* combined with an increase in *a* could help increasing sediment production during the dry season while keeping sediment production constant during the wet season. *n* and *o* have minor effects on the transport capacity of sediments. However, a decrease of *n* to its minimum value and an increase of *o* to its maximum value could lead to reductions in *SS* during the wet season.

- From the analysis of the results of the sensitivity analysis, Table 4.10 provides summaries of (a) the seasonal effectiveness of the selected parameters for the calibration of models on the Cau River watershed, and (b) suggestions of choices of combinations for the best possible calibration results in wet and dry periods.

- In the context of *SS* load calibration at the outlet of a watershed, the calibration procedure should be: (1) The *Dr* value should be estimated first. This could help to approach the observed average range of *SS* at monthly or total annual levels, providing a primary base for finer adjustments. (2) After that, depending on the overall pattern of the observations, a decision should be made to adjust, orderly, the total seasonal mass peak's position and amplitude. (3) Regardless of the decision, *SS* adjustment should be started orderly from the origin of sediment (soil) to the final process of *SS* delivery. In this case, sediment production on surface should be the first target, and surface transportation, the second; parameters *a* and *b* (for the first) and *n* and *o* (for the second) are the keys. (4) The guidelines for parameters calibration (Table 4.10) should then be used. The choices of combination between parameters (Table 4.10 b) should be used flexibly. The first parameter in each choice is always the primary for the intended calibration purpose. Other parameters in a choice can be selected depending upon the conditions and needs for a specific calibration.

- The re-calibration of the models can be done when a closer focus on a specified season or period of time is needed. However, at a longer time scale (a year or a period of several years), it is recommended to first complete the calibration for the months and/or season that bear the largest contribution to the sediments load. In the case of a tropical climate such as in the Cau River Basin, a special attention should be paid to the rainy season since the problem of erosion mainly occurs during this season.

Table 4.10: Summary of (a) seasonal effectiveness of parameters and (b) seasonal choices of combinations for calibration.

(a) Seasonal effectiveness of calibration parameter

Parameters	Wet	Dry	Significance
a	•	•	*Non-seasonal*
b	•	*Non*	*Dramatic effects in wet season*
c	*Non*	*Non*	*Very less sensitive*
$K_t n$	•	•	*Non-seasonal*
o	•	*Non*	*Influence in wet period*
Dr	•	•	*High influence in wet season*

(b) Seasonal choices of combinations for calibration

Factor	To increase *SS* in wet season and decrease *SS* in dry season	To decrease *SS* in wet season and increase *SS* in dry season	To increase *SS* in all seasons	To decrease *SS* in all seasons
R	*b*↑(for wet↑, dry→)	*a*↑(for dry↑)	*a*↑(for dry↑)	*a*↓ (for dry↓)
	a↓ (for dry↓)	*b*↓(for wet↓, dry→)	*b*↑(for wet↑, dry→)	*b*↓(for wet↓, dry→)
CTS	*n*↑ (for wet↑)	*o*↓ (for dry↑)	*n*↑ (for wet↑)	*n*↓ (for wet↓)
	o↑ (for dry↓)	*n*↓ (for wet↓)	*o*↓ (for dry↑)	*o*↑ (for dry↓)
Vc	*Dr*→	*Dr*→	*Dr*↑	*Dr*↓

Note:↑= *increase;*↓= *decrease;*→= *keep without change; Non = no or minor effect*

4.4.2 Analysis of the behaviour of observed SS data

Observed *SS* data play an important role during calibration and validation. In a modeling work, observation data serve as a base line to help modellers verify their work and check for the necessity of additional adjustments for modeling results to best match with observed data. Thus, more trustable observation data could definitely help in obtaining better results with a simulation model. As a consequence, a more accurate result could help the modeller to get more confidence to make additional decisions concerning calibration, parameter values modifications, model adjustments, and so on.

This section focuses on the verification of the observed *SS* data at Gia Bay station (outlet of the study area), which was used for the calibration and verification of the modifications made to the GIBSI models for their application to the Cau River Basin.

In the Cau River watershed, within the context of data limitation, it is hard to find a tool for the quantitative verification of observation data. Therefore, a qualitative examination is a solution in this case.

It is expected that variations in the *SS* concentration in rivers are closely related to (1) the variations of climate variables (precipitation) and (2) the river flow regime (river discharge). The verification of this relationship is limited here to its qualitative aspect, by considering the interrelations between the observed suspended sediment data and two main input data (precipitation, *P*, and river flow discharge, *Q*) at the same location and time scale whereas the *SS* was observed. Theoretically, an observation data set is considered reasonable when (1) a reasonable observation method was used, and (2) the behaviour of observed data is reflecting the variations, in different time scales, of its associated variables (here *P* and *Q*). The observation method for *SS* data in the Cau River has been discussed in Section 3.3.3, Chapter 3. The following sub sections focus on discussions about the behaviour of the data.

4.4.2.1 Behaviour of SS data at the long-term time scale

According to the method applied to estimate *SS* at Gia Bay station, a reasonable observed *SS* result must reflect the daily and seasonal variations of precipitation and river discharge, which are represented, qualitatively, as trends of variation and timing of peak occurrences.

For long term variation, an estimate of mean monthly variation of observed *SS* (1997-2006) to its corresponding mean monthly river discharge (*Q*) and mean monthly precipitation (*P*) was conducted. Figure 4.14 shows the trends of variation for the three parameters. It was recognized that observed *SS* results show a correlation with *Q* and *P*. *SS* data reflect the long-term and mean monthly variations of *Q* and *P* during a year. If we consider *SS* as a consequence of *P* and *Q* in a river basin, the variation of *SS* seems reasonable. Thus, to some extent, observed *SS* data from the Cau River watershed are reasonable at the long-term scale.

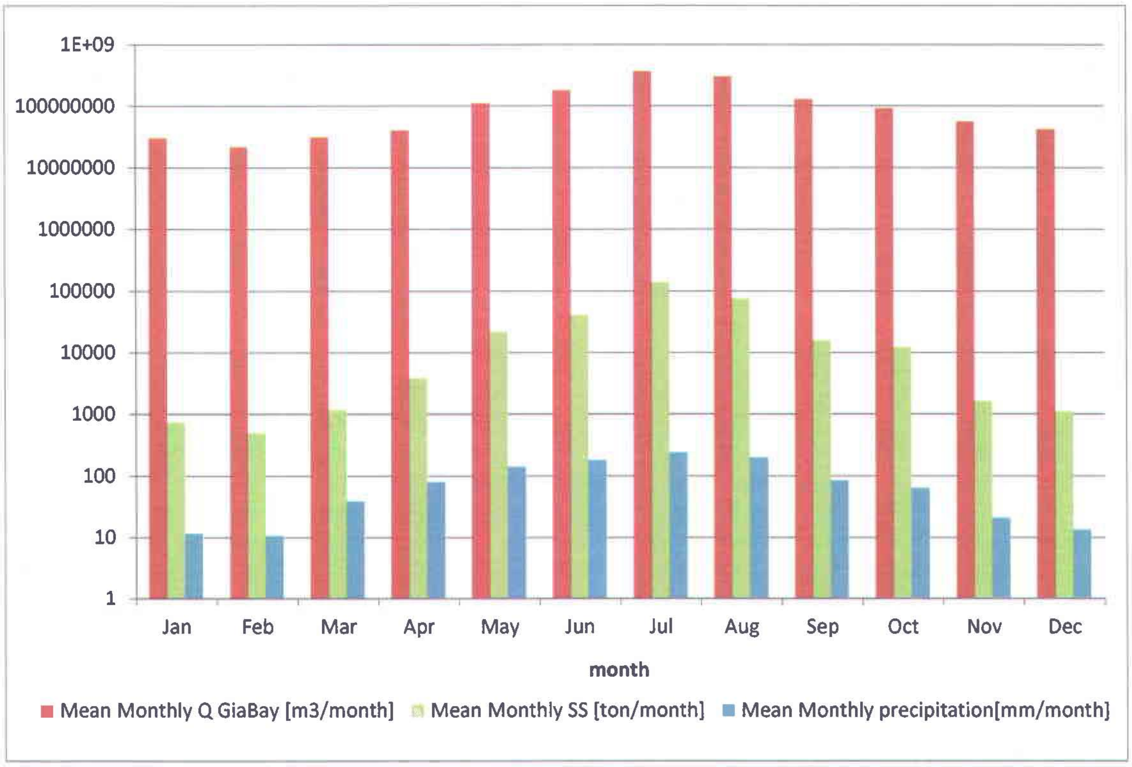


Figure 4.14: Mean monthly variation of observed *SS*, Q and P at Gia Bay station.

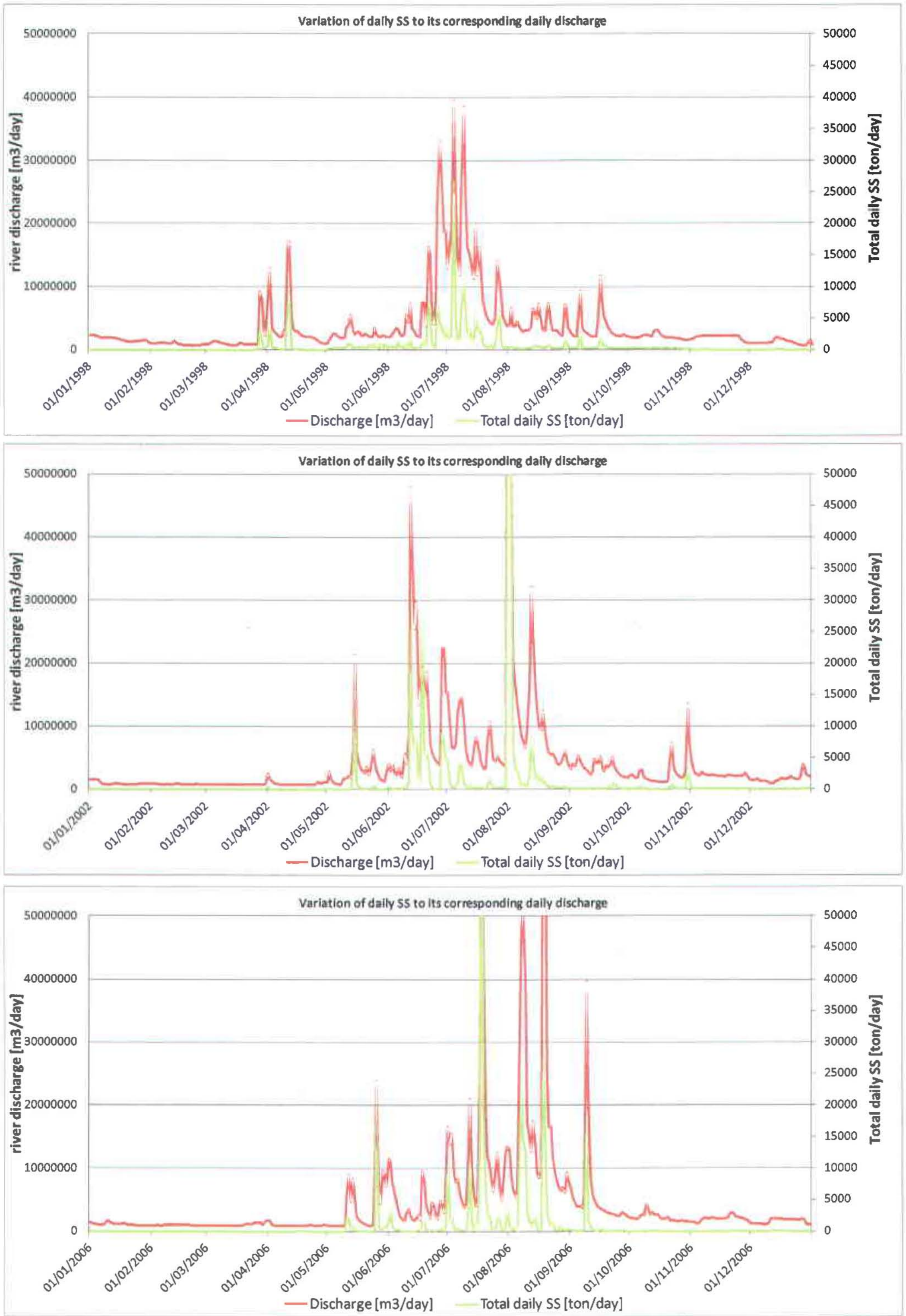


Figure 4.15: Examples of peaks timing of *SS* and *Q* at Gia Bay station in 1998, 2002, and 2006 (comparing the variation of daily *SS* to its corresponding daily discharge).

4.4.2.2 Behaviour of SS data at the daily and seasonal time scales

Figure 4.15 presents the daily variation of *Q* and *P* over three different years. Focusing on the shape of variation at the seasonal scale, *SS* tends to be more sensitive to high *Q* and *P* during the high rainfall and flooding period (from May to September). Occurrences of *SS* peaks were detected to coincide with those for *Q* and *P* (Figures 4.14 and 4.15). From a qualitative point of view, values of observed *SS* data at the daily time scale can be considered in agreement with hydrological conditions.

During the dry season (January to April and October to December), it was detected that there are some unusual peaks. These peaks (see examples of red-arrow-marked peaks in Figure 4.16) are considered unusual due to their timing. This could probably be explained by: 1) a time delay after the occurrence of a peak discharge; 2) other unnatural factors (human activities) which cause an increase in *SS* concentration while the discharge *Q* stays relatively steady. The first option, however, can be excluded because: (a) *Q* and *SS* were observed at the same times and (b) daily *Q* is a componential parameter used to calculate *SS* load and it has a direct relationship with *SS* (Equation 3.45, Section 3.3.3). Thus, with no rainfall anywhere in the watershed several days before and at the time of the observation of a *SS* peak, with no significant change in *Q*, the increase in SS could be considered as an abnormity. Details on peaks analyses are shown at Appendix 4.11.

4.4.2.3 Reasons for unusual peaks in observed SS data in the Cau River basin

The unusual peaks of *SS* mostly occur during the dry season when river runoff is relatively low and stable; water level and river width become low, which enables access to the river. Dry season in the Cau River Basin is also the season for construction works, landfills, mining, and river-related constructions activities (dyke, dam, road and bridge building). Especially, sand and gravel exploitation activities from the river bed are reported to be popular and rapidly increasing along the Cau River Basin, before the Gia Bay station. According to the statistic book (Thai Nguyen, 2007), in Thai Nguyen province only, the number of companies working on construction services has increased from 40 in 2002 to 292 in 2007. The commercial value for construction and mining services has also increased from about 637,000 CAD in 2002 to 2.6 million CAD in 2007 (Thai Nguyen, 2007). During the same period, the long-term observed *SS* load in the river (1998-2006) also shows unusual peaks that occur more frequently from year to year (Appendix 4.11). Thus, the effect of human activities on *SS* load in the Cau River Basin could be considerable. Appendix 4.12 shows some evident human activities in the Cau River Basin that are supposed to have an influence on the increase of *SS* load in dry season.

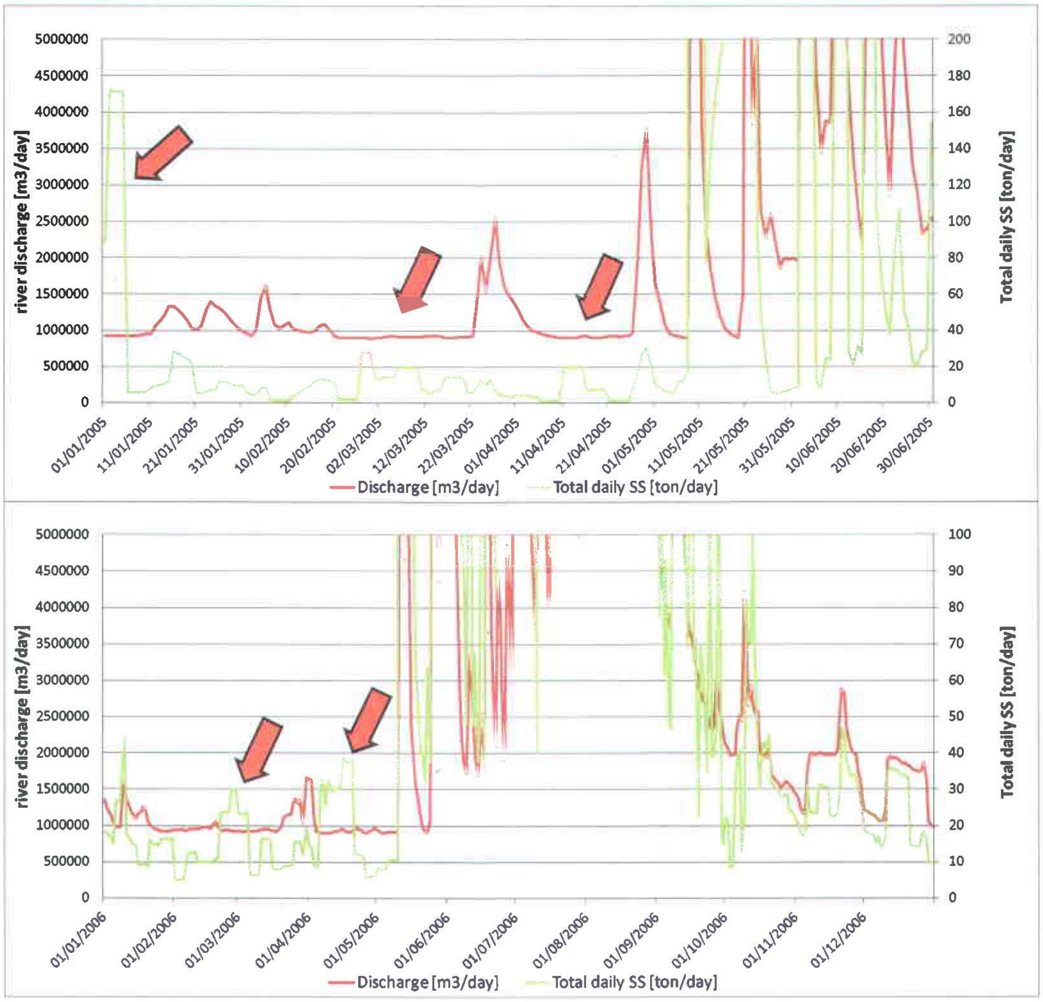


Figure 4.16: Samples of unusual daily peaks of *SS* load detected in dry months (comparison of the variation of daily observed *SS* with the corresponding daily discharge).

4.4.2.4 Synthesis

In general, the analysis of observation data leads to the following conclusions:

- From a qualitative point of view, values of observed *SS* data at the daily time scale can be considered to be in agreement with hydrological conditions.
- It detected some unusual increases in *SS* load that do not reflect the actual flow regime in the Cau River during dry season.
- Human activities, including construction works and especially sand and gravel exploitation in the river, were supposed to be the main factors responsible for the increase in *SS* concentration in the river during dry season. This subsequently results in unusual increases in the observed *SS* load during some days of the dry season. This issue could become a potential problem during calibration and even during the modeling of the soil erosion and transportation processes in the Cau River Basin.
- Although there were unusual values that occurred in some periods during the dry season, it showed the consistency of observed *SS* data during the wet season, when almost 95% of the total annual *SS* load is produced. The data, therefore, can be considered globally reasonable for model calibration.
- Observation data present a relatively better behaviour in the long term (mean monthly variation) rather than at the daily time scale. Thus, it is expected that model calibration at the daily time scale may not produce good results, especially in dry season or in low rainfall days. This fact suggests that the calibration and model analyses should focus on a more global time scale (monthly and seasonal) rather than only on a daily time step.

4.4.3 Model calibration

The selection of calibration parameters is based on the modified models, results of the sensitivity analysis, and formulas involved in all processes of erosion and sediment transport models in GIBSI. Table 4.11 shows the parameters chosen for calibration.

Table 4.11: Parameters selected for calibration of the models for the Cau River Basin.

No.	Process or model	Parameter	Referring range	Origin / Source
Soil erosion				
1	R_{tji} Total daily erosivity on USS *i*	*a*	0.18 - 0.19	(Duchemin, 2000)
2		*b*	1.5 - 2.2	(Duchemin, 2000)
3		*c*	0.1 - 0.6	(Duchemin, 2000)
Sediment transport on surface				
4	**T** Sediment transport capacity	K_t	0.5 - 1	(Duchemin, 2000) used for Chaudière watershed, Quebec
5	W_{ri} Width of flow on section *i*	*n*	start at 15.42	Flinker *et al.*, (1989)
6		*o*	start at 0.51	Flinker *et al.*, (1989)
Sediment transport on river channel				
7	V_c Fall velocity (Representative diameter of suspended particles)	D_r	0.15 mm - 0.3 mm	Bhargava and Rajagopal (1992)

4.4.3.1 Calibration method

The objective of model calibration is to determine a set of values for model parameters so that the model reproduces the most general behaviour of the studied basin (Villeneuve *et al.*, 1998).

Before getting into the details of the calibration method, it is necessary to mention that the main objective of this study is to find solutions and develop methods that allow for the implementation of a comprehensive model for water resources management in a basin of which characteristics are different from those of the basins where the model was previously applied, and with limited available data for calibration (*e.g.* GIBSI on the Cau River Basin). In this study, we will use simultaneously the model of erosion on surface and the model of transportation in rivers throughout the watershed to calibrate the models, although few data are available (limited quality and quantity) to make this calibration.

This study thus aims at estimating values for the selected parameters (Table 4.11) of the two models, after modifications and adaptations. As the consequence of all sedimentation processes throughout the whole watershed, the simulated *SS* result at the outlet of the watershed (Gia Bay station) will be used to calibrate the models. Model simulations carried out during the calibration process uses a daily time step. However, depending upon the results, a more global time scale (monthly and seasonal) could also be taken into account during calibration.

Calibration is performed using the simulation of daily *SS*, continuously from 1998 to 2002 (the period selected for calibration). Thus, the adjustment of calibration parameters, to obtain the most acceptable simulation results, is based on a global view of these five year estimates, but not on any single year among them.

4.4.3.2 Calibration of the soil erosion and sediment transport models

SS data in the Cau River watershed are available daily only for Gia Bay station, which is the outlet of the basin, for the years from 1998 to 2006. This date set was therefore selected for the calibration and validation of the erosion and sediment transport models. Parameters in both the erosion and sediment transport models were calibrated using the five-year period from 1998 to 2002 (Figure 4.17 a), while the validation was performed with data from 2003 to 2006 (Figure 4.17 b). It was assumed both periods are similar in terms of variations in rainfall, hydrological processes and erosion processes in the river basin. The calibration follows the guidelines (Table 4.10) and procedure introduced in sub section 4.4.1.5. The best values for parameters obtained during calibration are shown in Table 4.12.

Table 4.12: Estimated values of the parameters during calibration for the Cau River Basin.

No.	Process or model	Parameter	Default value used	Calibrated value
Soil erosion				
1	R_{tji} Total daily erosivity on USS i	*a*	0.181	0.2
2		*b*	1.5	1.4
3		*c*	0.1	0.025
Sediment transport on surface				
4	**T** Sediment transport capacity	K_t	0.5	0.45
5	W_{ri} Width of flow on section i	*n*	15.42	15.42
6		*o*	0.51	2.2
Sediment transport on river channel				
7	V_c Fall velocity (Representative diameter of suspended particles)	D_r	0.3 mm	0.11 mm

4.4.4 Result analyses

4.4.4.1 Qualitative analysis

This section focusses on the analysis of the behaviour of the calibrated *SS* results when compared with observations. According to the initial objectives of this research, the priority is set to verify the performance of the modified models in terms of simulated *SS* results.

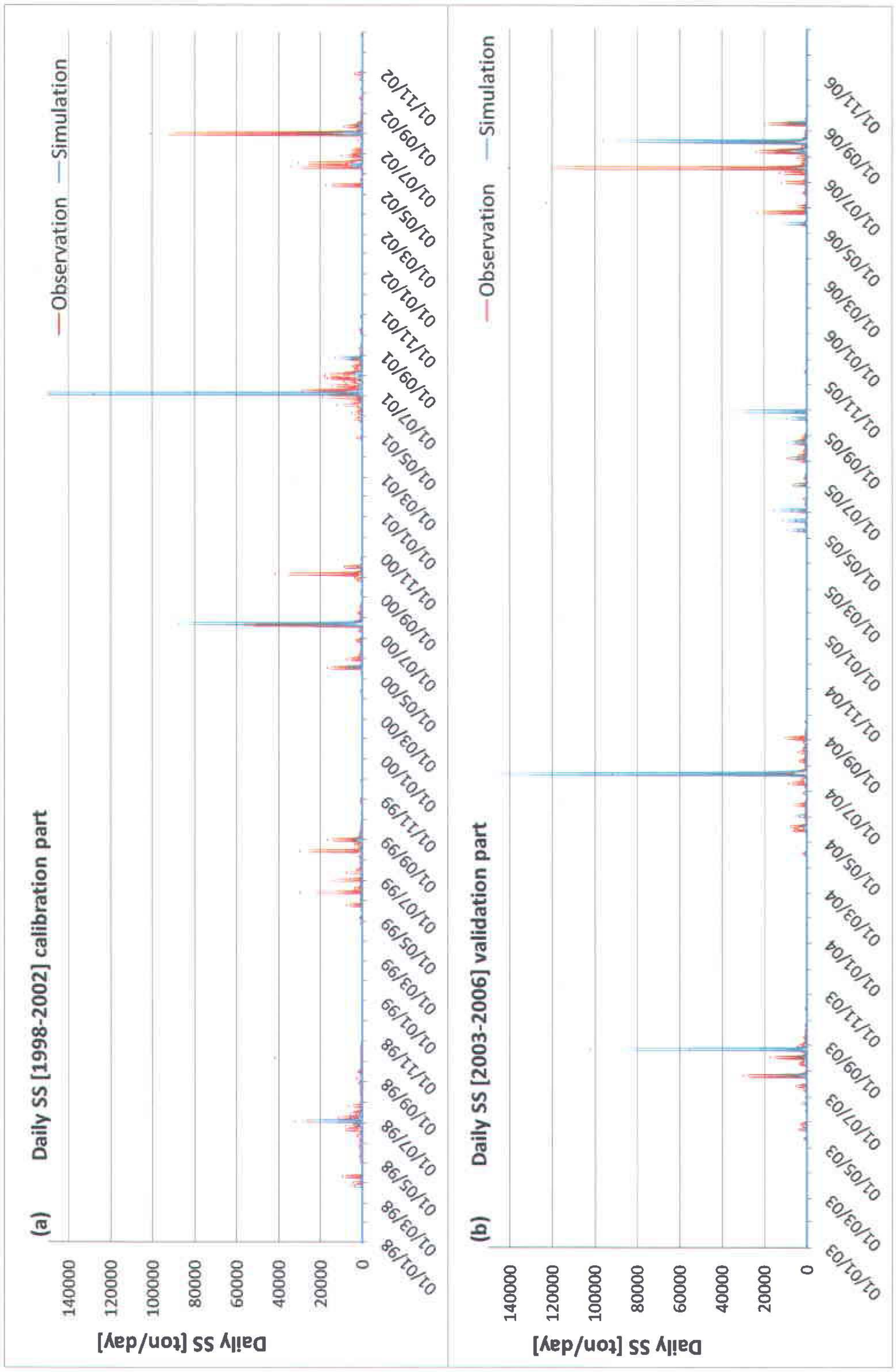


Figure 4.17a, b: Results of calibration and validation of *SS* at the daily time scale for the (a) calibration and (b) validation periods.

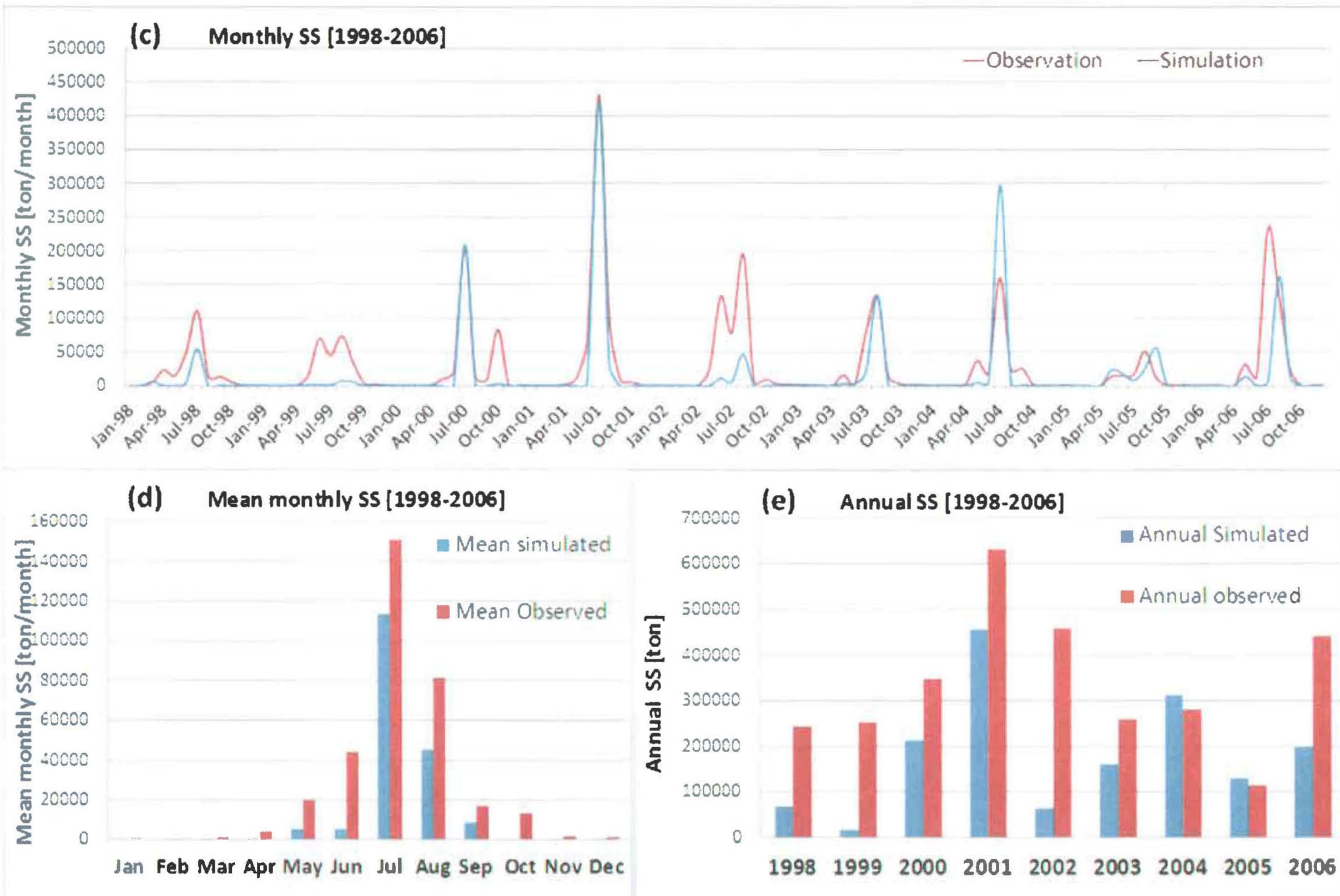


Figure 4.17 c, d, e: Results of calibration and validation of SS at: (c) monthly; (d) mean monthly; and (e)total annual scales.

The behaviour of calibrated *SS* results was analysed on the basis of four different time scales: 1) daily, 2) monthly, 3) mean monthly, and 4) annually, for both calibration and validation periods. Analyses lead to the following conclusions:

- On a daily basis (Figure 4.17 a, b), although this is not clear visually from the graph the peak value matched the highest observation found in 2001. The simulated *SS* results showed a good response in terms of timing of peak occurrence except for 2005 and 2006, and we know that in 2005, dams were put in service (Nguyen 2009, *pers. comm.*) in the upper stream of the Cau River; however, these dams could not be taken into consideration by the hydrological model due to the lack of data. A delay in the occurrence of peaks can be clearly seen on Figure 4.17c at the monthly scale for 2005 and 2006. Figure 4.18 shows another example of good timing response of the adapted soil erosion model. Components of the surface processes (including surface runoff, surface water height, and surface sediment production) have relatively the same pattern of daily variation. The appearance of a time delay between the simulated and observed peaks in 2005 and 2006, due to dams not taken into consideration by the hydrological model, indicates a good response of the adapted models to the change of flow regime in the watershed.

- At the monthly scale (Figure 4.17 c), results confirm again a good matching of simulated and observed values in the month with the highest observation, July 2001. It was also found that for the years when the total *SS* was mostly concentrated in the months of June, July and August, the calibrated model performs better. Problems are found during the years when: (1) peaks occur in the months of March to April and September to October (the months of the beginning and ending of the rainy season). During these months, the calibrated *SS* results were often lower than the observations; (2) there are two or more high floods (indicated by the occurrence of high peaks in a year).

- Generally, the calibrated SS results behave better at the monthly and seasonal timescales, as expected, rather than at the daily step. Peaks of simulated SS often appear to be narrower and higher compared to those observed (Figure 4.17a,b, and c). Thus, within the limitation of data availability, at least in the current application of GIBSI for the case of Cau River watershed, the reality in monthly and seasonal prediction is somewhat sufficient for several application purposes. In pratical application of the models, as for example for integrated water management at the basin scale and the comparison of scenarios, accurate SS estimates at monthly, seasonal or annual scales are more useful than the daily results.

4.4.4.2 Quantitative analysis

Introduction and methodology

The visual inspection of the simulations and observations curves is qualitative and can be subjective (Krause *et al.,* 2005), even if it is important during the calibration of simulation models. It is also important to make an objective assessment of a model based on the computation of quantitative criteria comparing the simulations and observations.

Figure 4.17 shows the comparison, at different time scales, of the calibrated *SS* results and observed data at Gia Bay station. Overall, after calibration, results at the daily time scale did not reflect observations well. At this time scale, results appeared mostly underestimated in dry season and overestimated in wet season (Figures 4.17 a and b). At the monthly and seasonal scales, the calibrated results are closer to the observations (Figures 4.17 c and d). This is because the monthly estimate helped balance daily differences by summing them in the monthly total. Figure 4.17e presents a comparison of the total annual simulated and observed values during both calibration (1998-2002) and validation (2003-2006) periods. Simulated values are generally lower than observations. However, the difference varies from one year to another.

Many performance criteria for simulation models can be found in the literature. Krause *et al.* (2005) made a complete review of these criteria for hydrological models. In this study, the simulated and observed *SS* results were used to analyze the model's efficiency according to three main criteria: 1) the Nash coefficient (Nash and Sutcliffe, 1970), 2) the coefficient of correlation between observations and simulations (R^2), and 3) the Root Mean Square Error (RMSE). Expressions for these criteria are given below.

- The Nash coefficient is expressed by:

$$NS = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O}_i)^2} \qquad (4.16)$$

where O_i = observation at time step i; S_i = simulated value at time step i; $\overline{O}_i$ = mean value of all observations during a specific period; n = total number of time steps for the specific period. The Nash efficiency (*NS*) may range from $-\infty$ to 1. An efficiency of 1 (*NS* = 1) corresponds to a perfect match between the modeled and observed *SS* data, while *NS* = 0 indicates that the model predictions are as accurate as the mean of the observed data, and *NS* < 0 occurs when the observed mean is a better predictor than the simulation model.

- The coefficient of correlation (R^2) analyzes the regression between the simulated and observed data. The closer R^2 is to 1, the better the correlation. It is expressed by:

$$R^2 = \frac{\sum_{i=1}^{n}(S_i - \bar{S})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{n}(S_i - \bar{S})^2 \sum_{i=1}^{n}(O_i - \bar{O})^2}} \qquad (4.17)$$

  where O_i = observation at time step i; $\overline{O}_i$ = Mean value of all observations during a specific period; S_i = simulated value at time step i; $\bar{S}$: mean simulated value.

- The differences between values predicted by the model and values actually observed can be quantified using the Root Mean Square Error (RMSE), expressed by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n^2}} \qquad (4.18)$$

  where O_i = observation at time step i; S_i = simulated value at time step i; and n = total number of time steps in the studied period. RMSE ranges from 0 to ∞. The RMSE is considered better when it gets closer to 0.

Another criterion commonly used to compare simulated and observed values is the total monthly or annual mass of sediments at the outlet of the watershed. As for the total annual runoff for hydrological models, this criterion is expressed in terms of relative difference (%) and helps appreciate how the model can simulate the total mass for each year (Krause *et al.*, 2005).

Results

Table 4.13 shows the values of the three efficiency criteria. Each criterion is computed for the periods of calibration (1998-2002) and validation (2003-2006) at a daily time step. Regardless of the seasons (dry or rainy), criteria are also calculated for each year to verify the performance of the model for individual years.

Table 4.13: Criteria of models' performance (daily time step).

Period	Criterion			
	Nash	R^2	RMSE	Relative variation (%)
1998	0.11	0.82	1.30	-24,6
1999	0.13	0.45	1.20	-19,6
2000	0.25	0.63	1.17	-21,5
2001	0.45	0.88	1.20	-17,4
2002	0.21	0.83	1.20	-21,7
2003	0.22	0.86	1.15	-14,2
2004	0.20	0.91	1.21	-11,1
2005	0.35	0.62	1.16	12,4
2006	0.32	0.20	1.17	1,7
Calibration period 1998-2002	0.35	0.71	1.02	-21,0
Validation period 2003 - 2006	0.30	0.56	1.09	-4,0

Analyzing the calibration results in the long term (period 1998-2002), the results can be summarized as follows:

At the daily time scale, the Nash coefficient was found to be relatively low for each year but much more accurate, at 0.35, for the whole period. This is due to the fact that calibration was performed for a long period (1998-2002) but not for a single year. The Nash coefficient for each year, however, shows that daily predictions are less accurate.

The Nash efficiency was found to be much better for years with a single high extreme event during the rainy season (2001, 2005, and 2006). The efficiency is lowered during the years with lower extreme events (1998) or which have more than one low extreme event during the rainy season (1999, Figures 4.18 a and b). This indicates again that the calibrated models perform better, globally, during the years with a single high rainfall event (Figure 4.17c). The best value of Nash was found in 2001 with 0.45. The highest observed peak of *SS* was found in 2001 (Figure 4.17c) and the model was calibrated to reproduce as much as possible the highest event while focussing less on moderate peaks and events.

The coefficients of correlation (R^2) were found to be relatively good for the whole calibration and validation periods as well as for individual years. Considering the annual variations, the results are more accurate for years with high and single peak occurrence, especially for the year 2001, and less accurate for years with two or more average or low peaks (Figure 4.17c).

R^2 alone is not a good criterion (Krause *et al.*, 2005) because it does not reflect the possibility of under/over estimation of the observation with a constant ratio (*e.g.* simulated values could be two times higher than the observed data). Full expression of regression lines between simulations and observations can help have a better appreciation of R^2 as a criterion, if necessary.

The values of RMSE varied for different years and tend to be more accurate for the longer periods of both calibration (1.02) and validation (1.09). All values were found to be around 1 (Table 4.13) and can be considered as good in the context of this watershed (data limitation, adaptations, scale of the study area, etc.).

Another criterion which can be taken into consideration is how the model can reproduce the total mass of sediments. In the framework of the present study, the difference between simulated and observed total *SS* annual mass was found to be from around -25% to 12% at the annual scale. This rate varies for different years and becomes the highest, at around 12% in 2005, when the observed *SS* were extremely low (see Figure 4.17d).

In general, the model can be considered to have a good performance in the context of this river basin. Some studies on erosion and sediment transportation found in the literature point out an almost similar performance: 0.35 to 0.85 for Nash at a daily time step and -33% to 19% for the difference in total annual mass of suspended solids (Beaudin *et al.,* 2006; Liébault *et al.,* 2005). It is important to highlight that these studies were carried out without the specific problem of data limitations.

There is a limitation in the calibration of suspended sediment for this study. This is caused by: (1) the irregular regime and large differences in volume of precipitation and runoff between the seasons in a year and between the years in the calibration period; (2) observed *SS* data in dry period may be considered as too high due to human activities (sand exploitation, etc.), which have not been taken into account in the simulations since no information is available to verify the possible impacts of human activities; (3) the accuracy of the simulated discharges used as input could also be a source of errors that affect the simulated daily *SS* values; (4) the dynamic of seasonal changes in land use in the Cau River Basin (Hoang, 2008) was not taken into consideration during the hydrological simulations, which may also affect the *SS* simulated results.

In general, the adapted models visually show their performance in reacting to the daily variation of the erosive parameters. In terms of quantitative sediment production, the results show a better match with observations on a monthly or seasonal time scale. The results are better for years when high *SS* occurred in a single high peak within the months of June, July or August. The model did not perform well in the years when *SS* peaks occur in early or late months of the rainy season or when *SS* loads are distributed evenly from April to September. This could be due partly to the lack of available data to develop the equation for the daily erodibility variation. In other words, the estimation of days when the minimal and maximal daily erodibility values occur is based on an assumption that these occurrences coincide with the variation of mean daily precipitation during a year, and that these mean daily precipitation values were computed based on a 10-year record. Having access to a longer record of daily precipitation would allow refining the proposed equation for the daily erodibility variation, which was not possible for the Cau River watershed.

4.5 Conclusion

Considering the requirements and limitations within the context of applying the soil erosion and transportation models of GIBSI to the Cau River watershed, a series of tasks with detailed descriptions, examinations and analyses have been done so far to present the contribution of this thesis work.

Setting up local conditions prior to simulations of a river watershed such as the Cau River is the key to enable the physical run of the models. It is possible to obtain input parameters in a watershed such as the Cau River by employing any available source of information, and analyzing them comprehensively. Modification methods for the preparation of input data are often necessary. These modifications, however, can be based on the available local information.

The sensitivity analysis is important to provide an overview of how calibration parameters influence the results of the models. It was found that each calibration parameter affects, at a different level, simulated suspended solids, and that the level of this effect depends on season. Thus, a list of calibration parameters with their levels of importance for different priorities can be introduced. Flexible use of these findings could help expand essential calibrations and could probably help users make decisions based on their needs. Guidelines and procedure for calibration were found to be useful in other watersheds. The procedure for calibration, with an order of selection and choices of parameter combinations according to the user's needs, provides an orientation to save time when performing calibration.

Analyzing observed *SS* data is important to verify the realism of data to be used as a base for calibration, especially for the case of watersheds where there are limitations to organize field observation campaigns, like the Cau River watershed. When a quantitative verification is impossible, a qualitative analysis should be carried out for the verification of, at least, the behaviour of data as compared to the corresponding available data, such as precipitation and river runoff. From a qualitative point of view, the values of observed *SS* data at the daily time scale in the Cau River watershed can be considered in agreement with the hydrological conditions. The analysis has also detected some anomalies in observed *SS* data that occurred in some periods during the dry season. Adapted models also showed some unusual changes in the simulation results that could be linked to the operation of dams since 2005. These suggest that human activities in rivers (sand exploitation, dam operation) could likely be the main cause of anomalies in observed *SS* data.

There is a big contrast in the simulated mass of suspended sediment between the wet and dry seasons in the Cau River watershed. The wet season is very sensitive to changes in calibration parameters. For a specified season or a period of time in a year, the model can be recalibrated by the user based on the suggestions and calibration procedures presented in sub-section 4.4.1.5 and Table 4.10. However, it is necessary to remind that calibration over a longer time scale (a year or a period of years) should be done with the highest priority given to the rainy season. This is due to the extremely large contribution of the rainy season to annual *SS* loads in tropical river watersheds.

Simulated *SS* results at the outlet of the watershed were analyzed. The performance of models after adaptations and modifications was confirmed. It was found that there is a limitation for models to reproduce the variation of daily *SS*. The quantitative result, however, is largely affected by the accuracy of the daily input data. Within the scope of this study and the capacity of the soil erosion and transportation models, many efforts have been made to improve the quantitative results of the models in the Cau River watershed.

Through the practical application of the models to the Cau River watershed and result analyses, it is recognized that there are some issues that could be potential sources of uncertainties: 1) There is a big contrast in total precipitation between the two seasons in tropical climates. Thus, the accuracy of calibration is lessened when a single set of calibration parameters is applied for an entire year or for a multi-year calibration period. 2) Unusually high observed *SS* data during some period of the dry season caused by human activities cannot be taken into consideration in the simulations. 3) The land use map employed is too general in its identification of agriculture land use classes and does not distinguish the classes that are essential for human activities in the Cau River watershed such as paddy fields, crop type, etc. Therefore seasonal dynamics was not taken into account by the hydrological model.

Current human activities in the Cau River watershed are supposed to affect both the hydrological and soil erosion processes. For instance, the construction and operation of dams and reservoirs affect the hydrological regime of the river; paddy fields could affect surface runoff and sediment trap on USS; sand exploitation could result in changes in the mass of observed suspended sediment that the model cannot account for. It is, definitely, necessary to pay a closer attention to the integration of local human activities into GIBSI, for conditions such as those in the Cau River watershed.

Many efforts were made in the framework of this thesis to adapt the models to the conditions of the Cau River watershed and calibrate them. Models will be useful not only for scientists but also for engineers and river basin managers. It is therefore important for managers and engineers to: (1) summarize the adaptations made to GIBSI for the Cau River Basin; (2) investigate, based on case studies, how the models can be helpful for land management and the simulation of other processes involved in a complete integrated watershed management (*e.g.* water quality). These aspects will be presented in the following chapter.

5. Application and verification

As stated previously, the objective of the application of GIBSI on the Cau River watershed is to provide a tool for the integrated management of surface water. While solving problems posed by climate differences and data limitations, a successful application must finally serve as an effective tool for (1) soil erosion prediction, (2) quantitative management of water quality, and (3) application of different land management scenarios.

In order to verify how GIBSI's soil erosion and sediment transport models perform when applied to the Cau River Basin as well as the effectiveness of the modifications made, this chapter focusses on (1) a summary of all proposed modifications and adaptations; (2) an evaluation of the effectiveness of the modified models in the Cau River watershed through the verifications of *SS* results in relation with some river water quality variables; and (3) an evaluation of the applicability of the modified models in the watershed through the examination of their performance to assess the impacts of changes in land use.

This chapter presents three main points, which are "expectations", "operation", and finally "verifications". The "expectations" and "operation" of the study are summarized respectively in sections 5.1 and 5.2. These sections, apart from stating the expected results of the study, also highlight model modification processes. The "verification" of the study is composed of three additional analyses concerning: (1) the realism of simulated suspended sediments (Section 5.3); (2) the variations of several water quality variables, such as organic nitrogen and organic phosphorus, simulated based on the modified models (Section 5.4); and (3) the responses of soil erosion and suspended sediment to different land management scenarios (Section 5.5). This step of "verification", in turn, can help confirm if the results of the "operation" satisfy the "expectations". Overall, it finally helps confirm if the study has succeeded in adapting the GIBSI models to the conditions of the Cau River watershed (Section 5.6).

5.1 Requirements

It is necessary to emphasise that the soil erosion and transportation models in GIBSI were initially set for the conditions of the Quebec region (Villeneuve *et al.*, 1998a). Climate, land use characteristics and observation data availability are completely different in a monsoon tropical climate like in the Cau River watershed. It is impossible to simply copy the models and apply the (1) input data preparation methods, (2) methods or related to climatic conditions, (3) formulas and their computing codes, which drive models, (4) methodology for model calibration. Thus, making the erosion and sediment transport models of GIBSI applicable to the Cau River watershed was definitely a big challenge. It required a huge work including revisions, adaptations and modifications to both the theoretical methodology and application procedures.

Due to the abovementioned limitations, some existing methods to obtain input data, formulas to estimate parameters, and model calibration procedures are not applicable for the conditions of the Cau River Basin. However, a proper adaptation of GIBSI to the Cau River basin should meet, at least, the following three main requirements:

- Adapted models must perform well, reflecting the realism of local conditions.
- Models must provide results that correspond to observed data, especially concerning variables related to water quality, considered as indicators for decisions about integrated management actions.
- Models outputs must show their capacity to respond to changes in different land management scenarios. This requirement may be considered as a useful example of how this model can help for land management actions in this watershed as well as in other areas in Vietnam, where a rapid change in land use was observed during the last two decades (Thai Nguyen 2008 and 2009; Valentin *et al.,* 2008) due to the rapid economic growth in this country. Changes in land use may also affect erosion and sediment transport (Vezina *et al.*, 2006).

5.2 Tasks performed for adaptations / modifications

In this thesis, the modifications and adaptations of GIBSI for the Cau River watershed were generally focussed on the two following models with their associated processes: (1) the soil erosion model (MODEROSS), and (2) the sediment transport model (ROTO), which are respectively representative of (1) surface processes, and (2) river segment processes of eroded sediments. Simulation results calculated with GIBSI for the Cau River watershed were the result of a series of adaptations and modifications in both models.

Table 5.1 presents the modifications and/or adaptations performed in the two models for the two main purposes of *"Setting the local conditions prior to simulations"* and *"Modifying formulas to adapt to local conditions".*

There are a total of 21 input data or parameters involved in the two models that were selected as necessary for modification and/or adaptation. Performed tasks were classified based on four main considerations, orderly, in: (1) theory, (2) local data use, (3) formulas, and (4) computing codes. Each parameter could require more than one consideration. Each consideration, depending on the nature of the work performed, was specified as a *"modification"* or an *"adaptation"* task. *"Modification"* means that an existing method, formula or computing code was replaced by a new one. *"Adaptation"* means that one or some parts of existing methods, formulas or computing codes were adjusted. Considerations were defined as follows:

- (1) *Theory*: represents a revision of a theory/methodology to adapt to the conditions of the Cau River watershed. Revisions were made for 15 among 21 parameters or input data.
- (2) *Use of local data*: has two meanings. First, it defines the input data prepared using local available information. Second, it concerns the preparation of input data within the context of few available data. The whole process is called *"Localization of input data with the available database"* and involved 17 among 21 input data and parameters.
- (3) *Formula*: depending on the needs of (1) and (2), as well as on the performance of existing formulas, it was decide to modify or adapt some formulas. 9 among 21 parameters or data needed a modification, while 7 parameters needed only an adaptation. Three variables in the ROTO model needed only the adaptation of their existing formulas.
- (4) *Computing code* is the consequence of (1), (2), and (3) to realize the modifications or adaptations into the GIBSI computer programs.

Table 5.1: Tasks performed for the adaptations / modifications of the erosion and sediment transport models in GIBSI for the Cau River watershed.

Model		Input data / intermediate variables	Definition	Tasks performed						Purpose	
				(1) in theory	(2) in use of local data	(3) in formula		(4) in computing code			
				Revision of basic theory / methodology	Localization with available database (adaptation)	New calculation / Formula (modification)	Formula adjustment (adaptation)	Computational code rewritten (modification)	Computational code adjustment (adaptation)	Setting the local condition prior to simulations	Modifications of formula to adapt to local conditions
MODEROSS	R_{tji} total daily soil erosivity	R_{pji}	*daily erosivity of precipitation*	•	•		•		•		•
		R_{pji} constraint	*lower limit of precipitation*	•			•		•		•
	K_{asi} mean annual soil erodibility	*cs*	*soil structure code*	•	•	•			•	•	
		cp	*soil permeability code*	•	•	•			•	•	
		MO	*organic matter (%)*	•	•	•			•	•	
		SL	*very fine sand and silt (%)*		•		•		•	•	
		SF	*very fine sand (%)*		•		•		•	•	
	K_{ji} mean annual soil erodibility	R_{an}	*mean annual rainfall erosivity*	•	•	•		•		•	

Table 5.1 (continuing).

		t_{min}	*day where K is min.*	•	•	•		•		•	
		t_{max}	*day where K is max.*	•	•	•		•		•	
		Δt	*period of frost free of soil*	•	•	•		•		•	
		K_{min}	*minimum annual soil erodibility*		•		•			•	
		K_{max}	*maximum annual soil erodibility*		•		•			•	
	LS *slope factor*	*m*	*exponential in different cases of rill/interill erosion*	•	•			•		•	
	C_{ji} *daily soil management*	*Land use 1(*)*	*stable group*		•		•		•	•	
		Land use 2(**)	*variable group*	•	•	•		•		•	
	P *soil conservation practice*	*Land use 1(*)*	*stable group*		•					•	
		Land use 2(**)	*variable group*	•	•	•		•		•	
ROTO	*CTS_{ji} daily transport capacity*	*T_{ji}*	*transport capacity*	•			•		•		•
	$PERO_{ti}$ re-entrainment	*IAS*	*index of sediment delivery*	•			•		•		•
	SED	*SED_i*	*quantity of sediment deposited*	•			•		•		•

(*) *Land use 1*: Stable group of land use classes, including *Urban*, *Forest*, *Water bodies* and *Bare soil*.
(**) *Land use 2*: Variable group of land use classes, including: *Agriculture land*, *Brush* and *Mixture*.

5.3 Comparison of suspended sediment (SS) results with observed discharge

Due to the availability of observed data, simulated *SS* results in the Cau River watershed could only be verified to some extent. Daily observation data (1998-2006) at Gia Bay station were used during the calibration process. According to the long term behaviour of *SS* and its response to variations in local hydrological conditions, the mean monthly variation of simulated *SS* is compared with the variations of observed river discharge (*Q*) at a selected location. The river section at Gia Bay station, where models were calibrated, was selected for this comparison.

Figure 5.1 presents the comparison of the mean monthly variation of simulated *SS* and daily observation *Q* at the Gia Bay station. Overall results of *SS* mass can be summarized as follows:

- Except for a few months, (*e.g.* June), *SS* results show a good relation with the mean monthly river discharge in the Cau River watershed.
- Over 90% of the total mass of *SS* is distributed within the months of the rainy season (April to October), which coincides with the occurrence of 85% to 90% of the total river discharge in a year.
- *SS* mass at Gia Bay in the single month of July accounts for almost 50% of the total annual mass, when the highest monthly value of *Q* also appears.

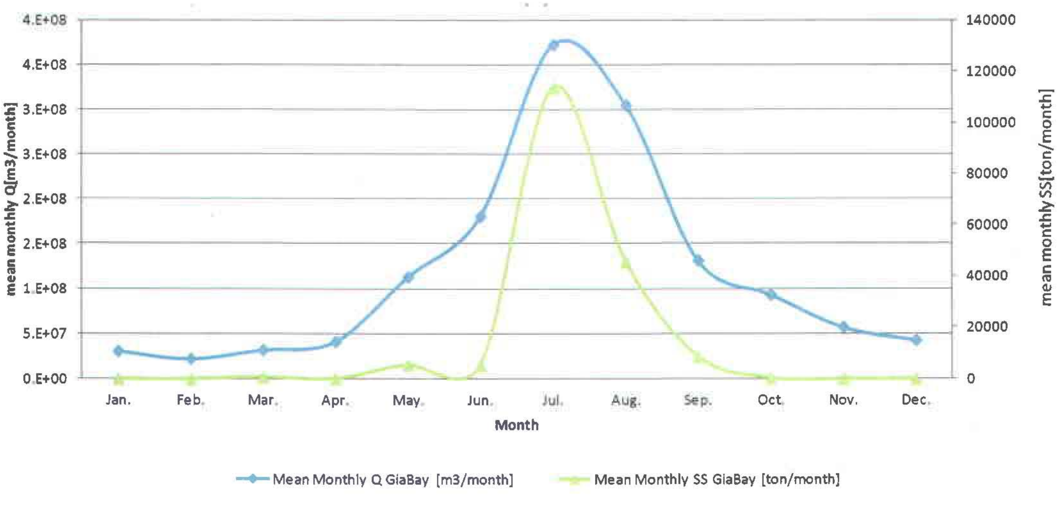


Figure 5.1: Mean monthly simulated *SS* results and observed river discharge (1998-2006).

5.4 Response of organic phosphorus and organic nitrogen to the modifications in GIBSI

It has been recognized that eroded sediments from soil and the resulting *SS* in river play the role of carriers of pollutants, including organic phosphorus (P_{org}) and nitrogen (N_{org}) (Brown *et al.,* 1987; Villeneuve *et al,* 1998a). A great part of these contaminants are attached to sediments and both sediments and contaminants are transported together to river reaches by runoff. In GIBSI, according to Villeneuve *et al.* (1998a), the models for nitrogen (*N*) and phosphorus (*P*) consider the runoff and erosion as dominant vectors of the transport of phosphorus and nitrogen. Transport depends mainly on eroded particles on soil surface and surface runoff, which move these particles to river segments.

Appendix 5.1 simplifies the procedures for the simulation and transportation of (a) nitrogen and (b) phosphorus models in GIBSI, indicating the role of sediment in the processes. The soil erosion and transportation models in GIBSI are involved in the simulation of some river water quality parameters. Consequently, river *SS* is a key factor to estimate contaminants such as organic phosphorus and organic nitrogen. Thus, (1) soil erosion and transportation models, through the *SS*, could help determine the mass of organic *P* and *N* delivered by eroded sediments for the purpose of river water quality simulation for a given river reach; and (2) the successful adaptation of the soil erosion and transportation models to the Cau River watershed is a key factor for a successful simulation of river water quality.

In this section, comparisons of simulated results of P_{org} and N_{org} with (1) observations and (2) simulated *SS* at Gia Bay station were used only as an addition to verify the realism of the modifications and adaptations made for the soil erosion and sediment transport models, and to verify how sediment transport affects some water quality parameters like P_{org} and N_{org}. This task also helps verify the necessity of adaptations and modifications to the two models for water quality simulations and management in the Cau River watershed. Verifying P_{org} and N_{org} content in different water quality management scenarios can be performed directly inside the soil erosion model based on the examination of land use change scenarios (*e.g.* change in agriculture land). This task was, however, excluded from this study and examined by other studies such as those of Pham (2013) and Nguyen (2013).

5.4.1 Results of N_{org} and P_{org}

Observation data of N_{org} and P_{org} at Gia Bay station was not available for the same periods as the *SS* observation. They were limited to a few observation days during short field surveys in 2008 and 2009. Each of the field surveys has only four days of N_{org} and P_{org} observations. Thus, it is impossible to validate the long-term simulated N_{org} and P_{org} with such observation data based on quantitative criteria. However, it is possible to make a visual inspection of the general behaviour of curves during the period of data availability, and also to analyze the changes with regard to seasons and occurrence of high *SS* values.

Figures 5.2 and 5.3 show the comparison of the long-term daily simulated N_{org} and P_{org} with the available observed data. Results show that: (1) Except for a few days in April 2009, observed and simulated values are closely matching. (2) It is possible that these short field survey campaigns were possible only when the weather was fine (with almost no rainfall), when the field was accessible. There was no observation found in the days when simulated peaks appear. Thus, we could see in Figures 5.2. and 5.3 that observations are relatively stable. Simulated values for the same periods are also stable. (3) Observation results, although limited, show the usefulness of simulated *SS* in both dry and wet periods, illustrated by the close matching of the observed and simulated values in January, April, and September.

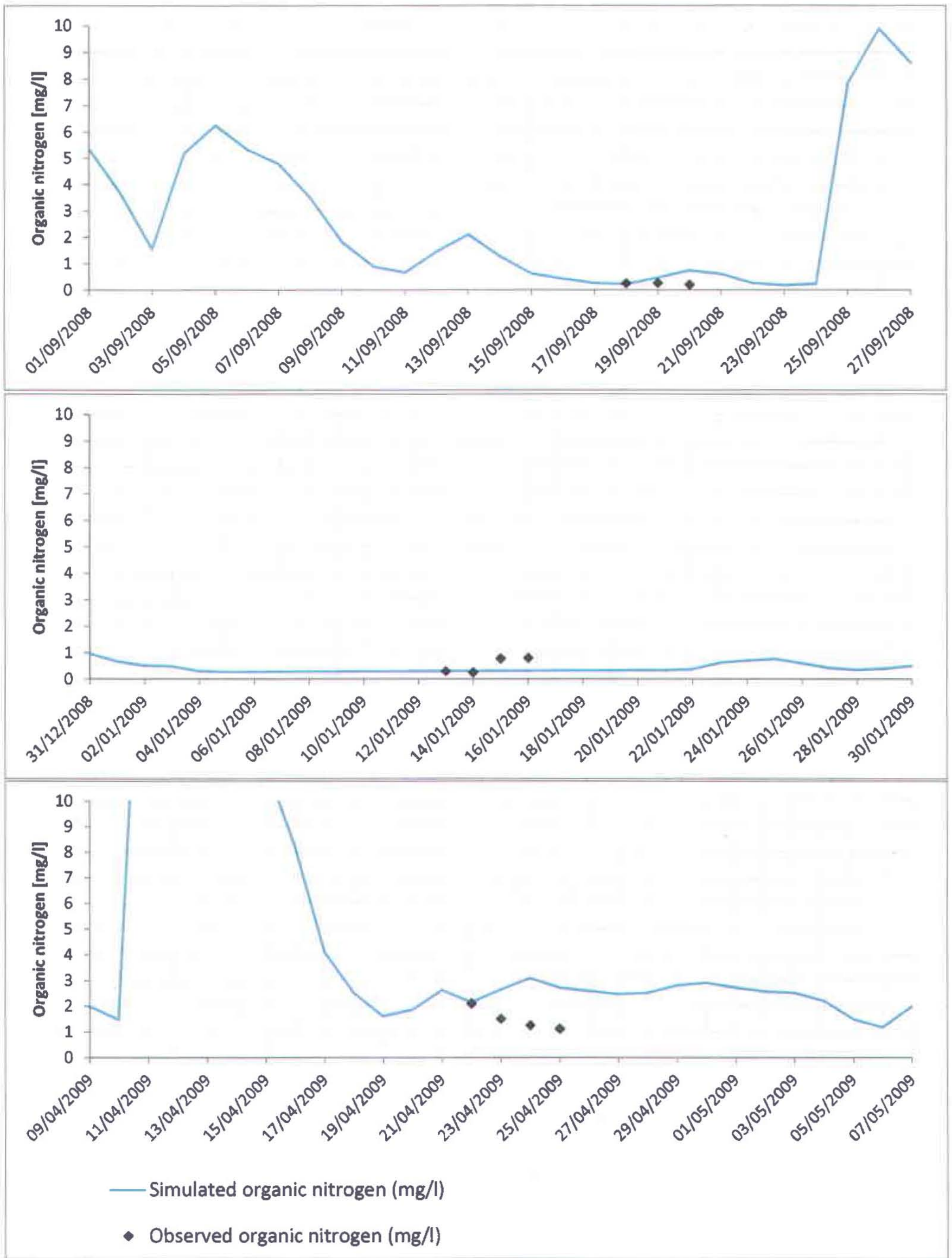


Figure 5.2: Comparison of simulated organic N_{org} results with few observed data at Gia Bay station in 2008 and 2009.

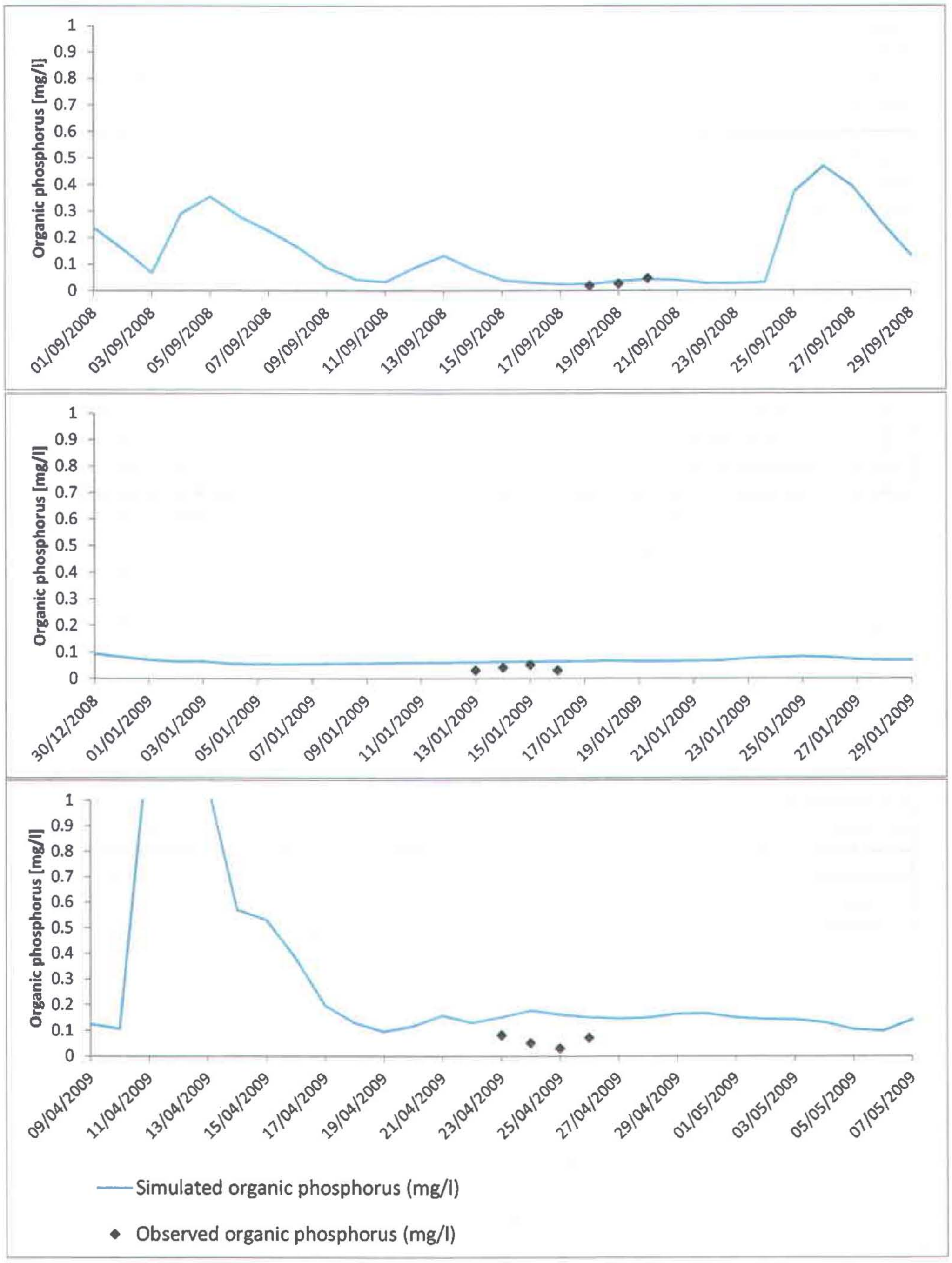


Figure 5.3: Comparison of simulated organic P_{org} results with few observed data at Gia Bay station, in 2008 and 2009.

5.5 Response of erosion and *SS* to the land use changes

5.5.1 Introduction

There are many factors affecting sediment production (S) and transportation (SS) in a watershed. In the context of watershed management, besides the factors considered as relatively common (*e.g.* meteorology, soil properties, hydrology, etc.), land cover change is supposed to be the driving factor for human effects on a watershed.

In general, different scenarios of land use change may result in different effects on the environment and water quality in a watershed. The quantification of the differences in applied scenarios always remains an attractive issue among scientists, land use planners and policy decision-makers. This section focuses on examining the capacity of the models to serve as a tool for quantifying the impact of possible land use scenarios on the Cau River watershed. Two key aspects will be considered: (1) different types of land cover change and (2) different locations where the land cover change takes place in the watershed.

It is well known in the literature that various types of vegetation (forest, agriculture land, brush, etc.) can help in different ways to reduce the risk of soil erosion and sediments transportation by runoff (Podwojewski *et al.,* 2008; Mohammad and Adam, 2010). Nowadays, the use of vegetation to prevent or reduce soil erosion is more and more known as an ecological engineering technique for environmental management (Stokes *et al.,* 2007; 2010). While some studies focus on understanding the mechanism of soil reinforcement by plants roots systems (Valentin *et al.,* 2008), others try to investigate how spatial distribution of vegetation types or land use change can influence soil erosion and suspended solids in river (Ranzi *et al.,* 2012).

There are seven land use classes in the Cau River watershed, namely forest, agriculture, agriculture-mixture, bare soil, brush, urban, and water surfaces. Except for the last two classes, the use of vegetation cover could be considered as a potential tool to change soil erosion on the watershed area. By focussing on the analyses of land use change scenarios and their location in the watershed, it could be possible to:

1. verify how useful the erosion model adapted for the Cau River Basin conditions can be for assessing the impacts of land use change on soil erosion;
2. analyze the possibility of using the models for several purposes such as integrated water management, decision support tool for land management, etc., once it is adapted to the Cau River watershed and calibrated;

3. understand how the watershed responds to changes in land use with emphasis on different types of vegetation (forest, brush, agriculture land, bare soil, etc.) and different locations of land use applications (different topography and distance from the outlet of the watershed), in order to provide suggestions for better land use planning and river water management;
4. Analyze factors affecting the influence of land use for different zones on *S* and *SS* in the watershed, suggesting priorities for land use planners and water managers by considering the influence of land use changes in the context of land use planning and watershed management.

5.5.2 Methodology

To analyze the response of the watershed to land use changes with a focus on different types of vegetation, the methodology adopted is based on a scenario approach. Three groups of scenarios are considered, based on different types of vegetation, by applying conversions from one land use to another: (1) deforestation for timber harvesting: from forest land to bare soil; (2) agriculture land: from forest land + mixed lands to agriculture land; and (3) reforestation: from agriculture land to forest land, because few "bare soil" land areas are available in the watershed for reforestation. The different types of conversion analyzed in the present study are considered as hypothetical conversions even if some of them appeared to be more realistic than others based on the past land use dynamics (Podwojewski *et al.,* 2008; Hoang, 2008) or the probable trend in the future.

It is necessary to mention that the analyses of effects of different land use scenarios are based on the same condition of input parameters. It means that only the land cover management factor (factor *C*) is assumed to vary while other input parameters of meteorological (rainfall), and other soil erosive factors (*R*, *K*, *LS*, *P*) are kept unchanged. The scenarios of land use changes, therefore, are expected to take effect on the process of sediment production (*S*). Also, the change of land cover scenario could affect the runoff on surface and the river channel. It can then cause changes in the delivery rate of sediment on surface to river channels (*CTS*). As a result, a change of sediment input into the river system could finally change the suspended sediment load (*SS*) at the output of the watershed.

The entire study area of the watershed was divided into 17 zones of land use. Figure 5.4 presents the map of these zones in the Cau River watershed. Due to the high heterogeneity of land use in the watershed, each zone was defined to get a dominant land use that represents more than 50% of the zone area (Table 5.2). Each zone was named according to its major type of land cover (Figure 5.4). A total of 17 zones were considered with a level of homogeneity of more than 68%, except for zone 15 (Table 5.2). Except for zones 1 and 3, all zones were found to be in the two main groups of “forest” and “mixture”.

In this section, scenarios are analyzed according to two aspects. First, the quantitative responses of *S* and *SS* to the different changes of land use throughout the groups of zones in the watershed are analyzed. Second, the responses of *S* and *SS* are quantified, but for specified scenarios/actions and at different locations. In particular, the targets of the study are not only to test the effects of different land use changes in the two groups, but also to compare the level of effects of land use changes for some selected similar zones with regard to their difference in topography and transport distance. While the first target helps quantify how much a land use scenario/action could affect the mass of sediment eroded from each zone, each group of zones, and the entire watershed, the second could specify how serious an effect could be when the same scenario/action is applied on similar zones but at different locations in the watershed.

Variations in eroded sediments (*S*) and suspended solids (*SS*) can be influenced by several characteristics of the watershed like water course (linear distance between the zone in which land use was converted into another and the outlet), topographical conditions (mountains, hills, plains), and total surface area affected. In this study, eroded sediments and suspended sediments were analyzed as a function of these characteristics in order to understand how they can explain the influence of each land use change.

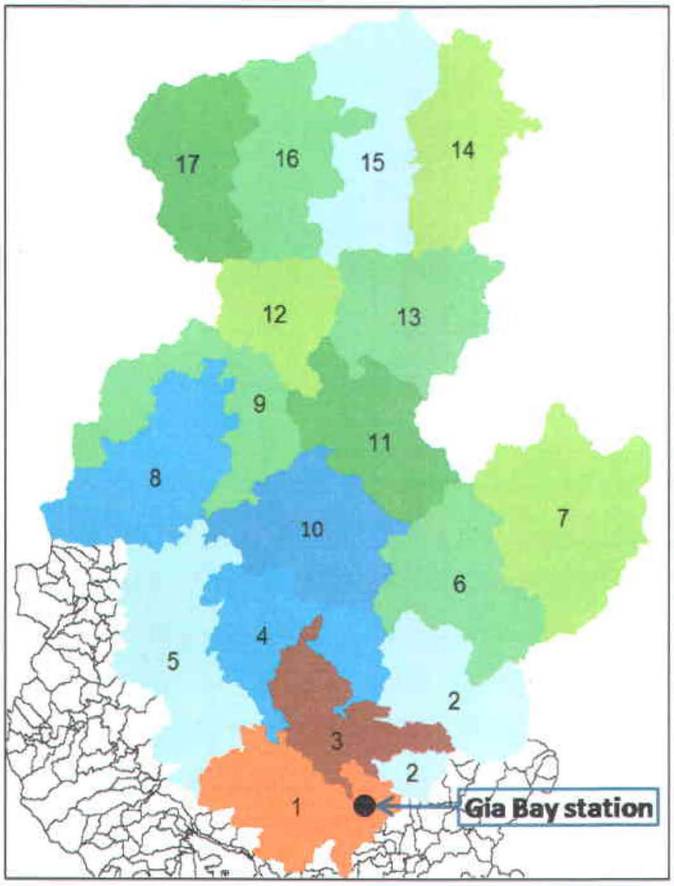
In order to understand how each group of scenarios can affect the behaviour of the watershed, the relative variations of total annual sediments production on soil surface (*S*) and suspended sediments at the outlet (*SS*) were determined with regard to the reference situation of the watershed based on the following expression:

$$\text{relative variation } = \frac{X_{scenario} - X_{reference}}{X_{reference}} * 100\ (\%) \qquad (5.1)$$

where *X* is the mass of sediment (*S*) to be delivered to the output of an USS or the suspended sediment load (*SS*) at the outlet of the watershed.

The reference for comparison of the different scenarios is the results of *S* and *SS* at current stage, after all adaptation and calibration processes of the models. The examinations of *S* and *SS* results according to different scenarios will be performed individually and compared to the reference scenario.

To support the comparison, the term "similar" is used for zones selected from the same group, with relatively similar ratios (%) and/or total area of the dominant land use. Table 5.2 provides information about the 17 selected zones.



Zone	Type
1	Urban and AgriHabPlant
2	Mixture
3	AgriHabPlant
4	Mixture
5	Mixture
6	Forest
7	Forest
8	Mixture
9	Forest
10	Mixture
11	Forest
12	Forest
13	Forest
14	Forest
15	Mixture
16	Forest
17	Forest

Figure 5.4: Divided 17 land use zones in the Cau River watershed.

Table 5.2: Classification of the 17 land use zones considered.

Zones	Occupation	Name assigned	Ratio of the major occupation (ratio of the zone, %)	Area of the major occupation (km^2)
1	Urban and AgriHabPlant	Non modifiable	--	--
2	Mixture*	Mixture	83.6	155
3	AgriHabPlant	Non modifiable	--	--
4	Mixture	Mixture	89.3	156
5	Mixture	Mixture	94.2	212
6	Forest	Forest	76.7	174
7	Forest	Forest	80.6	231
8	Mixture	Mixture	84.6	197
9	Forest	Forest	68.7	167
10	Mixture	Mixture	82.6	185
11	Forest	Forest	75.3	155
12	Forest	Forest	75.4	119
13	Forest	Forest	73.8	158
14	Forest	Forest	75.4	153
15	Mixture	Forest	54.2	186
16	Forest	Forest	78.6	174
17	Forest	Forest	81.5	157

(*) Mixture = AgrHabPlant class + forest class.

5.5.2.1 Considered land use scenarios and objectives of the analysis

Three types of land use change scenarios, namely reforestation, afforestation and deforestation, were considered on different zones to examine their possible impact on sediment production on surface and suspended sediment transport in river for the entire watershed (Sections 5.5.3 and 5.5.5). To analyze this impact in relation to, respectively, topography and distance from the outlet of the watershed, two groups of individual zones of similar dominant land use were selected (Sections 5.5.4 and 5.5.6). The analyses include:

- A deforestation scenario assuming that areas of the "forest" land use class are converted to the "agriculture" land use for the purpose of extending of agriculture lands (abbreviated "forest-agri");
- A deforestation scenario assuming that areas of the forest class are converted to bare soil for the purpose of timber harvesting (abbreviated "forest-bare soil").
- Reforestation and afforestation scenarios assuming that areas of the "AgriHabPlant" and mixture zones are converted to forest areas (abbreviated as "AgriMix-forest"). This type of conversion was taken into consideration for purposes like ecological engineering and management.
- An analysis of the effects of land use scenarios on *SS* in relation to different topographical conditions, to analyze the influence of local topographical conditions for each zone, such as elevation and slope steepness, on sediment production. This could be an addition to help land use planners to decide which scenario should be applied on which zone in order to minimize the negative effects on soil erosion and water quality.
- An analysis of the effects of land use scenarios on *SS* in relation to distance from the outlet of the water course. It is assumed that with the same land use scenario applied on two different zones (relatively similar in terms of major occupation and affected area), the changes in the zone which is closer to the outlet could result in higher effects on the mass of *SS* than the farther one. This analysis could be useful to consider the possible effect of changes in water quality at a river location devoted to specific activities of environmental protection.

5.5.2.2 Specifications for the analyses

In addition, analyses of the different scenarios are conducted as follows:

- Use of the final GIBSI project (after all modifications and calibration) as a base for simulations of the different land use change scenarios (afforestation and deforestation). This project, with the calibrated values for all parameters, was considered as the reference (or permanent) scenario.
- For the simulations, the years 2000 and 2001 were chosen (2001 is a year with high total rainfall and 2000 is a year with average total rainfall, see Figure 4.17). This choice was made to take into consideration different hydrological conditions. It is expected that a year with a low rainfall should lead to few impacts on erosion and *SS*.

- Comparisons of results for land use changes in zones that are similar in terms of type and rate of cover but that are located at different distances from the outlet of the basin.
- Comparisons of results for land use changes in zones that are similar in terms of type and rate of cover but are different in terms of topography. Ranges of elevations and mean slope angle were used as indicators for the selection of the zones. The elevation map of the Cau River watershed (Figure 3.6, Chapter 3) and the extracted map of slope steepness (Figure 5.6) were used as reference sources for this selection.

5.5.3 Sediment production in different land use scenarios

Figure 5.5 shows the comparison of the changes in sediment production on surface for the forestation and deforestation scenarios. According to these results, if forest land on the basin was transformed into agricultural fields, sediment production on the basin could increase by 20%. In the case of the conversion of the agriculture-mixture land into forest, the surface soil erosion would be reduced by as much as 51% in the Cau River watershed. In contrast, deforestation of the entire watershed, transforming the forests to bare soil, could result in a sediment production 14 times higher. Even if this scenario is not realistic and purely academic, it indicates that deforestation could result in dramatic changes in the capacity of the watershed surface to resist to water erosion. Analyses performed also show that (1) the modifications of parameters associated with the surface processes model have performed as expected and have the required sensibility to model the impact of changes in land cover conditions; and (2) for land management, this model can be used to understand the response of the watershed to assist managers.

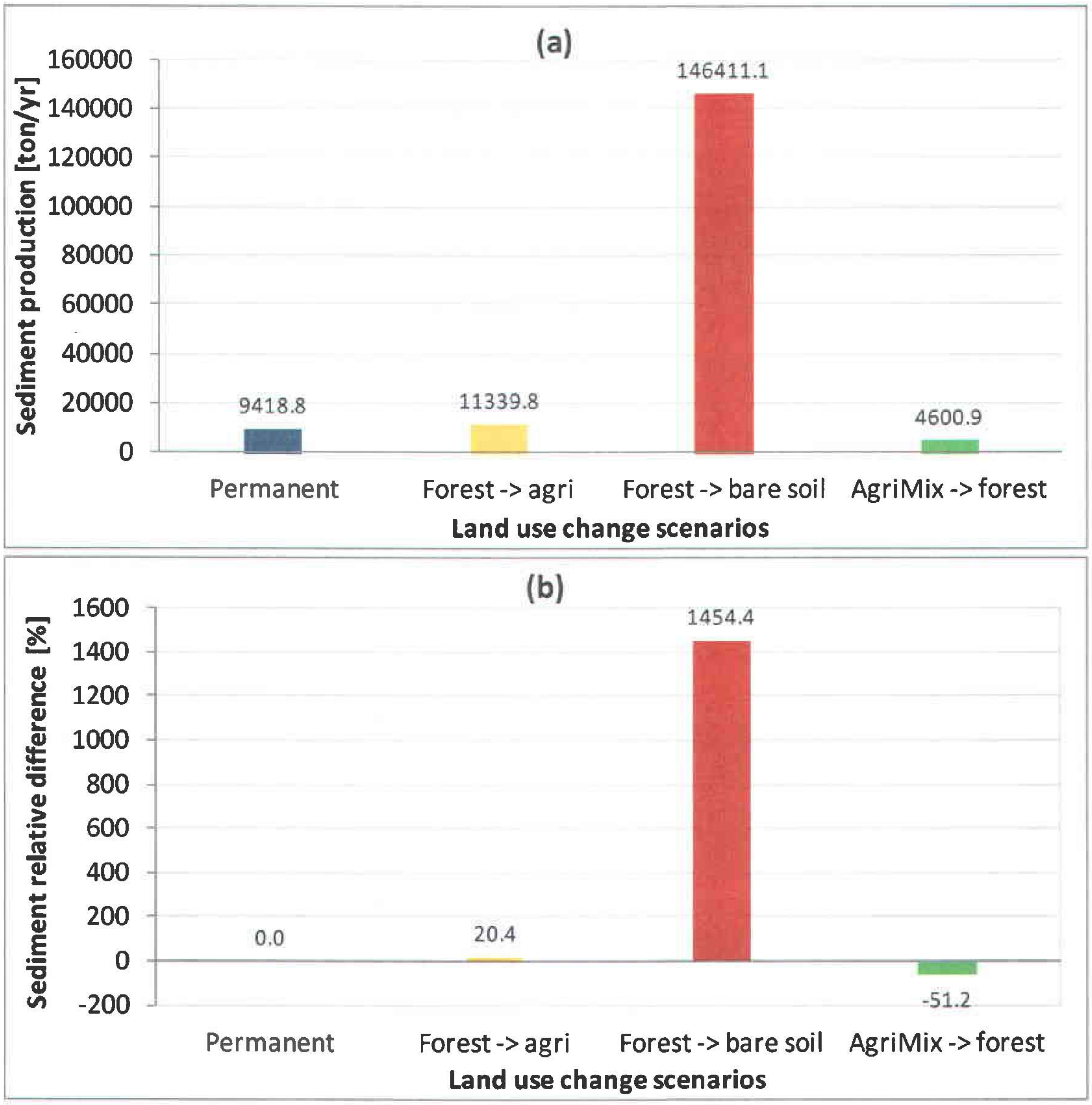


Figure 5.5: Comparison of (a) production and (b) relative difference of sediment produced for the forestation and deforestation scenarios.

5.5.4 Sediment production in different topography

The elevation of the Cau River watershed lowers from North to South, with a significant decrease, from > 1000 m to < 100 m (Figure 3.6) and with slope steepness that varies from 0% to 200%. It is expected that a good adaptation of the soil erosion model to the Cau River Basin must respond well to variations in different local erosive factors such as erosivity *R*, soil erodibility *K*, slope *LS*, land cover *C*, and land management practices *P*.

It is possible to verify the effectiveness of the model for each of the above erosive factors by applying land use scenarios and comparing their results for groups of selected zones. In this study, the model's response to variations in the slope factor and the impacts of land use changes were employed for verification. Also, as mentioned earlier in the section on the sensitivity analysis (Section 4.3.1.2), the slope parameter is a key parameter that determines the transport capacity of sediment (*CTS*) at different locations on the watershed.

Zones 4, 8, and 15 were selected based on their similarity and homogeneity concerning the major occupation (over 80% of mixture class), and because they are located in areas which have different variations of elevation (Figure 3.6) and slope steepness (Figure 5.6). The scenario applied here is the conversion of the mixture class to bare soil. Table 5.3 presents the simulated relative variation of *S* for the three zones, which have representative elevations of respectively < 100 m, < 100 – 300 m, and 300 – 500 m, and a mean slope steepness of 21%, 23%, and 32%. The relative variation presented in this table is defined as the rate of change (%) of the quantity of sediment production in the zone before and after the application of the scenario.

Figure 5.7 compares the relative variation of *S* in the three zones. Results confirm that there is an increase in soil erosion in the areas with higher mean slope steepness (*i.e.* higher variations in topography). Impacts of land use changes on *SS* production are evidently higher in areas with higher slope. In other words, with the same land use change scenario, areas with higher slope would suffer more from the effect of soil erosion.

In general, this verification confirms the good response of the model to variations in the slope parameter, demonstrating the effectiveness of the adaptations and modifications made to the models for the Cau River watershed.

Table 5.3: Zones selected for verification of S in relation to different mean slope.

Zone	Major occupation	Major occupation (%)	Converted to	Area converted /affected (km^2)	Elevation (m)	Mean slope (%)	Relative variation of S (%)
4	Mixture	89.3	Bare soil	156	< 100	21	114.7
8	Mixture	84.6	Bare soil	197	< 100 - 300	23	136.4
15	Mixture	82.6	Bare soil	186	300 - 500	32	156.9

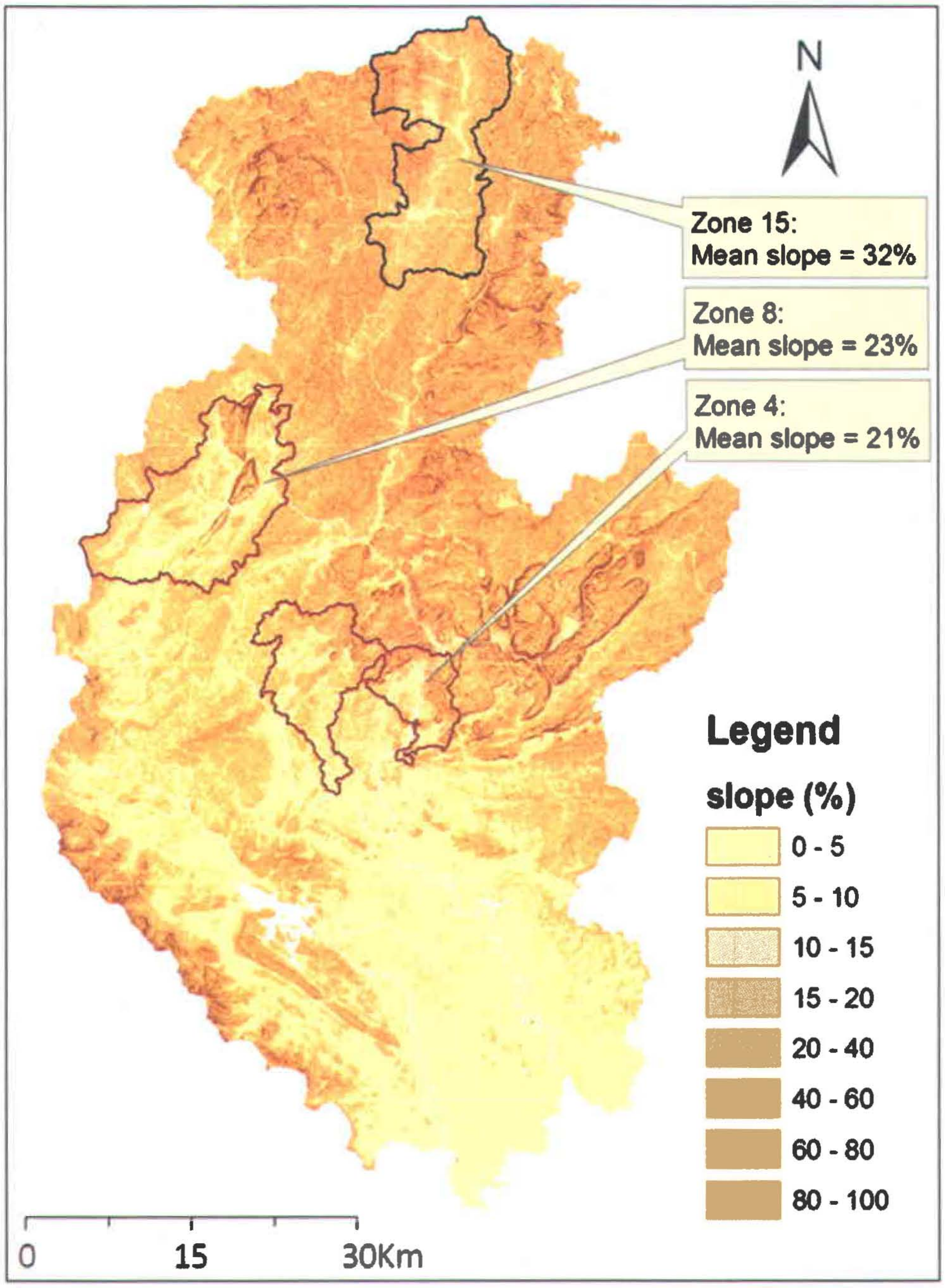


Figure 5.6: Map of slope steepness in the Cau River watershed and the selected zones.

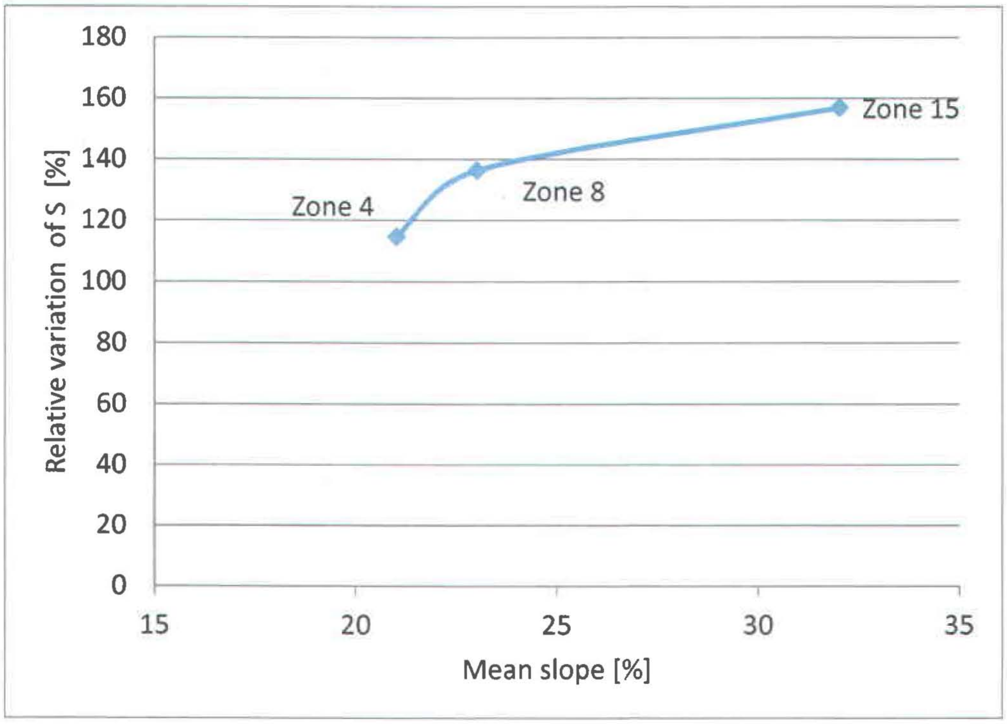


Figure 5.7: Example of the relative variation of S in relation with different mean slope steepness of the selected zones.

5.5.5 Suspended sediment for different land use scenarios

Results of the land use change scenarios in terms of *SS* load in the river are presented in Figure 5.8. According to these results, the forestation of agriculture and mixture land could help to reduce the *SS* load at the outlet of the watershed by about 27%. In the case of deforestation (forest to bare soil), the *SS* load could increase by 72% compared with the reference scenario. In some aspects, these facts indicate that (1) the adapted model, with its modified parameters and calibration, responds well in showing correlations between the changes in land use scenario and in the SS production and SS load at the exit of the watershed; and (2) the adapted and calibrated model is able to predict the quantitative responses of the watershed to different land use change scenarios.

While observing these results, one can note very high rates of sediment production on surface corresponding to average SS increases at the exit of the watershed (i.e. an increase of 1,400% in S production, Figure 5.5, versus a 72% increaes in SS concentration for the forest to bare soil scenario, Figure 5.8). It was found that the areas where the deforestation scenario took effect are mostly located in the upper part of the watershed (Figure 5.4). Although the production rates are high, after getting through a long distance in the river, with the transportation processes, the estimated SS load could increae by only 72% at the exit of the watershed. It is supported that if the SS analysis point was set closer to the location where a land use scenario takes effect, the increase in SS load would be higher.

The scenario of changing forest land to agriculture shows a slight increase in SS at the outlet compared to the current land use status (permanent scenario) of the watershed. This fact may interest agriculture planners. However, a further attention on selection of crop type with a proper farm land setting to prevent soil loss should be necessary.

Regarding the examination of the reforestation scenario, the results show a sharp reduction of annual SS load when agriculture land in the watershed was changed to forest. Also the scenario (agriculture land to forest) is somewhat unpratical due to the recent local conditions and the general trend of urbanisation in the watershed. However, the scenario's result has shown the importance of reforestation in preventating soil erosion.

In general, the comparison of SS results from the different scenarios shows a good performance of the modified models, which seem well adapted to local conditions. Results show the models capacity to serve as tools for water management, land use planning and policy decision-making. The distance from USS and the topography (slope) to the site of SS load analysis could be the key explanation for linking the increase in S production in an USS to the increase in SS concentraion at the exit of the watershed.

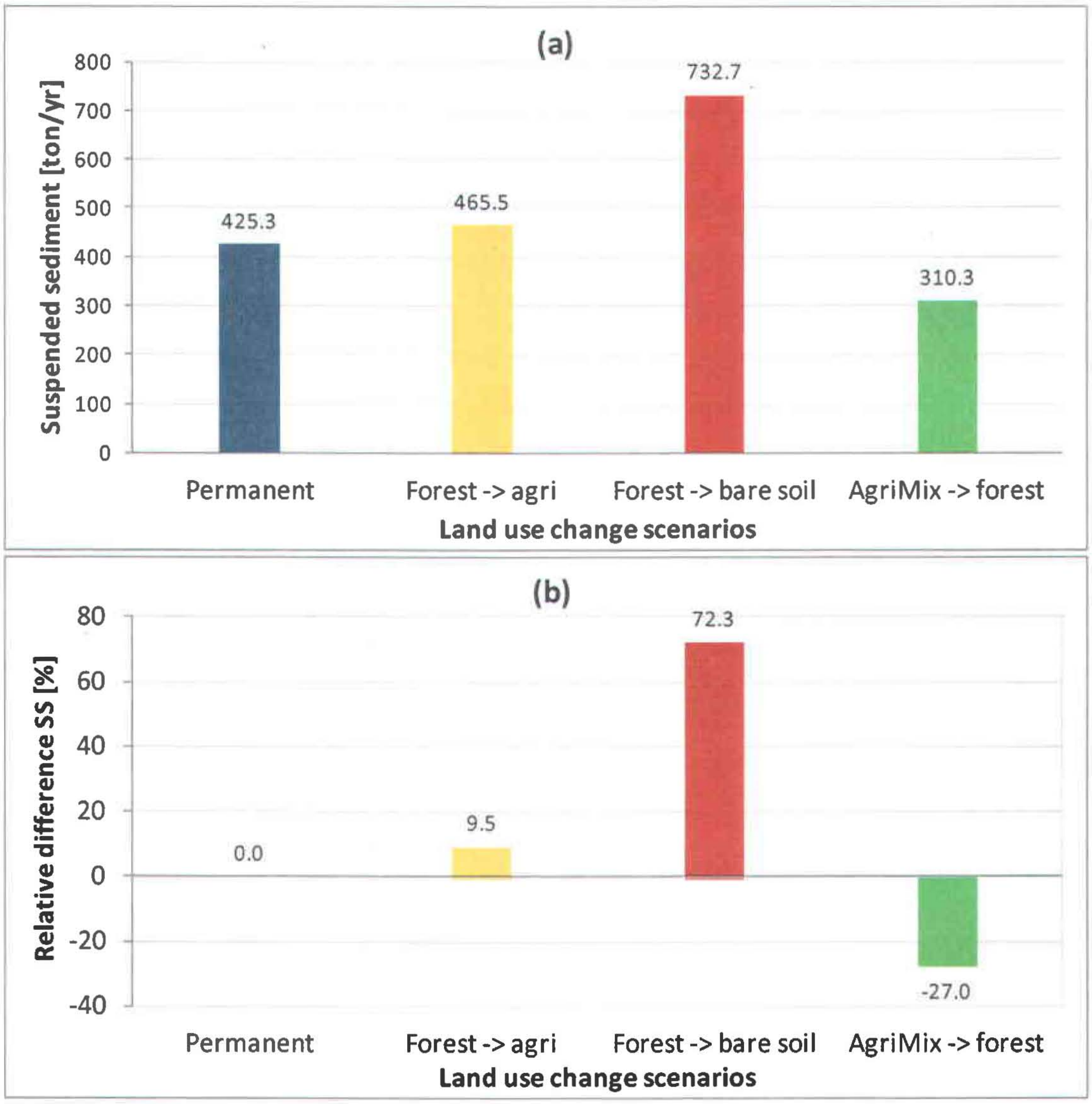


Figure 5.8: Comparison of (a) *SS* load and (b) relative difference of *SS* load at the outlet, for forestation and deforestation scenarios.

5.5.6 Suspended sediment for different transport distances

In order to verify variations in suspended sediment in river as a function of transport distance from site of sediment production to the outlet of the watershed, the results of scenarios were compared for four zones with similar occupation. Zones 17, 14, 13, and 9 were selected for the scenario of a change from forest to bare soil. These zones (Figure 5.4) are located at different distances from the outlet of the watershed (at Gia Bay station), respectively 148.9 km, 96.8 km, 77.9 km and 68.1 km.

As expected, simulated results indicate a more important increase in *SS* for zones that are closer to the outlet (Figure 5.9). Thus, due to the channel processes of sedimentation, areas closer to the outlet or to the observation point could have a bigger contribution to the amount of suspended sediment, when the same land use change action is applied. This demonstrates that the model is able to reproduce these processes.

Table 5.4: Zones selected for the verification of *SS* in relation to transport distance.

Zone	Major occupation	Major occupation (%)	Converted to	Area converted /affected (km^2)	Distance to outlet (km)	Relative variation of *SS* (%)
17	Forest	81.5	Bare soil	157	148.9	4.3
14	Forest	75.4	Bare soil	153	96.8	4.8
13	Forest	73.8	Bare soil	158	77.9	5.3
9	Forest	68.7	Bare soil	166	68.1	5.8

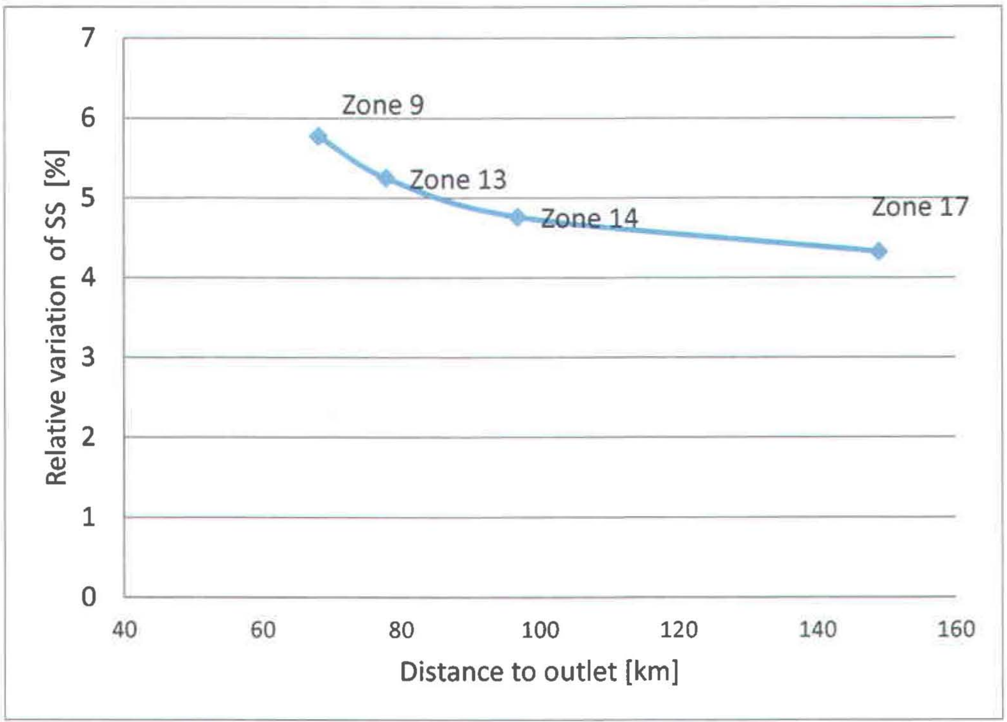


Figure 5.9: Relative variation of *SS* in relation to transport distance.

5.5.7 General comments on the influence of each zone on S and SS

It is possible to compare numerically the relative influence of each of the 17 zones (Figure 5.4) by applying scenarios. However, this section provides an overall analysis of the factors affecting the impacts of each zone on *S* and *SS* after a land use change is applied, rather than a numeric comparison of sediment rate between zones.

As confirmed through the above analyses, the variations of *S* and *SS* caused by land use change scenarios can be influenced by several parameters (in addition to common parameters of meteorology, hydrology, and soil properties) such as (1) the distance from each affected zone to the outlet; (2) topographical conditions, and (3) the total surface area affected by the change in each zone. Depending on the location and affected area of each zone in the watershed, each parameter defines the influence of that zone on *S* and *SS* in the watershed. Sometimes, in a zone, a parameter increases the impacts on *S* and *SS* while another decreases it. As for example, in the case of the Cau River, zones in the Northern part are located at a higher elevation with high slope steepness. Thus, sediment production in these zones will be promoted by the effect of topography. However, due to their far distance to the outlet, the influence on *SS* at the outlet of the watershed of land use changes in the zones in the North is reduced. Although the mean slope of the southern zones is lower than in the northern zones, and thus sediment production could be lower in the South, the contribution of the southern zones to *SS* at the outlet may be higher than for the northern zones.

In general, it is possible for land use planners and water managers to apply the models and the above zoning analysis to determine the possible sediment production in each specified zone, for each land use scenario, and its contribution to *SS* at (1) the outlet of the basin or (2) any section of the river which needs to be protected. Regardless of which land use scenario is applied when comparing the influence of the zones, it is necessary for planners and managers to put priority, orderly, on the consideration of (1) distance to the outlet or point of interest, (2) topography of the zone, and (3) area affected by the change.

5.6 Discussion and conclusion

This study helps confirm once more the effectiveness of the modifications and adaptations brought to the soil erosion and transportation models to be applied to the Cau River watershed, within the context of data limitations and climate specificities. The verifications have shown that the modified and adapted models are able to:

- Provide reliable runs of the soil erosion and transportation models in GIBSI for the Cau River watershed by setting up the basic conditions according to local climatic conditions and data availability. This setup was a combination of different tasks including adaptations and/or modifications in: (1) basic theory, (2) considerations of local data availability, (3) formulas, and (4) computing code.
- Show good responses in terms of suspended sediment in river, corresponding to the behaviour of local hydrological and meteorological observation data.
- Represent the quantitative variations of P_{org} and N_{org} that correspond to *SS* variation in the Cau River watershed, enabling the models to be applied for the modeling of water quality management scenarios.
- Assess the impact of changes in human activities and land use on *SS* in the watershed.

All these results confirm the necessity of the modifications and adaptations brought to the models for the purpose of making GIBSI a useful tool for the integrated management of the Cau River watershed.

It is necessary to mention that the modified soil erosion and transportation models have a larger applicability themselves. They can allow the application of land use scenarios and the examination of water quality. Based on these two models only, further examinations could be done to verify the effects of topography, climate changes, and human activities on *SS* and water quality. As for example: (1) the examination of temporal variations of *SS* and water quality variables with precipitation from year to year could illustrate an overview of how the variables could be affected by climate change; (2) the examination of the spatial variation of the input data by comparing different combination of topography and land cover could help verify the sensitivity of the models to each land use action on different topographic conditions in the Cau River watershed. This could help create a risk classification for each land use action, enabling the quantitative evaluation of land and water management scenarios on every single location of the Cau River watershed.

Within the scope of this thesis, the abovementioned applications and examinations were not carried out. These tasks were performed in two additional studies concerning (1) water quality modeling (Nguyen, 2013) and (2) integrated management scenarios (Pham, 2013), performed in the framework of the main project of the Cau River Basin integrated water resources management, using the models that were modified, adapted and calibrated in this thesis.

6. Conclusions, recommendations and perspectives

As initiated, the principal objective of the study is to develop methodologies for the application of erosion and sediment transport models at catchment scale and to suggest modifications to the models for their application in tropical climates where few data are available, in order to reduce the uncertainties associated with the model results in such conditions.

6.1 The tools

GIBSI is an integrated modeling system for watershed management, developed by *Institut National de la Recherche Scientifique,* INRS-ETE (Villeneuve *et al.*, 1995). It was designed to help stakeholders make decisions in water management at the watershed scale. It can either be used as a watershed management system or as an impact assessment tool to study the effect of management scenarios on the response of a watershed using mathematical models.

The soil erosion model MODEROSS (Duchemin, 2000) and sediment transport model ROTO (Arnold *et al.*, 1995a) are respectively representative for the surface processes and channel processes of soil erosion in a watershed. In the GIBSI system, they serve as intermediate-processing modules providing quantitative inputs to other models. Thus, they can provide means to setup management scenarios and reflect quantitative changes caused by these scenarios.

6.2 The main challenges

The soil erosion and transportation models were originally designed for small scale or single slope estimates. They were developed on farmland topography, for temperate climatic regions rather than for monsoon tropical conditions. Their mathematic formulas could result in errors when being applied for larger scale estimates such as the watershed scale. This therefore requires adjustment in formulas as well as a lot of good observation data for the calibration and validation of the models. Shortage of data (in both temporal and spatial aspects) to calibrate the models and differences in local climatic conditions could be important sources of uncertainties for the model results.

The main challenges of applying the models to the Cau River watershed are: (1) topographic and climatic conditions are largely different on this watershed as compared to the watersheds on which the models were previously applied and (2) limitations in both quality and quantity of observation data.

6.3 The requirements and tasks performed

Due to the abovementioned limitations, some of the existing methods to obtain data, formulas to estimate variables, and procedures for the calibration and verification of models are not applicable to the conditions of the Cau River Basin. A proper adaptation of GIBSI to the Cau River Basin should, at least, meet these main requirements: (1) the GIBSI system and its models must be, first, able to run properly after the modifications and adaptations for the conditions of the Cau River watershed; (2) the adapted models must perform well, reflecting the local conditions; (3) models must show a capacity to perform the quantitative estimates of water quality variables; and (4) models outputs must, finally, show their capacity to respond to changes in different land management scenarios.

In this study, a series of adaptations and modifications of the two models MODEROSS and ROTO were done for the two main purposes of *"Setting the local conditions prior to simulations"* and *"Modifying formulas to adapt to local conditions"*. A total of 21 input data or intermediate variables of the two models were selected as necessary for modification and/or adaptation. The performed tasks were classified based on four main considerations, orderly: (1) theory; (2) use of local data; (3) formulas; and (4) computing code.

6.4 Achievements

As initially proposed, data availability and differences in climatic conditions prevent the direct application of the models, methodologies and formulations of GIBSI to the Cau River watershed. This thesis has brought into practice the application of soil erosion and transportation models into the watershed. Through the application, problems posed by local conditions were identified and solved. A comprehensive analysis of data requirements for the models and of the most accessible local database helped finding the most acceptable solutions to setup the input data and to develop methods for obtaining missing data. These tasks were the first step to get the GIBSI system to be able to run in the conditions of the Cau River Basin.

Results of this study with adaptations and modifications of the models have confirmed the applicability of the models in an area where observation data are scarce and where climatic conditions are different from those of the watersheds where the models were first developed.

In the literature, many studies have been done so far to study: (1) the effects of vegetation on soil erosion (Podwojewski *et al.,* 2008; Mohammad and Adam, 2010); (2) its technical performance for erosion management (Stokes *et al.,* 2007; 2010; Valentin *et al.,* 2008); and (3) the influence of the spatial distribution of land use changes (Ranzi *et al.* 2012). Taking advantages from the existing GIBSI system, this research work advances steps towards providing a practical tool which has the capacity to conduct quantitative assessments at any spatial or temporal scale in a large river watershed in tropical climate conditions, in the context of data limitation such as in the Cau River watershed.

In addition to the contributions of the study, this thesis work has:

- provided solutions to obtain input data which are not available in the Cau River Basin. They are: soil structure codes (*cs*); soil permeability codes (*cp*); and organic matter content (*MO*), for the calculation of annual soil erodibility;
- provided methods to adapt, and re-write codes of erosive factors: slope (*LS*), land cover management (*C*), and conservation practices (*P*) in the soil erosion model MODEROSS, in the Cau River Basin where only a land use map is available;
- distinguished, for the first time, in the application of the MODEROSS model in GIBSI to the Cau River watershed in tropical climate conditions, two groups of land use classes for a better orientation, easier identification, and higher accuracy in the adaptation of *C* and *P*. The two groups include a "*stable group*" in the year (urban, water body, forest and bare soil) and a "*variable group*" in the year (agriculture, mixture, brush);
- provided guidelines and procedures for models calibration to improve the accuracy of the results of the sediment simulation in monsoon climatic areas, particularly for the Cau River Basin. The analysis also helped pointing out the influence of each calibration parameter on the model's behaviour in the climatic context of this watershed;

- allowed the analysis and guidelines for calibrations that also provide an effective tool to get finer calibrations of *SS* for specific periods (such as dry or wet season) which may be of interest for individual water management experts and water users for individual purposes (*e.g.* irrigation, domestic water supply. water quality control, etc.);
- ensured the realism of simulations with the GIBSI system in tropical climate regions such as the Cau River Basin in a context of data limitation while keeping certainty of the applied adaptations and modifications;
- enabled the capacity for temporal examinations of the effects of climate change, topography and land cover, and provided means for the quantitative evaluation of different management scenarios;
- contributed to setting up possibilities for studies on water quality modeling and integrated management scenarios in the Cau River watershed.

6.5 Recommendations and perspectives

The work has led to various recommendations as follows:

- *data constraint,* especially the lack of input data, is one of the biggest challenges. In most cases, missing data are difficult to obtain. This issue could be solved by: (1) Employing any available source of information. The analysis of these sources could help find the way to obtain, or to estimate, the needed data (such as the *cs*, *cp*, and *MO*, *C*, *P* in the case of the Cau River watershed). (2) Modifying or even changing the method to get the required input parameters (such as for rainfall erosivity *R* and daily soil erodibility K_{ji}, Section 4.1, Chapter 4);
- *the differences in topography and climate conditions* require the revision or even modification of both theory and formulas for calculations. They must be done together, with close attention to local specific conditions;
- *the distinction of land use classes into two groups* of (1) *Stable* and (2) *Variable*, based on the possible time variation caused by human activities, is necessary when the soil erosion model USLE is applied onto such a large watershed which has multiple categories of land use (sub-section 4.2.4.1);
- *the theory of crop cycle* in GIBSI should be replaced by the concept of *one-year land use and land cover cycle* to be able to estimate *C* daily for the watersheds where some land use classes have many short cycles of plantation (or cycles of cover indication) in a year. This is important to make a more accurate, more flexible and easier application of *C* daily calculations to local conditions on any other watershed (sub-section 4.2.4.3);
- *observation data* must be verified for realism and uncertainty if any, prior to any calibration. Observation data, obviously, is the result of many factors which actually happened in the watershed. Some of them (such as human activities) were not

integrated into the formulations of the models or they would be too complex to integrate. Verification prior to any calibration could allow a better understanding of the calibrated results. In some cases, it could help explain abnormity of results;

- *sensitivity analysis* is an important step before calibration. In the case of the Cau River Basin, the analysis confirmed the large difference in the models' sensitivity between parameters themselves and between wet and dry seasons. Results of these examinations provided key suggestions for the choices of values of parameters to calibrate;
- *selected parameters for the calibration* of models have shown different levels of effects on the results. The *b* and *o* parameters of the surface processes and the representative particle diameter (*Dr*) of the channel processes are most significant. Although *a* (with *af*, *ac*) and *c* (with *cf*, *cc*) were initially specified for seasonal differences, the combined adjustments of *b* and *o* was more effective in the case of the Cau River watershed. While the reduction of *b* helps reduce *SS* in the months of the highest rainfall period (June and July), the increase of *o* could reduce *SS* more in moderate to low rainfall periods (January to May and September to December). The combined adjustment of these two parameters helped adjust individual periods between high and low rainfall seasons, which is important for the high contrast of seasonal *SS* like in the Cau River watershed. The adjustment of *Dr* results in the broad and most significant *SS* changes. Varying the value of *Dr* was effective to control the level of high peaks in high rainfall season as well as to limit the total annual load of *SS*;
- *the guidelines* for selecting parameter values and the procedure to perform the calibration of the models were very helpful in giving orientations and suggestions for selecting priorities during calibrations. They should be used flexibly depending upon the needs of the users, or for a closer, finer focus on a selected period of time;
- *big contrast between seasons* and extreme events are found when modeling the sediment processes in the Cau River watershed. This could be similar for other watersheds in tropical regions. For a more accurate result reflecting seasonal variations, the separation of the analyses and calibration models into two different seasons is helpful. For example, two sets of calibration parameters could be used for the two different seasons;
- *priority for calibration* of *SS* in the tropical watersheds should be made to period of rainy season when it provides an extremely large contribution to total mass of *SS* in a year. *Recalibration of the models* is possible and necessary in the case of a specific period in a year that needs to be calibrated. This can be done with an additional adjustment of the set of calibration parameters. In both cases, it is important to follow the suggestions of calibration introduced in Section 4.4.1.5 and Table 4.10;
- *rapid changes of land use* could be another source for uncertainty of simulated *SS* result in the models. The rapid land use changes in the Cau River watershed were acknowledged in the literature. Their effects on the production and transportation of

sediments were also confirmed through examinations in this study (Chapter 5). When using observed data from different time periods for calibration and validation (in the case of the Cau River Basin, it is orderly 1998-2002 and 2003-2006), the actual conditions that define the observed *SS* during the period for validation may have been changed as the result of rapid land use changes. Thus, it is expected that there would be an addition to uncertainty caused by this issue, and this should be considered in the analyses of the results;

- *the research work,* within the scope of study, succeeded in overcoming some limitations to bring the soil erosion and sediment transport models of GIBSI into practice for the conditions of the Cau River watershed. Although further improvements would be needed, the completion of this work is an important step to enable follow up studies on water quality and watershed management scenarios in the Cau River watershed itself, as well as a good reference for similar applications on other watersheds;
- *application of the research work* to other similar watersheds is recommended with the following attentions: (1) Concerning the preparation of the input data, their availability, sources and formats should be analyzed first. Methods to obtain a dataset may be different depending on the local availability. However, the orientation to obtain missing data could be the same. (2) A careful verification of observation data is necessary. (3) Calibration is the must-have. It can be done with the provided guidelines, procedures and suggestions. The selected values of calibration parameters for the Cau River can be used as starting values. (4) A closer attention to different time periods for calibration would provide better calibration results;
- *direct applications* of the two models are possible for the purpose of land use planning and quantitative management of surface water quality in the basin. Through the examinations of the models' responses to land use changes, it is easy for managers to test assumptions and verify quantitatively the possible effects of different land use scenarios.

6.6 Limitations and expectations for further studies

Simulated results, however, showed that the models tend to simulate erosion and *SS* better during the rainy season than in dry season. This is due to many reasons: (1) the hydrological model used to simulate runoff was found to be less performing in dry period; (2) Problems to compute water levels in rivers. (3) Actual observed data of *SS* that were affected by human activities in the river during the dry period (sand excavation, land fill. etc.). It could be complex to model such a high variability of activities with limited information.

In general, through experiences obtained during this work, there are three main issues that should be improved in order to have more accurate results of suspended sediment and river water quality, improving the effectiveness of efforts done so far in this thesis work.

First, results of the calibrations and validations (Section 4.4) showed that the models performed less accurately at the daily time step. There could be many reasons that caused the problem. It is, therefore, necessary to take a closer look at the models that provide the daily inputs for the soil erosion and sediment transport models (*e.g.* variables of daily surface runoff and surface water height of the hydrological model are employed by the soil erosion model to estimate the production of sediment on surface). The accuracy at the daily time step of these variables could help to improve simulations at the same daily time step.

Second, it has been acknowledged that the observation data in the Cau River watershed was very limited. While we cannot expect longer, continuous field campaigns in the watershed, it should be better to focus on the timing of observations. All available field data showed that they were observed during low rainfall season or during periods when the weather was nice. Thus, data often miss the periods when peaks of rainfall and runoff occur. For further application of GIBSI to watersheds with similar limitations, it would be better to have a pre-estimate of local climatic regime and weather forecast to setup the field observation timing plan. At least, in the case of the Cau River watershed, a single number of field data in a good timing would be more valuable than many others.

Third, observation data was influenced by many factors, including human activities. A careful awareness of their effects on the observation is necessary. However, the integration in the models of modules that account for the effects of human activities on water quality, in general, and river *SS*, in particular, is an important key to approach a better performance of models and more accurate simulated results.

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APPENDIXES

CHAPTER 2

Appendix 2.1: Map of potential soil loss volume in Vietnam estimated using USLE model with the erosive factors R, K and LS in the Northeastern part of Vietnam (adapted from Tran, 1998).

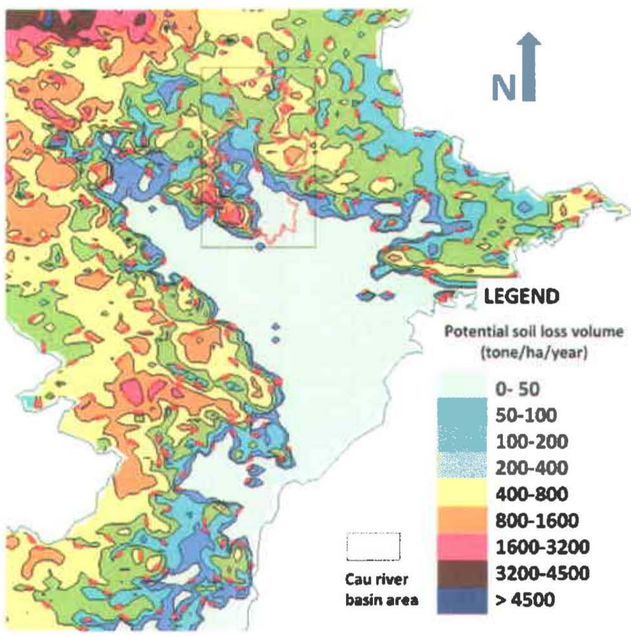


Table of classification of potential soil loss in Vietnam for 9 classes and their occupation ratio compared to the total country's area (*Tran, 1998*).

Classes	Soil loss volume (ton/ha/year)	Area of class (km^2)	Area ratio (%) compared to the entire country area
1	<50	100810	30.55
2	50-100	19840	6.01
3	100-200	31490	9.55
4	200-400	48110	14.58
5	400-800	68150	20.65
6	800-1600	50220	15.22
7	1600-3200	10880	3.29
8	3200-4500	470	0.14
9	>4500	30	0.01

CHAPTER 3

Appendix 3.1: Models and features included in GIBSI (after Mailhot *et al.*, 1997; Villeneuve *et al.*, 1998a; Duchemin, 2001).

MODEL	Simulated processes	Simulated variables	Required input data	Computational Time Step
Hydrology (HYDROTEL)	• Snowmelt • Evapotranspiration Saturated and non-saturated soil water flow • Runoff and river flow	• Runoff height • River flow rate • Soil water content in three soil layers • Snow cover	• Meteorological • Land use • Elevation model • Soil characteristics	• Day or less
Soil erosion and transportation (MODÉROSS+ ROTO)	• Detachment of soil particles • Transport of eroded soil particles • Sedimentation of eroded soil particles	• Production of sediment on soil surface • Sediment load	• Meteorological • Elevation model • Hydrological • Crop management • Tillage practices • Soil characteristics	• Day
Pollutant transport (SWAT/EPIC)	• Nitrogen cycle • Ammonium adsorption-desorption • Phosphorus cycle • Desorption of soluble phosphorus at soil surface • Pesticides adsorption-desorption • Pesticides degradation	• Nitrate and organic nitrogen • Mineral and organic phosphorus • Dissolved and particulate pesticides	• Soil characteristics • Meteorological • Hydrological • Crop management • Soil erosion	• Day
Water quality (QUAL2E)	• Nitrogen cycle • Phosphorus cycle • Algal growth • BOD_5 • Atmospheric reaeration	• Nitrite and nitrate • Ammonia • BOD_5 • Dissolved oxygen • Dissolved and organic phosphorus	• Simulated concentrations of water contaminants (point and non-point sources)	• Steady state or transient simulation. • Modified in GIBSI to simulate a succession of daily steady states

Appendix 3.2: List of possible urban, industrial, agricultural, land use, and river management scenario parameters in GIBSI (Mailhot *et al.*, 1997).

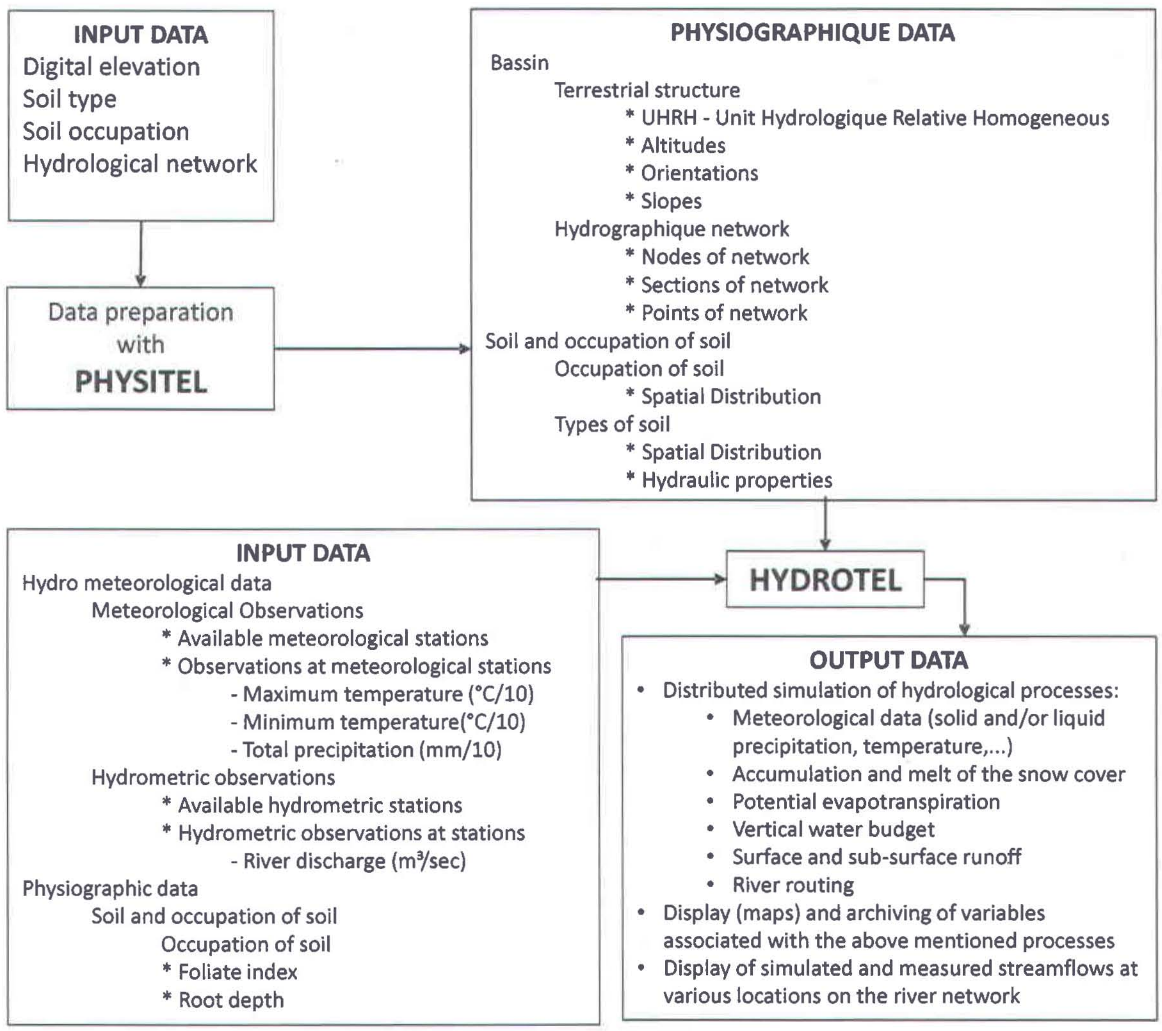
Type	Scenario parameter
Urban point load	Position
	Connected population
	Type of treatment
	Treatment efficiency
	Point load characteristics (volumes, water quality parameters)
Industrial point load	Position
	Type of industry
	Point load characteristics (volume, water quality parameters)
	Addition or withdrawal of industrial point load
Agricultural	Type and spatial distribution of cultures and livestock
	Loads and rates of applied organic fertilizer
	Crop management practices
	Loads and rates of applied chemical fertilizers
	Loads and rates of applied pesticides
Land use	Areal distribution and watershed fractions of agricultural land, forested areas.
River network	Addition or removal of dams
	Hydraulics characteristics of dams
	Withdrawal of river water (*e.g.* irrigation planning).

Appendix 3.3: The algorithm and structure of the runoff model HYDROTEL in GIBSI and example of simulated river discharge at Gia Bay station in the Cau river watershed

a) **Introduction of HYDROTEL model** (after Fortin *et al.*, 1995; Villeneuve *et al.*, 1998a)

Simulating Targets:	Flows in each waterway of a catchment area. Surface runoff, the stock of snow, water contents in the ground, etc. in any point of a catchment area.
Applications:	Estimate of the hydrological effects of scenarios of modifications of the characteristics of basin. Forecasts of the flows. Simulation of the risings corresponding to rains of various frequencies of return.

Structure:

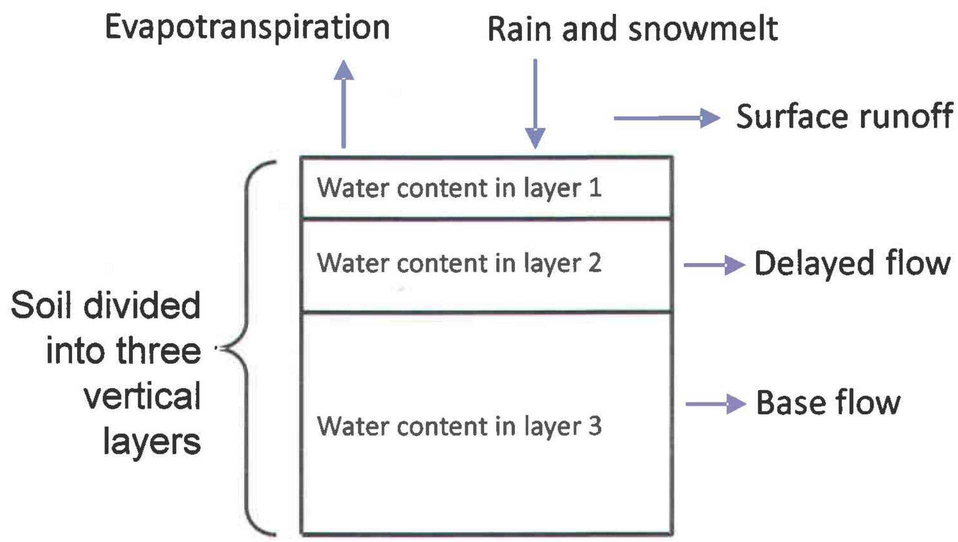


b) Vertical processes and algorithms simulated on each sub-basin by HYDROTEL (after Fortin *et al.*, 1995; Villeneuve *et al.*, 1998a; Nguyen, 2012)

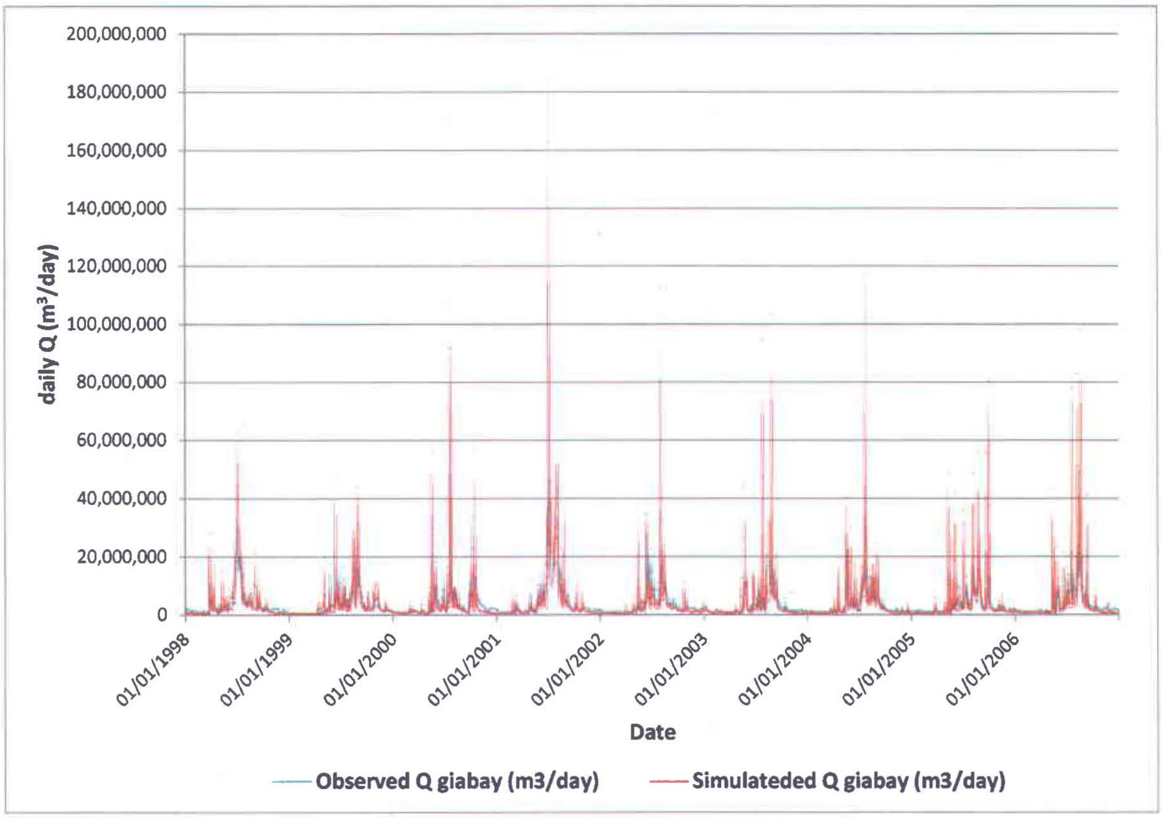
	Process		Algorithm (options)
1	Interpolation of precipitation	1.1	Polygons of Thiessen
		1.2*	Weighted average of three nearest stations
2.	Evolution of snow cover	2.1	Method of the degree-days
3.	Evapotranspiration potential	3.1	Thornthwaite
		3.2	Linacre
		3.3	Penman-Monteith
		3.4	Priestley-Taylor
		3.5*	Hydro-Québec
4.	Vertical Balance	4.1*	BV3C Bilan d'eau vertical dans le sol est le modèle de bilan vertical en trois couche (Fortin *et al.*, 1995).
		4.2	CEQUEAU (Morin *et al.*, 1995)
5	Flow on surface of the basin	5.1*	Kinematic wave
6	Flow by the hydrological network	6.1*	Kinematic wave
		6.2	Diffusing wave

Note : (*) : algorithms selected for simulation in the Cau river watershed by Nguyen (2012).

c) Ilustration of Vertical Balance (BV3C) to evaluate the quantity of water that will run off the surface and which will infiltrate, to store and run into the ground (after Fortin *et al.*, 1995; Villeneuve *et al.*, 1998a)



d) Simulated and calibrated result of HYDROTEL model for river discharge Q at Gia Bay station (1998-2006).



Appendix 3.4: Mean monthly temperature in Bac Kan and Thai Nguyen provinces

Month	Province	
	Thai Nguyen (°C)	Bac Kan (°C)
January	16.6	14.3
February	17.5	19.3
March	20.0	20.4
April	23.7	25.0
May	25.9	27.4
June	28.7	28.0
July	28.0	28.3
August	28.8	27.9
September	27.7	25.7
October	25.7	23.9
November	22.4	21.2
December	18.2	16.0

Source: Annual reports on environmental status of Bac Kan (2004) and Thai Nguyen (2004).

Appendix 3.5: Mean monthly humidity in the Cau River watershed from 2002 to 2004 (%).

Month	2002	2003	2004
January	75	75	79
February	85	82	83
March	82	79	83
April	83	81	87
May	82	81	82
June	83	79	80
July	84	83	87
August	84	84	84
September	80	83	83
October	79	77	75
November	78	73	80
December	81	70	78

Source: Annual reports on environmental status of Bac Kan (2004) and Thai Nguyen (2004).

Appendix 3.6: Mean monthly and mean annual wind velocity in the Cau River watershed (m/s).

No.	Station	Mean monthly												Mean annual
		1	2	3	4	5	6	7	8	9	10	11	12	
1	Bac Kan	1.4	1.5	1.3	1.2	1.2	1.0	0.9	0.8	0.9	1.1	1.4	1.3	1.2
2	Dinh Hoa	1.2	1.3	1.2	1.4	1.3	1.2	1.2	1.1	1.1	1.1	1.1	1.2	1.2
3	Thai Nguyen	1.4	1.5	1.5	1.7	1.8	1.5	1.5	1.3	1.3	1.4	1.3	1.5	1.5
4	Tam Dao	3.1	3.0	3.2	3.1	3.2	2.8	2.7	2.3	3.1	3.5	3.3	3.0	3.0

Source: Annual reports on environmental status of Bac Kan (2004) and Thai Nguyen (2004).

Appendix 3.7: Mean monthly and annual rainfall in the Cau River watershed (mm).

Station	Mean monthly												Mean annual
	1	2	3	4	5	6	7	8	9	10	11	12	
Bac Kan	22.5	30.0	55.5	110.1	176.5	263.3	280.5	290.5	158.5	83.2	43.6	18.6	1533
Dinh Hoa	22.2	29.7	54.0	106.3	210.5	277.5	332.5	320.4	185.1	108.4	43.1	17.3	1707
Thai Nguyen	26.7	34.6	61.5	121.3	237.3	335.7	423.9	360.6	248.7	146.4	52.3	25.3	2074
Tam Dao	38.0	45.8	84.3	141.4	229.1	377.2	439.9	466.7	325.3	219.5	93.7	34.3	2495

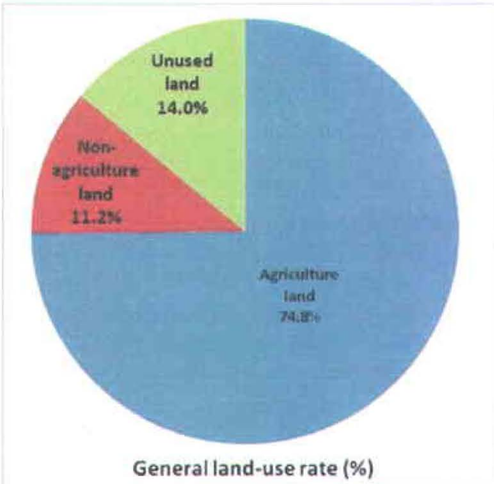
Source: Annual reports on environmental status of Bac Kan (2004) and Thai Nguyen (2004).

Appendix 3.8: Mean monthly and mean annual river discharge in the watershed (m^3/s).

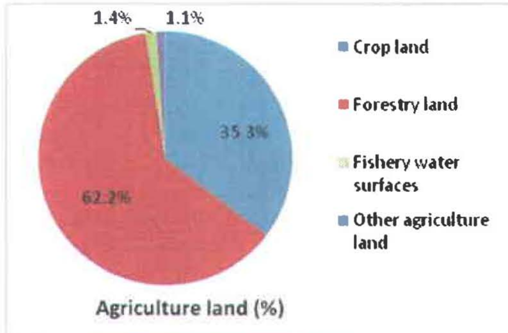
Location	River	Period	Mean monthly												Mean annual
			1	2	3	4	5	6	7	8	9	10	11	12	
Thac Rieng	Cau	1974-1981	5.31	4.93	5.15	8.41	16.4	28.7	34.6	41.4	29	16.4	10.6	6.55	17.3
Thac Buoi	Cau	1962-1996	13.2	12.1	14.1	24.8	45.2	85.3	127	123	93.7	47.1	27.7	15.7	52.4
Thac Huong	Cau	1961-1976	17.2	15.8	18.4	32.4	59	111	166	160	122	61.5	36.2	20.5	68.3
Giang Tien	Du	1961-1971	1.47	1.39	1.39	2.9	4.25	8.12	11.2	16	9.6	6.02	3.87	1.88	5.7
Cau Mai	Cau Mai	1970-1985	0.13	0.13	0.11	0.25	0.72	1.07	1.65	2.09	1.72	0.76	0.37	0.19	0.8
Nui Hong	Cong	1962-1969	0.89	0.85	0.96	2.37	2.45	5.03	5.11	6.19	4.33	3.18	2.05	1.07	2.9
Tan Cuong	Cong	1961-1976	2.92	3.15	3.5	8.7	14.8	23.4	25.8	39.2	31.2	17.7	8.65	3.86	15.2
Song Cong	Cong	1961-1976	4.8	5.18	5.76	14.3	24.3	38.5	42.4	64.5	51.3	29.1	14.2	6.35	25.1

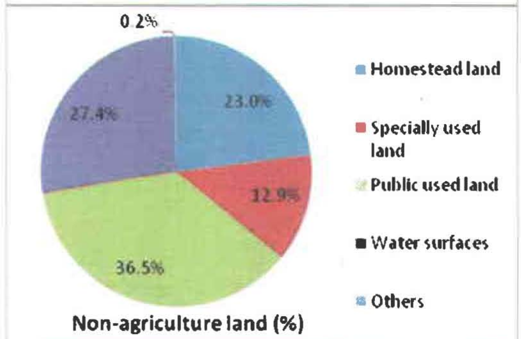
Source: Institute of Water Resource Planning (2008).

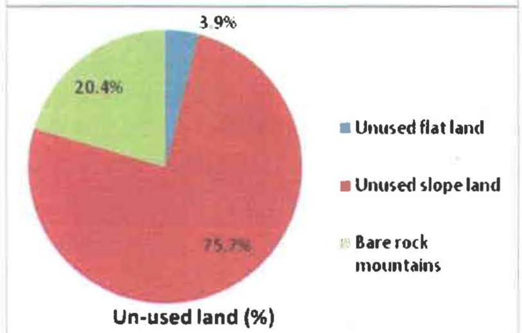
Appendix 3.9: Overview of land use status in Thai Nguyen province (Thai Nguyen, 2007).



Land-use	Area (hectare)	(%)
Agriculture land	265386.65	74.83
Non-agriculture land	39781.01	11.22
Unused land	49487.59	13.95
Total	354655.25	100%







Appendix 3.10: Calendar of crops and crop rotations for rice and vegetables for the upper and lower regions of the Cau River watershed.

a: Crop timing and crop rotations for rice and vegetables in the upper part of the Cau River watershed

Rice				**Vegetables and/or corn**			
Period	From date/month	To date/month	Total (days)	Period	From date/month	to date/month	Total (days)
Spring crop (pronounced as ***Vu chiem*** in Vietnamese)							
Planting-Cropping	15/02	13/06	120	Planting-Cropping	10/02	08/06	120
Summer - Fall crop (pronounced as ***Vu mua*** in Vietnamese)							
Planting-Cropping	10/07	27/09	110	Planting-Cropping	25/06	12/10	110
Winter crop (pronounced as ***Vu dong*** in Vietnamese)							
--	--	--	--	Planting-Cropping	10/10	08/01	95

b: Crop timing and crop rotations for rice and vegetables in the lower part of the Cau River watershed.

Rice				**Vegetables and/or Corn**			
Period	From date/month	To date/month	Total day	Period	From date/month	To date/month	Total day
Spring crop (Vu Chiem)							
Planting-Cropping	05/02	03/06	120	Planting-Cropping	01/02	31/06	120
Summer - Fall crop (Vu mua)							
Planting-Cropping	01/07	19/10	110	Planting-Cropping	20/06	07/10	110
Winter crop (Vu Dong)							
--	--	--	--	Planting-Cropping	10/10	08/01	95

Source: Department of Agriculture and Rural Development - Thai Nguyen 2008.

Appendix 3.11: Forest types and covering rate in the watershed.

Forest land	Bac Kan (ha)	Thai Nguyen (ha)	Total (ha)
Productive forest	105.817	81.379	312.768
Protective forest	49.212	55.577	194.560
Specially used forest	2.091	28.150	74.446
Total forest land	157.120	165.106	581.774
Covering rate (%)	**71.4 (%)**	**46.6 (%)**	**41.2 (%)**

Source: Institute of Water Resource Planning (2008).

Appendix 3.12: Data available in the Cau River watershed for the applications and verifications related to the study

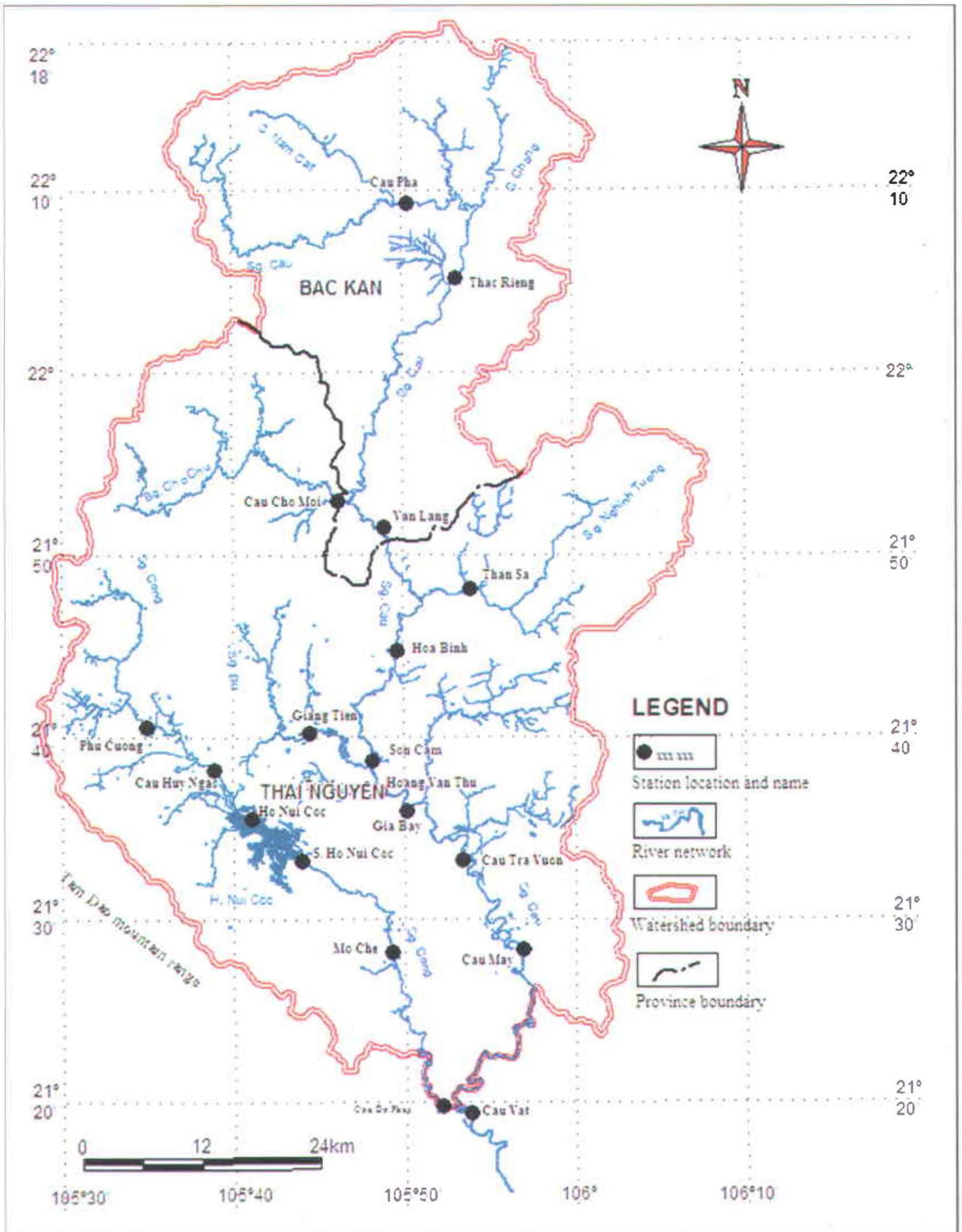
a: Map data

No.	Data	Technical notes	Source
1	Topographic map (DEM)	Digital raster map with grid resolution 30x30m. Created based on topographic map scale 1:25000	Remote sensing Center, Institute of Geological Science (VAST, 2005)
2	Pedology	Digital raster map with grid resolution 30x30m. With attribute data of: • Three layer of soil texture sand%, silt%, and clay%. • Applying of USDA's soil texture classification with 9 soil classes existing in the watershed.	Institute of Environmental Technology, (VAST, 2010).
3	Land use and land cover map	Digital raster map with grid resolution 30x30m. Extracted from Landsat ETM 7 satellite image. With attribute data of: • 7 classes of land use and land occupation (*Urban*, *Forest*, *Water bodies*, *Bare soil*, *Agriculture*, *Brush*, and *Mixture*).	Hoang (2008).
4	Organic matter content (MO)	Digital raster map with grid resolution 30 arc-second (approximate 1km). • Extracted from original organic carbon content (CO) of FAO's soil database (2008) • Original employing the equation MO = (%CO)*1.72 to estimate MO map. • Map has 4 MO zones for Cau river watershed	FAO's Harmonized World Soil Database HWSD (2008).

b: Monitoring data

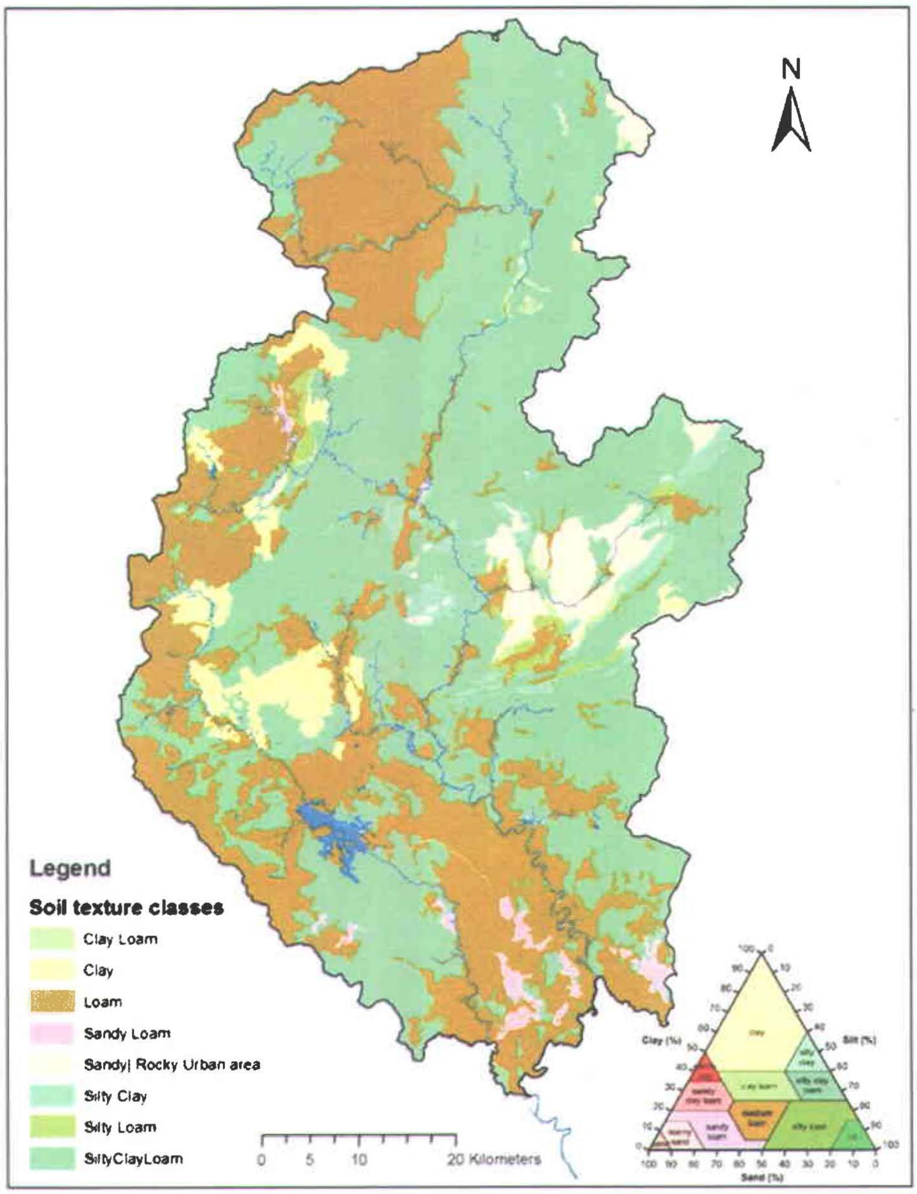
No.	Data	Technical notes			
1	• Temperature • Wind velocity • Evaporation • Humidity	Daily data:			
		Air temperature (°C)	Wind velocity (m/s)	Evaporation (mm)	Humidity (%)
		1997-2007	1997-2006	1997-2006	1997-2007
2	• Rainfall	Daily rainfall data period 1997-2006			
3	• River flow discharge	Station	Parameter		Period
			Water level H (m)	Discharge Q (m^3/s)	
		Thac Rieng	Daily		1997 - 2006
		Cho Moi	Daily		1997 - 2006
		Gia Bay	Daily	Daily	1997 - 2006
		Cha	Daily		1997 - 2006
4	• SS and TDS	Daily observation data in 20 locations for periods of 2005 to 2009: 2005 (October, November, December); 2006 (August); 2007 (January, August, December); 2008 (September); 2009 (January, February)			
	• SS	Daily observation data for the Gia Bay station from 1998 to 2006			
5	• Total organic phosphate Phosphoric	Daily observation data in 20 locations for periods of 2005 to 2009: 2005 (October, November, December); 2006 (August); 2007 (January, August, December); 2008 (September); 2009 (January, February)			

Appendix 3.13: Monitoring stations in the Cau River watershed.

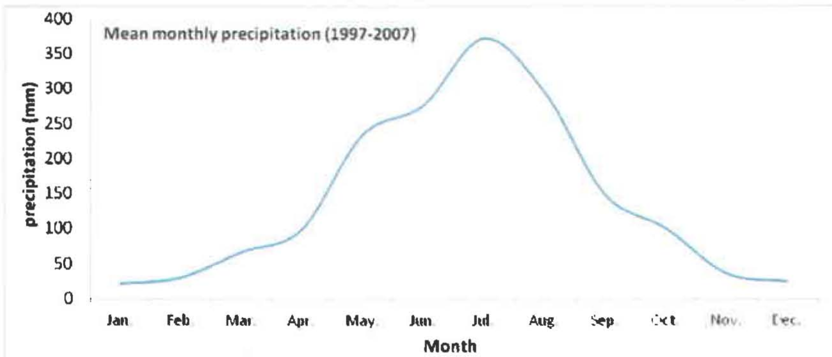


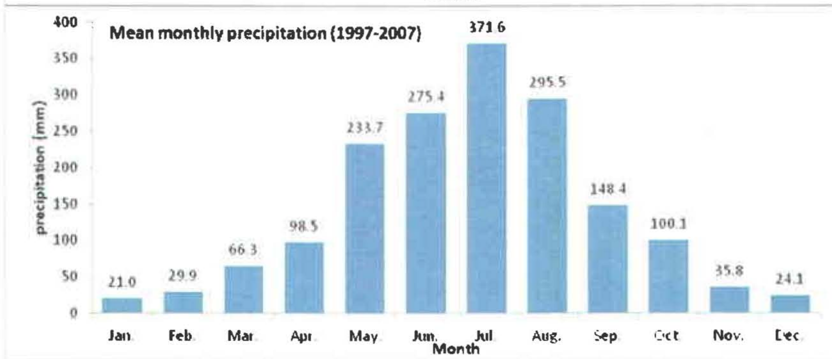
CHAPTER 4

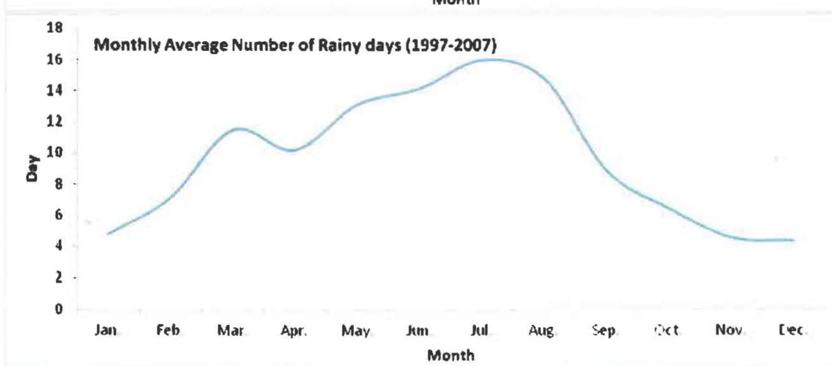
Appendix 4.1: Synchronization of soil pedology classes in the Cau River watershed corresponding to the USDA's soil texture classification. This map was adapted based on raw digital pedology map from VAST (2010).

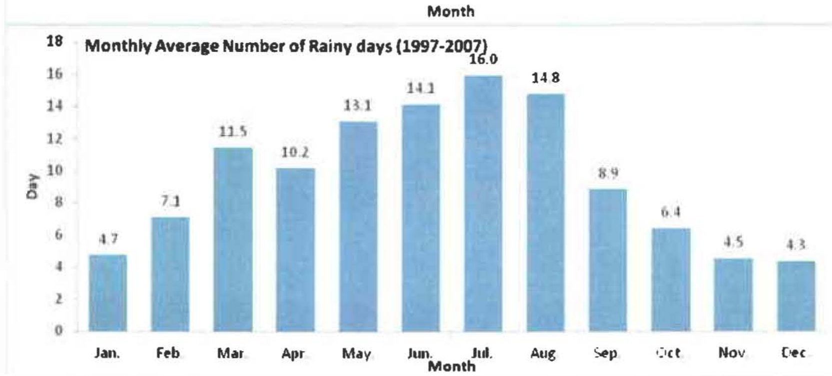


Appendix 4.2: Analysis of mean monthly rainy days and rainfall for the Cau River watershed.

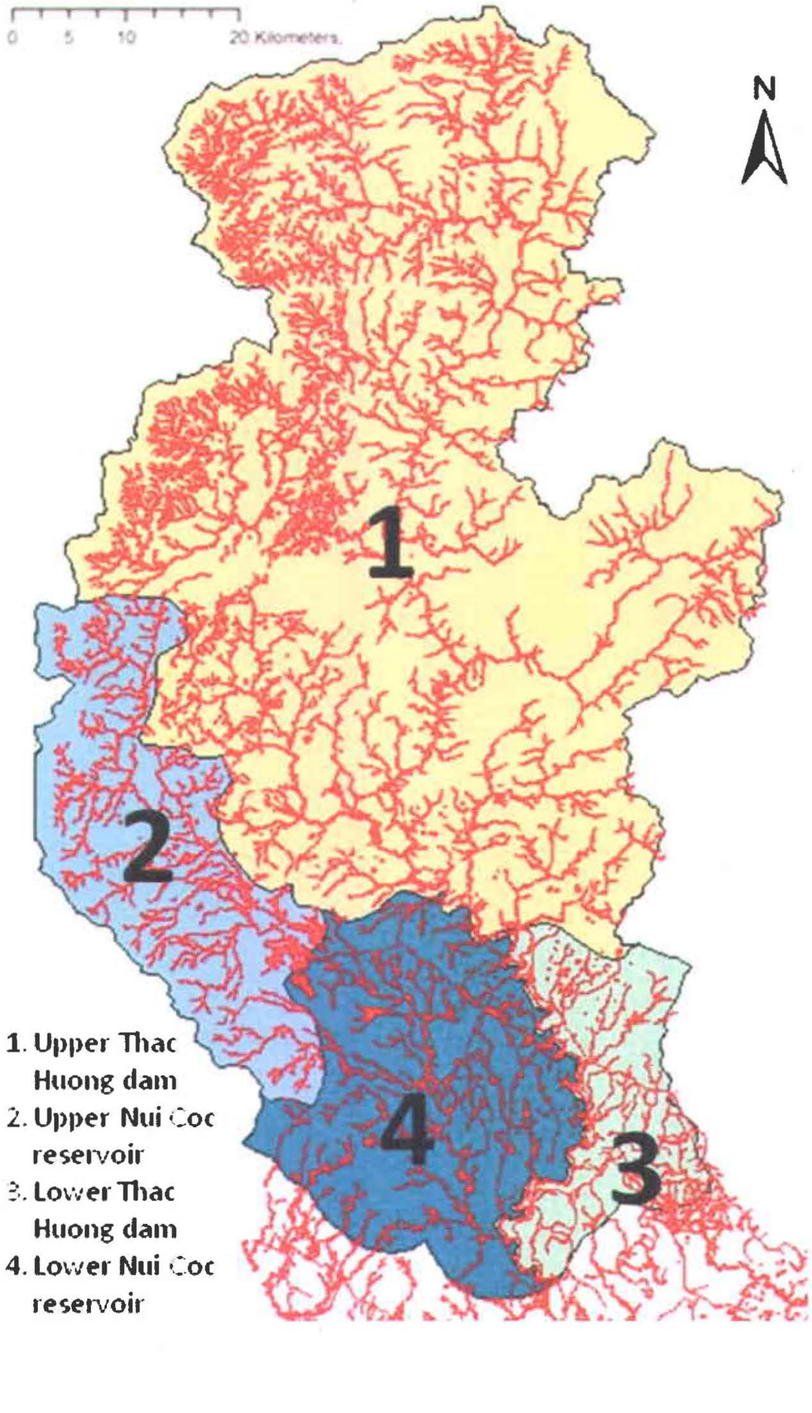








Appendix 4.3: Irrigation zones in the Cau River watershed.



Appendix 4.4: Stages specified and C values calculated for different land use classes in (a) upper and (b) lower parts of Cau river basin in a year.

(a) Crop timing and sub-C values at different crop stages (Cau River watershed - Upper part)

(1) for agriculture class (specified for rice plant)

Crop stages	Tc1	Tc2	Tc3	Tc4	Tc5	Tc6	Tc7	Tc8	Tc9	Tc10	Tc11	Tc12	Tc13	Tc14	Tc15	Tc16	Tc17	Tc18	END
	Grow 2	Grow 3	Soil work	**Seeding R1**	Grow 1	Grow 2	Submerged	Grow 3	Harvest	Soil work	**Seeding R2**	Grow 1	Grow 2	Submerged	Grow 3	Soilwork	**Seeding R3**	Grow 1	Grow 2
Julian day	**1**	**9**	**34**	**45**	**74**	**104**	**120**	**134**	**164**	**179**	**209**	**236**	**252**	**262**	**289**	**304**	**324**	**349**	**365**
Cplu	0.43	0.34	0.34	0.58	0.48	0.26	0.22	0.15	0.12	0.25	0.15	0.11	0.16	0.16	0.21	0.53	0.53	0.47	0.43
Ccc	0.49	0.45	1.00	1.00	0.79	0.58	0.45	0.36	1.00	1.00	0.79	0.58	0.45	0.36	1.00	1.00	0.79	0.58	0.49
Csc	0.85	0.85	0.85	0.86	0.85	0.82	0.82	0.75	0.70	0.69	0.63	0.66	0.75	0.75	0.81	0.85	0.84	0.85	0.85
Csr	1.00	1.00	1.00	0.01	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1E-05	0.74	0.99	1.00
Csm	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C	**0.18**	**0.13**	**0.29**	**2E-03**	**0.31**	**0.12**	**0.08**	**0.04**	**0.08**	**0.09**	**0.07**	**0.04**	**0.05**	**0.04**	**0.17**	**1E-03**	**0.26**	**0.23**	**0.18**

(2) for mixture/agriculture class (specified for vegetation and corn)

Crop stages	Tc1	Tc2	Tc3	Tc4	Tc5	Tc6	Tc7	Tc8	Tc9	Tc10	Tc11	Tc12	Tc13	Tc14	Tc15	Tc16	END
	Grow 3 / harvest	Soil work V1	**Seeding V1**	Grow 1	Grow 2	Grow 3 / harvest	Soil work V2	**Seeding V2**	Grow 1	Grow 2	Grow 3 / harvest	Soil work V3	**Seeding V3**	Grow 1	Grow 2	Grow 3 / harvest	
Julian day	**1**	**25**	**38**	**58**	**88**	**118**	**158**	**172**	**187**	**217**	**247**	**282**	**295**	**309**	**334**	**359**	**365**
Cplu	0.36	0.36	0.57	0.57	0.47	0.30	0.15	0.17	0.09	0.11	0.19	0.19	0.46	0.55	0.49	0.47	0.36
Ccc	0.42	1.00	1.00	0.79	0.58	0.45	1.00	1.00	0.79	0.58	0.45	1.00	1.00	0.79	0.58	0.45	0.42
Csc	0.86	0.86	0.86	0.86	0.85	0.83	0.76	0.63	0.55	0.60	0.74	0.74	0.81	0.85	0.86	0.86	0.86
Csr	1.00	1.00	3E-03	0.59	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00
Csm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00
C	**0.13**	**0.31**	**1E-03**	**0.23**	**0.23**	**0.11**	**0.11**	**0.05**	**0.04**	**0.04**	**0.06**	**0.14**	**0.18**	**0.37**	**0.24**	**0.18**	**0.13**

(3) for brush class (specified for vegetation and corn)

Crop stages	Tc1	Tc2	Tc3	Tc4	Tc5	Tc6	Tc7	Tc8	END
	Abandoned	Abandoned	Soil work V1	**Seeding V1**	Grow 1	Grow 2	Grow 3 / harvest	Abandoned	Abandoned
Julian day	**1**	**60**	**136**	**152**	**172**	**202**	**232**	**272**	**365**
Cplu			0.60	0.93	0.93	0.79	0.57		
Ccc			0.79	1.00	0.79	0.58	0.45		
Csc			0.98	0.98	0.98	0.98	0.98		
Csr			1.00	1.00	1.00	1.00	1.00		
Csm			1.00	0.50	1.00	1.00	1.00		
C	**0.04**	**0.04**	**0.46**	**0.46**	**0.72**	**0.45**	**0.25**	**0.04**	**0.04**

Note:
Tc = Crop stage; R= Rice; V= Vegetation.
(Cplu) = Prio land-use; (Ccc) = Canopy cover;
(Csc) = Surface cover;(Csr) = Surface roughness;
(Csm) = Soil moisture; (C) = C value

(b) Crop timing and sub-C values at different crop stages (Cau River watershed - Lower part)

(1) for agriculture class (specified for rice plant)

Crop stages	**Tc1**	**Tc2**	**Tc3**	**Tc4**	**Tc5**	**Tc6**	**Tc7**	**Tc8**	**Tc9**	**Tc10**	**Tc11**	**Tc12**	**Tc13**	**Tc14**	**Tc15**	**Tc16**	**Tc17**	**Tc18**	**END**
	Grow 2	Grow 3	Soil work	**Seeding R1**	Grow 1	Grow 2	Submerged	Grow 3	Harvest	Soil work	**Seeding R2**	Grow 1	Grow 2	Submerged	Grow 3	Soilwork	**Seeding R3**	Grow 1	Grow 2
Julian day	**1**	**4**	**24**	**35**	**64**	**94**	**110**	**124**	**154**	**169**	**199**	**226**	**242**	**252**	**279**	**294**	**314**	**339**	**365**
Cplu	0.43	0.34	0.34	0.58	0.48	0.26	0.22	0.15	0.12	0.25	0.15	0.11	0.16	0.16	0.21	0.53	0.53	0.47	0.43
Ccc	0.49	0.45	1.00	1.00	0.79	0.58	0.45	0.36	1.00	1.00	0.79	0.58	0.45	0.36	1.00	1.00	0.79	0.58	0.49
Csc	0.85	0.85	0.85	0.86	0.85	0.82	0.82	0.75	0.70	0.69	0.63	0.66	0.75	0.75	0.81	0.85	0.84	0.85	0.85
Csr	1.00	1.00	1.00	1E-04	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1E-05	0.74	0.99	1.00
Csm	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C	0.18	0.13	0.29	2E-05	0.31	0.12	0.08 `	0.04	0.08	0.09	0.07	0.04	0.05	0.04	0.17	4E-06	0.26	0.23	0.18

(2) for mixture/agriculture class (specified for vegetation and com)

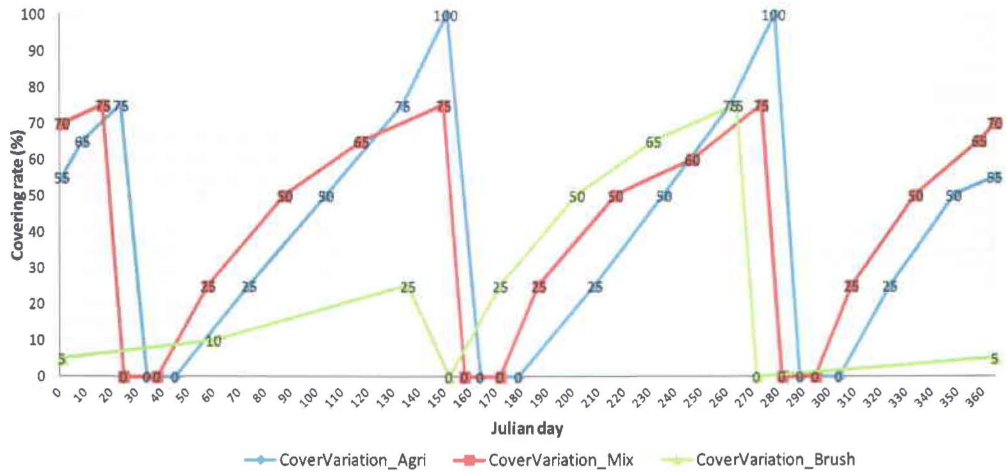
Crop stages	**Tc1**	**Tc2**	**Tc3**	**Tc4**	**Tc5**	**Tc6**	**Tc7**	**Tc8**	**Tc9**	**Tc10**	**Tc11**	**Tc12**	**Tc13**	**Tc14**	**Tc15**	**Tc16**	**END**
	Grow 3 / harvest	Soil work V1	**Seeding V1**	Grow 1	Grow 2	Grow 3 / harvest	Soil work V2	**Seeding V2**	Grow 1	Grow 2	Grow 3 / harvest	Soil work V3	**Seeding V3**	Grow 1	Grow 2	Grow 3 / harvest	
Julian day	**1**	**25**	**38**	**58**	**88**	**118**	**158**	**172**	**187**	**217**	**247**	**282**	**295**	**309**	**334**	**359**	**365**
Cplu	0.36	0.36	0.57	0.57	0.47	0.30	0.15	0.17	0.09	0.11	0.19	0.19	0.46	0.55	0.49	0.47	0.36
Ccc	0.42	1.00	1.00	0.79	0.58	0.45	1.00	1.00	0.79	0.58	0.45	1.00	1.00	0.79	0.58	0.45	0.42
Csc	0.86	0.86	0.86	0.86	0.85	0.83	0.76	0.63	0.55	0.60	0.74	0.74	0.81	0.85	0.86	0.86	0.86
Csr	1.00	1.00	3E-03	0.59	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00
Csm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00
C	**0.13**	**0.31**	**1E-03**	**0.23**	**0.23**	**0.11**	**0.11**	**0.05**	**0.04**	**0.04**	**0.06**	**0.14**	**0.18**	**0.37**	**0.24**	**0.18**	**0.13**

(3) for brush class (specified for vegetation and com)

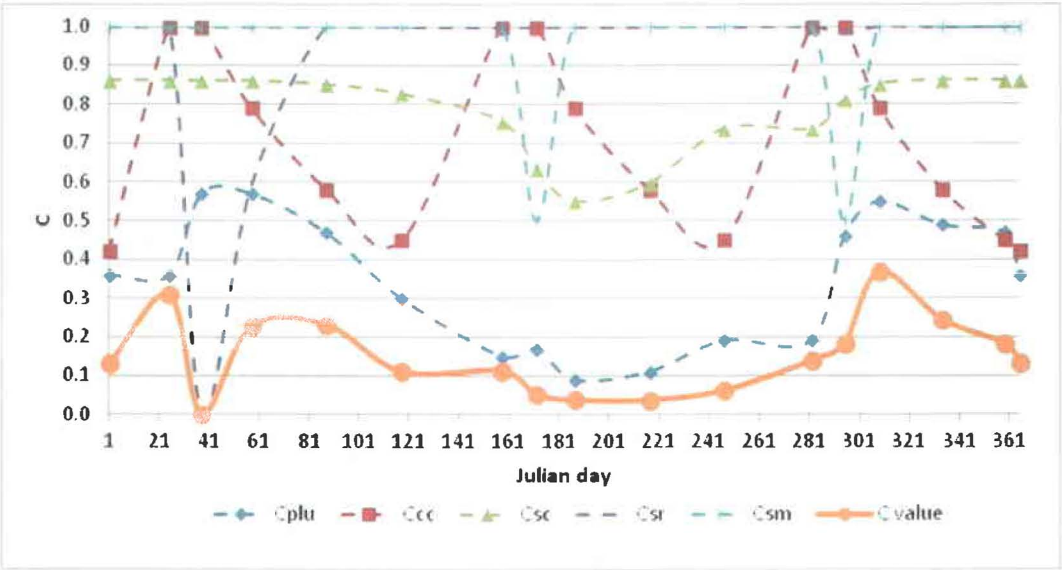
Crop stages	**Tc1**	**Tc2**	**Tc3**	**Tc4**	**Tc5**	**Tc6**	**Tc7**	**Tc8**	**END**
	Abandoned	Abandoned	Soil work V1	**Seeding V1**	Grow 1	Grow 2	Grow 3 / harvest	Abandoned	Abandoned
Julian date	**1**	**60**	**136**	**152**	**172**	**202**	**232**	**272**	**365**
Cplu			0.60	0.93	0.93	0.79	0.57		
Ccc			0.79	1.00	0.79	0.58	0.45		
Csc			0.98	0.98	0.98	0.98	0.98		
Csr			1.00	1.00	1.00	1.00	1.00		
Csm			1.00	0.50	1.00	1.00	1.00		
C	**0.04**	**0.04**	**0.46**	**0.46**	**0.72**	**0.45**	**0.25**	**0.04**	**0.04**

Note:
Tc = Crop stage; R= Rice; V= Vegetation.
(Cplu) = Prio land-use; (Ccc) = Canopy cover;
(Csc) = Surface cover;(Csr) = Surface roughness;
(Csm) = Soil moisture; (C) = C value

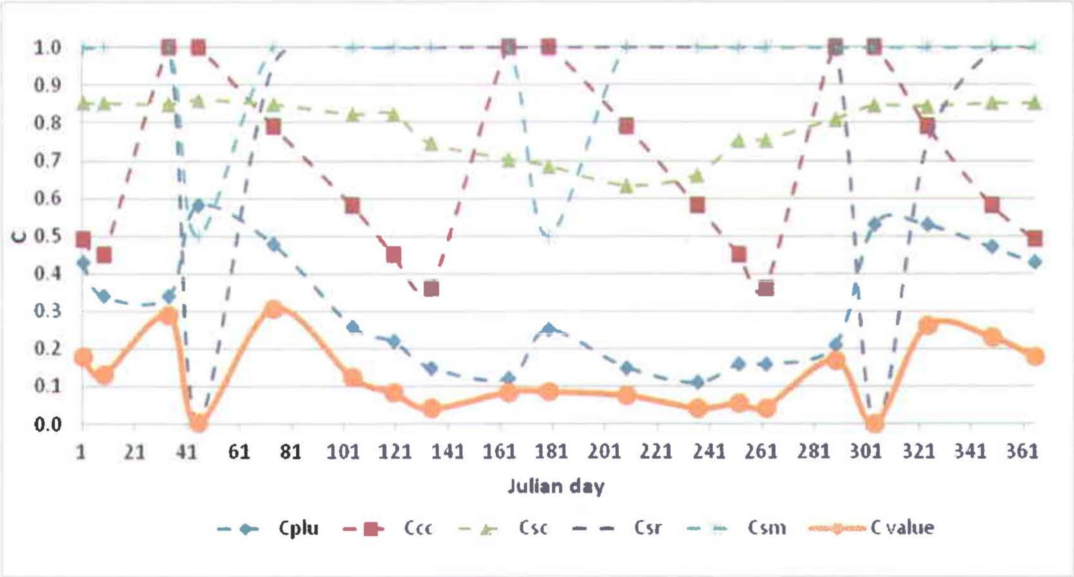
Appendix 4.5: Sub-*C* factor variations estimated in the Cau River watershed in a year. Where: (*Cplu*) = Prior land-use sub-factor; (*Ccc*) = Canopy cover sub-factor; (*Csc*) = Surface cover sub-factor; (*Csr*) = Surface roughness sub-factor; (*Csm*) = Soil moisture sub-factor; (*C*) = *C* factor value.



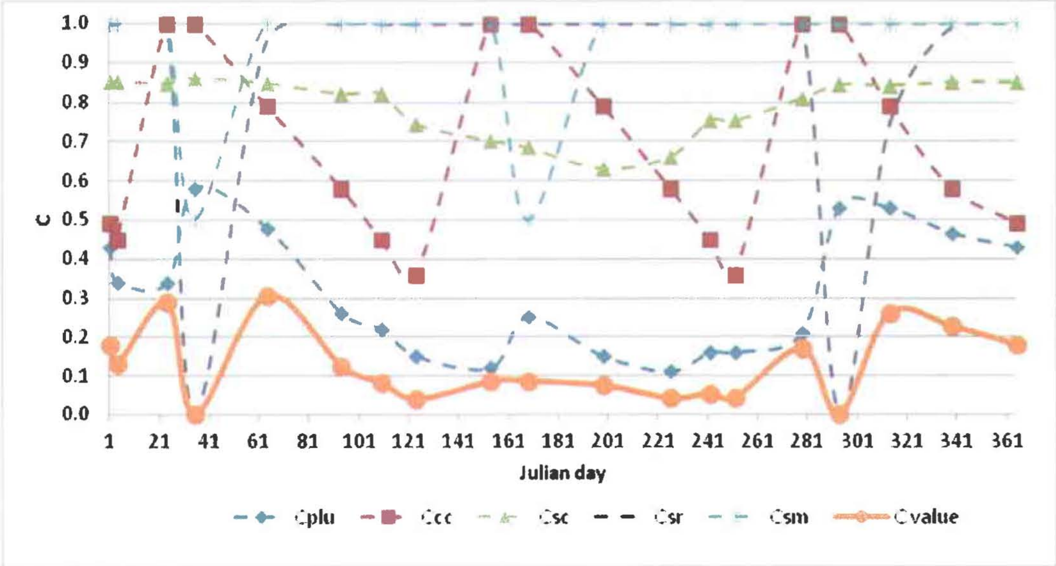
- *Seasonal variation of vegetation covering rate (%).*



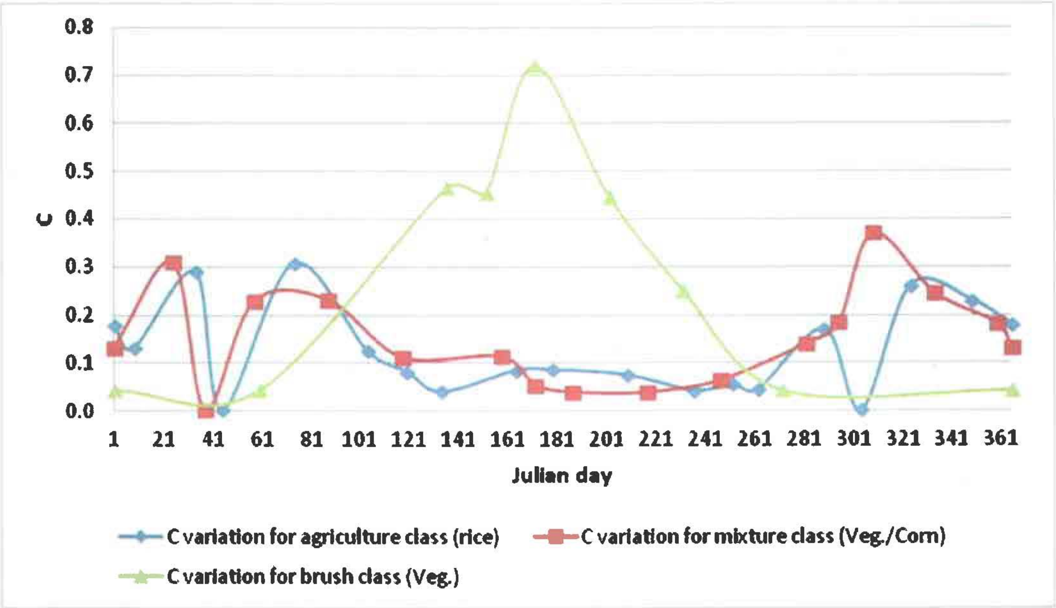
- *Daily variation of C and its sub-C values for the mixture land cover class.*



- *Daily variation of C and its sub-C values for the agriculture class (upper part of the watershed)*



- *Daily variation of C and its sub-C values for the agriculture class (lower part of the watershed)*



- *Comparison of the C daily variation of the mixture, agriculture and brush classes.*

Appendix 4.6: Tables of tabulated *P* factors for contouring, strip cropping, and contour terracing (after Wischmeier and Smith, 1978).

a) *P* factor values and slope length limits for contouring

Land slope (%)	P_{USLE}	Maximum length (m)[1]
1 – 2	0.60	122
3 – 5	0.50	91
6 – 8	0.50	61
9 – 12	0.60	37
13 – 16	0.70	24
17 – 20	0.80	18
21 – 25	0.90	15

Contouring is most effective on slopes from 3 to 8 percent.

[1] Limit may be increased by 25% if residue cover after crop seedings egularly exceeds 50%.

b) *P* factor values, maximum strip-width and slope-length limits for contour strip-cropping

Land slope (%)	P_{USLE} values[2]			Strip width (m)	Maximum length (m)
	A	B	C		
1 – 2	0.30	0.45	0.60	40	244
3 – 5	0.25	0.38	0.50	30	183
6 – 8	0.25	0.38	0.50	30	122
9 – 12	0.30	0.45	0.60	24	73
13 – 16	0.35	0.52	0.70	24	49
17 – 20	0.40	0.60	0.80	18	37
21 – 25	0.45	0.68	0.90	15	30

Strip-cropping is a practice in which contoured strips of sod are alternated with equal-width strips of row crop or small grain.

[2] *P* values:

A: For 4-year rotation of row crop, small grain with meadow seeding, and 2 years of meadow. A second row crop can replace the small grain if meadow is established in it.

B: For 4-year rotation of 2 years row crop, winter grain with meadow seeding, and 1-year meadow.

C: For alternate strips of row crop and winter grain.

c) *P* factor values for contour-farmed terraced fields[3]

	Farm planning		Computing sediment yield[5]	
(I) Land slope (%)	(II) Contour P factor[4]	(III) Strip crop P factor	(IV) Graded channels sod outlets	(V) Steep back slope underground outlets
1 – 2	0.60	0.30	0.12	0.05
3 – 8	0.50	0.25	0.10	0.05
9 – 12	0.60	0.30	0.12	0.05
13 – 16	0.70	0.35	0.14	0.05
17 – 20	0.80	0.40	0.16	0.06
21 – 25	0.90	0.45	0.18	0.06

These values apply to broadbase, steep backslope and level terraces.

[3]Slope length is the horizontal terrace interval. The listed values are for contour farming.
[4] Use these values for control of inter-terrace erosion within specified soil loss tolerances.
[5]These values include entrapment efficiency and are used for control of offsite sediment within limits and for estimating the field's contribution to watershed sediment yield.

Appendix 4.7: Popular rice field and vegetation mixture field design in the Cau River basin.

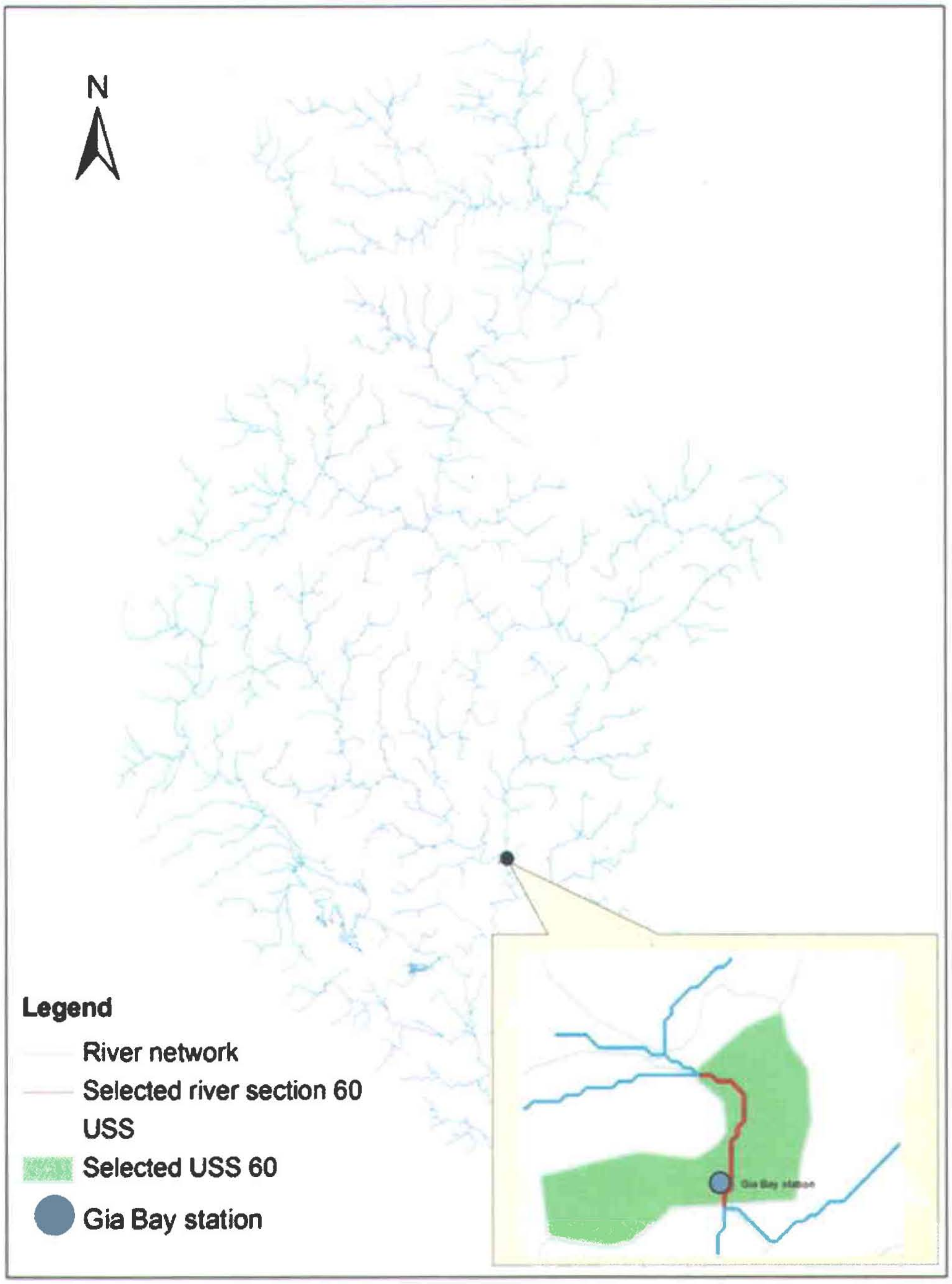
a) A *broadbase, steep back slope* and *level terraces* farm type in the study area (*Cho Don, Bac Kan province*).

b) A sample of *mixture of agricultural, dwellings* and other plantation (*Dai Tu, Thai Nguyen province*).

Appendix 4.8: Land use classes and *P* values applied in the Cau River watershed.

VALUE	Corresponding name	Applied *P* value	Conditions	
			if date of estimate varies within (Julian day)	and if slope varies within (%)
2	Agriculture	0.30	1 - 365	<1 - 2
		0.25	1 - 365	>2 - 8
		0.30	1 - 365	>8 - 12
		0.35	1 - 365	>12 - 16
		0.40	1 - 365	>16 - 20
		0.45	1 - 365	>20 - 25
		1.0	1 - 365	>25
3	Forest	1.0	1 - 365	<1 - 25
4	Water	1.0	1 - 365	<1 - 25
5	Urban	1.0	1 - 365	<1 - 25
6	Bare soil	1.0	1 - 365	<1 - 25
7	Mixture (Agri.)	0.30	1 - 365	<1 - 2
		0.25	1 - 365	>2 - 8
		0.30	1 - 365	>8 - 12
		0.35	1 - 365	>12 - 16
		0.40	1 - 365	>16 - 20
		0.45	1 - 365	>20 - 25
		1.0	1 - 365	>25
8	Brush	0.50	(1-90) & (305-365)	<1 - 25
		0.60	91- 304	<1 - 2
		0.50	91- 304	>2 - 5
		0.50	91- 304	>5 - 8
		0.60	91- 304	>8 - 12
		0.70	91- 304	>12 - 16
		0.80	91- 304	>16 - 20
		0.90	91- 304	>20 - 25
		1.0	91- 304	>25

Appendix 4.9: Location of the selected river section and its associated USS 60.



Appendix 4.10: Expressions for the theoretical and the numerical relative variations in sensitivity analyses of the soil erosion and sediment transport models.

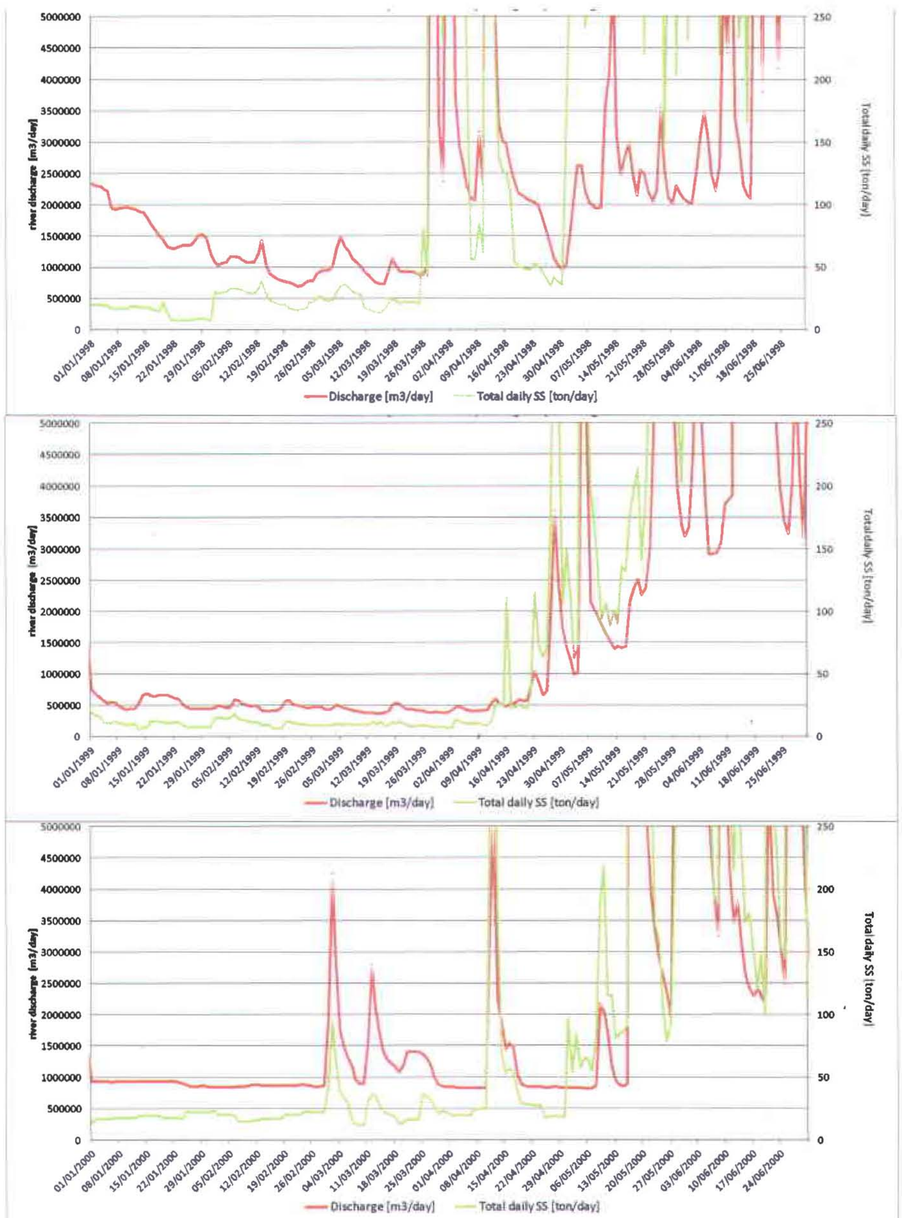
Relative variations of *R* with respect to parameters *a, b,* and *c*		
	Theoretical	**Numerical**
a	$R\_a\% = \frac{\frac{\partial R}{\partial a}}{R} * \Delta a$	$R\_a\% = \frac{R(a+\Delta a) - R(a)}{R(a)}$
b	$R\_b\% = \frac{\frac{\partial R}{\partial b}}{R} * \Delta b$	$R\_b\% = \frac{R(b+\Delta b) - R(b)}{R(b)}$
c	$R\_c\% = \frac{\frac{\partial R}{\partial c}}{R} * \Delta c$	$R\_c\% = \frac{R(c+\Delta c) - R(c)}{R(c)}$

Relative variations of CTS with respect to parameters K and o		
	Theoretical	**Numerical**
K	$CTS\_K\% = \frac{\frac{\partial CTS}{\partial K}}{CTS} * \Delta K$	$CTS\_K\% = \frac{CTS(K+\Delta K) - CTS(K)}{CTS(K)}$
o	$CTS\_o\% = \frac{\frac{\partial CTS}{\partial o}}{CTS} * \Delta o$	$CTS\_o\% = \frac{CTS(o+\Delta o) - CTS(o)}{CTS(o)}$

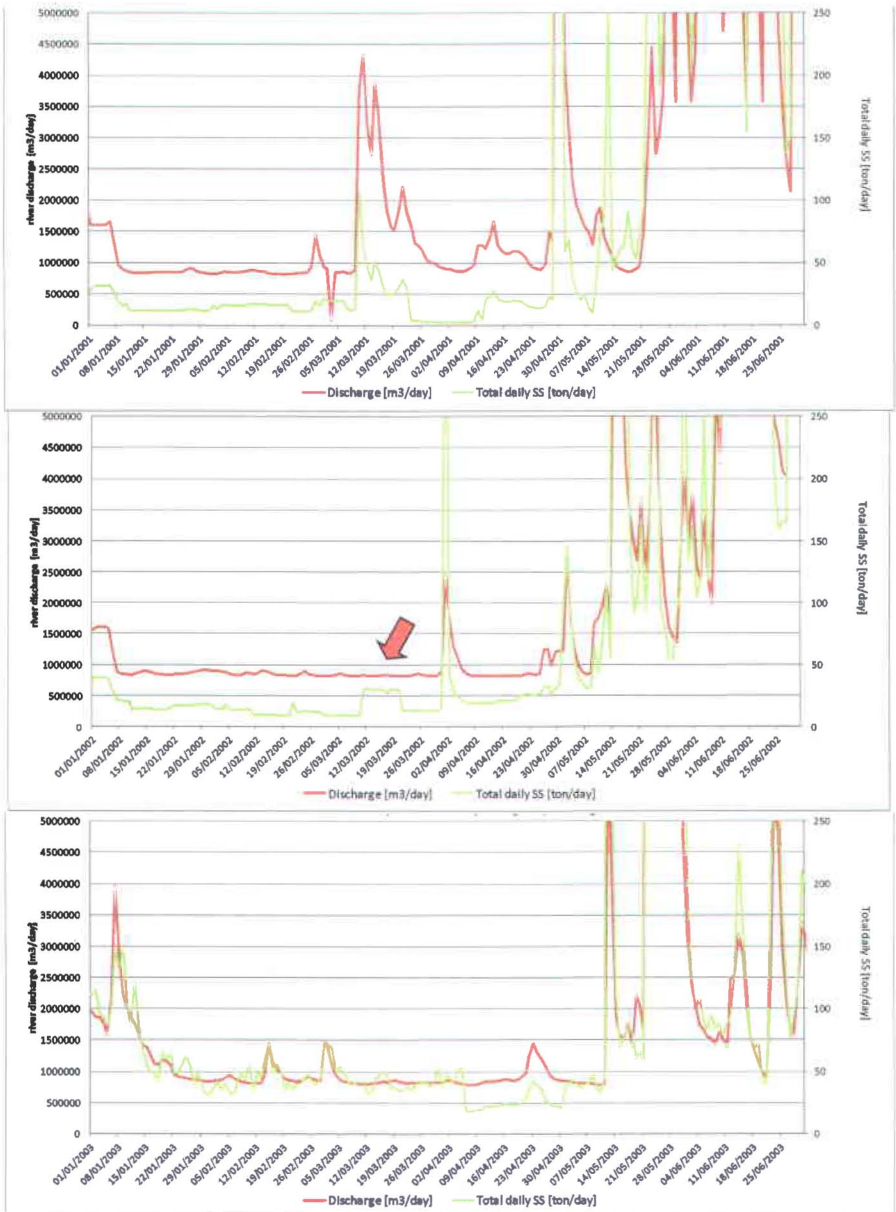
Relative variations of Vc with respect to parameter Dr		
	Theoretical	**Numerical**
D_r	$Vc\_D_r\% = \frac{\frac{\partial Vc}{\partial Dr}}{Vc} * \Delta D_r$	$Vc\_D_r\% = \frac{Vc(D_r+\Delta D_r) - Vc(D_r)}{Vc(D_r)}$

Appendix 4.11: Analysis of observed suspended sediment load data.

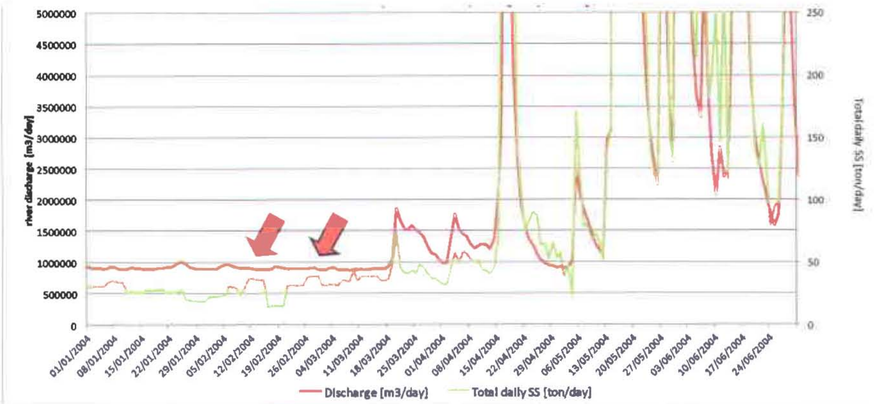
a) Behaviour of *SS* and *Q* in dry months from January to April (1998-2006). The red arrows identify the occurrence of unusual increase in observed *SS* during the dry season.

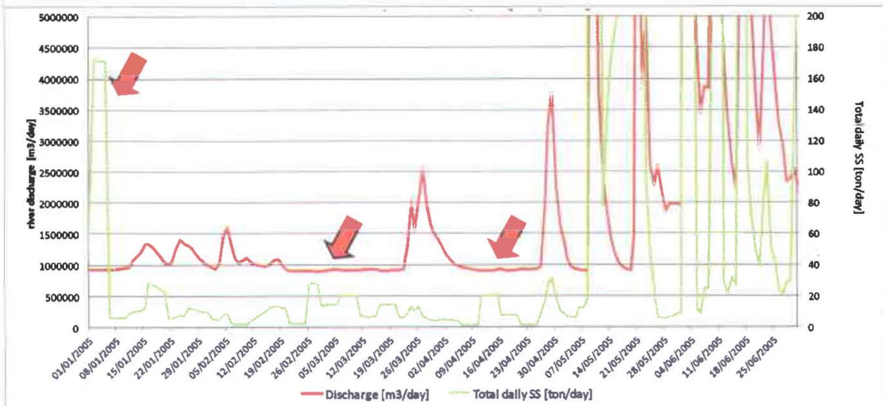


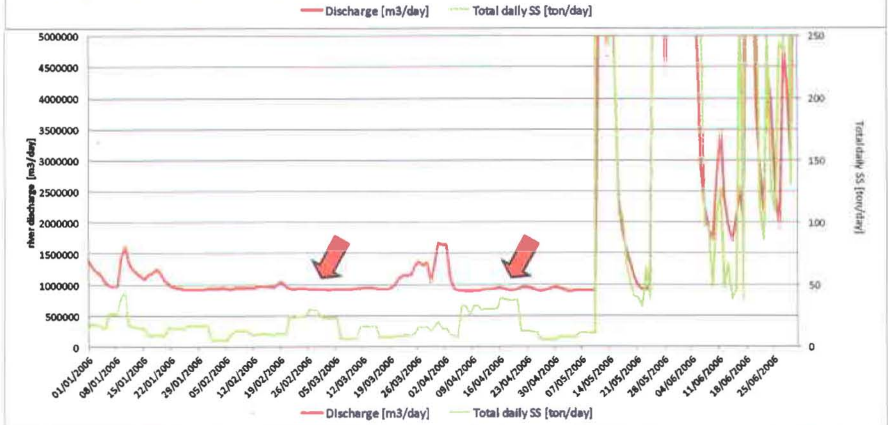
a) Behaviour of *SS* and *Q* *(continued)*.



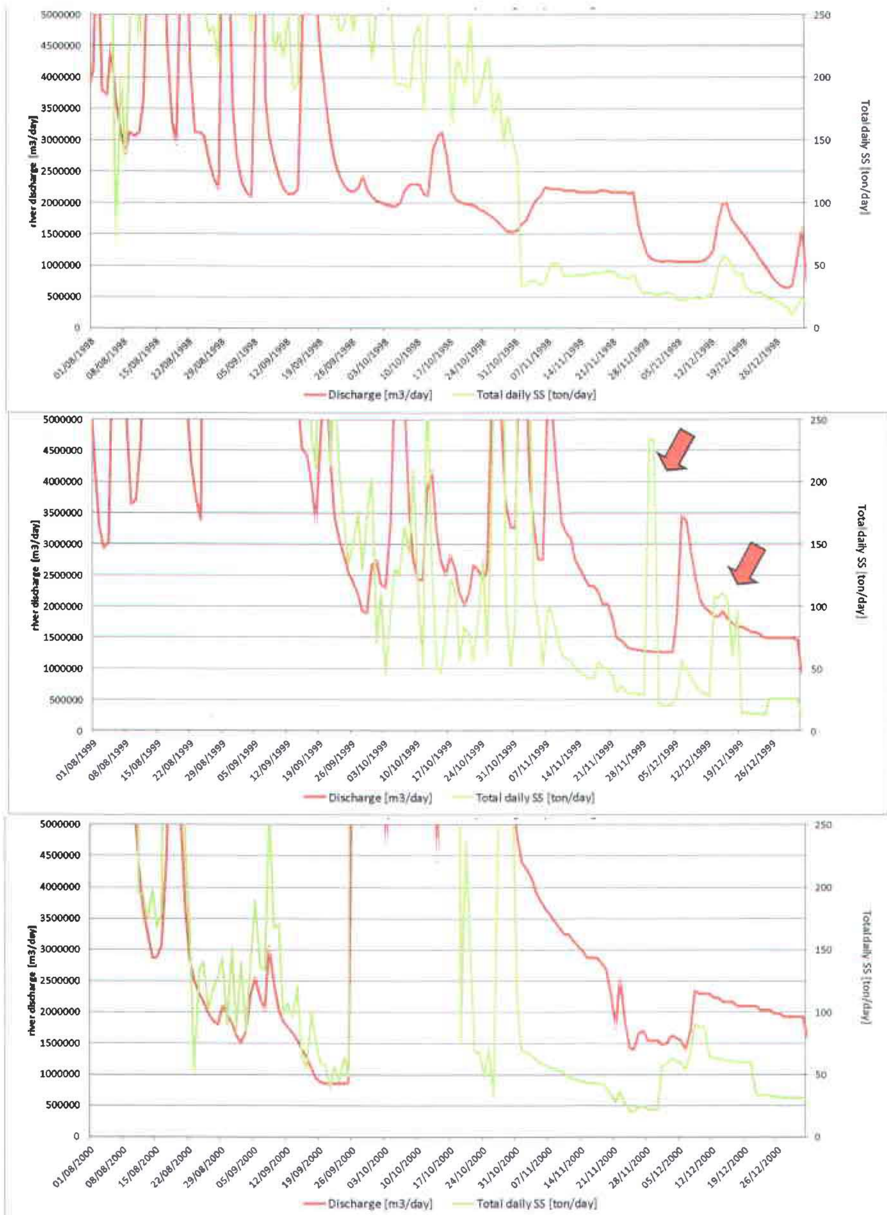
a) Behaviour of *SS* and *Q* *(continued).*



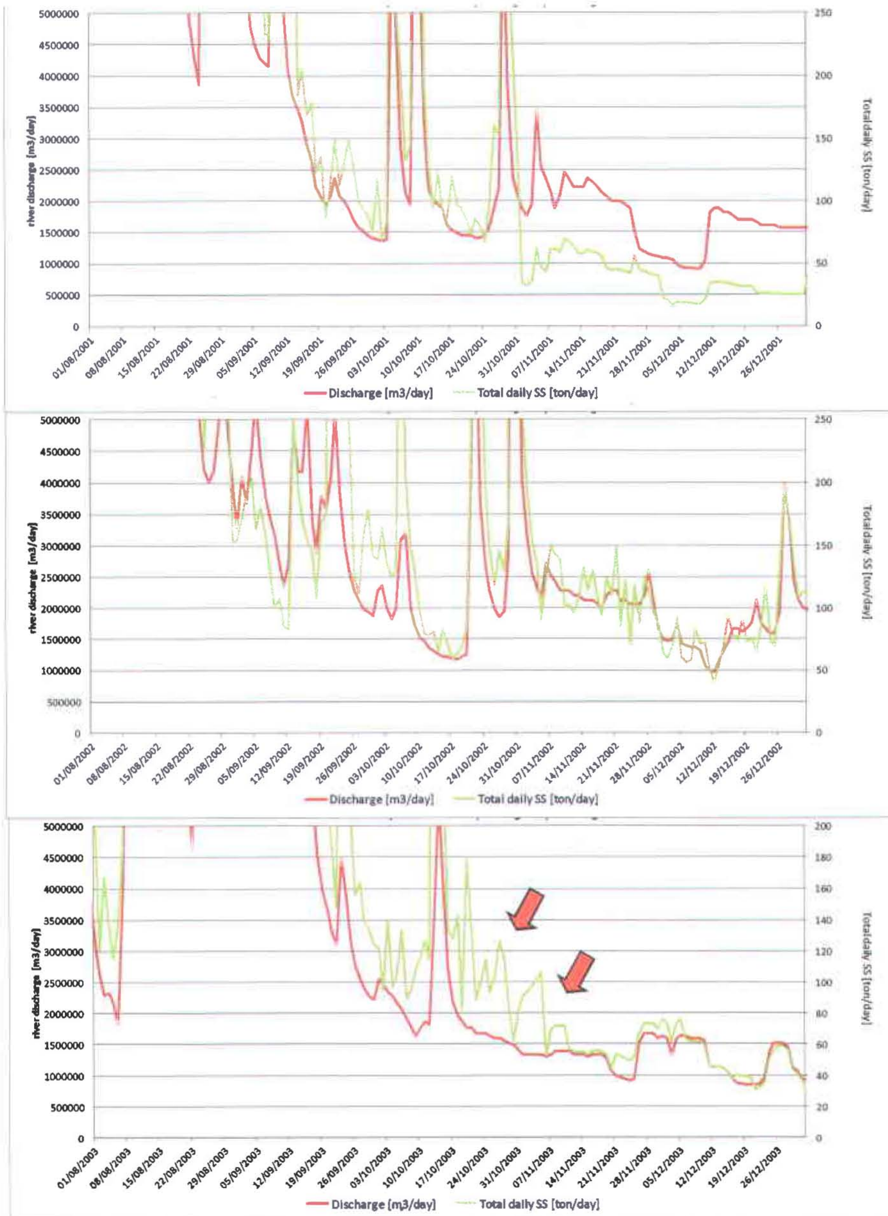




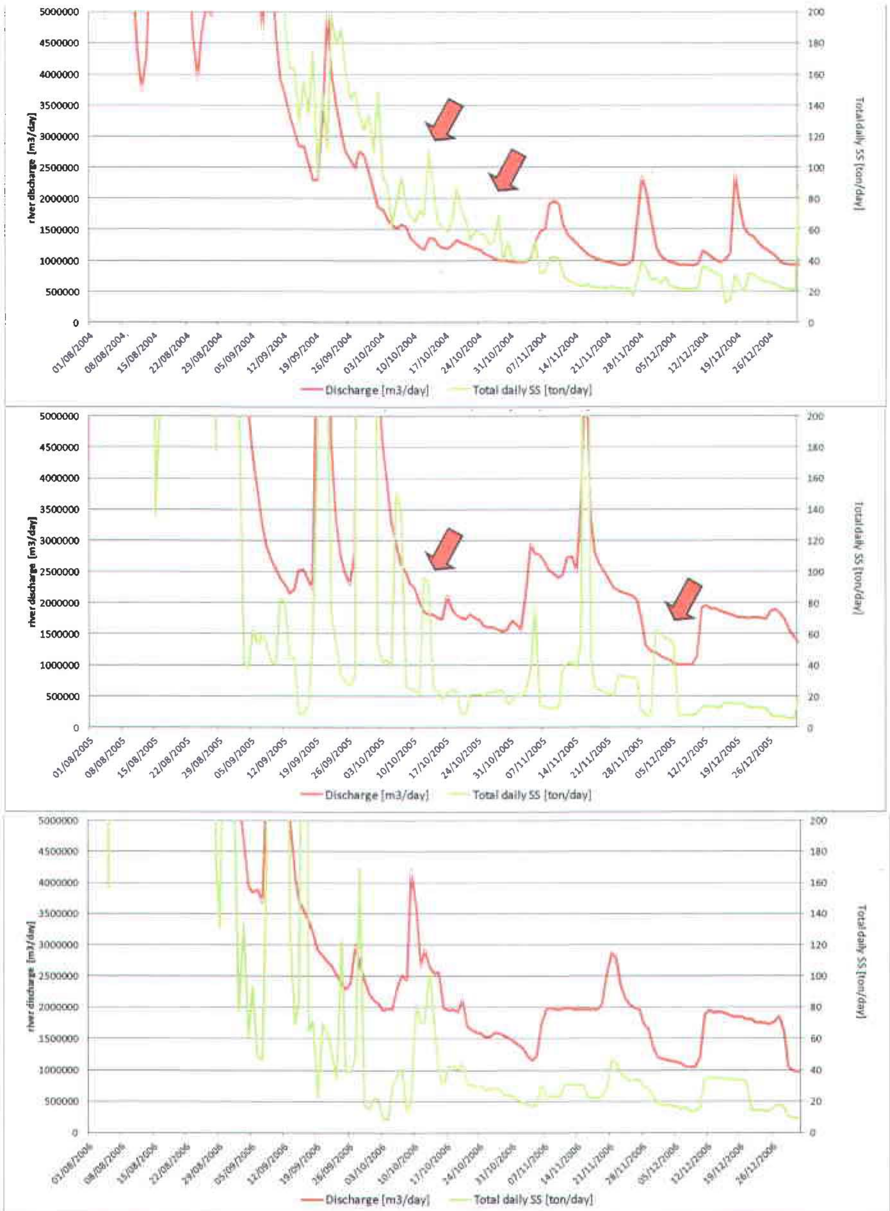
b) Behaviour of *SS* and *Q* in dry months from October to December (1998-2006). The red arrows indentify the occurrence of unusual increases in observed *SS* during the dry season.



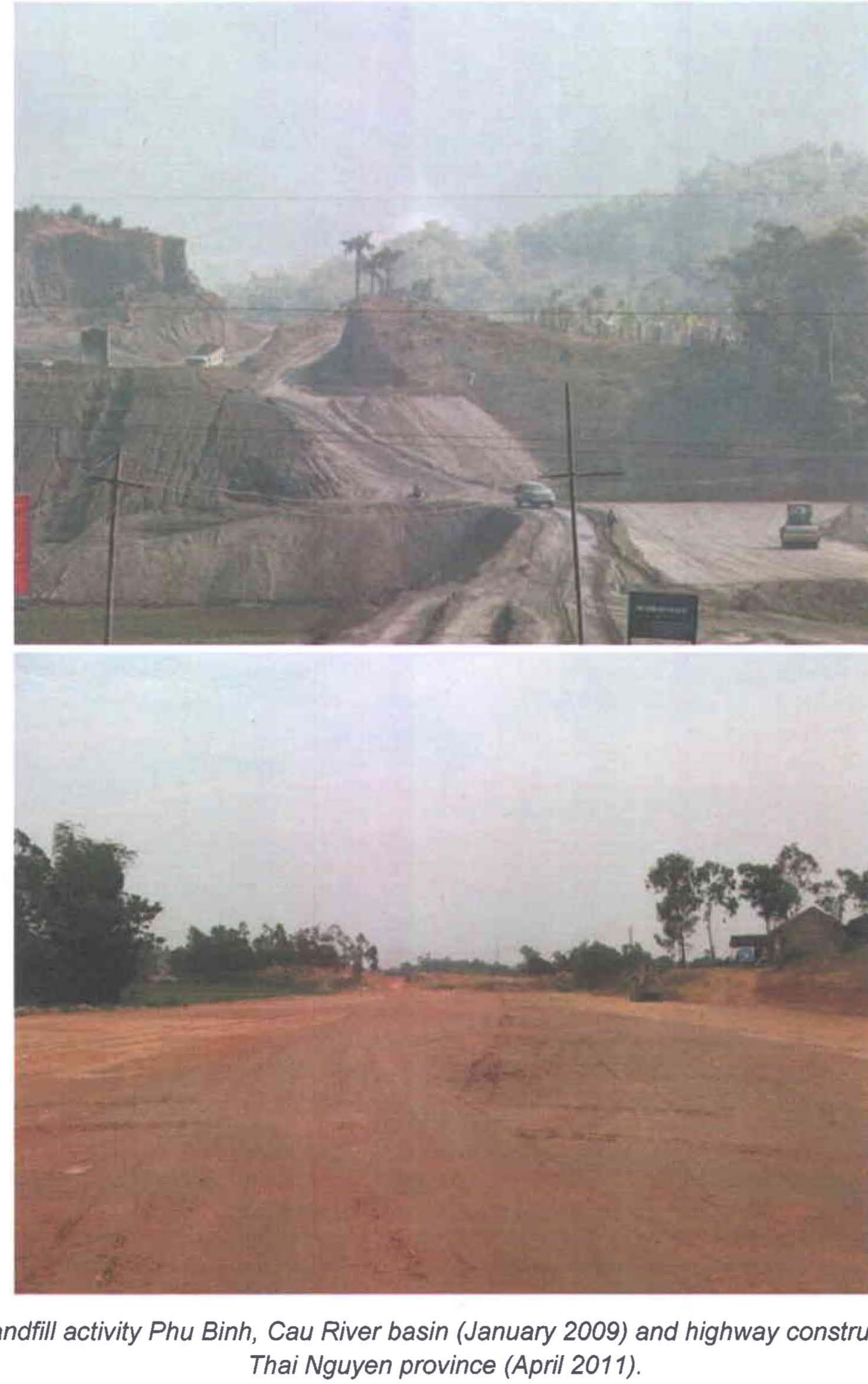
b) Behaviour of *SS* and *Q* *(continued).*



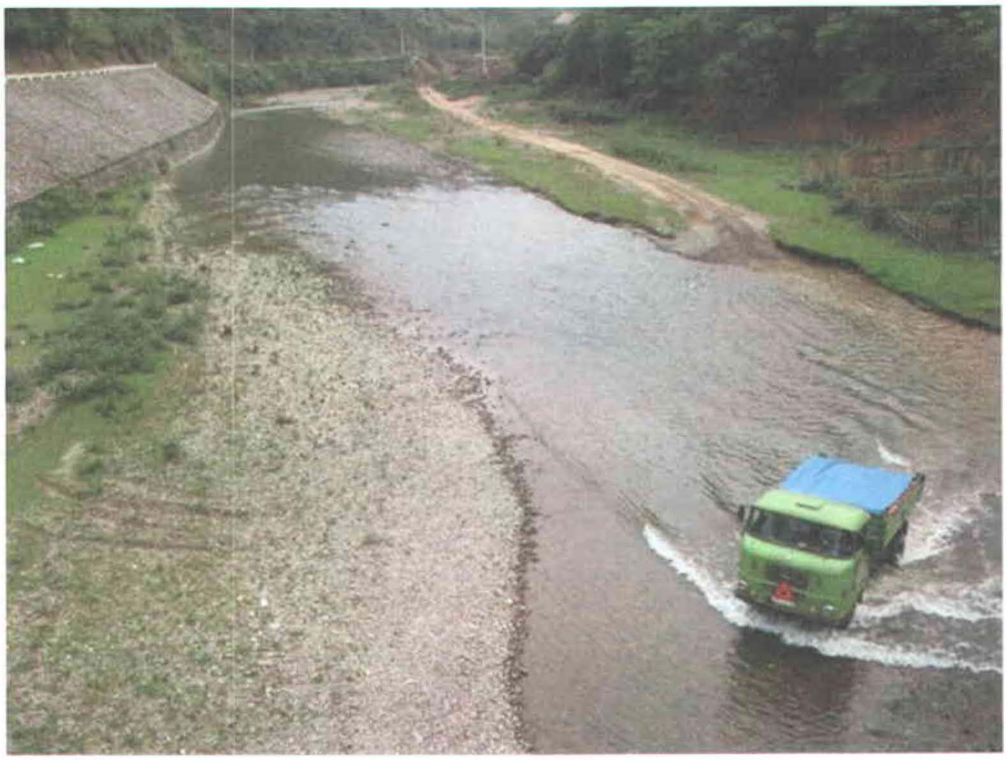
b) Behaviour of *SS* and *Q* *(continued)*.



Appendix 4.12: Pictures showing activities on Cau River watershed during dry season.

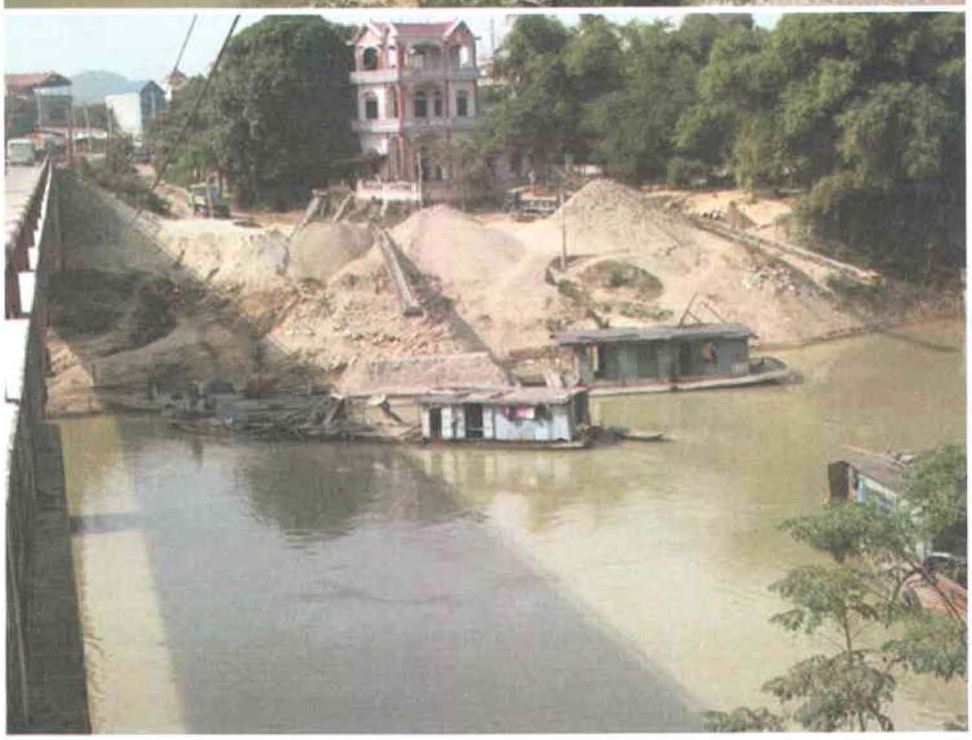


a: Landfill activity Phu Binh, Cau River basin (January 2009) and highway construction in Thai Nguyen province (April 2011).



b: Low water level during dry season in Cau River - Bac Can section (January 2009).

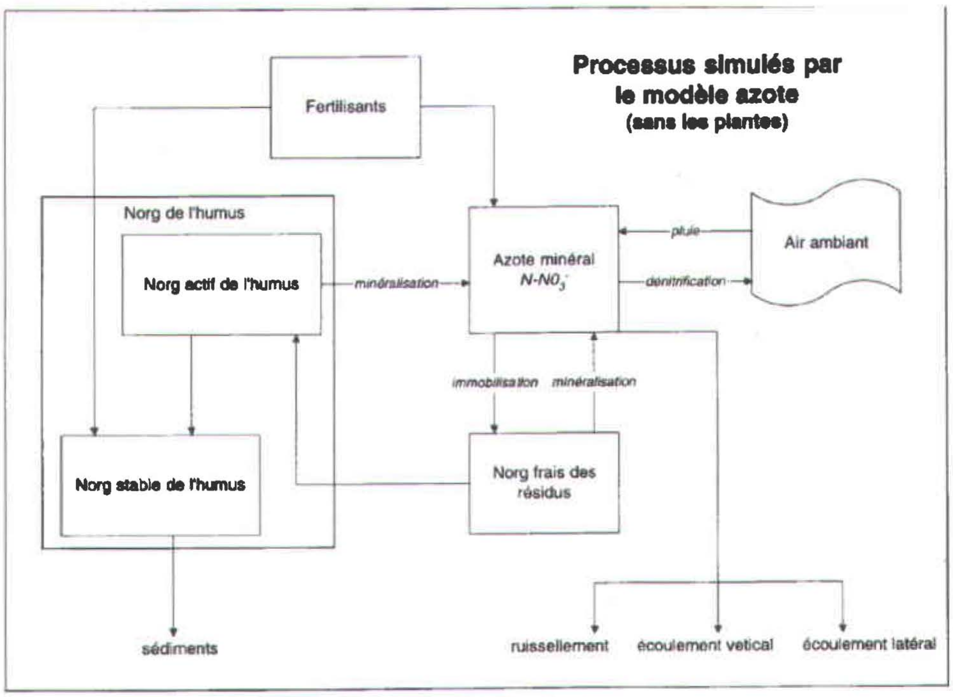
c: Sand and gravel exploitation on river during dry season, Cho Moi, Thai Nguyen province (January 2009)

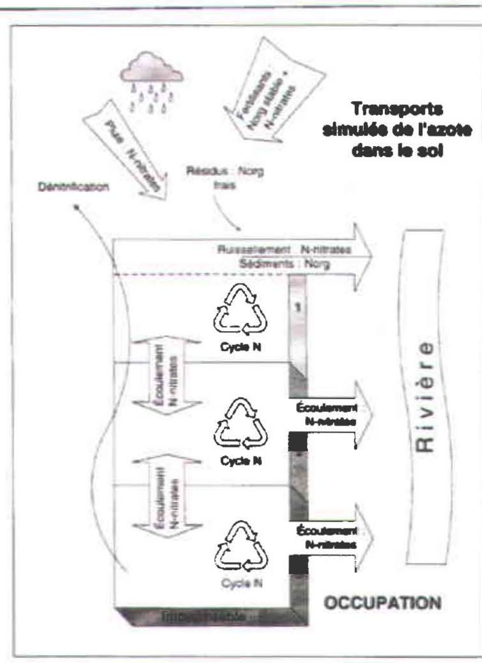


d: A sand and gravel market for construction needs of Thai Nguyen city. These come from all parts of the Cau River basin.

CHAPTER 5

Appendix 5.1: The PoPes model a) Procedures for simulation and transportation of nitrogen model (Villeneuve *et al.*, 1998a).





b) Procedure for simulation and transportation of phosphoric model (Villeneuve *et al.*, 1998a).