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CHOIX DES MEILLEURES INTERVENTIONS POUR L'AMÉLIORATION DE LA QUALITÉ DE L'EAU À L'AIDE D'UN OUTIL INFORMATIQUE DE GESTION INTÉGRÉE : CAS DU BASSIN VERSANT DE LA RIVIÈRE CAU AU VIETNAM

par

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Thèse présentée

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BOD: Biochemical oxygen demand

CBA: Cost - benefit analysis

COD: Chemical oxygen demand

DONRE: Department of Natural Resources and Environment

DO: Dissolved oxygen

FAO: Food & Agriculture Organization

GCMs: General Circulation Models

GIBSI: Gestion Intégrée des Bassins versants à l'aide d'un Système Informatisé

INRS: Institut National de la Recherche Scientifique

JICA: Japanese International Cooperation Agency

MCA: Multi-criteria analysis

MONRE: Ministry of Natural Resources and Environment

N-NH_3 or NH_4^+: Ammonium

SS: Suspended solids

SWAT: Soil and Water Assessment Tool

UNEP: United Nations Environment Programme

UNFCCC: United Nations Framework Convention on Climate Change

VAST: Vietnamese Academy of Science and Technology

VEPA: Vietnam Environmental Protection Agency

WHO: World Health Organization

WQSs: Water quality standards

ABSTRACT

Cau River Basin is located in the North-East of Vietnam. Its surface water has become more and more polluted due to social-economic development activities. Thus, the environmental improvement of this river basin is one of the priorities and important tasks of the Vietnamese government.

River basin integrated management is more and more interesting because it can deal with conflicts between social-economic development and environmental protection. The approach of river basin integrated management was used in this research to identify and prioritize interventions to improve the water quality of Cau River in Vietnam. This included building and comparing future social-economic development scenarios to the present situation of the river basin in terms of impact on water quality.

Cau River Basin covers seven provinces, but this study mainly focussed on the parts of Cau River Basin which belong to two provinces: Bac Kan and Thai Nguyen. Appropriate methods for building development scenarios for the study area in the context of few available data were proposed. Seven factors were taken into consideration to build the scenarios: population, domestic wastewater, industry, livestock, agricultural fertilizer, forest and climate change.

Fourteen scenarios were developed in order to assess the impacts of future social-economic develoment on the water quality of Cau River by using a river basin integrated management computer tool named GIBSI. This tool includes hydrology, soil erosion and river water quality models adapted to and calibrated for Cau River Basin. Simulations of water quality in GIBSI showed that population, domestic wastewater and industry are three factors which may have visible impacts on water quality in the future in the study area. Four other factors, namely livestock, agricultural fertilizer, forest, and climate change showed negligible impacts on water quality in the future.

A multi-criteria analysis method for this case study was proposed to compare and select the optimal scenarios among the fourteen developed scenarios. This analysis was based on three assessments: (1) taking the ideas of stakeholders about the scenarios, (2) assessing the impacts of each scenario on surface water quality in Cau River Basin, and (3) analyzing cost comparison for each scenario. Therefore, besides the assessment of the impacts of fourteen scenarios on water quality of the Cau River system, cost comparison analysis and ideas of

experts and stakeholders for these scenarios were also taken into consideration. Based on weights given to water quality simulation, ideas of stakeholders and cost comparison analysis results, a score was given to all scenarios.

As a result, three scenarios were found to have the highest scores and were selected. Interventions in these scenarios are therefore recommended in the future to improve surface water quality of Cau River Basin: (1) increase the capacity of the domestic wastewater treatment plant in Bac Kan town to 20,000 people; (2) keep the projection of domestic wastewater treatment plant for 100,000 people in Thai Nguyen City; and (3) install a treatment plant for the town of Song Cong town for 10,000 people. Besides these interventions, controls of population and industrial wastewater discharge in order to meet the standard were also recommended.

This research contributes to a systematic evaluation of the impacts of future social-economic development on surface water quality in Cau River Basin, in Bac Kan and Thai Nguyen provinces, helping the decision-makers select the optimal interventions for the management of Cau River Basin.

RÉSUMÉ

Le bassin versant de la rivière Cau est situé dans le nord-est du Vietnam. Ses eaux de surface sont devenues de plus en plus polluées en raison des activités de développement socio-économique. Ainsi, l'amélioration de l'environnement de ce bassin versant est l'une des *priorités du gouvernement* vietnamien.

La gestion intégrée par bassin versant est de plus en plus intéressante car elle permet de trouver l'équilibre entre le développement socio-économique et la protection de l'environnement. L'approche de gestion intégrée par bassin versant est utilisée dans cette étude pour identifier et prioriser les interventions afin d'améliorer la qualité de l'eau de la rivière Cau au Vietnam. Cette approche inclut l'élaboration de scénarios de développement socio-économique futurs qui sont comparés à la situation actuelle de la rivière, comme scénario de référence, en matière d'impact sur la qualité de l'eau.

Le bassin versant de la rivière Cau couvre sept provinces, mais cette étude porte principalement sur la partie amont du bassin versant appartenant à deux provinces : Bac Kan et Thai Nguyen. Des méthodes appropriées sont proposées pour l'élaboration de scénarios de développement dans un contexte de manque de données. Ainsi, sept facteurs sont pris en considération pour construire les scénarios. Il s'agit de la population, des eaux usées d'origine domestique, des rejets d'eaux usées industrielles, du cheptel, des fertilisants agricoles, des forêts et du changement climatique.

Quatorze scénarios sont créés afin d'évaluer les impacts dù développement socio-économique futur sur la qualité de l'eau de la rivière Cau en utilisant un outil informatique de gestion intégrée par bassin versant (GIBSI). Cet outil intègre, entre autres, les modèles hydrologique, d'érosion des sols et de qualité de l'eau qui sont adaptés et calibrés pour le bassin versant de la rivière Cau. Les simulations de la qualité de l'eau dans GIBSI ont montré que la population, les eaux usées d'origine domestique et les rejets d'eaux usées industrielles sont les trois facteurs qui peuvent avoir des impacts visibles, dans le futur, sur la qualité de l'eau dans la zone d'étude. Quatre autres facteurs, à savoir le cheptel, les fertilisants agricoles, les forêts et le changement climatique devraient avoir des effets négligeables sur la qualité de l'eau dans le futur.

Une méthode d'analyse multicritère est proposée pour comparer et sélectionner les meilleurs scénarios parmi les 14 scénarios proposés. Cette analyse est basée sur la combinaison de trois critères : (1) recueillir les idées des experts et des parties prenantes sur les scénarios; (2) évaluer les impacts de chaque scénario sur la qualité des eaux de surface du bassin versant

de la rivière Cau; et (3) comparer les coûts des scénarios. En se basant sur la pondération des résultats des trois critères pour tenir compte de leur poids dans le résultat final, un score est attribué à chaque scénario. Cela a permis d'identifier et de sélectionner trois scénarios comme ceux ayant le meilleur score. Il s'agit : (1) d'accroître la capacité des usines de traitement des eaux usées domestiques de la ville de Bac Kan de 20 000 personnes; (2) de maintenir la projection actuelle de la capacité des usines de traitement des eaux usées domestiques à 100 000 personnes dans la ville de Thai Nguyen; et (3) d'installer une usine de traitement des eaux usées domestiques pour la ville de Song Cong d'une capacité de 10 000 personnes. Les interventions correspondant à ces scénarios sont donc recommandées pour améliorer la qualité de l'eau du bassin versant de la rivière Cau. Outre ces interventions, les contrôles de la croissance démographique et des rejets d'eaux usées industrielles, afin que ceux-ci respectent les normes de rejets dans l'environnement, sont également recommandés.

Cette recherche contribue à une évaluation systématique des impacts, dans le futur, du développement socio-économique sur la qualité des eaux de surface dans le bassin versant de la rivière Cau, dans les provinces de Bac Kan et de Thai Nguyen. Elle permet ainsi aux décideurs de choisir les meilleures interventions pour la gestion du bassin versant de la rivière Cau au Vietnam.

SOMMAIRE DE LA THÈSE EN FRANÇAIS

1. Introduction

1.1 Contexte

La rivière Cau est située au nord du Vietnam. Son bassin versant couvre une superficie de 6 030 km^2, ce qui représente environ 2 % de la superficie totale du pays (Environment Report of Vietnam, 2006). Le réseau hydrographique comporte plusieurs affluents qui s'écoulent à travers des villes et des zones agricoles. En raison de l'industrialisation rapide durant ces dernières décennies, le bassin versant de la rivière Cau comporte aujourd'hui 200 villages artisanaux et plus de 800 industries de différentes tailles (Environment Report of Vietnam, 2006). L'agriculture intensive s'est aussi développée dans le bassin, entraînant une utilisation d'engrais et de fertilisants provenant du cheptel. L'une des principales conséquences de ces activités est la pollution de l'eau de la rivière Cau et de certains de ses affluents. Cette pollution devient de plus en plus sérieuse et constitue aujourd'hui un problème majeur dans certaines parties de ce bassin versant. Dans la partie intermédiaire du bassin, située dans la province de Thai Nguyen, la rivière est polluée surtout au niveau de la ville de Thai Nguyen. Dans la partie aval du bassin, dans les provinces de Bac Giang et Bac Ninh, l'eau est très polluée par des substances organiques et la demande biologique en oxygène dépasse les critères de qualité de l'eau de surface pour les différents usages.

La pollution de l'eau peut affecter la santé publique, l'équilibre de l'écosystème aquatique (faune et flore) et la disponibilité d'une eau de bonne qualité pour répondre aux besoins des développements social et économique. Par conséquent, il est urgent de protéger l'environnement du bassin versant de la rivière Cau. Ceci représente aujourd'hui l'une des priorités du gouvernement vietnamien. Ainsi, la décision du premier ministre du gouvernement, portant sur « le plan directeur de protection de l'environnement, du développement durable et de la promotion d'un environnement écologique dans le bassin versant de la rivière Cau » a été signée le 28 juillet 2006. Cette décision porte sur les orientations générales suivantes : 1) lutter progressivement contre la pollution dans le bassin versant de la rivière Cau; 2) améliorer la qualité de l'eau de la rivière de sorte qu'à l'horizon 2020, la qualité de l'eau de la rivière soit meilleure qu'avant; 3) assurer la disponibilité de l'eau pour l'agriculture et l'ensemble du développement socio-économique dans le bassin versant, etc. Ainsi, cette thèse de doctorat a pour objectif de contribuer à atteindre les objectifs fixés par ce plan directeur.

1.2 Objectifs

Le principal objectif de cette thèse est d'élaborer une méthodologie de développement et de comparaison de scénarios socio-économiques afin d'effectuer les meilleurs choix d'interventions pour améliorer la qualité de l'eau de la rivière Cau dans un contexte de gestion intégrée par bassin versant.

Comme objectifs spécifiques, la présente recherche vise à :

- développer plusieurs scénarios d'interventions;
- évaluer l'impact de différents scénarios d'intervention sur la qualité de l'eau;
- évaluer les coûts et les bénéfices des différents scénarios relatifs à l'amélioration de la qualité de l'eau;
- élaborer une méthodologie de sélection des scénarios retenus en tenant compte des critères de qualité de l'eau, du coût-bénéfice des scénarios et de l'idée des experts et des parties prenantes.

1.3 Originalité de la thèse

La première originalité de cette thèse est d'élaborer des méthodes appropriées pour développer des scénarios pour le bassin versant de la rivière Cau dans un contexte de rareté de données. La deuxième originalité est l'utilisation d'un outil de gestion intégrée par bassin versant pour évaluer les impacts sur la qualité de l'eau des scénarios futurs de développement socio-économique. La dernière originalité de la thèse est de développer une méthodologie adaptée au contexte du bassin versant pour la sélection des scénarios retenus.

2. Revue de la littérature

Dans le cadre de cette thèse, la revue de la littérature porte essentiellement sur les approches et les méthodes qui ont été développées dans la littérature et portant sur de précédentes études similaires aux objectifs de cette thèse.

2.1 Gestion intégrée par bassin versant

Depuis les années 1990, de plus en plus de recherches portant sur la gestion intégrée de l'eau par bassin versant ont été effectuées dans des sous-régions de l'Asie. Dans cette thèse, deux études portant sur la gestion intégrée par bassin versant ont été considérées comme parmi les plus importantes dans ces sous-régions. Premièrement, il s'agit des travaux de Scoccimarro *et al.* (1999), effectués au nord de la Thaïlande. Cette étude porte sur le développement d'une méthodologie qui reflète le caractère multiobjectif de la gestion intégrée des ressources en eau à partir de modèles physiques et socio-économiques de gestion intégrée pour l'aide à la décision. La deuxième étude a été effectuée par Liu *et al.* (2007) dans le nord de la Chine. Elle a également considéré la gestion par bassin versant comme un système comprenant des politiques, des techniques et le développement économique à différentes échelles spatio-temporelles.

2.2 Approche d'optimisation basée sur l'analyse de scénarios

La méthode d'optimisation peut être considérée comme le fait d'effectuer le meilleur choix parmi plusieurs alternatives à un problème. Ainsi, l'étude de Liu *et al.* (2007), qui propose une méthode d'optimisation basée sur l'analyse de scénarios, a été présentée. L'analyse du système (les méthodes de projection, l'analyse des scénarios et la contribution des experts et parties prenantes) a été prise en compte dans cette étude. Cette méthode a servi de base pour l'approche d'optimisation développée dans ce doctorat.

2.3 Scénarios d'utilisation du territoire

Les changements d'utilisation du territoire sont les changements de la couverture du sol qui entraînent des changements dans le processus de ruissellement de surface avec une influence sur d'autres processus hydrologiques dans le bassin versant (Wang *et al.*, 2008). Les effets des changements d'utilisation du territoire sur les processus hydrologiques incluent l'infiltration, la recharge des nappes souterraines et le ruissellement de surface dans un bassin versant (Lin *et al.*, 2007a). Par conséquent, comprendre la réponse hydrologique d'un bassin versant aux changements futurs d'occupation du territoire est un aspect important de la gestion par bassin versant.

2.4 Scénarios de changements climatiques

Des études portant sur les scénarios de changements climatiques au Vietnam ont été rapportées dans la littérature. Il s'agit, par exemple, de plusieurs projets-clés considérés par les pouvoirs publics comme les orientations à suivre pour la prise en compte des changements climatiques dans les études au Vietnam. L'un de ces projets a étudié les « Impacts des changements climatiques sur les ressources en eau et les mesures d'adaptation » (IMHE, 2010a et b). Les données nécessaires (températures et précipitations futures) pour construire les scénarios de changements climatiques dans le cadre de cette recherche doctorale proviennent de ce projet.

2.5 Scénarios industriels

La croissance industrielle est de plus en plus forte dans les pays en voie de développement. Cependant, il est bien connu que cette croissance contribue à la pollution de l'eau. Ainsi, l'élaboration de scénarios industriels et l'évaluation de leurs impacts sur la qualité de l'eau sont nécessaires pour aider les pouvoirs publics à élaborer les politiques appropriées pour la protection de l'environnement. L'étude de Leal-Neto *et al.* (2006), portant sur le développement de scénarios industriels pour le bassin versant de la rivière Sepetiba au Brésil, est l'une des illustrations du développement de scénarios industriels et l'analyse de leurs impacts sur la qualité de l'eau dans un bassin versant.

2.6 Projection de la population et impacts sur la qualité de l'eau

La projection de la population est une estimation de la population future pour des besoins de planification et de gestion (Keilman, 2007). Les différents usages de l'eau dans le futur peuvent avoir des impacts sur la qualité de l'eau et sur la santé publique. Si les eaux usées d'origine domestique sont rejetées dans les cours d'eau sans aucun traitement, la qualité de l'eau en rivière sera affectée (Leal-Neto *et al.*, 2006). Par conséquent, il est important de pouvoir connaître le taux de croissance de la population dans le but d'analyser ses impacts sur la qualité de l'eau. Dans cette étude, les auteurs ont analysé les relations entre l'accroissement de la population et les niveaux de charges de demande biochimique en oxygène dans des cours d'eau.

2.7 Analyse coût-avantage

L'analyse coût-avantage peut être définie comme l'analyse des coûts et des avantages pour différentes alternatives avec pour objectif de déterminer si les avantages dépassent ou non les coûts. Plusieurs études peuvent être rapportées comme exemples d'utilisation de cette analyse dans un processus de prise de décision. Salvano *et al.* (2006) ont eu recours à cette approche pour évaluer les avantages potentiels de l'amélioration de la qualité de l'eau dans un bassin versant au Québec. La deuxième étude est celle de Peng *et al.* (2007) qui ont étudié les coûts de programmes de reforestation et les avantages pour l'environnement.

2.8 Analyse multicritère

L'analyse multicritère est un outil d'aide à la décision pour des problèmes complexes (Mendoza *et al.*, 1999). Il existe deux différentes approches : l'approche descendante et celle ascendante (Mendoza *et al.*, 1999). Dans l'approche descendante, une série précédente de données et d'indicateurs est utilisée comme jeu de données initial pour la sélection finale des critères et des indicateurs. L'approche ascendante, quant à elle, a recours aux informations spécifiques, en particulier celles provenant du terrain, pour définir un ensemble de critères et d'indicateurs finaux. Un exemple d'analyse multicritère basée sur l'approche ascendante a été rapportée dans cette thèse (Liu *et al.*, 2007). L'étude a procédé à la sélection optimale des politiques et des techniques d'ingénierie par analyse comparative des scénarios dans le cadre de la gestion intégrée du bassin versant du lac Qionghai en Chine.

3. Zone d'étude et outil d'implémentation

3.1 Zone d'étude

La zone d'étude qui fait l'objet de cette thèse est la partie amont du bassin versant de la rivière Cau, appartenant aux deux provinces de Bac Kan et de Thai Nguyen (Figure S.3.1). La topographie dans le bassin versant est composée de montagnes, de collines et de plaines. Quant au climat, il est tropical de type mousson avec une saison de pluies (juin-octobre) et une saison sèche (novembre-mai). La température moyenne annuelle varie entre 18 °C et 24 °C, et la pluviométrie totale annuelle se situe entre 1 500 mm et 2 500 mm, avec un écoulement total estimé à 4,9 milliards de m^3. L'évapotranspiration varie entre 541 et 1 000 mm/an (FAO, 2011).

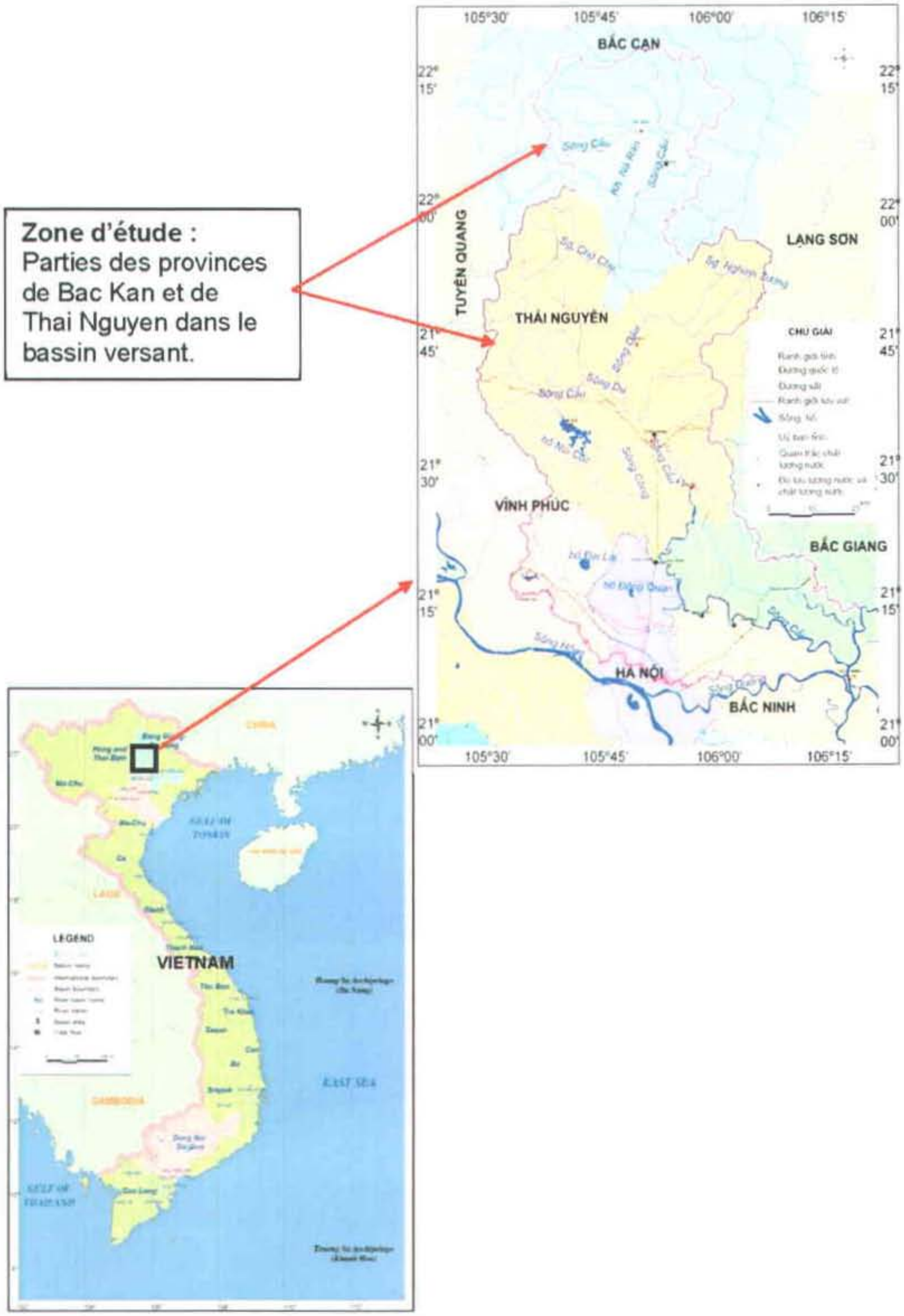


Figure S.3.1. Carte du bassin versant de la rivière Cau et sa localisation sur une carte du Vietnam.

3.2 Outil d'implémentation : GIBSI

GIBSI (*Gestion intégrée des bassins versants à l'aide d'un système informatique*) est l'outil informatique qui est utilisé dans le cadre de cette recherche. Cet outil comporte quatre principaux modèles de simulation adaptés et calés pour le bassin versant d'étude dans le cadre du projet de gestion intégrée des ressources en eau, qui fait l'objet d'un partenariat entre l'Institut national de la recherche scientifique et l'Académie des Sciences et Technologies du Vietnam. GIBSI est un système d'aide à la décision qui permet d'appuyer les décideurs dans l'évaluation de scénarios d'intervention dans un bassin versant (Villeneuve *et al.,* 1998). C'est un outil qui peut être utile pour évaluer l'impact de divers scénarios d'intervention sur l'hydrologie, l'érosion ou la qualité de l'eau de surface dans un bassin versant. Les différentes composantes et la structure générale de GIBSI sont illustrées à la figure S.3.2.

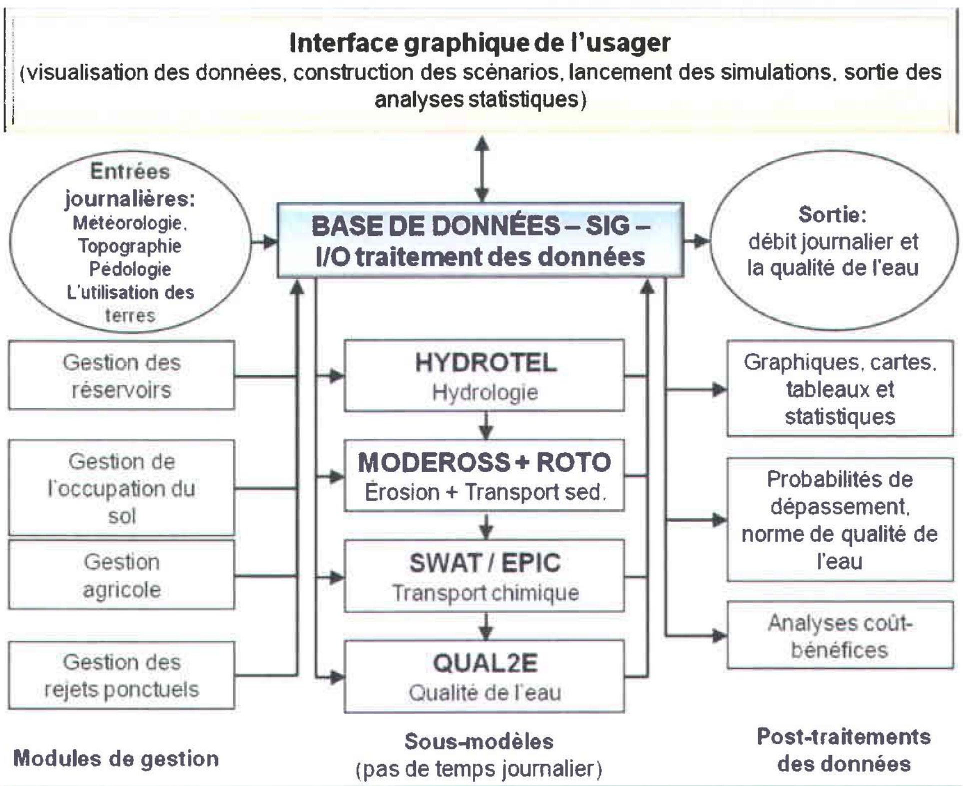


Figure S.3.2: Composantes et structure de GIBSI (d'après Quilbé et Rousseau, 2007).

Cet outil dispose de plusieurs composantes (Quilbé et Rousseau, 2007) :

1) Un système de gestion de bases de données incluant un système d'information géographique (SIG).

2) Un module de gestion de scénarios qui permet de créer des scénarios d'intervention dans le bassin versant : scénarios de rejets ponctuels, scénarios de changements d'occupation du territoire, etc.

3) Des modèles, au nombre de quatre, pour la simulation des processus au pas de temps journalier : HYDROTEL (Fortin *et al.,* 1995) qui est le modèle hydrologique, MODEROSS (Duchemin, 2000) et ROTO (Arnold *et al.*, 1995, cité dans Villeneuve *et al.,* 1998), qui sont des modèles de simulation de l'érosion et du transport de sédiments en rivière, SWAT/EPIC (Arnold *et al.,* 1995, cité dans Villeneuve *et al.,* 1998) qui permettent de simuler le transport d'azote, du phosphore, de pesticides, etc., du sol vers le réseau hydrographique, et QUAL2E (Brown et Barnwell, 1987) qui est le modèle de qualité de l'eau en rivière.

4) Des outils permettant d'analyser et de visualiser les variables de sorties des modèles de simulation sous différents formats (ex. : graphes). Ils incluent également un outil d'analyse coût-avantage pour chaque scénario d'intervention en s'appuyant sur le coût d'implémentation du scénario et des bénéfices qui peuvent en découler pour l'environnement.

Avec une telle structure, l'utilisation de GIBSI, en appui à cette recherche, permettra de développer différents scénarios de développement socio-économique et d'évaluer l'impact de ces scénarios sur la qualité de l'eau de surface du bassin versant de la rivière Cau.

4. Méthodologie d'étude

4.1 Approche d'optimisation

La méthodologie proposée dans cette étude peut être résumée par la figure S.4.1.

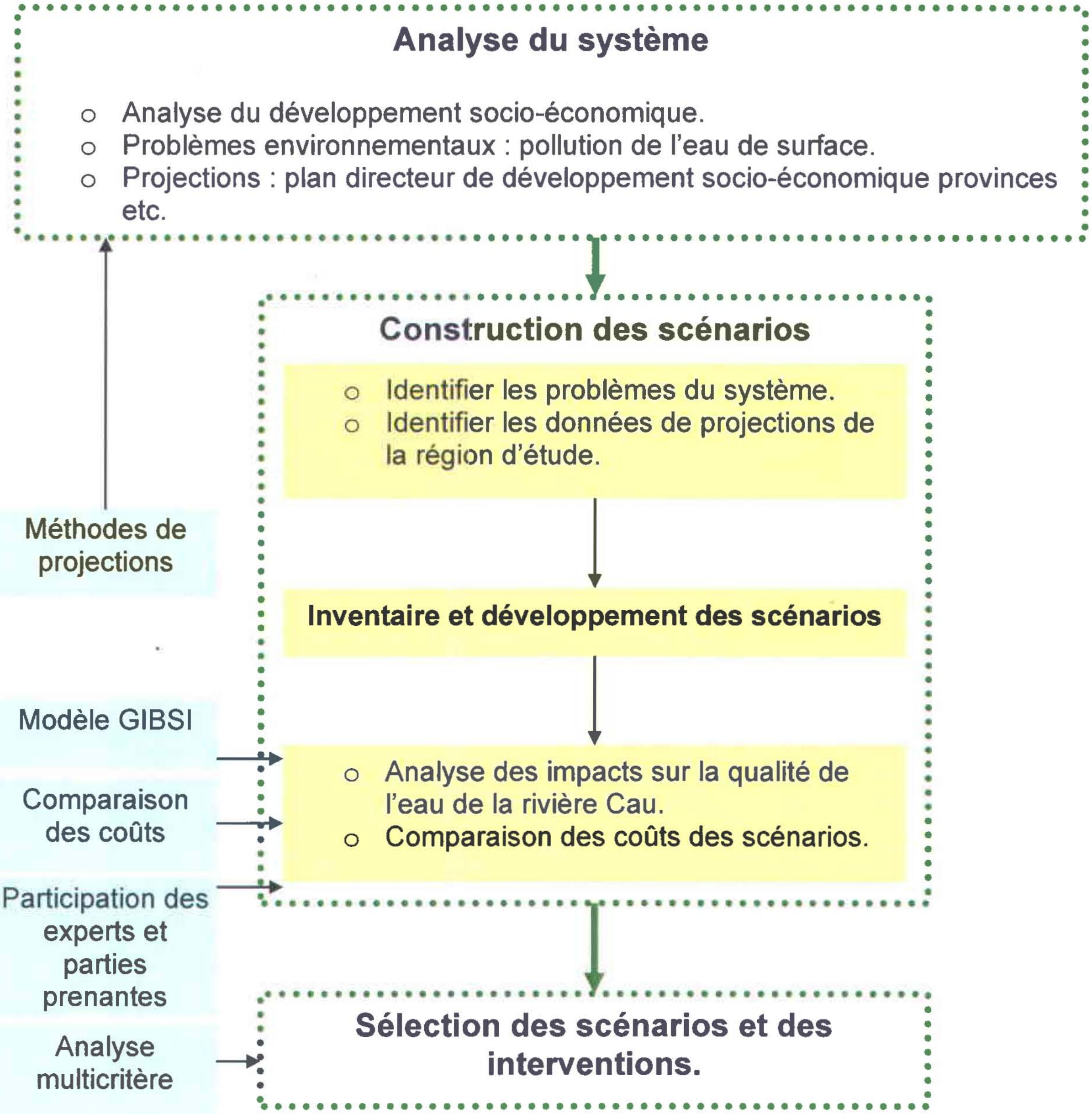


Figure S.4.1: Méthodologie d'optimisation basée sur l'analyse de scénarios.

La méthodologie comporte trois étapes :

(1) *Étape 1 : Analyse du système.* Il s'agit de l'étape d'analyse du système. Pour ce faire, il faut identifier les problèmes et les facteurs, analyser les données et les méthodes de projections, etc. Les facteurs suivants ont été identifiés comme étant les plus importants dans le plan de développement futur : la croissance démographique, la gestion des eaux usées d'origine domestique, la croissance industrielle, l'agriculture, l'occupation du territoire et les changements climatiques.

(2) *Étape 2 : Développement des scénarios.* Il s'agit ici de développer des scénarios de manière à tenir compte des changements futurs prévus dans le bassin versant. Pour cela on doit : (a) identifier les problèmes pouvant affecter la qualité de l'eau de la rivière Cau; (b) élaborer des scénarios à partir des données de projection et de la connaissance des facteurs les plus importants pour les pouvoirs publics; (c) évaluer l'impact des différents scénarios sur la qualité de l'eau avec GIBSI; et (d) comparer les coûts.

(3) *Étape 3 : Sélection des scénarios et identification des interventions.* Cette dernière étape permet de choisir les meilleurs scénarios pour améliorer la qualité de l'eau de la rivière Cau et d'identifier les interventions nécessaires en tenant compte des résultats de simulation de la qualité de l'eau, de comparaison des coûts et des idées des experts et parties prenantes.

4.2 Méthodes de projection et développement des scénarios

Projection de la population et scénarios

À partir de l'analyse des avantages et des inconvénients des différentes méthodes d'estimation de la population future, la méthode qui s'appuie sur le taux d'accroissement annuel de la population a été retenue. Cette méthode permet d'estimer, à partir d'une année de référence et du taux d'accroissement annuel, la population future pour différentes années dans la zone d'étude.

Stations de traitement des eaux usées d'origine domestique

Les eaux usées d'origine domestique sont déjà un problème majeur dans cette zone d'étude, compte tenu de l'absence de stations de traitements d'eaux usées. Ce problème s'accentuera avec la croissance démographique et la croissance industrielle prévues entre 2010 et 2020. Par conséquent, la construction et la mise en service de stations de traitement d'eaux usées sont prévues dans les plans de développement futur des provinces avec des capacités connues (nombre total d'habitants connectés à la station). Seule une partie des eaux usées domestiques correspondant aux capacités prévues sera collectée et traitée.

Industries

L'impact du développement industriel sera pris en compte à partir des points de rejets industriels, d'autant plus qu'une augmentation des activités des industries actuelles est prévue et un développement de nouvelles zones industrielles est envisagé dans le futur.

Changements climatiques

Pour ce facteur, un changement des températures et des précipitations a été considéré pour tenir compte du changement, quoique faible sur dix ans, du climat futur. Il s'agit d'un accroissement relatif des précipitations et des températures dans le futur.

Occupation du territoire

Le changement d'occupation du territoire a été pris en compte à partir de données d'extension future des aires forestières prévues par les gouvernements des provinces. L'augmentation des surfaces forestières se fera en y ajoutant les terres non utilisées et les terres occupées par des arbustes.

Agriculture

Dans le futur, deux secteurs de l'agriculture feront l'objet d'une attention particulière dans le bassin versant : il s'agit de l'augmentation du cheptel et de celui du rendement des rizières. Le fumier provenant du cheptel, utilisé comme fertilisant, augmente la pollution diffuse d'origine agricole. En ce qui concerne le rendement des rizières, il s'agira d'augmenter les quantités de fertilisants utilisées à partir des données disponibles.

4.3 Sélection des variables de qualité de l'eau pour la comparaison des scénarios

Il existe plusieurs variables de qualité de l'eau : oxygène dissous, demande biochimique en oxygène, azote, phosphore, sédiments en suspension, etc. Cette étude s'est appuyée sur le contexte du bassin versant pour sélectionner les variables les plus pertinentes pour la comparaison des scénarios. Les critères suivants ont été utilisés pour sélectionner les variables.

- Capacité de simuler la variable pour la rivière Cau à partir du calage de GIBSI aux conditions spécifiques du bassin versant d'étude.
- Caractéristiques et importance de la variable dans l'évaluation de la qualité de l'eau.
- Relation entre la variable et la pollution due aux activités socio-économiques.
- Intérêt de la variable pour l'état actuel de la qualité de l'eau et de l'environnement dans le bassin versant.

Sur la base de ces critères, quatre variables ont été retenues : le débit en rivière, la demande biochimique en oxygène, l'ammoniaque et les sédiments en suspension.

4.4 Analyse coût-avantage

L'analyse coût-avantage s'est appuyée sur la méthode proposée par Salvano *et al.* (2006). Par ailleurs, les avantages liés au traitement des eaux usées d'origine domestique ont été considérés. Quant aux coûts, une estimation du coût de chaque intervention, comme l'installation d'une station de traitement des eaux usées, a été faite à partir des données disponibles.

4.5 Analyse multicritère

Dans cette étude, l'approche ascendante a été utilisée pour appliquer l'analyse multicritère pour la sélection optimale des scénarios. Le cadre proposé est résumé à la figure S.4.2.

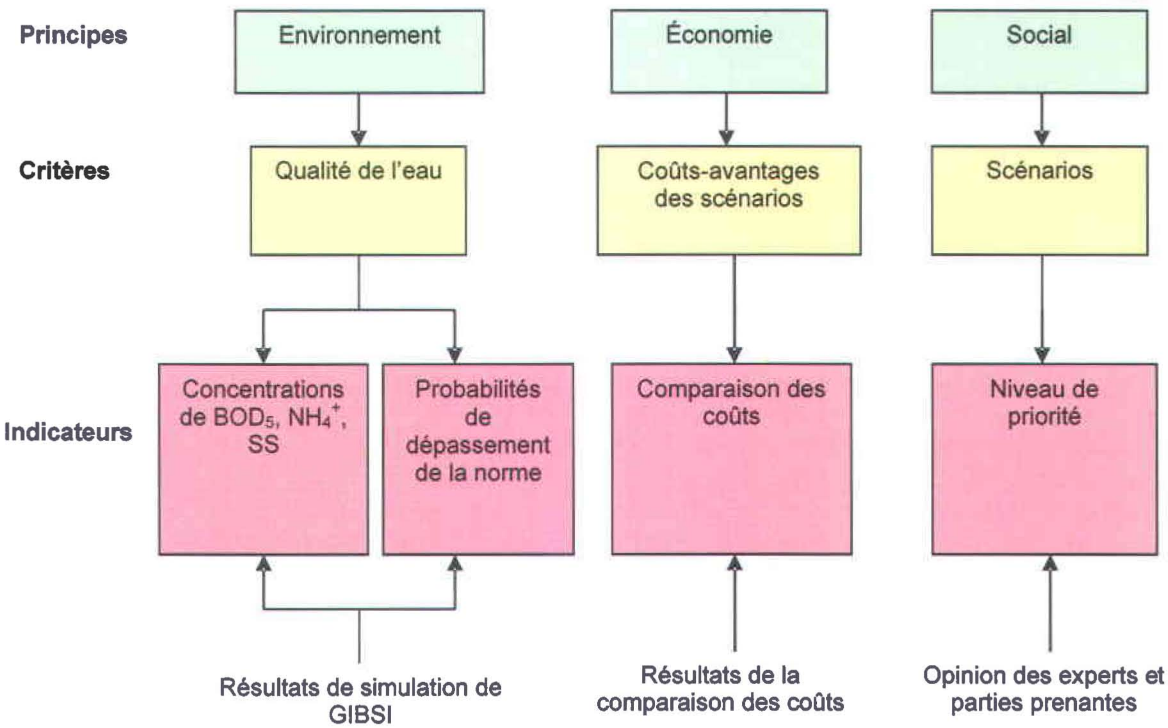


Figure S.4.2. Principes, critères et indicateurs pour l'analyse multicritère.

Trois indicateurs ont été considérés pour la sélection des scénarios. Il s'agit des résultats de simulation de la qualité de l'eau, de l'analyse coût-avantage et de l'opinion des experts et parties prenantes. Pour classer les scénarios, l'étude s'est appuyée sur un système de points accordés à chaque scénario, en affectant un score au résultat de chaque critère sur la base du niveau de priorité : 1 pour une priorité faible, 2 pour une priorité moyenne et 3 pour une priorité élevée. Le scénario dont le total des points est le plus élevé serait recommandé aux pouvoirs publics.

Le total des points de chaque scénario a été calculé de la manière suivante, en tenant compte du poids de chaque indicateur dans l'analyse:

$$Score_{Final} = Score_S \times \mathrm{Im}_S + Score_{WQ} \times \mathrm{Im}_{WQ} + Score_{CB} \times \mathrm{Im}_{CB}$$

Avec: $\mathrm{Score}_{\mathrm{Final}}$: Total des points du scénario.

$\mathrm{Score}_{\mathrm{S}}$: Point du scénario pour le critère de l'idée des experts et parties prenantes.

Im_{S} : Poids du critère de l'idée des experts et des parties prenantes (= 2).

$\mathrm{Score}_{\mathrm{WQ}}$: Point du scénario pour le critère de qualité de l'eau.

$\mathrm{Im}_{\mathrm{WQ}}$: Poids du critère de qualité de l'eau (= 2).

$\mathrm{Score}_{\mathrm{CB}}$: Point du scénario pour le critère coût-avantage.

$\mathrm{Im}_{\mathrm{CB}}$: Poids du critère coût-avantage (= 1).

Notons que l'affectation du poids le plus faible au critère coût-avantage se justifie par le fait que très peu de données sont disponibles pour une analyse approfondie de ce critère. Par conséquent, le total des points de chaque scénario s'est plus appuyé sur les deux autres critères ayant moins d'incertitudes que celui du coût-avantage.

5. Résultats du développement des scénarios

Tous les scénarios ont été développés à partir des résultats de projection des différents facteurs pour chacune des deux provinces Bac Kan et Thai Nguyen. Ces scénarios ont été développés pour deux années dans le futur, soit 2015 et 2020. Étant donné que l'évolution de certains facteurs (ex. : l'occupation du territoire) d'une année à l'autre ne peut pas être prise en compte par GIBSI, la sélection de l'année de la fin de cette période du plan directeur (2020) et d'une année intermédiaire (2015) permettra de porter un jugement sur l'impact des facteurs sur la qualité de l'eau dans le futur. En effet, l'objectif de cette recherche n'est pas de déterminer une tendance d'évolution temporelle des variables de qualité de l'eau dans le futur, mais de disposer de points de comparaison dans le futur. L'année de référence est 2009, car elle est quasiment identique sur le plan météorologique à la plupart des années de la période d'étude (1998-2009) dans le cadre du projet de gestion intégrée des ressources en eau du bassin versant de la rivière Cau.

5.1 Analyse du système

Les données de projection des sept facteurs pouvant affecter la qualité de l'eau dans le plan futur de développement socio-économique ont été utilisées. Ces facteurs sont : la population, les stations de traitement des eaux usées domestiques, les rejets industriels, le cheptel, les fertilisants agricoles, l'extension des surfaces forestières et les changements climatiques. Un degré d'importance a été accordé à chaque facteur par les pouvoirs publics dans le plan de développement futur 2010-2020. Ainsi les facteurs sont classés selon leur niveau de priorité :

- élevé ou 1 : population, eaux usées domestiques et rejets industriels;
- moyen ou 2 : cheptel, fertilisants;
- faible ou 3 : forêts, changements climatiques.

(1) Population

La population future a été calculée pour les différents districts de la zone d'étude à partir des statistiques de l'année de référence et du taux d'accroissement de la population dans le futur. Ce facteur étant d'un niveau de priorité élevé, trois niveaux d'accroissement de population ont été pris en compte à partir d'hypothèses supplémentaires : un niveau faible, un niveau moyen et un niveau élevé.

(2) Eaux usées d'origine domestique

Selon les projections des gouvernements locaux, la mise en place d'une station de traitement d'eaux usées domestiques est prévue dans la capitale de chacune des deux provinces (Bac Kan et Thai Nguyen) avec des capacités respectives de 10 000 habitants et de 100 000 habitants. Compte tenu de la priorité accordée à ce facteur (niveau élevé), deux autres valeurs de capacités ont été considérées à partir d'hypothèses supplémentaires :

- 20 000 habitants dans la province de Bac Kan et 110 000 habitants dans celle de Thai Nguyen;
- 30 000 habitants dans la province de Bac Kan et 150 000 dans celle de Thai Nguyen.

(3) Rejets industriels

Selon le plan de développement des provinces, 14 zones industrielles sont prévues dans le futur et les années de mise en service sont connues. À partir des données existantes, les débits et la concentration des divers contaminants dans les rejets ont été déterminés. La concentration de ces contaminants devrait respecter les normes de rejets industriels qui seront appliquées dans le futur. Trois valeurs de rejets industriels ont été considérées :

- Débits des rejets industriels actuels avec les rejets industriels futurs.
- Accroissement de 10 % des rejets industriels actuels avec les rejets industriels futurs.
- Accroissement de 20 % des rejets industriels actuels avec les rejets industriels futurs.

(4) Cheptel

Le cheptel considéré est composé de bovins, porcins, volailles, etc. Les projections ont été faites à partir des statistiques et des projections des gouvernements locaux. Comme il s'agit d'un facteur de niveau de priorité moyen, une seule valeur de projection a été considérée.

(5) Fertilisants

Il s'agit de l'augmentation des quantités de fertilisants à utiliser pour accroître la production de riz. Les projections pour les quantités d'azote et de phosphore dans les fertilisants ont été faites à partir des données des gouvernements locaux. Une seule valeur a été considérée pour ce facteur.

(6) Forêts

Un plan détaillé a été élaboré par les gouvernements locaux pour l'accroissement des surfaces forestières pour chaque district dans le futur. L'accroissement de ces surfaces se fera à partir des terres non utilisées et de celles occupées par les arbustes.

(7) Changements climatiques

Une valeur moyenne d'accroissements relatifs des températures et des précipitations à l'ensemble des stations météorologiques et pluviométriques du bassin versant a été considérée. Cette valeur est celle du scénario moyen de changement climatique au Vietnam sur la période 2010-2020.

5.2 Identification des problèmes majeurs et des projections futures

Les problèmes environnementaux majeurs de première importance pour les pouvoirs publics sont les eaux usées domestiques et les rejets industriels. Les projections futures les plus importantes sont celles de la population et du développement industriel.

5.3 Combinaison pour le développement des scénarios

Des combinaisons avec les différentes valeurs dans le futur ont été considérées pour créer les scénarios (Figure S.4.3). Ces combinaisons ont été faites en s'appuyant sur les hypothèses suivantes.

- Pour les trois facteurs de niveau de priorité élevée, des niveaux identiques ont été combinés (ex. : la valeur minimale de la population future avec la valeur minimale des rejets industriels), tandis que les facteurs de niveau de priorité moyen ou faible sont considérés à leur niveau de référence (celui de 2009). L'objectif est d'évaluer l'impact sur la qualité de l'eau des facteurs de niveau de priorité élevée.

- Pour un facteur de niveau de priorité moyen ou faible, son impact sur la qualité de l'eau a été évalué (seul ou en combinaison avec un autre facteur) dans un scénario en considérant les facteurs de niveau de priorité élevée à leur valeur moyenne dans le futur.

Pour tous les scénarios, une comparaison avec le scénario de référence (année 2009) a été effectuée afin d'identifier les améliorations éventuelles de la qualité de l'eau.

Tableau S.5.1: Scénarios d'analyse considérés pour le bassin versant de la rivière Cau.

Niveau de priorité	Facteurs		Scénarios													
	Nom	Valeurs	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
1	Population	Basse	X			X			X							
		Intermédiaire		X			X			X		X	X	X	X	X
		Haute			X			X			X					
	Eaux usées domestiques	Basse	X						X							
		Intermédiaire		X						X		X	X	X	X	X
		Haute			X						X					
	Industries	Industries actuelles + futures				X			X							
		Augmentation intermédiaire					X			X		X	X	X	X	X
		Augmentation haute						X			X					
2	Cheptel	Projection intermédiaire										X				X
	Agriculture	Projection intermédiaire											X			X
3	Forêt	Projection intermédiaire												X		X
	Changement climatique	Projection intermédiaire													X	X

6. Comparaison des scénarios et sélection

6.1. Idées des experts sur les scénarios

Selon l'opinion des experts et parties prenantes, d'après un sondage réalisé au cours d'un atelier, cinq scénarios peuvent être considérés comme de niveau de priorité élevée : S2, S3, S5, S8 et S14. Trois scénarios sont considérés comme étant de niveau de priorité moyenne : S6, S9 et S10. Les autres scénarios (S1, S4, S7, S11, S12 et S13) ont un niveau de priorité faible.

6.2. Résultats de simulation de la qualité de l'eau de la rivière Cau

Le choix des tronçons de rivière pour les résultats de simulation avec GIBSI a été fait sur la base de plusieurs critères qui sont :

- le tronçon doit être situé à une station de suivi de la qualité de l'eau afin de prendre en considération les données observées dans le scénario de référence.
- le tronçon devrait être à l'endroit ayant un intérêt pour l'analyse coût-avantage dans la zone d'étude telle qu'une usine de traitement d'eau potable.

Sur la base des critères énoncés, cinq tronçons de rivières ont été sélectionnés dont trois dans la rivière Cau (Thac Rieng, Thac Buoi et Gia Bay) et deux autres dans un affluent qui est la rivière Cong (tronçon de prélèvement pour l'usine de traitement d'eau potable de la ville de Song Cong et le pont de Da Phuc) (Figure S.6.1).

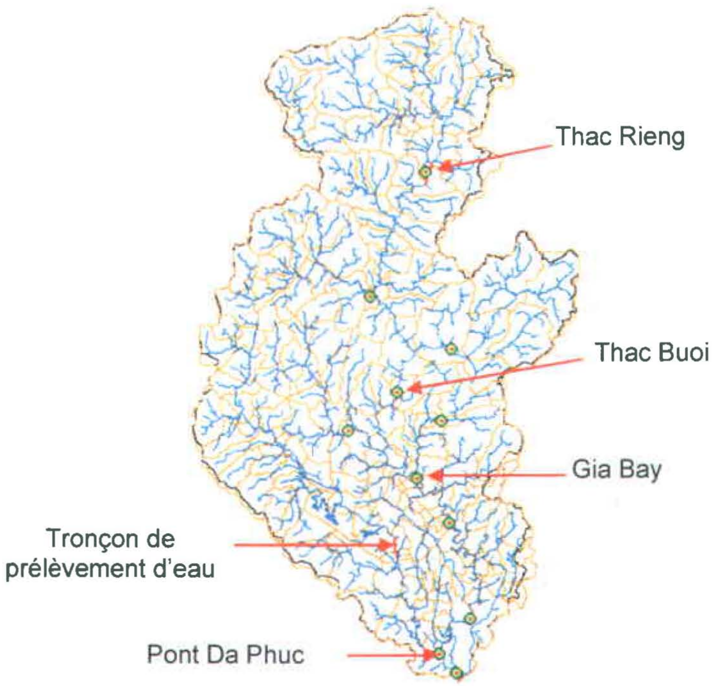


Figure S.6.1: Situation des cinq tronçons de rivière sélectionnés.

Les résultats des simulations montrent que pour l'ensemble des cinq tronçons sélectionnés, l'impact des scénarios (forêts et changements climatiques) qui pourraient affecter le débit en rivière est négligeable ou mineur. Il en est de même pour la variable sédiments en suspension. En effet, pour les cinq tronçons de rivière, la plantation forestière et les changements climatiques n'ont qu'un impact mineur sur la concentration de sédiments en suspension.

Pour ce qui concerne les concentrations de la demande biochimique en oxygène (DBO_5) et de l'azote ammoniacal (NH_4^+), quelques résultats parmi les plus pertinents sont présentés aux figures S.6.2 et S.6.3. Ces résultats sont présentés sous forme de diagrammes en boîte avec la valeur médiane représentée par le trait de couleur rouge. En absisce, sont représentés les scénarios avec l'année de simulation (ex. : S1_2015 sur la figure S.6.2.a représente l'ensemble des 365 valeurs journalières du scénario S1 en 2015). En ordonnées, se trouvent les concentrations de la variable. Sur ces figures, les traits en couleur verte représentent les critères de qualité de l'eau pour l'eau potable (valeur la plus basse) et pour les autres usages (valeur la plus élevée) dans les normes vietnamiennes.

Thac Rieng :

Une croissance future rapide de la population a un impact significatif sur l'augmentation des concentrations de NH_4^+ et de DBO_5. Les concentrations en NH_4^+ et en DBO_5 pour les scénarios S4, S5, S6 (scénarios de l'industrie), dans les années futures, sont les mêmes que celles de l'état actuel (voir exemple du NH_4^+ à la figure S.6.2). Cela peut être expliqué par le fait que dans la partie amont de ce tronçon il n'y a aucune nouvelle zone industrielle prévue dans le futur. De plus, l'augmentation de la quantité des eaux usées dans le futur des usines actuelles dans cette région n'a quasiment aucun impact sur la qualité de l'eau étant donné que la norme de rejets d'eaux usées industrielles doit y être respectée selon le plan directeur de développement futur.

Thac Buoi :

En général, dans cette partie du bassin versant, les résultats ont démontré que la croissance démographique future a généralement un impact significatif sur l'augmentation des concentrations en DBO_5 et en NH_4^+. Les autres facteurs ont moins d'impact sur cette partie intermédiaire de la rivière Cau.

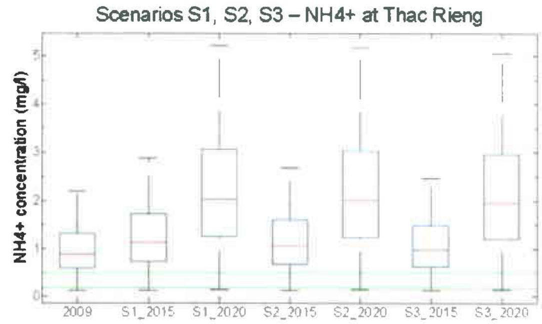
Gia Bay :

La qualité de l'eau dans ce tronçon est améliorée si les deux usines de traitement des eaux usées d'origine domestique dans les villes de Bac Kan et de Thai Nguyen sont installées, même lorsque leur capacité est au niveau le plus faible (voir le scénario S1_2015 pour la DBO_5 à la figure S.6.3). La concentration en DBO_5, influencée par les facteurs industriels en 2015 et 2020, est en général améliorée en comparaison avec l'état actuel en 2009.

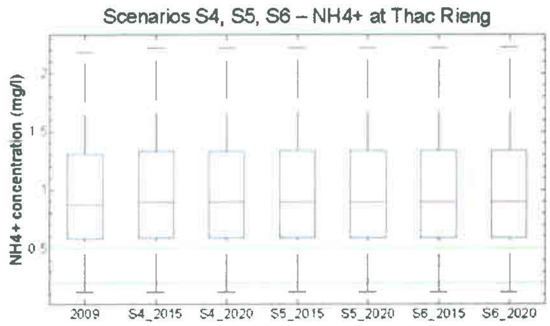
Tronçons dans la rivière Cong :

De manière générale, les critères de qualité de l'eau sont respectés dans le futur en ces deux tronçons de rivières (Da Phuc et Song Cong). Malgré la mise en service de certaines industries qui se situent en amont du tronçon de Da Phuc, le respect de la norme de rejets industriels explique le fait que l'eau reste de bonne qualité. Par ailleurs, l'installation d'une usine de traitement des eaux usées d'origine domestique (capacité de 10 000 habitants) dans une ville située en amont de ce tronçon a eu un impact positif sur la qualité de l'eau.

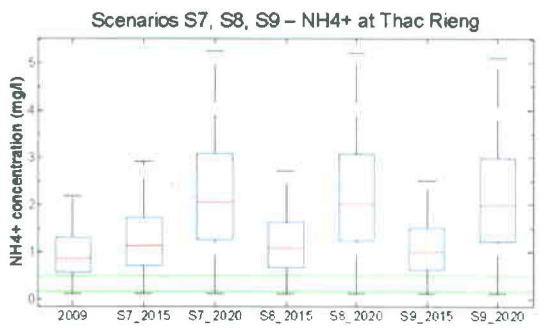
Pour tous les autres facteurs considérés (cheptel, fertilisants, forêts, changements climatiques), les simulations ont démontré un impact mineur sur les variables de qualité de l'eau sélectionnées lorsqu'on combine avec un niveau moyen pour les facteurs de niveau de priorité élevée.



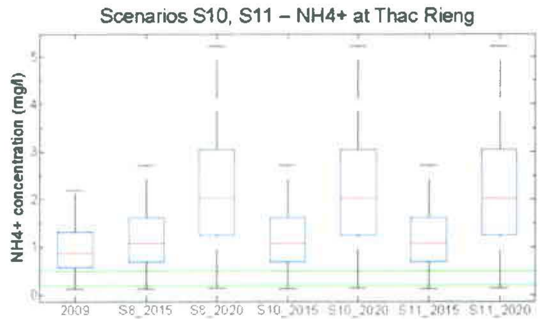
a. Scénarios de croissance de la population et des eaux usées domestiques (S1, S2, S3)



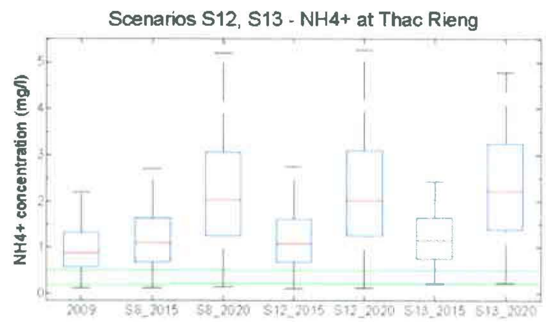
b. Scénarios de l'industrie (S4, S5, S6)



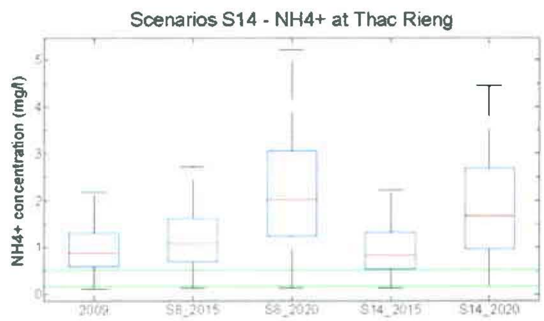
c. Scénarios de la population, des eaux usées domestiques et de l'industrie (S7, S8, S9)



d. Scénarios de l'agriculture: cheptel et fertilisants (S10, S11)

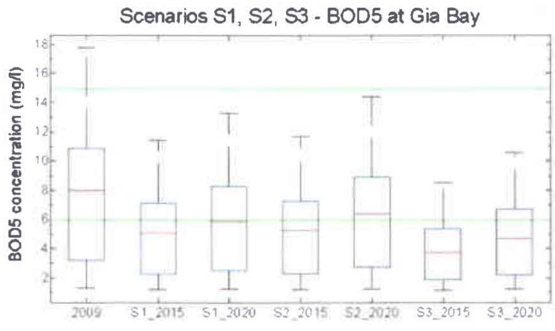


e. Scénarios de forêt et de changement climatique (S12, S13)



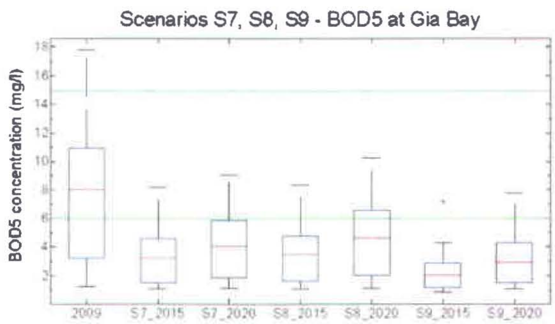
f. Scénario de tous les facteurs (S14)

Figure S.6.2: Résultats de simulation de la concentration en NH_4^+ en 2015 et 2020 à Thac Rieng pour 14 scénarios comparés à l'année de référence de 2009.

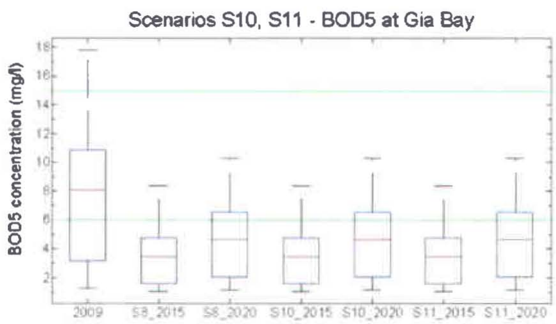


a. Scénarios de croissance de la population et des eaux usées domestiques (S1, S2, S3)

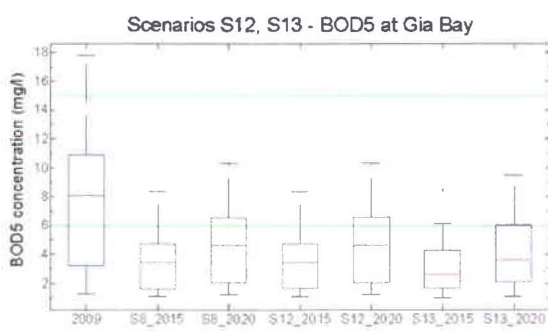
b. Scénarios de l'industrie (S4, S5, S6)



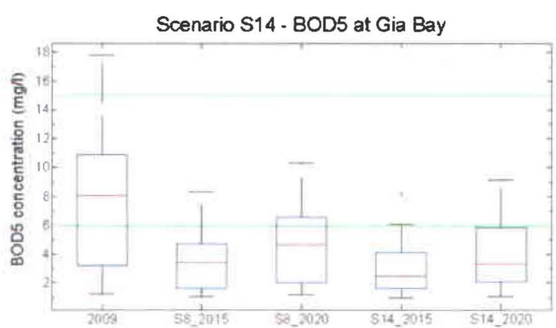
c. Scénarios de la population, des eaux usées domestiques et de l'industrie (S7, S8, S9)



d. Scénarios de l'agriculture : cheptel et fertilisants (S10, S11)



e. Scénarios de forêt et de changement climatique (S12, S13)



f. Scénario de tous les facteurs (S14)

Figure S.6.3: Résultats de simulation de la concentration en DBO_5 en 2015 et 2020 à Gia Bay pour 14 scénarios comparés à l'année de référence 2009.

6.3. Analyse coût-avantage : comparaison des coûts

6.3.1. Avantages

Dans le cadre de cette étude, il n'a pas été possible d'évaluer les avantages financiers résultant de l'amélioration de la qualité de l'eau en raison du manque de données. Par conséquent, ce critère (avantages de l'amélioration de la qualité de l'eau) n'est pas pris en compte pour établir les niveaux de priorité pour les scénarios dans l'analyse coût-avantage. Cependant, il est important de noter l'amélioration de la qualité des eaux de surface comporte plusieurs avantages : la diminution des coûts de production d'eau potable, la santé publique, la conservation de la biodiversité dans les systèmes d'eau douce, etc. En effet, les écosystèmes peuvent être affectés sur le court terme par la pollution lorsqu'un seuil est dépassé. Un autre avantage de l'amélioration de la qualité de l'eau est dans le domaine agricole avec la disponibilité d'une eau de bonne qualité pour l'irrigation par exemple. Par ailleurs, d'autres avantages sont prévus pour les activités récréatives telles que la baignade.

6.3.2. Comparaison des coûts des scénarios

Les coûts des différentes interventions (ex. : l'installation de systèmes de collecte et de traitement des eaux usées domestiques) que les gouvernements locaux doivent assumer pour améliorer la qualité de l'eau sont considérés. Toutefois, en raison du manque de données, seule une comparaison entre les coûts des différents groupes de scénarios a été faite pour déterminer leur niveau de priorité.

Scénarios de croissance démographique et des eaux usées d'origine domestique (S1, S2, S3)

Le scénario S1 a le coût le plus bas pour ce groupe car les capacités des deux usines de traitement sont les plus faibles. Le scénario S2 a le coût moyen tandis que le scénario S3 a le coût le plus élevé. Par conséquent, on attribue à S1 le niveau de priorité le plus élevé, à S2 le niveau de priorité moyen et à S3 le plus faible niveau de priorité.

Scénarios de l'industrie (S4, S5, S6)

Les différents niveaux de risques pour la santé publique et les écosystèmes sont considérés ici afin de comparer les différents niveaux de coûts que le gouvernement local aurait à assumer pour résoudre le problème si un événement majeur se pose. Le scénario S4 a le plus faible niveau de risque, et donc, le plus faible niveau de coût, car les rejets industriels pour ce scénario sont plus faibles que ceux des deux autres scénarios. Le scénario S5 a le niveau de risque et de coût moyens, tandis que le scénario S6 a les niveaux de risque et de coût les plus élevés en raison de ses rejets industriels qui sont plus élevés que ceux des deux autres scénarios. Par conséquent, on attribue à S4 le niveau de priorité le plus élevé, à S5 le niveau de priorité moyen et à S6 le niveau de priorité le plus faible.

Scénarios de la population, des eaux usées domestiques et de l'industrie

Le scénario S7, qui est la combinaison des scénarios S1 et S4 (voir tableau S.5.1), a un niveau de priorité élevé étant donné que ces deux scénarios ont chacun un niveau de priorité élevé. Le scénario S8, qui est la combinaison des scénarios S2 et S5, a un niveau de priorité moyen compte tenu du niveau de priorité moyen de chacun des scénarios dont il dérive. Le scénario S9, qui est la combinaison des scénarios S3 et S6, a un niveau de priorité faible car ces deux scénarios ont chacun un niveau de priorité faible.

Les scénarios S10, S11, S12, S13 sont respectivement la combinaison du scénario S8 et : (1) de l'augmentation du cheptel; (2) des fertilisants; (3) des forêts; et (4) du changement climatique. Le scénario S14 est la combinaison d'un niveau moyen de tous les facteurs. La comparaison des coûts ne pouvant pas se faire pour cause de manque de données sur les coûts inhérents à l'augmentation du cheptel, à l'utilisation des fertilisants, à la reforestation, etc., le niveau de priorité moyen est attribué à chacun des cinq scénarios S10 à S14, niveau identique à celui du scénario S8.

6.4. Comparaison et choix des scénarios

En utilisant la méthode multicritère (voir section 4.5), la comparaison et le choix des scénarios sont effectués sur la base des résultats des niveaux de priorité de scénarios pour les trois critères (les idées des experts, les résultats des simulations de la qualité de l'eau et l'analyse coût-avantage). Le calcul du score final pour chaque scénario a également pris en compte le poids de chaque critère (voir section 4.5). Les résultats (Tableau S.6.1) indiquent que les trois scénarios S2, S8 et S14 ont le score le plus élevé. Cela signifie qu'ils ont le niveau de priorité le plus élevé parmi les 14 scénarios. Par conséquent, ces scénarios peuvent être recommandés aux pouvoirs publics dans le plan de développement socio-économique futur.

Les interventions recommandées pour améliorer la qualité de l'eau du bassin versant de la rivière Cau sont : (1) l'augmentation de la capacité de l'usine de traitement des eaux usées domestiques de la ville de Bac Kan pour 20 000 habitants au lieu de 10 000 habitants (prévision du gouvernement local); (2) le maintien de la projection de l'usine de traitement des eaux usées domestiques pour 100 000 personnes pour la ville de Thaï Nguyen; et (3) l'installation d'une usine de traitement pour la ville de Song Cong, pour 10 000 habitants, dans la province de Thai Nguyen.

Tableau S.6.1: Score final pour les 14 scénarios analysés pour l'ensemble du bassin versant.

Scénario	Idées des experts			Qualité de l'eau			Coût-avantage			Score final
	Priorité	Score	Poids	Priorité	Score	Poids	Priorité	Score	Poids	
S1	Faible	1	2	Faible	1	2	Élevé	3	1	7
S2	Élevé	3	2	Élevé	3	2	Moyen	2	1	14
S3	Élevé	3	2	Élevé	3	2	Faible	1	1	13
S4	Faible	1	2	Faible	1	2	Élevé	3	1	7
S5	Élevé	3	2	Faible	1	2	Moyen	2	1	10
S6	Moyen	2	2	Faible	1	2	Faible	1	1	7
S7	Faible	1	2	Faible	1	2	Élevé	3	1	7
S8	Élevé	3	2	Élevé	3	2	Moyen	2	1	14
S9	Moyen	2	2	Élevé	3	2	Faible	1	1	11
S10	Moyen	2	2	Moyen	2	2	Moyen	2	1	10
S11	Faible	1	2	Moyen	2	2	Moyen	2	1	8
S12	Faible	1	2	Moyen	2	2	Moyen	2	1	8
S13	Faible	1	2	Moyen	2	2	Moyen	2	1	8
S14	Élevé	3	2	Élevé	3	2	Moyen	2	1	14

7. Conclusion, recommandations et perspectives

Cette étude, effectuée dans le cadre de la gestion intégrée des ressources en eau du bassin versant de la rivière Cau au Vietnam, a permis de développer et de comparer différents scénarios d'intervention pour l'amélioration de la qualité de l'eau à l'horizon 2020. La comparaison entre l'état de référence (2009) et le futur montre que les facteurs qui pourront significativement influencer la qualité de l'eau dans le futur sont la croissance démographique et les eaux usées d'origine domestique. Si les normes de rejets industriels sont respectées, les industries devraient avoir un impact mineur sur la qualité de l'eau. Les autres facteurs ont des impacts mineurs sur la qualité de l'eau selon les résultats de simulation de la qualité de l'eau.

Dans cette étude, on a élaboré une méthode de développement de scénarios dans un contexte de données rares et une méthode de sélection de scénarios basée sur l'analyse multicritère. Cela a permis de choisir trois scénarios parmi les 14 analysés comme étant les meilleurs, soit S2, S8 et S14. Par conséquent, diverses interventions correspondant à ces scénarios sont recommandées en 2015 pour améliorer la qualité des eaux de surface dans ce bassin versant.

Il est important de noter que cette recherche contribue à une évaluation systématique de l'impact du développement socio-économique futur sur la qualité des eaux de surface dans le bassin versant de la rivière Cau, notamment dans les provinces Bac Kan et Thai Nguyen, par l'identification des meilleures interventions optimales pour l'amélioration de la qualité de l'eau.

Outre les recommandations pour les interventions, les facteurs tels que la population et l'industrie doivent être contrôlés afin d'améliorer la qualité de l'eau. Des analyses effectuées à partir d'hypothèses d'absence de systèmes de traitement d'eaux usées d'origine domestique ou industrielle (pour les usines actuelles) ont permis de mettre en relief une dégradation de la qualité de l'eau en l'absence de systèmes de traitement d'eaux usées ou, au mieux, une qualité dans le futur similaire à celle de la situation de référence. En effet, la croissance future rapide de la population dans la ville de Bac Kan (à contrôler pour la période allant de 2016 à 2020 étant donné le flux migratoire prévu) est la raison pour laquelle les concentrations de certaines variables de qualité de l'eau sont supérieures à celles de 2009 et de 2015 dans la partie amont du bassin versant. Les normes de rejets industriels doivent être respectées pour que les niveaux de charges dans les rejets ne soient pas plus élevés que celles recommandées par la norme. Cela modifierait les conclusions de cette étude. Même si l'effet n'est pas significatif, le programme de reforestation prévu est également recommandé pour réduire les effets négatifs de l'érosion et du transport de sédiments dans la région montagneuse en amont du bassin versant.

Par ailleurs, les années de prévision considérées ne dépassent pas 2020. Cela constituerait une courte période de prédiction pour permettre une étude exhaustive de l'impact du changement climatique sur la qualité de l'eau. Par conséquent, d'autres études considérant une période de prévision plus longue devraient être menées.

L'un des défis majeur de cette étude est le manque de données dans la zone d'étude. Pour pallier en partie à cette situation, plusieurs hypothèses ont été formulées pour compléter les données d'entrée de GIBSI et élaborer des scénarios. Bien entendu, il aurait été préférable d'avoir des données plus complètes afin de réduire les incertitudes sur les résultats de la qualité de l'eau du bassin versant de la rivière Cau.

Chapter 1: Introduction

1.1. Context of the research

Cau River is a river in the North of Vietnam. The natural area of the river basin is 6,030 km^2, representing 2% of the total country area (Environment Report of Vietnam, 2006). The Cau River system has some major branches which flow through many cities, towns and industrial zones.

The region of Cau River Basin includes 200 craft villages, and around 800 industries at different scales due to the economic development (industrialization) during the last decades (Environment Report of Vietnam, 2006). Intensive agriculture is also developed in this area with the use of pesticides and fertilizers. One of the major consequences of all these activities in the river basin is the pollution of surface water of the Cau River system in some river segments. Nowadays, the water pollution in the Cau River system has become more and more serious in several parts of the river basin. For example, in the upstream of Cau River, concentrations of water quality variables have exceeded in some locations in the river system the Vietnamese standard for surface water quality for domestic purposes (see TCVN 5942-1995 (A), figure A1.1 in Appendix A1) in Bac Kan province.

In the mid-stream of Cau River in Thai Nguyen province, Cau River is clearly polluted, especially at the part flowing through Thai Nguyen City. In the segment of Cau River flowing through Thai Nguyen, metallurgy factory, some variables describing water quality such as SS, BOD_5, and chemical oxygen demand (COD) exceeded 2 to 3 times the water quality standard for domestic and other purposes (see TCVN 5942-1995 (A), figure A.1.2 in Appendix). In some locations in Phuong Hoang stream flowing through Tan Long ward in Thai Nguyen City, the stream water is also seriously polluted by organic pollutants, caused by untreated wastewater from a paper manufacture directly discharging into the stream. In Cong River in Thai Nguyen province, the second largest river in the basin, the water has initial signs of organic and oil pollution (Environment Report of Vietnam, 2006). This river segment is impacted by tourism activities on Nui Coc Lake, sand exploitation in the river, wastewater from mining activities and from Song Cong industrial zone.

In the downstream of Cau River flowing through Bac Giang and Bac Ninh provinces, the water has been severely polluted by organic substances. Concentration of BOD_5 in this segment has exceeded the standard of surface water quality for domestic purpose (see TCVN 5942-1995 (A), Figure A.1.3 in Appendix).

Water pollution can affect population health (diseases) and water ecosystem (decline of fauna and flora), water availability for economic development, water flow, etc. It is therefore urgent to ensure an environmental improvement of Cau River Basin, as one of the priorities and important tasks of Vietnamese government. In fact, the decision N° 174/2006/QD-TTg of the Prime Minister on "Approving the master plan on the protection and sustainable development of the landscape and ecological environment of Cau River Basin" has been signed on 28th July 2006. This decision mentioned that the general orientation of this master plan is to gradually carry out pollution treatment, improve river environment quality in order to, by 2020, make Cau River clean and to ensure water balance for social-economic development demands in the basin, maintain stable water flow, ensure safety for irrigation works as well as beautiful natural landscape.

This doctoral research aims at contributing to the achievement of the goals of water quality improvement and sustainable water use in Cau River Basin by identifying and prioritizing the interventions. This can help the decision-makers selecting the optimal interventions to "make Cau River clean" which the above master plan mentioned.

1.2. Research objective

1.2.1. Principal objective

The objective of the research is to develop a methodology for social-economic scenarios building and comparison in order to identify the best interventions to improve water quality in Cau River in the context of river basin integrated management.

1.2.2. Sub-objectives

- Sub-objective 1: Propose various scenarios of interventions
- Sub-objective 2: Evaluate the impacts of different scenarios on water quality of Cau River Basin.

- Sub-objective 3: Evaluate the costs and benefits of various interventions related to the improvement of water quality.
- Sub-objective 4: Elaborate a methodology of scenario comparison and selection. Participation of stakeholders is considered in scenario selection.

1.2.3. Specific tasks

** To achieve the sub-objective 1:*

- Establish social - economic projections for Cau River Basin for 10 years ahead (until 2020), for example: population, industry, land use, etc. and projections of climate change.
- Propose various scenarios of interventions.
- Verify if these proposed scenarios correspond to the expected evolution of the activities on this river basin, as well as to the political wishes of leaders.

** To achieve the sub-objective 2:*

- Evaluate the impacts of the scenarios on water quality of Cau River system with the aid of the computer tool of integrated management GIBSI which was previously calibrated according to the characteristics of Cau River Basin in the framework of the project of Cau River Basin integrated management between INRS (Institut National de la Recherche Scientifique) and VAST (Vietnamese Academy of Science and Technology).

** To achieve the sub-objective 3:*

- Evaluate the economic benefits related to the improvement of water quality (reduction of the cost for treatment of drinking water, increase of tourism, etc.).
- Evaluate the costs of various interventions for improving the water quality (construction of waste water treatment systems, etc.).
- Compare the costs and the benefits for each of these scenarios (based on the results of the simulations of GIBSI).

** To achieve the sub-objective 4:*

- Establish a set of criteria to evaluate and select the scenarios.
- Take the ideas of stakeholders to rank the importance level of each scenario.

1.3. Originality of the thesis

One of the main objectives of this thesis is to build future social-economic development scenarios for Cau River Basin in Vietnam in the context of few available data in the study area. Therefore, the **first originality** of this thesis is to find out the appropriate methods for building development scenarios for the study area. The **second originality** of this thesis is to elaborate a methodology of selection of the developed scenarios. The ideas of stakeholders and cost comparison will be considered to select scenarios. The **third originality** of this thesis is the use of a river basin integrated management computer tool GIBSI to assess impacts of future social-economic development scenarios on water quality in the study area in Vietnam.

1.4. Plan of the thesis report

In this report, the following parts are presented:

- **Chapter 2:** Literature review

This chapter concerns the approaches and methods which were developed or used in previous studies related to the objective of this doctoral study.

- **Chapter 3:** Case study and implementation tool

+ *Case study:*

General information about the study area, such as natural characteristics of Cau River Basin in Vietnam, current social conditions of Bac Kan and Thai Nguyen provinces, and a previous related study on Cau River Basin are presented. A comparison of the differences between the previous project in Vietnam and the present doctoral study is made.

+ *Implementation tool:*

The main reasons which justified the choice of GIBSI as the implementation tool in this research are given. The information about GIBSI system, as well as its functions of scenario development and simulation are also presented.

- **Chapter 4:** Methodology

This section of methodology concerns the approaches and methods which are used in this doctoral study in order to achieve the objectives.

- **Chapter 5:** Scenario development

This chapter talks about the steps to develop scenarios and the scenario development for Cau River Basin in Bac Kan and Thai Nguyen provinces.

- **Chapter 6:** Scenario comparison and selection

Three results of scenario assessment: (1) taking the ideas of stakeholders about the scenarios, (2) assessing the impacts of each scenario on surface water quality in Cau River Basin, and (3) analysing cost/ benefit for each scenario, and the result of scenario selection for Cau River Basin in Bac Kan and Thai Nguyen provinces are presented in this chapter.

- **Chapter 7:** Conclusions, uncertainties, recommendations and perspectives

Several conclusions, recommendations and perspectives are given in this chapter. Besides, several uncertainties and how to solve these uncertainties in this research are also presented in this chapter.

Chapter 2: Literature review

This chapter talks about the approaches and methods which were developed or used in previous studies related to the objective of this doctoral research.

2.1. Watershed integrated management

River basin integrated management has been studied, for most of the related researches, from the 1990s. Earlier, Villeneuve *et al.* (1975) conducted a study on the basin of the St. François River in Quebec. They established planning use of water resources and also provide useful facilities for this purpose. It is in the context of a pilot study that a methodology for appropriate development to Quebec conditions has been developed. Shin (1999) wrote: "River basins are inherently complex systems comprising many interdependent components. Management practices that respond to a single water user, a single population segment, or a single economic sector, have often caused inadvertent disruption to other activities in the river basins (Lee and Dinar, 1996). Thus, in watershed planning, an integrated approach has received much attention in recent years (Gardiner 1994, Jacobs 1994, Burton 1995, Howard *et al.* 1995; Miloradov *et al.* 1995)".

Since this period of the 1990s, more and more researches concerning the approach of integrated management of river basin have been done. For example, the work of Scoccimarro *et al.* (1999) carried out in northern Thailand for developing a methodology which reflects the multi-objective nature of resource management through integrating models of physical and social-economic decision making. The objective of this study was to describe a multi-disciplinary methodology which can be used to assess water resource management in northern Thailand. The methodology identified and integrated contributions from biophysical, economic and social-cultural aspects in the development of a scenario-modeling Decision Support System (DSS). Linkages between the four components in the DSS are summarized in Figure A.2.1 in Appendix.

In this study, the modeling unit is called "Resources Management Unit", a key in the DSS. This unit will be the basic of scenario assessment. The DSS is used to see the effects of the various scenarios on multiple indicators. The needs of different stakeholders were also considered in this research. The multiple indicators in this study were defined based on the outputs of biophysical, social-cultural and economic aspects. For example, for the biophysical aspect, the indicators were the quantity and quality of surface water resources at various nodes in the catchment. For the social-cultural aspects, the indicators were the level of conflict between ethnic groups, or between village groups and government agencies. For the economic aspect, the indicators were the trends and variability in agricultural production and the opportunities for investment. These indicators help stakeholders to assess various scenarios according to multiple objectives. However, Scoccimarro *et al.* (1999) mentioned that there was no single software tool which could meet the three requirements to obtain their objectives: (1) a geographical information system for storage and display of spatial (and some non-spatial) data, (2) a customised user interface to manage scenario investigation and (3) a simulation and optimisation engine. That's why their study used three separated software: (1) *ArcView* - a geographical database, for the storage of data sets and for the spatial display of outputs, (2) *Visual Basic* for the graphical interface and (3) *Extend* package (http://www.extendsim.com) for the simulation and optimisation. And after that, a graphical interface was created in *Visual Basic* by overlaying *ArcView* and *Extend*. This interface could manage the scenarios and provide links between the spatial database and the simulation results.

In the North of China, a study carried out by Liu *et al.* (2007) also mentioned the watershed management system as a process comprising policies, techniques, and development on different temporal and spatial scales. According to this research, a watershed management system is often divided into social, economic, environmental, and resource subsystems. Relationships between these subsystems can be summarized (Figure A.2.2 in Appendix).

Like in the work of Scoccimarro *et al.* (1999), scenario analysis for watershed management was also mentioned in the study of Liu *et al.* (2007). Scenario analysis is used to forecast changes in social-economic system as well as the environmental problems. It is helpful for watershed management (Shiftan *et al.* 2003), and optimisation for watershed management can only be developed in the context of specific scenarios (Liu *et al.* 2007). Therefore, it can be said that, the approach of watershed integrated management is necessary to deal with the conflicts between social-economic development and the environment for a sustainable development. Other authors also highlighted the main components necessary to undertake integrated management of river basins. In fact, according to Villeneuve *et al.* (2009), there are five principal components which should be taken into consideration:

(a) Social development options.

(b) Development scenarios.

(c) Knowledge of study area:

(i) inventory of the resources usage level and land uses of the area;

(ii) information on the physical and hydrological characteristics of the river basin; and,

(iii) *information* on the quality and quantity of water resources.

(d) Modelling tools:

(i) computational tools to model the concerning processes; and

(ii) human resources to implement and use the modelling tools intelligently.

(e) Political wish of leaders with the resulting recommendations and apply the retained scenario during the process of integrated management.

Also according to Villeneuve *et al.* (2009), in order to undertake this approach, various stakeholders must be engaged. There are four groups of stakeholders:

- The first group: watershed users whose role is to find and build social consensus concerning resources' usage level and land use, helping to elaborate various development scenarios.
- The second group: governmental agencies whose role is to supply data acquisition (usage, land use, water resources, resource quality, basin characteristics, etc.).
- The third group: scientific and technical analysts who will use the computational tools and the models to simulate and evaluate the impacts of the proposed scenarios and to identify which scenarios should be retained.
- The fourth group: decision-makers who will apply the selected scenario and determine how it will be funded. And they are also the people who make priority action within the plan based on the scenarios retained by the technical group.

2.2. Optimization method based on scenario analysis

The major goal of this part is to provide some definitions about optimization. The study of Liu *et al.* (2007), proposing an optimization method based on scenario analysis, is later presented in this part. This method is used as orientation to propose an optimization approach in chapter 4 of methodology in this report.

"Optimization is an act, process, or methodology of making something (as a design, system, or decision) as fully perfect, functional, or effective as possible" (http://www.merriam-webster.com/dictionary/optimization). Another definition can be found in http://www.businessdictionary.com: "Optimization refers to finding an alternative with the most cost effective or highest achievable performance under the given constraints, by maximizing desired factors and minimizing undesired ones. In comparison, maximization means trying to attain the highest or maximum result or outcome without regard to cost or expense".

In the study of Liu *et al.* (2007), an optimization method based on scenario analysis was proposed to deal with the uncertainties of watershed management. System analysis, forecast methods, scenario analysis, and the contributions of stakeholders and experts were integrated into this method. The four steps of this optimization method are summarized in Figure 2.1.

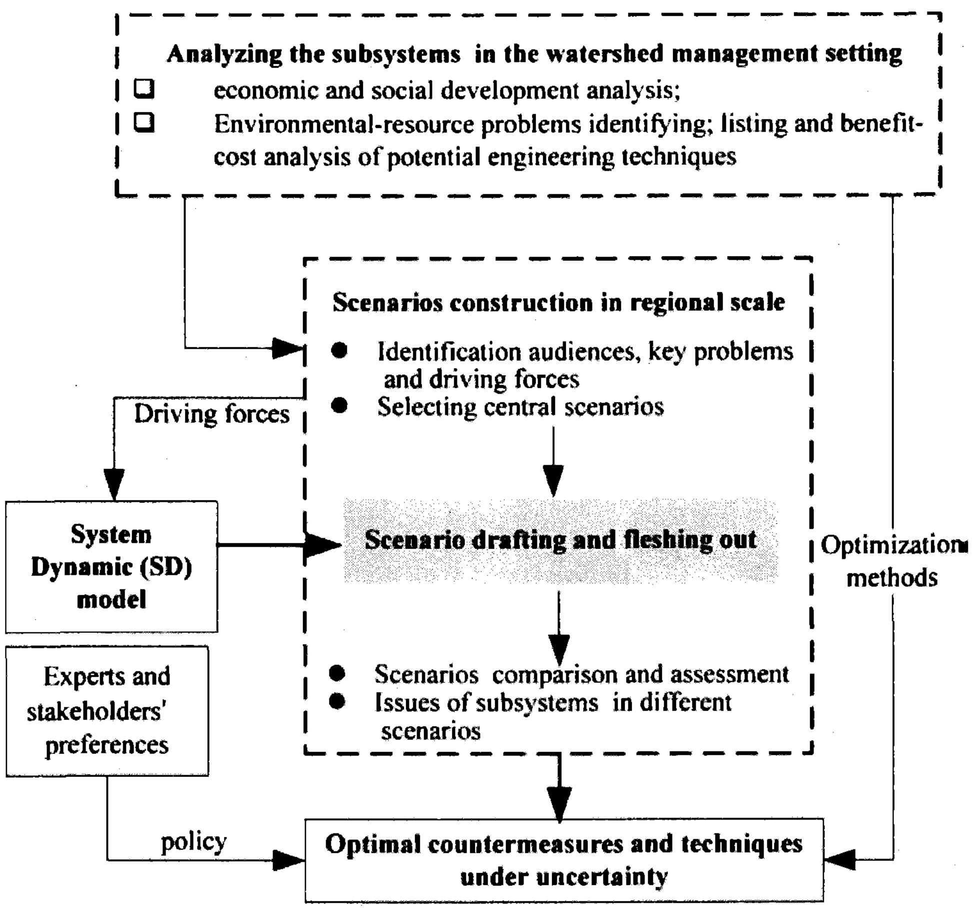


Figure 2.1: The study approach of scenario analysis as an optimizing method for watershed management under uncertainty (from Liu *et al.* 2007).

This study mentioned that uncertainties include four categories: (1) intrinsic uncertainties in sub-systems related to social, economic and environmental aspects, (2) external uncertainties related to the stress of factors beyond the watershed, (3) uncertainties related to raw data and model variables, and (4) uncertainties related to human factors (Jamieson 1996; Hamed and El-Beshry 2004 cited in Liu *et al.* 2007) (Figure A.2.3 in Appendix).

There is a difficulty in predicting and addressing intrinsic uncertainties, and because of that an understanding of the system and a forecast of potential changes in the system are required (Liu *et al.* 2007). This is the first of the four steps necessary for an optimization based on scenario analysis which can be detailed as follows:

Step 1: Watershed management system analysis

A watershed management system includes social, economic, environmental, and resource subsystems (Figure 2.2). In this step, these subsystems are analyzed. The potential social-economic development and the existing or potential problems in environmental and resource subsystems are examined.

Step 2: Listing of potential policies and engineering techniques

This step lists the possible policies and engineering techniques implemented for watershed management, based on the system analysis, such as wastewater treatment, ecological engineering, wetland and water resource utilization techniques.

Step 3: Scenario analysis

In this step, scenarios are developed and analysed. Liu et al. (2007) constructed scenarios in five stages like in other studies (Richard and Scott 1996; Ringland 1998; Ratcliffe 1999; Hugues 2000) in order to forecast and simulate potential changes in the watershed management system.

(1) Identify the audience, key problems, and driving forces

The audiences are people involved in watershed management. Key problems are existing difficulties such as environmental pollution, scarcity of water resources, and local poverty. Driving forces are important factors such as financial budget and national policies, affecting changes in the watershed. Experts and stakeholders participate in identifying key problems and driving forces.

(2) Select central scenarios

The central scenarios are selected based on the ranking of driving forces or factors. Driving factors are grouped into four parts based on their importance and uncertainty (Figure 2.2).

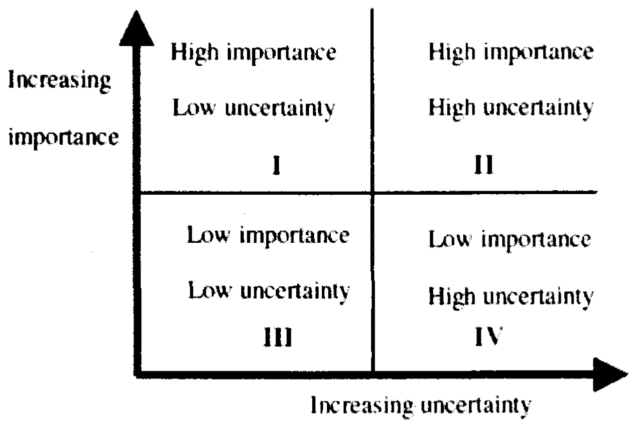


Figure 2.2: Ranking of driving forces for importance and uncertainty in the scenarios building (from Liu *et al.* 2007).

In parts I and II, factors located there, called U_1, U_2 in the following, are important for the selection of central scenarios.

n_1 different changes are presents for U_1.

n_2 different changes are presents for U_2.

Then, based on the example of two factors, n_1 n_2 scenarios are drafted based on the following equation:

$$S = f(U_1, U_2) = f\left(\{U_{1,1}, \ldots U_{1,j}, \ldots U_{1,n_1}\}, \{U_{2,1}, \ldots U_{2,j}, \ldots U_{2,n_2}\}\right) = \{S_{1,1}, \ldots S_{i,j}, \ldots S_{n_1,n_2}\} \quad \text{(Eq. 2.1)}$$

Where:

S: a set of scenarios,

f: the function from U_1 and U_2 to S,

$U_{1,i}$ and $U_{2,j}$: the potential changes in U_1 and U_2,

$S_{i,j}$: a scenario.

The central scenarios are the scenarios derived from the most important driving factors U_1, U_2.

For example, Liu *et al.* 2007 selected two key driving factors for their case study of Qionghai Lake watershed in Southern China, those were: the economic growth (U_1) and the government decisions (U_2). Then, the potential changes in U_1 and U_2 were determined and four scenarios under U_1, namely S_{E1}, S_{E2}, S_{E3}, S_{E4}, and two scenarios under U_2, namely S_{P1}, S_{P2}, were identified for consideration as follows:

- S_{E1}: maintain the existing growth rate;

- S_{E2}: induce a relatively high growth rate;

- S_{E3}: limit the growth of industry while promoting the growth of the service industry;

- S_{E4}: promote the growth of industry;

- S_{P1}: maintain the existing policies and plans concerning watershed management;

- S_{P2}: adopt strict policies concerning pollution and resource utilization in the watershed;

After that, eight scenarios were drafted based on the following equation:

$$S = f(U_1, U_2) = f(\{S_{E1}, S_{E2}, S_{E3}, S_{E4}\}, \{S_{P1}, S_{P2}\}) = \{S_{1,1}, S_{1,2}, S_{1,3}, S_{1,4}, S_{2,1}, S_{2,2}, S_{2,3}, S_{2,4}\} \quad \text{(Eq. 2.2)}$$

(3) Draft and flesh out the scenarios

In the study of Liu *et al.* (2007), a system dynamics (SD) model was used to forecast the driving factors. Scenario drafting and fleshing out is an interactive process related to model results, researchers, and stakeholders.

(4) Evaluate the scenarios

All central scenarios should be evaluated in order to identify which among them are the most reasonable and useful. This evaluation is based on the ideas of stakeholders and experts, as well as various integrated assessment tools, such as multi-criteria evaluation.

(5) Conduct comprehensive analysis

It is necessary to analyse comprehensively the potential issues under specific scenarios to select future countermeasures, policies, or techniques.

Step 4: Optimize policies and engineering techniques

Based on the scenario analysis, policies and engineering techniques will be selected using cost-benefit analysis and multi criteria analysis. The participation of experts and local stakeholders plays an important role during the final selection process.

2.3. Land-use scenarios

Land-use changes are changes of land-cover types, changing surface runoff generation, and consequently influencing watershed hydrological processes (Wang *et al.* 2008). The effects of land-use changes on hydrological process include effects on infiltration, groundwater recharge, base flow and runoff in a watershed (Lin *et al.* 2007a). Therefore, understanding the hydrological response to future land-use change scenarios is an important aspect for watershed management. This part will present some examples about developing land-use scenarios. There are three studies presented in this section: two studies of Lin *et al.* (2007a, b) and one of Wang *et al.* (2008).

In a region or a country, the future land use scenarios are normally developed based on the land use demands and conversion policies in this specific region or country. For example, in the study of Lin *et al.* (2007a) conducted in northern Taiwan, based on annual birth rates of 1.17 and 1.50%, two land-use demands (low and high development demands) were used to develop land-use scenarios from 2000 to 2020. Besides, the 1995 agricultural land release policy of the Council of Agriculture, Executive Yuan, Taiwan which involves two land-use conversion rules (free conversion and agricultural protection conversion) was used to create scenarios in this research. According to the free conversion rule, agricultural land, forest and grasslands can be converted to each other, but built-up area and water bodies cannot be converted into other land uses. According to the agricultural protection conversion rule, agricultural land is not allowed to be converted into built-up area and forest. So, based on two land-use demands and two conversion rules, four land-use scenarios were developed: (1) scenario I: low development demand and free conversion, (2) scenario II: high development demand and free conversion, (3) scenario III: high development demand and agricultural protection conversion, and (4) scenario IV: low development demand and agricultural protection conversion.

Also, in another study of Lin *et al.* (2007b) for the case study of Wu-Tu watershed in Northern Taiwan, based on an annual birth rate of 1.05%, land use demands were calculated for simulating land use scenarios from 2000 to 2020. It can be noticed that agricultural, forested and grassed area demands were assumed to decrease, build-up area demand to increase and water body was assumed to be constant in this research. Four scenarios were created based on two different spatial policies which are set based on governmental regulations in Taiwan's Water Resources Protection Act and the Hillside Protection Act (the baseline policy: a regular baseline plan to protect water supply resources and sections of forested areas; and the conservation policy: a conservation plan for protecting hillsides, water supply sources and large forested areas) and two conversion rules (free conversion and agricultural protection conversion). The four different scenarios were: (1) scenario A, based on the baseline policy and the free conversion, (2) scenario B, based on the conservation policy and the free conversion, (3) scenario C, based on the baseline policy and the agricultural protection conversion and (4) scenario D, based on the conservation policy and agricultural protection conversion.

Besides, in another research (Wang *et al.* 2008), land use scenarios are created based on the current land-use conditions to build some different assumptions of land-use changes. In this study, the land-use types in the Zamu River basin in northwest China showed that grassland and forestland dominated and occupied 80.5% of the total catchment area. Therefore, three land-use scenarios were developed based on the assumptions of conversion of these two land-use types: (1) scenario 1 assumed that all the current grassland was converted into forestland, and the remaining land uses remained constant; (2) scenario 2 assumed that 25% of the current grassland was converted into forestland; and (3) scenario 3 assumed that all the current forestland was converted into grassland for grazing.

2.4. Climate change scenarios

Climate change will affect local and regional hydrological regimes (Lin *et al.* 2007a). The amount and distribution of regional precipitation and temperature will be affected by climate change, influencing catchment runoff (Wang *et al.* 2008). So, it is necessary to study the hydrological response of river basins to different climate-change and therefore consequences for surface water quality. Selection of climate change scenario is an important step to investigate effects of climate change on water resources.

Different types of climate change scenarios can be found in the literature. The Handbook of United Nations Environment Programme (UNEP) on "Methods for Climate Change Impact Assessment and Adaptation Strategies" (Feenstra *et al.* 1998) presented a complete review of different families of scenarios.

(1) General circulation Models (GCM) for greenhouse gases which outputs can be used to build climate change scenarios. They are mathematical models representing atmosphere, ocean, ice cap, and land surface processes and following physical rules and physically-based empirical relationships.

(2) Synthetic scenarios based on assumptions on some changes in meteorological variables (temperature and precipitation) over a study area.

(3) Analogue scenarios (temporal analogue scenarios and spatial analogue scenarios). Temporal analogue scenarios use data from past climate to create a scenario of future climate. There are two data (weather observations, paleoclimatic record) to build temporal analogue scenarios. Spatial analogue scenarios are current climate in another location which can help to create a scenario of future climate in a study area.

Because of uncertainties to determine climate in the future, a complete review on advantages and disadvantages of each type of family of climate change scenarios, as well as combinations of scenarios based on outputs from GCMs and synthetic scenarios are recommended by UNEP (Feenstra *et al.* 1998). For example, based on synthetic scenario approach, Wang *et al.* (2008) conducted a study in China to analyse how the flow response to (1) precipitation under the same temperature condition and (2) air temperature under the same precipitation condition. They found that increase of air temperature affects snowmelt, making more runoff, more potential evaporation, leading to less flow at the outlet of watershed.

In Vietnam, being aware of the impacts of climate change, the Government has approved the "National target program to cope with the climate change" in 2008. One of the important targets of this program is to develop and update climate change scenarios. The objective of the development of climate change scenarios for Vietnam is to bring out the basic information of the trend of climate change in Vietnam in the future, with respect to different scenarios of global social-economic development. An example of simulations results of future temperature in Vietnam is shown (Figure A.2.4 in Appendix). The scenarios will be the initial orientation for various sectors, local governments, etc. to assess the possible impacts of climate change on developing and implementing action plans for the purpose of adaptation and mitigation to climate change in the future. The development of climate change scenarios for Vietnam is based on several studies such as the reports of Institute of Meteorology and Hydrology published in 2006 and 2008 on climate change scenarios for Vietnam using different methods (IMHEN, 2010a and b).

Based on the initial orientation a project of "Impacts of climate change on water resources and adaptation measures" was carried out in 2010 by the Vietnam Institute of Meteorology, Hydrology and Environment. This project was one of the practical activities to implement the National target program. The immediate objectives of this project were to assess the impacts of climate change on water resources in many river basins of Vietnam and to propose adapting measures to water resources changing due to climate change (IMHEN, 2010a & b).

The project selected scenarios of greenhouse gases' emission in order to develop the climate change scenarios for the study river basins. In these scenarios, the mean monthly variations of two important meteorological elements (rainfall and air temperature) were computed and analyzed for each meteorological station in the study areas until the end of the 21st century. Besides, potential evapotranspiration, sea level rise, etc. were also analysed. The period of time used for comparison is 1980-1999. Based on calculation of future air temperature and rainfall, impacts of climate change on natural flow, water and power uses, flooding and salinity intrusion etc., were determined by using a rainfall - runoff model, a water balance model and a hydrodynamic model (IMHEN, 2010a).

The results of this project provided basic information concerning the impacts of climate change on water resources in Vietnam, as well as a scientific basis for future studies. The computed values of future precipitation and air temperature from this study for several meteorological stations are used in this doctoral research for building climate change scenario in order to assess their impacts on water quality variables in Cau River Basin. To deal with uncertainties inherent to scenario selection, the study recommended climate change scenario based on average greenhouse gases emission as the most reliable scenario to carry out studies in Vietnam.

2.5. Industrial scenarios

Industry is one of the major important components in economy. It more and more develops, especially in the developing countries where industrialization becomes one of the main concerns of government. However, the facts show that industrial activities have been causing water pollution. Therefore, creation of industrial scenarios and their impact assessment on the environment are necessary to help managers in making policies concerning industrial development and environmental protection.

Few examples on industrial scenarios were found in the literature. Therefore, this part will give an example of the study of Leal-Neto *et al.* (2006) which created some industrial scenarios for the Sepetiba Bay watershed, Brazil. The Sepetiba watershed is the major area for industry development in the Rio de Janeiro Metropolitan Area. This research considered three scenarios for this region: "Business as usual", "Industry concentration in Itaguaı´" (Itaguaı´ is the county where the port of Sepetiba is located), and "Intense secondary industrialization in the watershed".

- The first scenario means that the present industrial process is expected to continue. Industries will gather in the sites that were already considered as priority options for industrial investment decisions.
- The second scenario concentrates in a cumulative industrial development in Itaguaı´ County.
- The third scenario means that industrial development will be diversified with an internal integration in the region.

These industrial scenarios were then assessed together with other agents affecting the Sepetiba Bay environment such as population, commerce, services and tourism, land use, infrastructure.

2.6. Population forecast and impact

There are several populations forecast methods. A review of some methods can be found in the literature (Smith and Sincich, 1992). This part talks about the population forecast and population impact on water environment and gives the study of Leal-Neto *et al.* (2006) as example.

Population forecast

Population forecasts estimate population size in future, which are important for planning and management purposes (Keilman, 2007).

Because future population depends on the present population and future fertility, mortality and migration rates, it is necessary to forecast these rates in order to predict distribution of population in future (William, 1988).

Okita *et al.* (2009) also said in their study on forecasting Japan's population that: "To forecast the population in subsequent years, we use the population of the previous year, age it forward by one year, and apply the forecasts for fertility, mortality and migration to update the population numbers".

An example is the study of Leal-Neto *et al.* (2006): the future population varies as a function of net birth rates (birth rate minus death rate) and net migration (immigration minus emigration). The net migration depends on the "attraction factor" of each country-which is the number of jobs available in the country (see employment effect variable, Figure A.2.5 in Appendix). The employment effect is the ratio between the number of work places and the estimated labour force in the county.

Population impact on water quality

The use of water by population can have impacts on water quality and population's health. If the house sewage discharges without any kind of treatment into streams and rivers, it will affect the water quality (Leal-Neto *et al.* 2006). Investigation of Hinrichsen and Robey (2000) showed that contaminated water together with poor sanitation kills more than 12 million people each year, especially in developing countries. Water-related diseases affect people's food and livelihood, especially in developing countries. About 90% of the diseases which occur in developing countries are caused by lack of clean water (Pimentel *et al.*, 1997). There are about four billion cases of water-contracted diseases in the world and 6 million deaths caused by water-related diseases each year (Pimentel *et al.*, 1997). Moreover, population increase will lead to the environmental problems such as water pollution, increasing the water-related diseases (Pimentel *et al.*, 1997). Therefore, it is especially important to forecast population growth in order to analyze its effects on the environment.

For example, in the study of Leal-Neto *et al.* (2006), after forecasting the population, they authors analysed BOD load caused by population on the period 1996-2020. This study considered the major source of BOD increase as due to the population. The concentration of BOD was calculated using the following equation with the attempt to model situations at different stages of the sewage treatment plants (STPs) implementation along several time periods:

$$BOD(t) = BODc \times TR \times POPa(t) + BODc \times (P(t) - POPa(t)) \qquad \text{(Eq. 2.3)}$$

Where:

BOD(t): Total BOD at time t (mg/L)

BODc: BOD per capita (mg/L/inhabitant)

TR: treatment reduction (according to the technology employed in the STP)

POPa(t): population assisted by the treatment plant at time t

P(t): Population of the sub-watershed at time t.

2.7. Cost-benefit analysis

"Cost-benefit analysis is a formal analysis of the impacts of a measure or programme, designed to assess whether the advantages (benefits) of the measure or programme are greater than its disadvantages (costs)" (SafetyNet, 2009). This is an effective method to assess the feasibility of a project in economic aspect (Zhou *et al.*, 2005). Before the implementation of a project, the CBA can help to determine the best choice among several alternatives with regards to the objectives to be achieved. This part summarizes three studies of Peng *et al.* (2007), Salvano *et al.* (2006) and Liu *et al.* (2007).

To assess the cost and environmental benefits of a reforestation program, Peng *et al.* (2007) built a method for CBA. They assessed economically the "Grain-for-Green (GFG)" project which aims to turn cultivated lands on steep terrains into forests to solve or prevent the problem of erosion and landslides in Western China. This study assessed the costs and benefits for the farmers who participated in the project in order to see whether farmers could obtain benefits from this project as well as the project's feasibility.

The data concerning household income and expenses for CBA were collected through the questionnaire survey. Costs and benefits were calculated through the net income of households on different years of farmland reforestation or bare mountain forestation implementation, as follows:

$$I_{02}G_{02} = A_{02} \times (B_{02} - C_{02} - D_{02} + E_{02}) \qquad \text{(Eq. 2.4)}$$

Where:

$I_{02}G_{02}$: the net income of households resulting from conversions from cultivated lands into forest or grassland in 2002.

A_{02}: the total area of lands which were converted in 2002 (ha).

B_{02}: Government's subsidy for farmers.

C_{02}: the costs of land conversion.

D_{02}: the net profits before conversion.

E_{02}: the net income from other jobs.

The study of Salvano *et al.* (2006) proposed another benefit/cost (B/C) methodology. They used the benefit transfer approach to evaluate potential benefits from the improvement of water quality. Benefit transfer uses the past empirical estimates of benefit to evaluate the current management (Rosenberger and Loomis, 2001). Normally, when financial resources are not enough for implementing large-scale studies, benefit transfer is the only way to evaluate the environmental benefits (Barbier *et al.* 1997). The proposed B/C methodology of Salvano *et al.* (2006) showed five steps to evaluate benefit/cost (Figure 2.3).

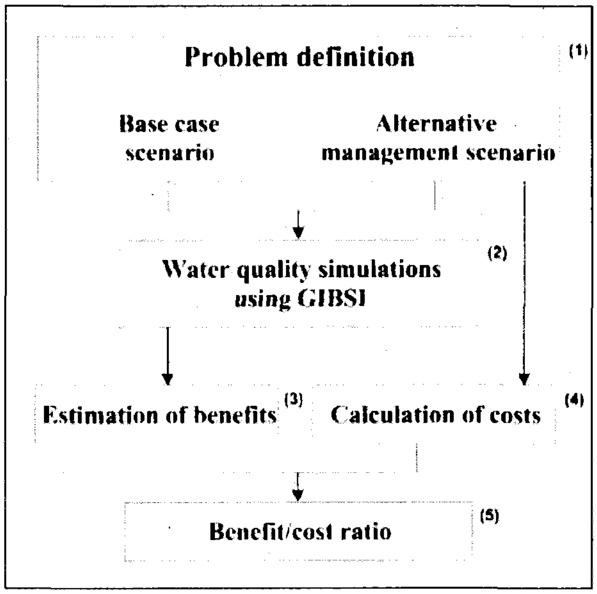


Figure 2.3: Five-step B/C methodology (from Salvano *et al.*, 2006).

- The first step describes the study area such as the current or potential water uses.
- The second step needs the water quality simulations of scenarios. Comparison of simulating results between base case scenario and alternative management scenario

indicates if water-based recreational activities or other water uses will be improved or recovered. The probabilities of exceeding water quality standards (WQSs) in river segments of interest are evaluated through simulation results for a given period such as summer period (Rousseau *et al.* 2000; 2002). If probabilities of exceeding WQSs of alternative management scenario are lower than those of the base case scenario, water quality will be improved. The lower the probabilities of exceeding WQSs are, the larger the number of potential days of water-based recreational activities is.

- The third step estimates monetary benefits from potential recovery of water uses. This study only evaluated the monetary benefits related to water-based recreational activities such as swimming, fishing, camping, canoeing. Calculation of monetary benefits is based on the daily monetary value per activity and the number of days that activity is possible (see Figure A.2.6 in Appendix):

+ The daily monetary value per activity was evaluated based on the willingness-to-pay for the enjoyment provided by nature through the survey on the importance of nature for Canadians. The value of willingness-to-pay is the sum of the actual expenditures for participation in nature-related activities (*e.g.* accommodation, transportation, food and equipment) and the consumer's surplus. The values of expenditures and consumer's surplus for outdoor activities and sport fishing for Quebec during 1996 can be found in the paper of Salvano *et al.* (2006).

+ The number of days that activity is possible was calculated by multiplying the total number of days for the activity of interest and probabilities of non-exceeding WQSs. To determine the total number of days for the activity of interest, it is necessary to collect two kinds of data: rate of participation and number of days of activity per participant. This study also used the data of participation rates for outdoor activities and sport fishing in Quebec from the survey on the importance of nature for Canadians. The data of the average number of days per participant also come from the same source. There are two ways to estimate the number of potential users in the study region: (1) specify a value by the investigator; or (2) estimate the potential users using population distributions.

- The fourth step calculates the cost related to the alternative management scenarios - those are the agricultural best management practices (BMP) scenarios in this study. The costs related to livestock production, crop production and fertilization practices were estimated. Calculation of the net cost related to the BMP implementation was based on comparison between the costs of the base-case scenario and those of the BMP scenario.

- The fifth step calculates the B/C ratio based on the results of the third and fourth steps.

Finally, the study of Liu *et al.* (2007) about "An optimization method based on scenario analysis for watershed management under uncertainty" also used CBA method to analyze the cost and benefit of the engineering techniques used for the Lake Qionghai watershed management. They listed the available engineering techniques, their corresponding costs and annual benefits from applying these techniques in the watershed were also estimated by the authors. These techniques are related to the control of point and nonpoint sources of pollution, the prevention of soil loss and debris flows, the reduction of lake sedimentation, better water resource utilization, and ecological maintenance techniques.

The results of the cost-benefit analysis of these techniques were used as a criterion for optimal selection of policies and engineering techniques under scenario analysis in this study. The detail of this selection is mentioned in the following section, concerning multi-criteria analysis.

2.8. Multi-criteria analysis

Multi-Criteria Analysis (MCA) is a decision-making tool to help dealing with complex problems in a decision-making process (Mendoza *et al.* 1999). There are two different approaches for applying MCA: those are the top-down and bottom-up approaches (Mendoza *et al.* 1999). The choice of one of the two approaches depends on the goal and specific conditions of the research.

Top-down approach:

In this approach, a previous set of *criteria and* indicators is used as an initial set and the basis for selecting the final set of criteria and indicators.

An assessment team including professionals or experts from different disciplines is established in order to:

- Adapt and modify the initial set of criteria and indicators for local situation;
- Assess the relative importance of each element in the modified set of criteria and indicators.

The Bottom-up approach:

The bottom-up approach uses specific information, especially from the field, to establish a set of criteria and indicators. The purpose of this approach is to organize in such a way that various stakeholders are involved.

The bottom-up approach is not as easy as the top-down approach because researchers themselves have to create a set of criteria and indicators without a similar initial set. However, the bottom-up approach with the involvement and participation of stakeholders is very important in any decision making process to make it more suitable for the study site.

For example, the study of Liu *et al.* (2007) used the bottom-up MCA for the optimal selection of policies and engineering techniques under scenario analysis for the Lake Qionghai watershed management. Three criteria were used to evaluate the importance of different engineering techniques for watershed management under each scenario.

- The first criterion depends on the scenario itself. The different environmental problems of scenarios led to different technical applications for watershed management.
- The second criterion is related to the techniques themselves and the financial abilities of the local governments. The techniques were assessed based on cost-benefit analysis, as mentioned in the above section concerning cost-benefit analysis.
- The third criterion is related to the opinions of stakeholders to assess the importance of each technique.

Then, a comprehensive assessment of the techniques was obtained by using multi-criteria evaluation of these three criteria.

2.9. Role of stakeholders in integrated watershed management

Stakeholders play an important role in integrated watershed management. One of the criteria that watershed management plans are considered integrated is the combination of the needs of diverse watershed stakeholders (Manitoba Water Stewardship, 2013). Participation of stakeholders, including governmental agencies, research institutions, non-government organizations, local industries and businesses, landowners and watershed residents, in order to develop an integrated watershed management plan is a collaborative process using all partner's expertise, ideas and willingness to take action (Oldman Watershed Council, 2013). Effective participation by all relevant groups of stakeholders leads to successes in integrated watershed management programmes (Mutekanga *et al.* 2013).

The study of Mutekanga *et al.* (2013) mentioned the importance of stakeholder participation in Ngenge watershed management in Ugandan highlands. The policy interventions to manage soil erosion in this watershed have not been successful because existing policies and legislation for natural resource management are inadequate and often formulated without consulting local communities. Analysis of ideas of stakeholders was performed in this study to identify key groups who participated in workshops and jointly developed concrete action and work plans. The analysis includes an assessment of natural resource problems and involved stakeholders, an analysis of roles, interests, and objectives of each stakeholder and their degree of importance for the implementation of integrated watershed management. The ideas of stakeholders are good indicators for supporting the development of integrated watershed management strategies.

The study of Liu *et al.* (2007) also considered the contributions of stakeholders and experts to the identification of key problems and driving forces, the scenario evaluation, and the selection of policies and engineering techniques for Lake Qionghai watershed management in southwestern China. For the identification of key problems and driving forces, seven groups of stakeholders were considered: fishermen; the staff of the Bureau for the Lake Qionghai watershed; the staff of related bureaus for environmental protection, forestry, fishery, agriculture, and tourism; local residents; the rural population in upstream of the watershed; tourists; and the staff of tourism firms and wastewater treatment plants. The concerns of these different stakeholders were assessed based on several sample interviews which focused mainly on the interests, concerns, and opinions of watershed management. For scenario evaluation, four scenarios related to different levels of economic growth rate were considered to take ideas of stakeholders and experts, and they agreed that these four scenarios were reasonable and practical. The selection of policies and engineering techniques for the watershed was the final result of this research, in which opinion of stakeholders was one of three criteria used to evaluate the importance of different engineering techniques. The two other criteria were the scenario itself for the environmental problems differed across the scenarios; and the techniques themselves and the financial abilities of the local governments.

2.10. Discussion

The studies mentioned in the literature review did not assess many factors of social-economic development and environment at the same time. For example, the study of Liu *et al.* (2007) in China only selected two factors of economic growth rate and governmental policies to build scenarios, or the study of Leal-Neto *et al.* (2006) mainly focused on population and industrial scenarios. Some other studies in the literature did not take into consideration the ideas of experts and stakeholders. There is therefore a lack of studies with a global approach for all social-economic and environmental factors of population, domestic wastewater, industry, livestock, agricultural fertilizer, forest planting, climate change to build scenarios and analyse the impacts on water quality. Therefore, this doctoral research proposes its own methodology for Cau River Basin in order to assess the global impacts of all future factors' changes on water quality. This proposed methodology will be described in detail in Chapter 4.

Chapter 3: Case study and implementation tool

This section presents the study area which is Cau River Basin with its characteristics, and the computer tool GIBSI used in the framework of the present doctoral research.

3.1. Case study

In this part, general information about the study area, such as natural characteristics of Cau River Basin in Vietnam, current social conditions of Bac Kan and Thai Nguyen provinces, and a previous related study on Cau River Basin are presented. Then, a comparison of the differences between the previous project in Vietnam and the present doctoral study is made.

3.1.1. General information about the study area

The case study in this doctoral research is the Cau River Basin, and the selected study areas are the parts of Cau River Basin which belong to Bac Kan and Thai Nguyen provinces (Figure 3.1).

Vietnam is divided into 59 provinces and 5 municipalities which have an executive and administrative organization similar to provinces. Province is the highest administrative level of Vietnam (http://www.vnlink.net/Dia_Phuong/). And among those, there are seven provinces/ municipalities related to the Cau River Basin: Bac Kan, Thai Nguyen, Vinh Phuc, Bac Ninh, Bac Giang and Hai Duong provinces and Hanoi capital. Bac Kan and Thai Nguyen provinces are up-stream and mid-stream areas of the Cau River Basin (Environment Report of Vietnam, 2006).

3.1.1.1. Natural characteristics of the Cau River Basin

Cau is one of the largest rivers in Thai Binh River system which is one of the largest river basins in Vietnam (see Figure 3.1). It derives from Phia Deng mountainous zone at the altitude of 1,527 m, on the south-east of Pia-Bi-Oc mountain range in Bac Kan province and flows into Thai Binh River at Pha Lai in Hai Duong province.

Cau River Basin occupies mainly Bac Kan and Thai Nguyen provinces, and a part of Bac Ninh, Bac Giang, Vinh Phuc provinces, two districts of Hanoi (Dong Anh and Soc Son districts), and a related province (Hai Duong province).

The main river in this watershed is the Cau River whose length is 288 km. This river basin has 68 rivers and streams of length over 10 km. The major tributary rivers are distributed almost steadily along the main river, including Cho Chu, Nghinh Tuong, Du, Cong, Ca Lo and Ngu Huyen Khe rivers. However, almost all of these tributary rivers are on the right bank of the river basin (Environment Report of Vietnam, 2006).

The geology in Cau River Basin is classified into three main regions: mountainous, hilly and delta areas. The mean annual temperature ranges from 18^0C to 24^0C, in which the lowest is in Tam Dao area (18^0C) and the highest is in Hanoi (23.9^0C). The mean annual rainfall varies from 1,533 mm (in Bac Kan province) to 2,495 mm (in Tam Dao). The mean annual runoff in the watershed is about 4.9 billion cubic meters. The mean evaporation per year ranges from 541 mm/year at Tam Dao to 1,000 mm/year in Bac Giang province (FAO, 2011).

The hydrographical regime of rivers in Cau River Basin divides into two seasons: flood and dry seasons. The flood season goes from June to October, presenting about 75% of the total annual water flow of the river basin. The dry season often lasts from seven to eight months, presenting 18% - 25% of the total annual water flow. The lowest water months are January, February and March with flows contributing only for 5.6% - 7.8% of the annual flow (Environment Report of Vietnam, 2006).

Figure 3.1: Map of Cau River Basin in Vietnam and the study area.

3.1.1.2. Administrative units of Bac Kan and Thai Nguyen provinces

Bac Kan and Thai Nguyen provinces are divided into districts, wards, cities, or towns. Districts, wards, towns and cities are in the group of second administrative level in Vietnam, under the provincial level. There are eight administrative units in Bac Kan province and nine units in Thai Nguyen province (Table 3.1). The capital of Bac Kan province is Bac Kan town and of Thai Nguyen province is Thai Nguyen City.

Table 3.1: Districts in Bac Kan and Thai Nguyen provinces.

Bac Kan province		**Thai Nguyen province**	
Capital	*Bac Kan Town*	Capital	*Thai Nguyen City*
District	Pac Nam	Town	*Song Cong Town*
District	Ba Be	District	*Dinh Hoa*
District	Ngan Son	District	*Vo Nhai*
District	*Bach Thong*	District	*Phu Luong*
District	*Cho Don*	District	*Dong Hy*
District	*Cho Moi*	District	*Dai Tu*
District	Na Ri	District	*Phu Binh*
		District	*Pho Yen*

<u>Sources:</u> *JICA and MONRE, 2009.*

Four among eight administrative units in Bac Kan province are related to Cau River Basin (see units written in italics in Table 3.1). Those are Bac Kan town, Bach Thong, Cho Don and Cho Moi districts. For Thai Nguyen province, all of nine administrative units are relative to Cau River Basin. The location of these administrative units is indicated in the maps of Bac Kan and Thai Nguyen provinces (Figures A.3.1 and A3.2 in Appendix).

3.1.1.3. Area and population

Bac Kan province has an area of 4,868 km^2 with a population of 295,296 persons in 2009 (Table A3.1 in Appendix). According to the statistical data, population of Bac Kan province tends to increase from 2001 to 2009 (Figure A3.3 in Appendix). The area of Thai Nguyen province is 3,526.2 km^2. It is smaller than Bac Kan province; however, the population of Thai Nguyen province was 1,127,430 persons in 2009, nearly four times more than in the Bac Kan province (Table A3.2 in Appendix). The population of Thai Nguyen province also tends to increase from 2001 to 2009 (Figure A3.4 in Appendix).

3.1.1.4. Land use

Land use in Bac Kan province in 2009 is summarized in Figure 3.2. Forest is dominant compared to the other types of land use in Bac Kan province, presenting 68% of total current land use. It is remarkable to note that unused land occupies 19.8% of the total area, standing at the second rank after forest.

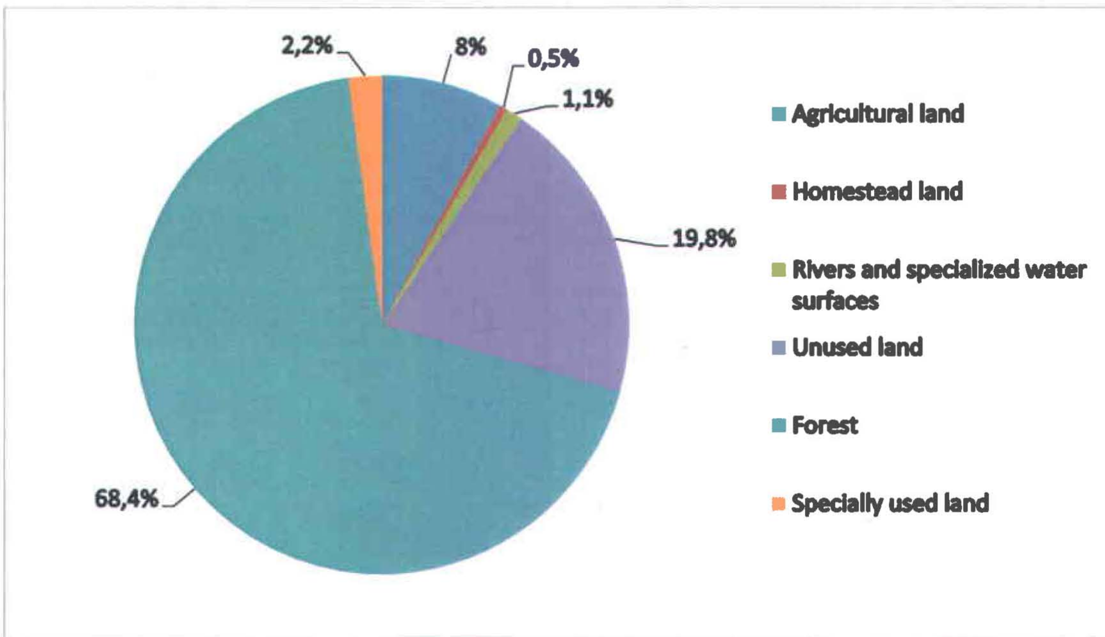


Figure 3.2: Land use (%) of Bac Kan province in 2009 (*Source: Backan Statistics Office, 2010).*

Land use in Thai Nguyen province in 2009 is summarized in Figure 3.3. Forests occupy only about 49% of total area of Thai Nguyen province, but is still the dominant type of land use. Agriculture represents 29% of total land, and is mainly distributed in the southern part of Thai Nguyen province.

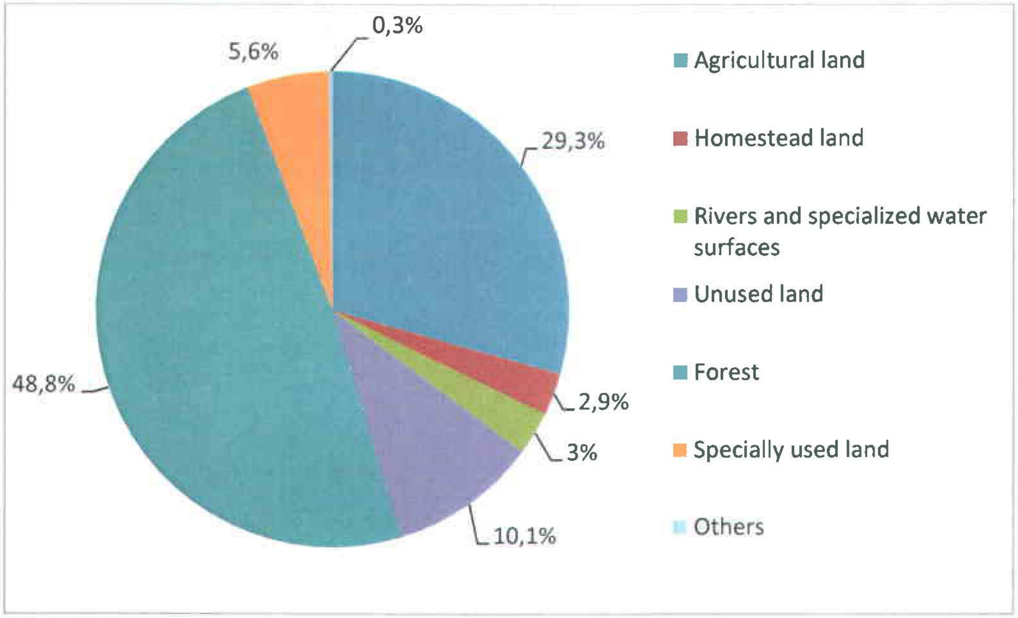


Figure 3.3: Land use (%) of Thai Nguyen province in 2009 *(Source: Thainguyen Statistics Office, 2010).*

3.1.2. Previous related study on Cau River Basin in Vietnam

In Vietnam, there was a two-year project entitled "The study for water environment management on river basins in Vietnam" carried out by the Japan International Cooperation Agency (JICA) and the Vietnamese Ministry of Natural Resources and Environment (MONRE) from the beginning of 2008. The aim of this project was to strengthen the overall capacities of the governmental management organizations in order to ensure the effectiveness of water environment management for river basins and to support the implementation of "the Master Plan on the Protection and Sustainable Development of the Landscape and Ecological Environment of Cau River Basin".

The upstream area of Cau River Basin was selected as a pilot area of this project. This target area is from the upstream of Cau River in Bac Kan province to the confluence point with Cong River in Thai Nguyen province (Figure 3.4).

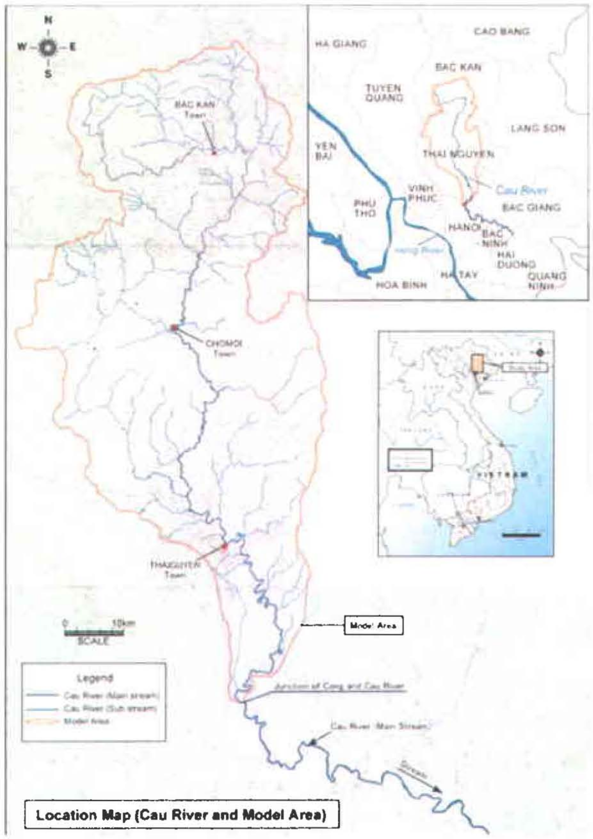


Figure 3.4: Target Area of JICA/MONRE project (from JICA and MONRE, 2009).

To achieve its objective, this project developed social-economic scenarios of Bac Kan and Thai Nguyen provinces until 2020, and assessed their impacts on water quality of Cau River by using a simple model developed by a Japanese team.

This project considered some items in the social-economic scenarios which were used to estimate future pollution load, water balance and to simulate water quality in the model area from 2008 to 2020 (Table 3.2).

Table 3.2: Items considered in social-economic scenarios in JICA and MONRE project.

Items	Unit	Used for
Population (urban and rural)	Person	Calculation of future pollution load from domestic wastewater
Gross regional domestic product (industrial and agricultural sector)	VND	Calculation of water balance and future pollution load
Turnover (industrial and agricultural sector)	VND	Calculation of water balance and future pollution load
Number of livestock	Head	Calculation of future pollution load from livestock industry
Land use area (agriculture, urban and forest)	ha	Calculation of future pollution load from non-point source

Source: *JICA and MONRE, 2009.*

These social-economic scenarios were developed for the three target years (2012, 2015 and 2020) based on the social-economic development master plans of Bac Kan and Thai Nguyen provinces (Table A3.3 in Appendix). The forecast of future population, turnover, etc., was done by multiplying the latest statistic by the growth rates mentioned in the master plans.

After that, the project estimated future pollution load for BOD (without observed data) based on different scenarios (see Figure A3.5 in Appendix). Future water quality was therefore simulated based on the results of pollution load estimation and water balance study of each scenario (Figure A3.6 in Appendix).

Then, three alternative scenarios were considered as pollution load reduction and comparison of pollution load flowing into the Cau River system between the situations "Without (No measures)" and "With (alternative scenarios)" were made; BOD concentration was also predicted for each alternative scenario. However, this project considered only point sources as its main targets because their polluters can be identified clearly and effectiveness of water pollution control can be evaluated (JICA and MONRE, 2009).

This project used a simple self-purification model developed in Japan to simulate the water quality of Cau River system. Comparison between this model and two others, like QUAL2E (Brown and Barnwell 1987, cited in Villeneuve *et al* 1998) which is implemented in the simulation tool GIBSI we plan to use, and MIKE-11 (http://www.dhisoftware.com) is presented in Table 3.3.

Table 3.3: Comparison between water quality simulation models.

Item	Factor	Water Quality Simulation Model		
		MIKE-11	**QUAL2E**	**Simple Self-purification Model**
Basic functions	Source	Danish Hydraulic Institute	USEPA	JICA Study Team
	Predictable variables	BOD, COD, DO, temperature, nitrate, (NO_3), ammonium (NH_4^+), coliforms	BOD, COD, temperature, conductivity, DO, SS, nitrogen (N), NO_3, NH_4^+, phytoplankton	BOD, COD, DO
Easiness to link with GIS database		Difficult to link the database of pollution load	Possible but necessary to customize	Possible
Cost	License, maintenance fee	Expensive	No cost	No cost
Necessary input data	Geological data	Longitudinal data	Data at representative points	Data at representative points
	Pollution Load	Estimated pollution load	Estimated pollution load	Estimated pollution load
	Water Quality	Monitoring data	Monitoring data	Monitoring data
	Hydrological data	Daily data	Data at representative season	Data at representative season
	Meteorological data	Daily data	Data at representative day	-

<u>Source</u>: *JICA and MONRE, 2009.*

The simple self-purification model can simulate three variables: BOD, COD and DO. However, it is found that the JICA project simulated only BOD. And in this project, river mean discharge was calculated based on the results of a current water balance study only in February in the last 10 years (1998-2007). The reason why February was set as the target month in this project is that the water quality in this month tends to be worst due to the least river discharge (JICA and MONRE, 2009). Therefore, the results of simulated water quality were the average data for February.

3.1.3. Differences between the JICA and MONRE's project and this doctoral study

This doctoral study will also create future scenarios for Cau River Basin in Bac Kan and Thai Nguyen provinces and analyse their impacts on water quality of Cau River system. However, there are some new and different things in this doctoral research compared with the above project as follows (Table 3.4):

Table 3.4: Differences between JICA and MONRE project and this doctoral study.

Project of JICA and MONRE	This doctoral study
Developed the social-economic scenarios: population, industry, agriculture, land use, and focus on point sources (industrial and domestic wastewater)	Will create not only social-economic scenarios but also climate change scenarios even on short term (10 years). It will take into account point and non-point sources of pollution.
Did not mention how to calculate the population for its study area, which is not the same as the broadly used area of Cau River Basin defined by MONRE.	Proposes a method to calculate population forecast for the study area. The study area is not exactly the same as the one of the project of JICA and MONRE. So population forecast will be different, leading to different pollution loads flowing into the Cau River system.
Simulated BOD for assessing the future water quality of Cau River system.	Will simulate more variables such as BOD, NH_4^+, SS, etc.
Used the input data of river discharge only in February, resulting in water quality simulation in February for each year.	Will use a day by day approach to determine the daily evolution of water quality of Cau River system for several years.

3.2. Implementation tool

This research used a computer tool of integrated river basin management namely GIBSI (*Gestion Intégrée des Bassins versants à l'aide d'un Système Informatisé*; Villeneuve *et al.* 1998) which is calibrated for the specific conditions of Cau River Basin. This part will mention the main reasons which justified the choice of GIBSI as the implementation tool in this research. After that, information about the GIBSI system, as well as its functions of scenario development and simulation, will be presented.

3.2.1. Why choose GIBSI?

GIBSI is an integrated modelling system for watershed management (Villeneuve *et al.* 1998). It was chosen because it satisfies all conditions which help this doctoral study to achieve its objective. In fact, it allows creating development scenarios and assessing their impacts on water quality of a river basin. Besides, water quality simulation variables of this integrated modelling system are currently being calibrated for the conditions of the study site chosen as a case study for this doctoral research, in the framework of the project of Cau River Basin integrated management between INRS (*Institut National de la Recherche Scientifique*) and VAST (Vietnamese Academy of Science and Technology).

3.2.2. About GIBSI

GIBSI is a decision support system with the aim of assisting decision makers in their assessment of various river basin management scenarios. GIBSI began to be developed in 1995 and the first version was used in 1998 (Villeneuve *et al.* 1998). GIBSI is an integrated modelling system which can be used either as a data management system or as a tool of impact assessment on surface water quality from various management scenarios at the river basin scale. The components and general structure of GIBSI are described in Figure 3.5.

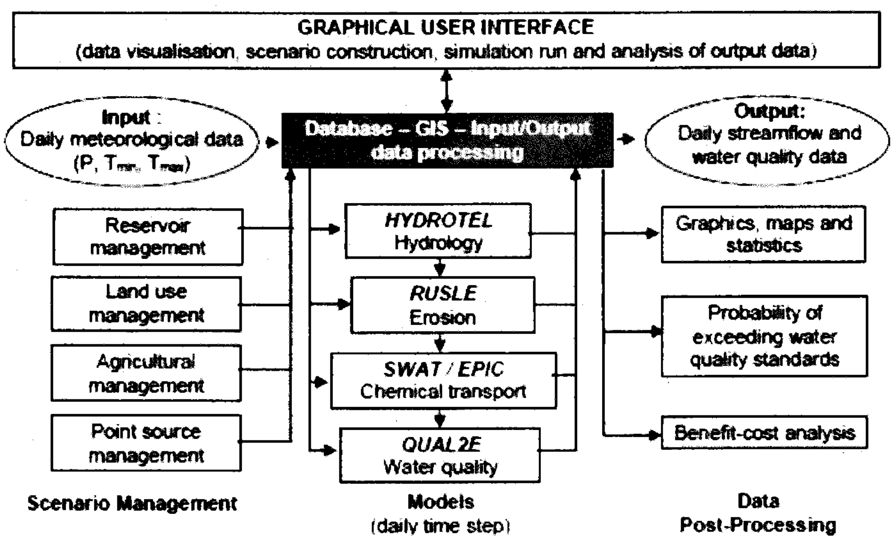


Figure 3.5: Representation of GIBSI components and structure (from Quilbé and Rousseau, 2007).

GIBSI includes the following basic components (Quilbé and Rousseau, 2007):

- *A data management system*: it is a relational database management system of all relevant attribute data that, together with a geographical information system (GIS); it enables to display information at any point in space and time. The database includes spatial data (e.g. gauge station locations) and attribute data (i.e. all data concerning spatial data, e.g. meteorological series, soil database, etc.) required for developing a scenario and running a simulation.
- *Scenarios management modules*: they allow users to create various river basin management scenarios. The types of management scenarios which can be created in GIBSI are described in section 3.2.2.1 below.
- *Simulation models*: there are four simulation models in GIBSI, those are:

+ HYDROTEL (Fortin *et al.* 1995): is a distributed physically-based hydrological model compatible with remote sensing and GIS;

+ MODEROSS (Duchemin, 2000) and ROTO (Arnold *et al.* 1995 in Villeneuve *et al.* 1998): are used to simulate soil erosion and sediment transport in river;

+ SWAT/EPIC (Arnold *et al.* 1995 in Villeneuve *et al.* 1998): integrates the pollutant transport algorithms of SWAT and EPIC to model the nitrogen, phosphorus and pesticide transport and transformations on cropland.

+ QUAL2E (Brown and Barnwell, 1987): is a water quality model simulating the dispersion and advection of water contaminants, algal growth, nitrogen and phosphorus cycles, coliform decay, re-aeration, and water temperature in rivers.

These models work at a daily time step. Daily meteorological series (*e.g.* precipitation, minimum and maximum temperatures) are their input data.

- *Post-processing tools*: they are used to analyze the results of simulation. The simulation results can be visualized in tables, graphs or maps. More specifically, the probability of exceeding water quality standards is useful when assessing water quality for specific purposes of water use, such as irrigation or drinking water. Finally, the tool of benefit/cost analysis can be applied for each scenario based on the cost of implementing management practices and the environmental benefits from water quality improvement.

With the above structure and components, GIBSI allows users to elaborate agricultural, land use, dam, industrial, and climate change scenarios, and then simulate the impacts of these scenarios on stream flows and water quality.

3.2.2.1. Scenario elaboration

In GIBSI, different scenarios are created by modifying the characteristics of river basin (land use, agricultural attributes, point sources and dams). These changes are defined by the users. After that, these scenarios will be simulated and the simulation results will be compared with the results of other scenarios or with the results of the reference scenario (permanent scenario). The permanent (or base) scenario comprises the most recent information concerning the river basin which is used for the model calibration. Several types of management scenarios can be created in GIBSI as follows:

Agricultural scenarios

Agricultural scenarios are elaborated by modifying the agricultural attributes such as livestock, mode of fertilizing, mode of soil improvement, pesticides to apply, dates of cultural practices and cultures.

In GIBSI, there are three items which allow modifying the agricultural attributes as follows:

- Item of animal production: includes the information concerning mode of fertilizing, pesticides and livestock such as beeves, pigs, chickens and ducks.
- Item of vegetable production: allows modifying the classes of present cultures in the selected zones with their codes of rotation and the types of cultures for five years.
- Item of nitrogen and phosphorus balances: allows calculating the offer, the demand and the balances of nitrogen and phosphorus according to the attributes specified in the items of animal production and vegetable production.

Land use scenarios

GIBSI allows changing the types of land use in the selected zones of the river basin. It allows changing specific areas, from agricultural to forested, from forested to urban, from a type of land use to breeding, etc. The ability offered by GIBSI to change a land use from a type to another will be helpful in the framework of the present study to assess impacts on water quality of different types of future land use scenarios in the Cau River Basin.

Point sources management

The function of point sources management in GIBSI allows adding, destroying and visualising the point sources presented in the map of river basin. This function also allows defining and modifying the input data concerning point sources such as names, types and numbers of point sources, type of treatment station, etc.

Climate change scenarios

GIBSI allows modifying the meteorological input data such as temperature, precipitation in its data files in order to create climate change scenarios. These changes will be simulated in GIBSI, resulting in the water flows and water quality for the future years.

Dam management

The function of dam management in GIBSI allows adding, destroying and visualising the map of dams. This function also allows defining and modifying the input data concerning dams such as name, physical characteristics, operation mode, etc.

3.2.2.2. Scenario simulation

After the management scenarios are created, GIBSI allows the users to run simulations for each scenario. The simulation results of daily stream flow and water quality can be visualized in tables, graphs and maps for the selected variables.

Chapter 4: Methodology

This chapter talks about the approaches and methods which are used in this doctoral research in order to achieve the objectives.

4.1. Optimisation approach

The methodology developed in this study basically follows the three main steps of optimisation approach of Liu *et al.* (2007) mentioned in literature review (Chapter 2), including steps of system analysis, scenario construction, and optimal selection. However, methods to implement these steps for Cau watershed in this doctoral research are different from those used in the study of Liu *et al.* (2007). The proposed optimisation method for Cau River Basin management is shown on figure 4.1.

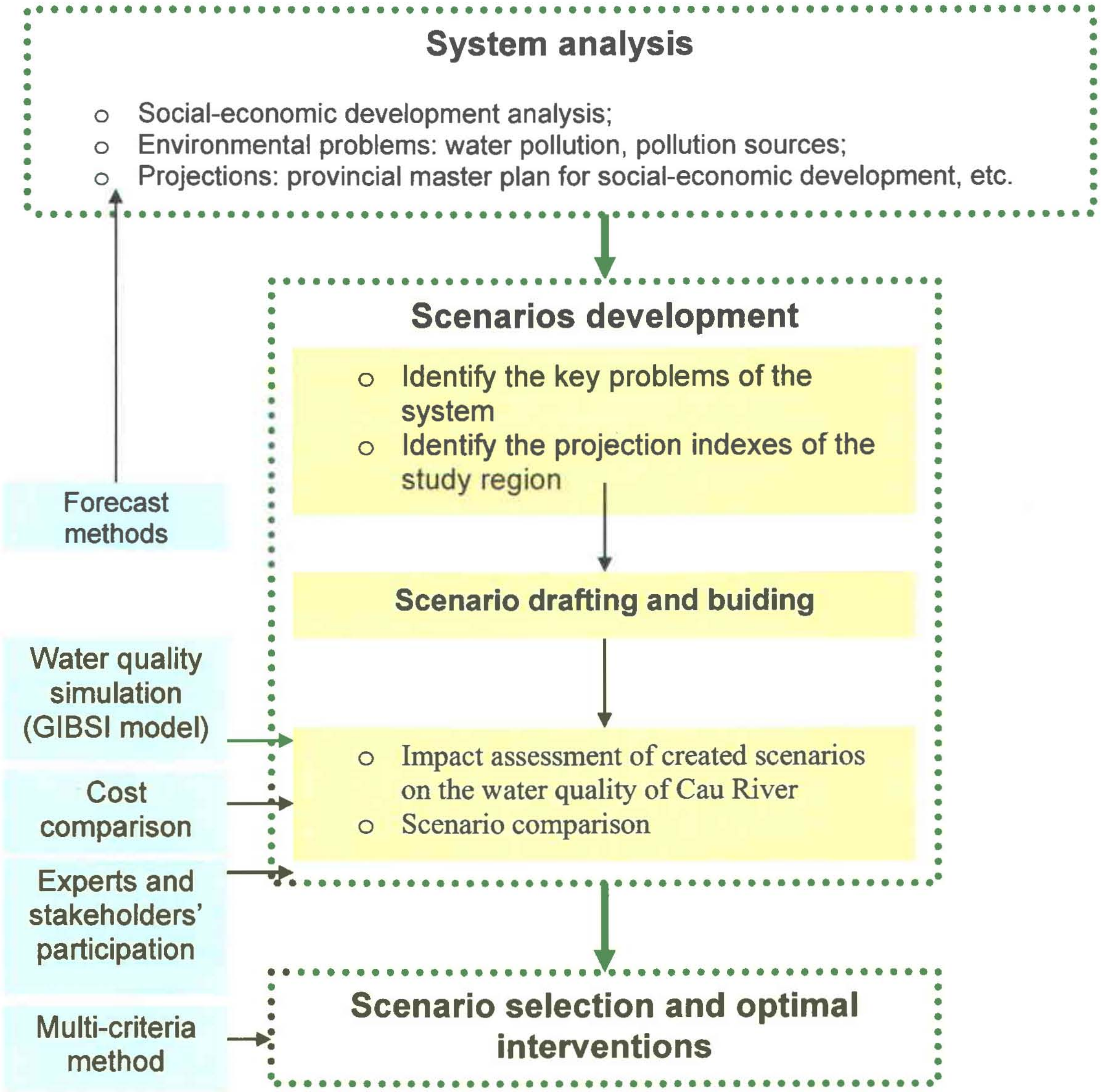


Figure 4.1: Optimization method based on scenario analysis for watershed management.

The three steps of this procedure are described below. More details about how these steps will be implemented in our project are given in the following chapter.

Step 1: System analysis

In this step, the economic, social, environmental, and industrial projection data of the watershed are analyzed. System analysis concerns the potential social-economic development, and the existing or potential problems concerning the environment. Specific forecast methods are applied for forecasting the future changes of population, climate, etc.

Step 2: Scenario construction at a regional scale

In this step, scenarios are built in order to forecast and simulate potential changes in the watershed.

(1) Identify the key problems and projection indexes

The key problems are the major existing difficulties related to environmental pollution. Projection indexes are the local future targets, which can greatly influence changes in the watershed. Based on system analysis, the key problems and projection indexes concerning Cau River Basin can be identified.

(2) Draft and build the scenarios

The scenarios are drafted and created based on the forecasting results and the combination of driving factors such as population, climate change, land use, etc.

(3) Conduct comprehensive analysis

These scenarios need to be analyzed comprehensively for the selection of future scenarios and interventions. The GIBSI model will be used to assess the impacts of these scenarios on water quality of Cau River and the cost comparison will be implemented to help the scenario comparison. The participation of experts and stakeholders is also taken into consideration for scenario comparison.

Step 3: Scenario selection and optimal countermeasure

Once scenario analysis has been conducted, the optimal choice of scenarios and environmental management interventions are given based on the results of various criteria such as the impacts on water quality, cost comparison, and opinions of experts and stakeholders.

4.2. Methods to develop scenarios

4.2.1. Population forecast and scenarios

Population forecast

The three following methods are proposed to forecast the population of Cau River Basin in Bac Kan and Thai Nguyen provinces:

Method 1

With this method, we will use the population statistic data from 2001 to 2009 and a linear regression equation to forecast the population up to 2020.

- Advantages: Population data from 2001 to 2009 of the two provinces are available.
- Disadvantages: Components of population change and the age structure of the population cannot be taken into consideration. Moreover, projection of population growth rate in the master plan for social-economic development up to 2020 cannot be used.

Method 2: With this method, we will use the following equation to forecast the population:

$$N_t = N_{(t-1)}(birth\ rate_{(t)} - death\ rate_{(t)})\ /100 + R \qquad \text{(Eq. 4.1)}$$

Where: N_t = population at time t and N_{t-1} = population at time t-1 and R = *Immigrants – Emigrants.*

The current population distribution in 2009 was used as the starting value for this method.

- Advantages: This method is more accurate than method 1. The future population depends only on the present population and future survival, fertility, and migration rates. Thus, predictions can be based on forecasts of these rates. The starting value is therefore the population in 2009. It is more accurate because it considers the different components of population change. However, it does not consider the age structure of the population.
- Disadvantages: we have access only to the data on birth rate and death rate of Bac Kan and Thai Nguyen from 2002 to 2009.

Also, we cannot use directly the projection of population growth rate in the master plan for social-economic development of Bac Kan and Thai Nguyen up to 2020.

Method 3: Use the following equation to forecast the population:

$$N_t = N_{(t-1)}(population\ growth\ rate_{(t)}/100) \qquad \text{(Eq. 4.2)}$$

Where: N_t = population at time t and N_{t-1} = population at time t-1.

The current population distribution in 2009 was also used as a starting value for this method.

- Advantages: The future population predictions can use the projection of the population growth rates for each period in the master plan for social-economic development up to 2020. The current population distribution in 2009 can be used as a starting value. So, the main advantage is that they refer to official documents. This can be a good point for the acceptation by other users, particularly official users, of the results.
- Disadvantages: this method does not take into consideration the factors such as survival, fertility, and migration rates which can make prediction more accurate.

The three methods, with their advantages and disadvantages are summarized in Table 4.1.

Table 4.1: Summary of the three proposed methods for forecasting future population.

	Advantages	Disadvantages
Method 1	Data are available.	Projection of local areas is not considered. Survival, fertility, migration rates, and age structure of the population are not considered.
Method 2	Different components of population change (survival, fertility, migration rates) are considered. Prediction is more accurate.	Available data are not sufficient to apply this method. Projection of local areas is not considered.
Method 3	Projection of local areas is considered, more easily accepted by other users, particularly official users.	Survival, fertility, and migration rates, and age structure of the population are not considered.

According to the advantages and disadvantages (Table 4.1), method 3 is chosen in this research to forecast the population up to 2020 because population projection of local areas can be used. This choice can be affirmed through the project JICA and MONRE which was mentioned (section 3.1.2, chapter 3). This project also used the trend of population growth in the social-economic development master plans of Bac Kan and Thai Nguyen provinces to forecast population and build scenarios for target years (2012, 2015 and 2020).

Once the forecast method is chosen, the current population in the study area is necessary. As mentioned in chapter 3, all districts of Bac Kan and Thai Nguyen provinces are not belong to Cau River Basin. But statistic data are available at provincial and district levels. Population of the parts of Bac Kan and Thai Nguyen provinces which belongs to Cau River Basin therefore need to be calculated. Two ways are possible:

(1). Based on the percentage of the districts area which belongs to the river basin.

(2). Based on the percentage of the district population that lives really in the river basin.

Bac Kan and Thai Nguyen are mainly mountainous provinces. The population there distributes unequally in the whole provinces in general, as well as at the district or community levels in particular. There are some districts or communities with large areas with population lower than in other areas because most of this area is mountainous. Meanwhile, in Vietnam, the administrative units are often specified based on population for management purposes. So, the above first way should bring more errors than the second way. Therefore, the second way, which is based on population, will be used in this research to calculate the population of Cau River Basin for these two provinces.

For population forecast data, the areas in each province with the population which belongs totally or partly to the study area are taken into consideration:

- Bac Kan province: Bac Kan Town, Bach Thong district, Cho Moi district (87.5% of the population), Cho Don district (18.2% of the population).
- Thai Nguyen province: Thai Nguyen City, Song Cong Town, Dinh Hoa district, Phu Luong district, Dong Hy district, Dai Tu, Phu Binh district, Pho Yen district, Vo Nhai district (64.3% of the population).

Data needed for current population in the study area was estimated based on values from statistic data in the provinces in 2009 (see results in chapter 5).

Population scenarios

The future is inherently uncertain, so we should create more than one scenario of population to be able to compare the scenarios and assess their impacts on water quality. Therefore, besides the population forecast based on the projection of Bac Kan and Thai Nguyen provinces, we should make two more assumptions of higher and lower values of this projection. The different forecast assumptions will lead to different forecast outcomes. So, we will have three scenarios of population for each province based on three population forecast outcomes.

4.2.2. Climate change scenarios

As mentioned in section 2.4.3, this study uses the data of precipitation and air temperature change of several meteorological stations, combined with synthetic scenarios for building climate change scenarios in order to assess their impacts on water quality of the Cau River Basin. It means that climate change scenarios will be developed by assuming some changes in temperature and precipitation in the study area, based on the data collected from the project "Impacts of climate change on water resources and adaptation measures" (IMHEN, 2010a & b).

There are three kinds of selected scenarios for climate change in Vietnam: (1) according to the low greenhouse gases' emission scenario (B1), (2) according to the average greenhouse gases' emission scenario (B2), and (3) according to the high greenhouse gases' emission scenario (A2). The climate change scenarios for Vietnam according to the average emission are now recommended by MONRE. Therefore, the present study will only use the results according to the B2 scenario as recommended.

The projections of changes in temperature and precipitation for four meteorological stations, Bac Kan, Dinh Hoa, Thai Nguyen and Tam Dao, according to the B2 scenario for years 2009, 2015 and 2020 are compared with the observed values on the period 1980-1999 to develop climate change scenarios for this doctoral research, are detailed in Appendix 1.

4.2.3. Land use scenarios

Land use scenarios are developed by making some conversions from bare soil and scrub land into forest land based on projections of local governments in the study area. In this research, projections of forest planting for Bac Kan and Thai Nguyen provinces are considered to create land use scenarios.

4.2.4. Industrial scenarios

Industrial scenarios are created by assuming the development of industrial zones, or installation of wastewater treatment systems for enterprises. Then, the impacts of these industrial changes together with other scenarios (climate change, land use, etc.) on water quality will be assessed by using GIBSI. Also, the cost-benefit analysis for these scenarios will be done.

4.2.5. Agricultural scenarios

Agricultural scenarios are created based on the projection from local governments of number of livestock and the increase of paddy yield in the future in Bac Kan and Thai Nguyen provinces.

4.3. Variables selection for water quality simulation and scenario comparison

There are a lot of variables which can be used to evaluate river water quality such as dissolved oxygen (DO), biochemical oxygen demand (BOD), nitrogen, etc. Discharge at a specific point in the river network can also be taken into consideration because water it plays an important role in self-cleaning process of water. However, it is more realistic to select the most important variables for simulations and scenarios comparison in terms of water quality. Several criteria are used for the selection.

The variables selection to evaluate the simulation performance and to compare the scenarios is based on the following criteria:

- **Criterion 1**: The variable can be simulated with GIBSI for Cau River Basin

With GIBSI, twelve water quality variables can be simulated for Cau River Basin: discharge (Q), dissolved oxygen (DO), biochemical oxygen demand (BOD5), organic nitrogen, ammonium (N-NH3), nitrite (NO2), nitrate (NO3), organic phosphorus, dissolved phosphorus, coliforms, suspended solids (SS) and chlorophyll-a.

Other variables which are also important sources of river water pollution in the river basin such as heavy metals and pesticides are not selected in the framework of this study because of lack of observed data to calibrate the model for Cau River Basin even if GIBSI can simulate variables like pesticides.

- **Criterion 2**: The characteristic and importance for water environment of each variable.

+ Dissolved oxygen (DO)

DO is very important for the aquatic life and biochemical processes. It is necessary to maintain aerobic conditions in the water sources that receive pollutants. Concentration of DO will decrease in contaminated waters. The major source of DO in water environment is atmospheric re-aeration. The other source is the supply from algal photosynthesis. The main consumption of dissolved oxygen in water environment is the oxygen demand for biological decomposition of organic compounds by aerobic bacteria. The other consumptions are nitrification, algal respiration, and sediment oxygen demand. DO depends on natural factors which vary with season such as solar radiation, temperature, atmospheric reaeration, etc.

+ Biochemical oxygen demand (BOD5) and chemical oxygen demand (COD)

BOD and COD indicate the quantity of oxygen necessary for the oxidation of organic compounds in water environment by biological or chemical ways. The higher the values of BOD or COD are, the more polluted the water is.

+ Organic nitrogen

Total nitrogen includes organic and inorganic nitrogen compounds. Although the inorganic nitrogen compounds such as ammonium, nitrite and nitrate play the most important role in biochemical processes in water environment, some organic nitrogen compounds may also be significant. (Source: http://www.lenntech.com/periodic/water/nitrogen/nitrogen-and-water.htm).

A significant amount of organic nitrogen can be found in domestic wastewater. Normally, organic nitrogen compounds represents about one-third of total nitrogen. The rest is ammonium salts. No more than 3% nitrites and nitrates exist in domestic wastewater (http://www.lenntech.com/periodic/water/nitrogen/nitrogen-and-water.htm).

Organic nitrogen participates mainly in mineralization and settling processes in water environment.

+ Ammonium

Ammonium is composed of mineral and organic nitrogen, and is the important food for aquatic plants and algae. In the condition of high pH and temperature in river, ammonium transforms into ammonia (NH3) whose small concentration is toxic for fish. For example, a neutral pH and a temperature of 25°C in summer are good conditions for ammonium to transform into NH3.

The main sources of ammonium are fertilizers, domestic wastewater and industries such as chemical factories, food processing, milk, etc. It is therefore specific for social-economic activities.

+ Nitrites and nitrates

Nitrites and nitrates are also dietary requirements for algae and plankton. Nitrate concentration over 10 mg/l is a good condition for algal development (Pham et *al.*, 2008). Nitrites are formed from ammonium oxidization, and then they are oxidized to form nitrates. This process in water is so-called nitrification which decreases dissolved oxygen concentration in water. However, nitrification may be important in water environment because in this process, concentration of nitrite which is toxic at low pH values for higher plants decreases (http://www.lenntech.com/periodic/water/nitrogen/nitrogen-and-water.htm).

Nitrates generally are not toxic. However, high concentrations of nitrate may be converted by the body into nitrites which is a toxic salt for the body. This salt disrupts blood oxygen transport, causing nausea and stomach aches for adults and is extremely risky for infants because of rapid declination of blood oxygen (http://www.lenntech.com/periodic/water/nitrogen/nitrogen-and-water.htm).

In the QUAL2E model, which is used in GIBSI to simulate water quality, the nitrogen cycle comprises four variables: organic nitrogen, ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen. The processes related to nitrogen balance in QUAL2E are mineralization and settling of the organic nitrogen, nitrification which is divided into the oxidation of ammonia into nitrite and then the oxidation of nitrite into nitrate, uptake by the algae, regeneration from the sediment and from algal respiration (http://www.bae.ncsu.edu/www3/acad/Regional-Bulletins/Modeling-Bulletin/qual2e.html).

+ Phosphorus

Phosphorus, like nitrogen, is an important food for plants and algae. In water, there are four forms of phosphorus, those are: undissolved inorganic, undissolved organic, dissolved inorganic, and dissolved organic compound (Pham et *al.* 2008).

The high concentrations of phosphorus and nitrogen in water cause the strong growth of algae. Eutrophication will happen if the concentrations of nitrogen and phosphorus are equal or over 30-60 mg/l and 4-8 mg/l respectively, resulting in oxygen deprivation and fish deaths (Pham et *al.*, 2008).

The sources of phosphorus in water environment are from erosion, and man-made sources such as agricultural, industrial, domestic wastewater.

In Qual2E model, the phosphorus cycle is similar to, but simpler than the nitrogen cycle. It includes only two variables: organic phosphorus and dissolved phosphorus. The considered processes related to phosphorus balance in QUAL2E are settling and mineralization of the organic phosphorus into inorganic phosphorus, regeneration from the sediment, uptake and respiration from the algae (http://www.bae.ncsu.edu/www3/acad/Regional-Bulletins/Modeling-Bulletin/qual2e.html).

+ Coliforms

Coliforms are the indicator of pathogen contamination in surface water. In QUAL2E, a simple first order decay function is used to calculate the concentration of coliforms, which only take into account coliforms die-off (Brown et *al*., 1987). There is no relationship between coliforms and other variable in QUAL2E. It means that the concentration of coliforms depends only on the input sources which are given and the coliforms die-off rate which is temperature dependent.

+ Suspended solids (SS)

Suspended solids play an important role in water environment because they hinder the photosynthesis by reducing the diffuse ability of light into water, affecting the aquatic life. Moreover, it is an important variable to assess impacts of erosion on surface water quality because they play a major role in contaminants transportation from soil to river. They can also gradually settle down due to gravity, affecting the habitat of bottom organisms in water.

+ Chlorophyll a

Chlorophyll a is one type of chlorophyll which is most common and predominant in all of the oxygen-evolving photosynthetic organisms like higher plants, red and green algae (*Source*: http://www.biology-online.org/dictionary/Chlorophyll_a). It depends on concentrations of nitrogen and phosphorus which are the food of algae. It has a close relationship with algal development and degradation in water environment. Chlorophyll a is used as a variable for concentration of phytoplanktonic algal biomass (Brown et al., 1987).

- **Criterion 3**: The selected variables should be specific for pollution from social-economic activities.

The scenarios which are developed in this thesis are based on the social-economic activities that may happen in the future in the study area, as well as some assumptions for the future activities. One of the aims of this thesis is to assess the impacts of these social-economic activities on the water environment. Therefore, the selected variables for simulation performance and scenario comparison should be specific for pollution from social-economic activities. For example, BOD and COD indicate a pollution of organic compounds from domestic wastewater, industrial activities, etc., or ammonium is specific for pollution of fertilizers, domestic wastewater and industries.

- **Criterion 4**: The selected variables should be the most appropriate to evaluate the current environmental state.

Variables which are the most appropriate to evaluate the current environmental state (DONRE Bac Kan, 2010; DONRE Thai Nguyen, 2010) will be considered. According to the report of the current environmental state of Bac Kan province in 2010, during the period from 2007 to 2010, three variables total suspended solids (TSS), biochemical oxygen demand (BOD) and chemical oxygen demand (COD) were over or have reached the limit of Vietnamese standards for surface water quality in some areas of the Cau River Basin (*e.g.* Thanh Binh community in Bac Kan province). In Thai Nguyen province, during the period from 2007 to 2010, four variables BOD, COD, TSS and oil were reported as over the Vietnamese standards in some locations (*e.g* the reach of Cau River which flows through Thai Nguyen City). Thus it can be said that in the study area, the more important variables are BOD/COD, TSS and oil.

Based on analysis of all criteria, four variables were chosen: discharge, dissolved oxygen, biochemical oxygen demand and suspended solids (Table 4.2). The selected variables will be useful for water quality simulations in order to compare scenarios.

Table 4.2: Variables selection for scenario comparison.

Simulated variables	Importance and roles	Result of selection
Discharge (Q)	Important role in the self-cleaning process of water.	Selected
Dissolved oxygen (DO)	Not specific for pollution from social-economic activities.	No
Biochemical oxygen demand (BOD5)	Specific for pollution from social-economic activities. Important to evaluate current environmental state.	Selected
Organic nitrogen	Minor importance in biochemical processes in water.	No
$N\text{-}NH_3$ (ammonium)	Can be transformed into ammonia toxic for fish. Specific for pollution from social-economic activities.	Selected
$N\text{-}NO_2$ (nitrite)	Not specific for pollution from social-economic activities. Minor importance in the evaluation of current environmental state.	No
$N\text{-}NO_3$ (nitrate)	Not specific for pollution from social-economic activities. Minor importance in the evaluation of current environmental state.	No
Organic phosphorus	Similarities (in QUAL2E) between phosphorus and nitrogen cycles.	No
Dissolved phosphorus		No
Coliforms	No relationship (in QUAL2E) between coliforms and pollution sources. Minor importance in the evaluation of current environmental state.	No
Suspended solids (SS)	Important role in erosion assessment, contaminants transport. Important in the evaluation of current environmental state.	Selected
Chlorophyll a	Depends on the concentrations of nitrogen and phosphorus. Minor importance in the evaluation of current environmental state.	No

4.4. Cost/benefit analysis

The present study will follow the benefit/cost (B/C) methodology proposed by Salvano *et al.* (2006) which was mentioned in chapter 2. There are five steps in this methodology:

- The first step describes the study area, especially the information concerning current or potential water uses.
- The second step uses GIBSI to simulate the impacts of each scenario on water quality of Cau River in the study area. The results of this step will be used to estimate benefits from improvement of water quality.
- The third step estimates monetary benefits from potential recovery of water uses. The present study will evaluate monetary benefits related to: (1) water-based recreational activities and (2) reduction of treatment cost for domestic water.

  To estimate the monetary benefits from water-based recreational activities such as swimming, fishing, camping, the method of Salvano *et al.* (2006), which is based on the daily monetary value per activity and the number of days that the activity is possible, will be used. The selected water quality variables BOD_5, NH_4^+ and SS will be considered to simulate the probability of non-exceeding water quality standards by GIBSI, and then estimate the days that the activity is possible.

  The evaluation of the monetary benefits related to reduction of treatment cost for domestic water will be based on the unit cost for treatment and the simulation results of water quality improvement.
- The fourth step calculates the cost related to the alternative management scenarios. The costs of different interventions for improving water quality such as installation of wastewater treatment systems, etc., will be estimated.
- The fifth step calculates the B/C ratio based on the results of the third and fourth steps.

4.5. Multi-criteria method

In this research, the bottom-up approach, which is mentioned in section 2.8, is used to apply multi-criteria analysis for optimal selection of scenarios. The criteria and indicators are developed based on the simulation results of water quality of Cau River and the benefit/cost analysis. Besides, the ideas of stakeholders are also taken into consideration in this analysis.

To apply multi-criteria analysis, it is necessary to develop a framework of criteria and indicators. The proposed framework for this doctoral study is summarized in Figure 4.2. There are three important components of this framework, namely: principles, criteria and indicators:

- **Principles** which include environmental, economic and social aspects provide the primary framework based on which criteria and indicators are built.
- **Criteria** are the intermediate points into which the information provided by indicators can be integrated in order to assess an issue. There are three criteria: water quality, cost-benefit of each scenario and scenarios themselves, respectively with the three principles.
- **Indicators** are variables used to indicate the status of a particular criterion. Under each criterion, there are several indicators. In this study, under the criterion of water quality, there are two indicators to evaluate this criterion, those are: (1) Concentrations of BOD_5, NH_4^+, SS, and (2) Probabilities of exceeding water quality standards. GIBSI is used to simulate the results for these two indicators. To estimate the criterion of cost-benefit of each scenario, the indicator of cost comparison obtained by the results of cost comparison will be used. For the criterion of scenarios, ranking will be used to show the priority levels from the ideas of experts and stakeholders: high, average and low priority.

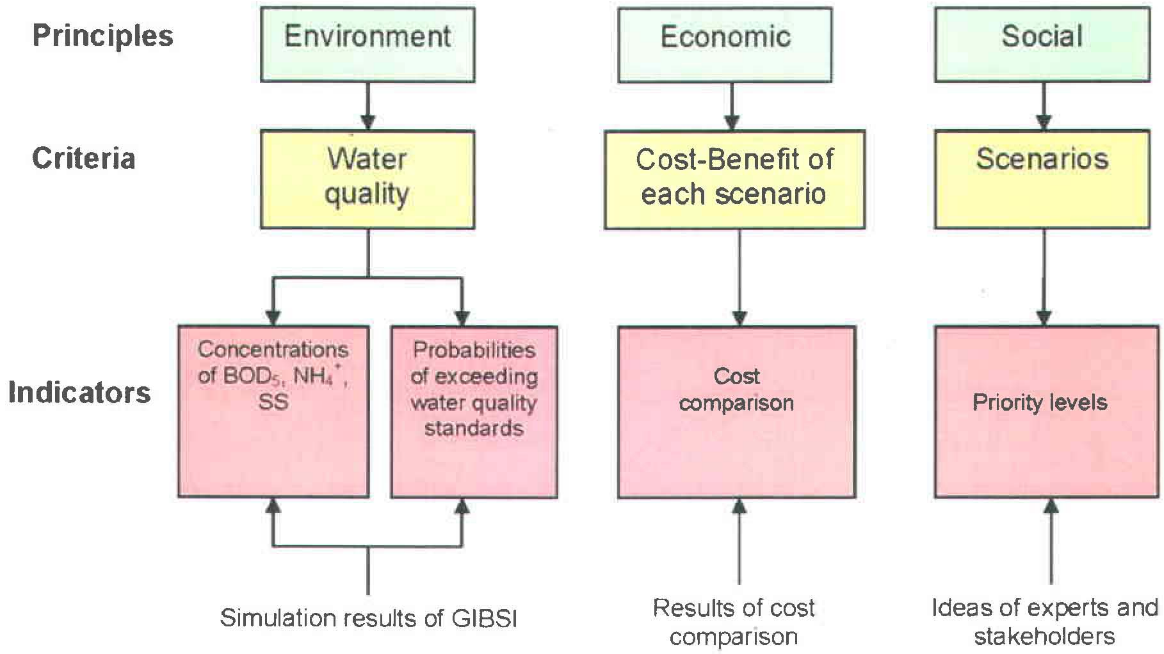


Figure 4.2: Principles, criteria and indicators framework for multi-criteria analysis.

Figure 4.2 indicates that there are three main criteria for scenario selection: water quality, cost comparison, and scenarios (ideas of experts and stakeholders). The scenario selection will be based on the ranking, *i.e.* priority levels for each scenario of each of these three main criteria. It is possible to notice that the indicators of the criterion of scenarios show three priority levels. Therefore, for water quality and cost comparison, three priority levels (high, average and low) will also be given to each scenario after analysis of the indicators for the purpose of ranking.

After giving the priority levels to each scenario for the three main results, scores for each priority level are also given: 1 for low priority, 2 for average priority, and 3 for high priority. Besides, the importance of each main result is also considered. The three results are not considered to be of the same importance. It is assumed that the importance of water quality and ideas of experts and stakeholders is considered as being of double importance as compared to cost comparison for the following reasons:

- Results of water quality: the objective of this research is to identify and prioritize the interventions for improving the water quality of Cau River. The results of water quality simulation are therefore considered to be one of the most important.

- Results of ideas of experts and stakeholders: besides the water quality, the ideas of experts and stakeholders, including the local managers, are also very important because they are the persons who have experience and have the right in making decision.
- Results of cost comparison: the importance of cost comparison result is lower than the two other results because even if the cost of one intervention is high (low priority level related to the cost) but the water quality much improves and the experts and local managers think it should be implemented, this intervention is still in high priority level.

The final score for each scenario will be estimated based on the score and the importance of each result as follows:

$$Score_{Final} = Score_S \times \mathrm{Im}_S + Score_{WQ} \times \mathrm{Im}_{WQ} + Score_{CB} \times \mathrm{Im}_{CB} \qquad \text{(Eq. 4.3)}$$

Where:

$Score_{Final}$ is the final score for each scenario;
$Score_S$ is the score of scenario related to the ideas of experts and stakeholders;
Im_S is the importance for the ideas of experts and stakeholders = 2;
$Score_{WQ}$ is the score of scenario related to water quality;
Im_{WQ} is the importance for water quality = 2;
$Score_{CB}$ is the score of scenario related to cost comparison;
Im_{CB} is the importance for cost comparison = 1.

Ranking of all scenarios will be done in order to identify scenarios with the highest final scores. These scenarios will be recommended for implementation.

Chapter 5: Scenario development

This chapter presents the steps to develop scenarios for the future up to 2020 and the results of all these scenarios for Cau River watershed. There are four steps to develop scenarios: (1) System analysis which is the step of data analysis for all factors involved in this study based on the environmental and social econonomic developement plans; (2) Identification of key problems for the environment and main projections based on the plan for social economical development of local government of each province; (3) Determination of priority levels for all factors based on the identified key problems and main projections; and (4) Combination of factors to draft and create scenarios for the Cau River watershed. Since the study area is divided into two provinces: Bac Kan and Thai Nguyen provinces, this chapter therefore presents in detail the application of these steps and the results of scenario development for each province. Based on the results for each province, developed scenarios for the whole study area will be presented.

5.1. Steps to develop scenarios

In order to develop scenarios for the Cau River Basin in Bac Kan and Thai Nguyen provinces, the optimisation approach and proposed methods which were mentionned in chapter 4 were applied. Following these approach and methods, four steps to develop scenarios were proposed in order to make it easier for creating scenarios for study area. Since the data are different from a province to another, these steps for scenario development was applied to each province in the study area.

Step 1: system analysis

In this step, all the collected data of Cau River Basin in Bac Kan and Thai Nguyen provinces were analysed, focussing on seven factors: population, domestic wastewater treatment, industry, livestock, agricultural fertilizer, forest and climate change. The considered factors are in relationship with the social-economic development plans of local goverments and can have direct or indirect impacts on water quality of the river system.

Available information in the river basin were analyzed to define the state considered as "current state". Projection for future were also analyzed, and forecasts were calculated for each of these seven factors in order to provide the necessary data to develop scenarios. Methods to forecast and develop scenarios which are mentionned in chapter 4 of methodology were applied.

Step 2: identification of key problems and main projections

After system analysis, the key problems for environmental management such as the major pollution sources, and the main projections for social-economic development which can create changes in the watershed's hydrology and water quality were identified in order to help the determination of the priority levels for the seven factors.

Step 3: identification of the priority levels for factors

Scenarios are developed based on the combination of the seven factors. In order to reduce the number of possible combinations and keep realistic scenarios, the priority level is defined for each of the seven analysed factors. The priority levels of these factors are divided into three groups: high, middle and low priorities, and determined based on the following criteria:

- *High priority (or priority 1)*: includes the factors which are the main environmental pollution sources and/or the major factors in the future development plans defined by the local government which can have great influence on the water quality.
- *Middle priority (or priority 2)*: includes the factors which are direct water pollution sources but considered to be less important with regard to the development plan defined by the local governments.
- *Low priority (or priority 3)*: includes the factors which are considered to have indirect and less important impacts on the water quality of rivers than the factors in middle priority.

Step 4: combination of factors to draft scenarios and scenario creation

Different combinations of the seven factors were used to create and draft scenarios in the form of a matrix. Based on the system analysis and priority levels of factors, several scenarios for the Cau River Basin in each province (Bac Kan and Thai Nguyen) were developed.

5.2. Reference state of the seven factors

Before developing scenarios for the future, the current state of the seven considered factors should be clarified in order to make it easier to compare the future scenarios and the current state. The data used for the current state in the study area is basically those of 2009, except for the land use map that was built in 2003.

(1) Population

The population for each municipality of the study area in 2009 is considered as the current state in this research. The detail data of population in 2009 is indicated in the following sections in order to make it easier to compare the future population and the current state. Two kinds of population can be considered:

- Urban population: people living in urban areas. The domestic wastewater is collected in a sewage system and discharges into the streams as point pollution sources (Nguyen, 2013).
- Rural population : people living in rural areas. The domestic wastewater is not collected in a sewage system and discharges into the environment as non-point pollution sources (Nguyen, 2013).

(2) Domestic wastewater

For the current environmental state, domestic wastewater is one of the biggest existing environmental problems in both provinces because there is no treatment plant for domestic wastewater for both urban and rural population (DONRE Bac Kan, 2010 and DONRE Thai Nguyen, 2010). There are 16 point sources of domestic wastewater without treatment in urban areas which were established in GIBSI (Figure 5.1). For rural areas, domestic wastewater is considered as non-point pollution sources; therefore contaminants are included in surface contaminants transport processes (Nguyen, 2013).

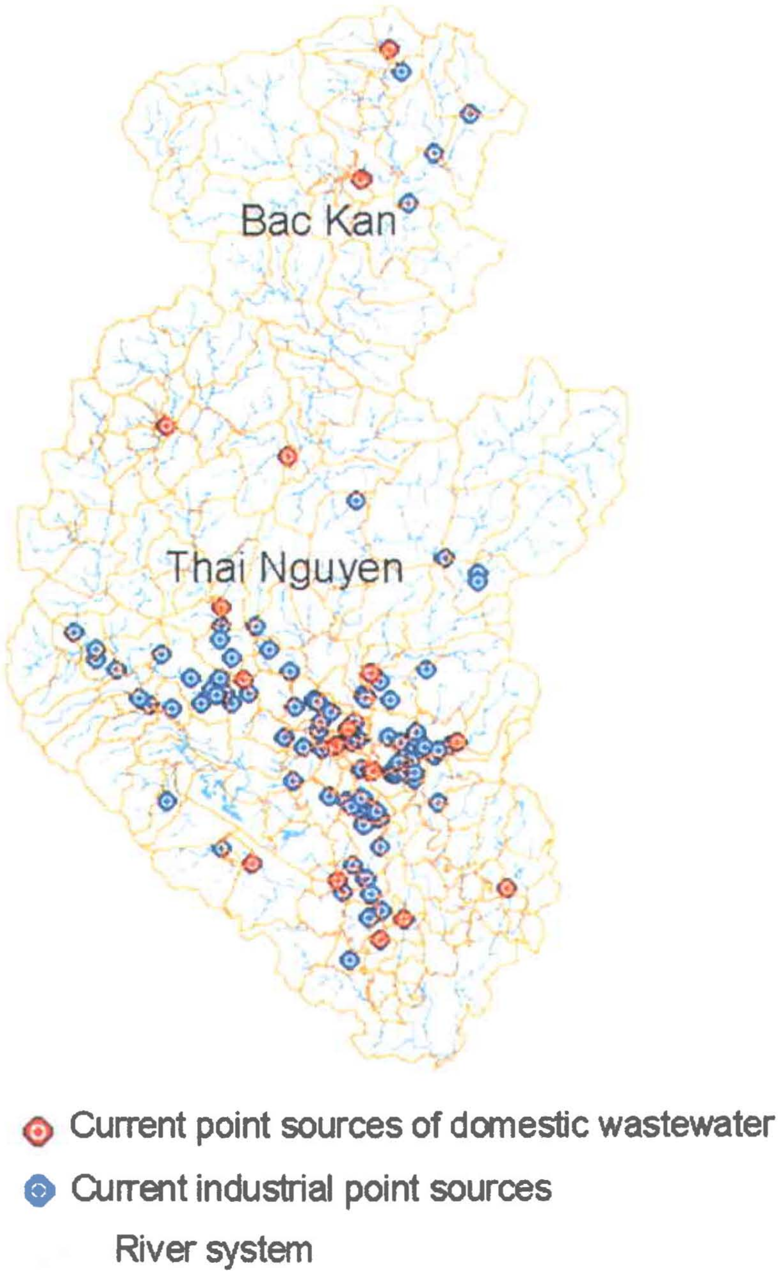


Figure 5.1: The current point sources of domestic wastewater and industry in the study area.

(3) Industry

Industrial wastewater is currently one of the biggest existing environmental problems in Bac Kan and Thai Nguyen provinces (DONRE Bac Kan, 2010 and DONRE Thai Nguyen, 2010). According to the collected data, there are 94 industrial point sources, which were also set up in GIBSI for the purpose of river water quality simulation (Nguyen, 2013, see Figure 5.1).

Currently, there are about 50% of the enterprises in Bac Kan and 80% of those in Thai Nguyen province who have installed a wastewater treatment plant (JICA and MONRE, 2009). However, it is not sure if the enterprises continuously operate their wastewater treatment plants or just run them when local environmental managers come for inspection (JICA and MONRE, 2009).

(4) Livestock

The number of livestock in 2009 is considered as the current state in this research. Based on the statistical data of livestock in 2009, the total number of heads or each type of animal in the study area was determined (see Table A5.1 in Appendix). It is necessary to collect this data because the feces of livestock is used for the nearby agricultural lands (Nguyen, 2013), together with the fertilizer which is put down. It is possible to simulate transportation of excess amount of nitrogen and phosphorus from soil surface to the river system.

(5) Agricultural fertilizers

The quantity of nitrogen and phosphorus fertilizer used to cultivate paddy, maize and other plants in agriculture is considered as potential pollutants for the water environment. Currently in Vietnam, 100 kilograms of nitrogen fertilizer and 60 kilograms of phosphorus fertilizer are put down into one hectare of soil used for planting paddy, and the quantities for growing maize are 120 kilogram of nitrogen fertilizer and 90 kilogram of phosphorus fertilizer per hectare (http://www.knowledgebank.irri.org/rkb/vietnam).

(6) Forest

The land use map for 2003 was used in GIBSI. Therefore, the current state for forest in this research is the forest area in 2003. The natural forest area in the whole Bac Kan province in 2003 represents around 55% of the total province area (Source: Backan Statistics Office, 2004). In Thai Nguyen province, the forest area in 2003 represents about 44% of the total provincial area (Source: Thainguyen Statistics Office, 2004). The detail data of current forest area in the study area is indicated in the following sections in order to make it easier to compare the changes of forest area in future and the current state.

(7) Meteorological conditions

Meteorological data necessary to define the reference state in the study area are data available in the period from 1998 to 2009 (Nguyen, 2012). In this research, meteorological conditions in 2009 are considered as the current state. In fact, in the framework of the project of integrated water resources management in Cau River Basin between, the hydrometeorological observations used for hydrological modelling covered the period 1998-2006 (Nguyen, 2012) completed with 2007-2009 (Kokutse, personal communication). Analysis of the whole period highlighted that, except 2001 during which extreme precipitations occurred (Nguyen, 2012), all other years have more or less moderate hydrometeorological conditions. 2009 was therefore considered as reference years for the hydrometeorological conditions. The location of all meteorological and rainfall stations in the river basin can be found in Figure A5.2 in Appendix.

5.3. Climate change

Among the seven factors, only data of climate change are analyzed at the level of the whole study area. Therefore, one scenario of climate change will be developed. As mentioned in chapter 4, climate change scenarios are developed by assuming changes in temperature (ΔT) and rainfall (ΔP) based on available data for each month until 2020 for 4 among 16 meteorological stations in the watershed (see Figures A5.1 and A5.2 in Appendix).

5.4. Scenario development

Due to the fact that the study area includes two parts (part of the Cau River Basin in Bac Kan province and the part in Thai Nguyen province), the four steps for scenarios development will be applied to each part at the same time. Therefore the final scenarios will be developed for the whole province.

5.4.1. Step 1: system analysis

Except for climate change, information on the six other factors are analyzed based on available data at the province level.

(1) Population

Population data necesary for scenario development are future population for the period of study in the study area. According to the method 3 that was chosen to forecast the population (see section 4.2.1), the future population was calculated based on projections of the local governments and statistical data (JICA and MONRE, 2009). Due to uncertainties, the highest and lowest population growth rates were also used based on past (2001-2009) in order to determine the possible values for population in the future. These values are: (1) Bac Kan province: 1.45%/year and 0.57%/year; and (2) Thai Nguen province: 1.17%/year and 0.19%/year.

Some adjustments were necessary for some districts in Bac Kan province. In fact, for Bac Kan town, according to the Master plan of social-economic development of Bac Kan, this town will become a city in 2015. Its population should therefore increase faster than in other districts of the province of Bac Kan (Bang, Header of Bac Kan Statistic Department, personal communication).

The forecast results of population for both provinces in the Cau River Basin are summarized in Tables 5.1 and 5.2.

Table 5.1: Population forecast results for the Cau River Basin in Bac Kan province.

Districts	2009 (Base)	2015			2020		
		Low	Medium(1)	High	Low	Medium(1)	High
Bac Kan town	37,585	55,876	57,314	58,752	81,245	84,699	88,153
Cho Don	8,764	9,068	9,454	9,555	9,329	9,926	10,268
Bach Thong	30,228	31,277	32,606	32,955	32,178	34,237	35,415
Cho Moi	32,169	33,285	34,700	35,071	34,244	36,435	37,689
Total	**108,746**	**129,506**	**134,074**	**136,333**	**156,997**	**165,297**	**171,524**

(1): According to the projections of local government.

Table 5.2 Population forecast results for the Cau River Basin in Thai Nguyen province.

Districts	2009 (Base)	2015			2020		
		Low	Medium(1)	High	Low	Medium(1)	High
Thai Nguyen City	279,710	282,914	293,717	299,929	285,612	308,402	317,890
Song Cong town	50,000	50,573	52,517	53,614	51,055	55,143	56,825
Dinh Hoa district	86,200	87,187	90,583	92,431	88,019	95,112	97,966
Vo Nhai district	41,113	41,584	43,192	44,085	41,981	45,352	46,725
Phu Luong district	105,250	106,456	110,583	112,858	107,471	116,113	119,617
Dong Hy district	112,970	114,264	118,661	121,136	115,354	124,594	128,390
Dai Tu district	158,700	160,518	166,763	170,172	162,049	175,101	180,362
Phu Binh district	133,500	135,029	140,276	143,150	136,317	147,290	151,723
Pho Yen district	137,150	138,721	144,092	147,064	140,044	151,296	155,871
Total	**1104,593**	**1117,246**	**1160,385**	**1184,440**	**1127,900**	**1218,404**	**1255,370**

(1) According to the projections of local government.

(2) Domestic wastewater

As mentioned in section 5.2, domestic wastewater is one of the biggest existing environmental problems in the study area, especially in Bac Kan City and Thai Nguyen City. Currently there are no treatment plant for domestic wastewater (DONRE Thai Nguyen, 2010). The local government of each province planned to install and operate a domestic wastewater treatment plant in the future for Bac Kan town ad Thai Nguyen City. The projections for the treatment plants are summarized in Table 5.3 and were considered for domestic wastewater scenario development.

Table 5.3: Information for sewerage projects of Bac Kan town and Thai Nguyen City.

Item	Bac Kan town	Thai Nguyen City
Service site	Central area of Bac Kan town	Northern center of Thai Nguyen City
Service population	10,000 people	100,000 people
Sewerage system	Separate drainage system	Semi-separate drainage system
Quality of wastewater after treatment	Vietnamese standard (TCVN 7222: 2002)	Vietnamese standard (TCVN 7222: 2002)
Total cost	206.3 billion VND (11.6 million US$)	579.9 billion VND (32.2 million US$)
Service commencement	2015	2013

<u>Sources</u>: (JICA and MONRE, 2009 and Bac Kan Department of Construction, 2010).

In Bac Kan town, about 17.9% in 2015 and 12.3% in 2020 of the low future population in Bac Kan town will be connected to the treatment plant. In Thai Nguyen City, only half of the population in 2015 and 2020 were considered to be connected to the treatment plant because GIBSI was calibrated for the Cau River Basin only from the upstream in Bac Kan province to Gia Bay monitoring station, in the middle of Thai Nguyen City. Therefore only the northern part of Thai Nguyen City was taken into consideration. GIBSI was not calibrated for the southern part of Thai Nguyen City because this region is affected by the tide from downstream which cannot be taken into consideration by the hydrological model.

Alternative interventions were considered for scenario development because the domestic wastewater treatment plant is considered as one of the key points in future social-economic developments in the provinces.

Two hypotheses for domestic wastewater treatment plant in order to develop alternative scenarios were made by increasing the capacity of the plant as follows:

- Bac Kan province: 20,000 and 30,000 people;
- Thai Nguyen province: (1) 150,000 people in Thai Nguyen City and (2) 100,000 people in Thai Nguyen City and 10,000 people in Sonc Cong town (like the capacity of the projected treatment plant in Bac Kan Town). Song Cong town is a big town in this province and located in the study area.

(3) Industry

In the future, according to the Master plan of social-economic development, industry will continue to develop in order to promote the local economy in the province. Industrial developement can affect water quality in the environment. The projections for industrial growth are: (1) In Bac Kan province, the growing rate of the industry-construction sector will be around 26%/year in the period from 2011 to 2015 and 20%/year in the period from 2016 to 2020; (2) In Thai Nguyen province, the growth rate of the industry-construction sector should increase from 13.5% to 14.5%/year from 2006 to 2020.

Currently, in Bac Kan province, there is one industrial zone (see Thanh Binh in Figure 5.2) which is under construction. The main information concerning the Thanh Binh industrial zone can be found in Table A5.2 in Appendix.

Thai Nguyen province plans to develop thirteen new industrial zones at different scales (seven new industrial zones at small scale and six new ones at large scale) until 2015. The locations of the thirteen future industrial zones in Thai Nguyen province can be found in Figure 5.2.

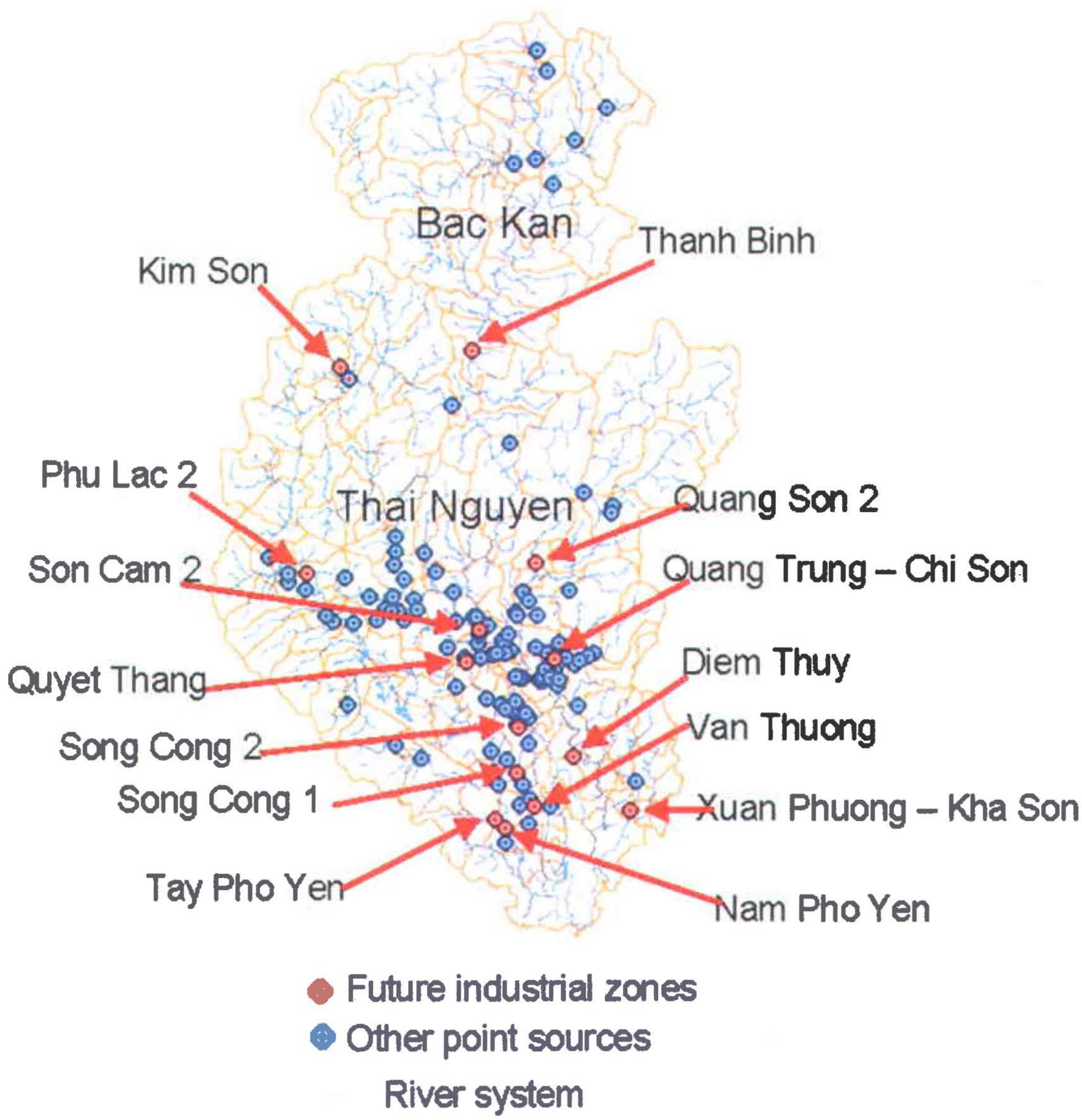


Figure 5.2: Location of fourteen future industrial zones in the study area.

Because of the lack of the data concerning discharges from 13 new industrial zones in Thai Nguyen province, these discharges were estimated by using the following equation (*Source*: Government of Socialist Republic of Viet Nam, 2007):

$$Q_{discharge} = 0{,}8 \text{ x } Q_{supply} \quad \text{(Eq. 5.1)}$$

Where: Q_{supply} = 22 m^3/day/ha multiplied by the area in use of the industrial zone (ha) (*Source*: Vietnamese standard TCXDVN 33:2006 of Ministry of Construction about Water Supply - Distribution System and Facilities, Design Standard).

Due to the lack of data concerning the effective use of the industrial zone, it was assumed that the industrial zones for which data are missing represent 50% of the area that should be in use in 2015 and 100% the area that should be in use in 2020. The estimated discharges as well as the main information on all the industrial zones are summarized in Table A5.2 in Appendix.

According to the Master plan of social-economic development, it is planned to build a wastewater treatment plant for all future industrial zones. Therefore, in the future, when the facilities in this industrial zone will be under operation, their wastewater will be collected and treated to meet the Vietnamese standards for wastewater release (DONRE Bac Kan, 2010).

To develop industrial scenarios in the future, it was assumed that wastewater from all future industrial zones meet the Vietnamese standard for industrial wastewater, because all industries must meet this standard. Apart from the operation of new industrial zones in the future, three different assumptions were considered:

- Keep the current wastewater discharge of the current factories in 2015 and 2020;
- Increase of the wastewater discharge of the current factories by 5% in 2015 and 10% in 2020;
- Increase of the wastewater discharge of the current factories by 10% in 2015 and 20% in 2020.

Point sources corresponding to the treatment plants of the 14 new industrial zones in the study area with the different three assumptions were used to develop industrial scenarios for the Cau River Basin in the future.

(4) Livestock

The necessary data of livestock for creating scenarios are the number of buffaloes, cattle, pigs and poultry. They were calculated based on annual growth rates data available for buffaloes, cattle and pigs. For poultry, the assumption of constant linear growth rates from statistic data in past (2001-2010) was used for future projections (Figure A5.3 in Appendix). Moreover, the livestock's growth rates are assumed to be the same for each district in the province due to a lack of forecast data for each district. For Bac Kan province, the future numbers of livestock for some years in the future are summarized in Table 5.4.

Table 5.4: Projections for livestock in Bac Kan province.

Projection of numbers of unit heads of animals	2009[4]	2010[1]	2011[2]	2012[2]	2013[2]	2014[2]	2015[2]	2020[3]
Buffaloes	75,215	73,925	83,000	87,000	91,000	95,000	100,000	170,000
Cattle	30,984	27,110	39,000	42,500	45,500	47,500	50,000	85,000
Pigs	189,564	190,146	177,500	185,500	194,000	202,000	210,000	357,000
Poultry	1,207,868	1,212,734	-	-	-	-	-	-

Source: [1] : Bac Kan provincial Committee of the Party, 2011.

[2] : Department of Agriculture and Rural Development of Bac Kan province, 2011.

[3] : Master planning of social-economic development in Bac Kan province up to 2020: Estimating that the total number of livestocks in 2020 increases 1.7 times compared with 2015.

[4] : Backan Statistics Office, 2010.

- : No data.

In Thai Nguyen province, available data are projections for three years in the future with 2008 as the reference year for buffaloes, cattles and pigs (Table 5.5). For poultry, there are projections for two years, 2010 and 2020 (see Table 5.6). So, the projected data for each year in the future was calculated by assuming a constant linear growth between two consecutive years.

Table 5.5: Livestock projections data (%) in Thai Nguyen province from 2008 to 2020.

Items		Thai Nguyen			
		2008	2012	2015	2020
Number of livestock [heads]	Buffaloes & cattle	100%	110%	122%	148%
	Pigs	100%	147%	170%	208%

Source: *JICA and MONRE (2009).*

Table 5.6: Current state and projection for poultry in Thai Nguyen province.

		Current state					Projection	
	Unit	2005 [1]	2006 [1]	2007 [1]	2008 [1]	2009 [1]	2010 [2]	2020 [2]
Poultry	x1000 heads	4,669	4,956	5,071	5,295	6,067	6,500	9,200

Source: [1]: Thainguyen Statistics Office, 2010.

[2]: Institute of Agricultural Design and Planning, Report of five-year plan of Thai Nguyen (2005-2010).

The livestock growth rates for future years of 2015 and 2020 compared with 2009 (current state) for Cau River Basin in Bac Kan and Thai Nguyen provinces are shown in Appendix 1 - Figures A5.4 and A5.5.

(5) Agricultural fertilizer

According to the projections, the areas of paddy will stay constant until 2020. However, their yield and productivity will increase in the future. The increase of these yield and productivity results in the increase of nitrogen and phosphorus fertilizer quantities put down into the soil. In order to assess the impacts of this increase of fertilizer on river water quality, the data of the increase of yield and productivity, as well as the needs of nitrogen and phosphorus fertilizers for plants, were collected. This research integrates the impacts of the fertilizer increase for paddy fields on the surface water quality in the study area. The collected projection data for paddy are summarized (Table 5.7).

Based on data collected, in Bac Kan province the yield of paddy in 2020 is the assumption number which was calculated by assuming the same growth rate as in the period from 2009 to 2015: 4.4 ton/ha in 2009, 4.9 ton/ha in 2015 and 5.4 ton/ha 2020. In Thai Nguyen province, the yields of paddy were found to be 4.9 t/ha in 2009, 5.1 t/ha in 2015 and 5.4 t/ha in 2020.

According to the objective of raising rice production in Vietnam, the needs for creating 0.1 ton of rice are 2 kg of N and 0.9 kg of P_2O_5 (Vietnamese rice knowledge bank). These changes in agricultural fertilizers are used in order to build agricultural scenarios.

Table 5.7: Current states and projections for paddy in Cau River Basin.

	Bac Kan province						
Projections for paddy	**2009**[(1)]	**2011**[(2)]	**2012**[(2)]	**2013**[(2)]	**2014**[(2)]	**2015**[(2)]	**2020** (Assumption)
Area of paddy (ha)	21,822	21,000	21,000	21,000	21,000	21,000	-
Yield of paddy (ton/ha)	4.407	4.555	4.65	4.74	4.83	4.915	5.338
Production of paddy (ton)	96,167	95,655	97,650	99,540	101,430	103,200	-
	Thai Nguyen province						
	2005 [(3)]	**2006** [(3)]	**2007** [(3)]	**2008** [(3)]	**2009** [(3)]	**2015**	**2020** [(4)]
Area of paddy (ha)	70,066	70,144	70,224	68,856	69,829	-	67,000
Yield of paddy (ton/ha)	4.598	4.655	4.620	4.726	4.859	-	5.373
Production of paddy (ton)	322,153	326,547	324,468	325,381	339,283	-	360,000

Source: [(1)]: Backan Statistics Office, 2010.

[(2)]: Department of Agriculture and Rural Development of Bac Kan province, 2011.

[(3)]: Thainguyen Statistics Office, 2010.

[(4)]: Institute of Agricultural Design and Planning, Report of five-year plan of Thai Nguyen (2005-2010).

- : No data.

(6) Forest

Over the five past years in the provinces, the forest cover increased and it is planned that it will continue to increase in the future according to the local projection (Table 5.8).

Table 5.8: Current state and projection for forest covering.

	Bac Kan province								
	2005(1)	**2007(1)**	**2010(1)**	**2011(2)**	**2012(2)**	**2013(2)**	**2014(2)**	**2015(2)**	**2020(3)**
Forest covering (%)	53.8	55	58	58.8	59.6	60.4	61.2	62	≥65%
	Thai Nguyen province								
	2005(4)	**2006(4)**	**2007(4)**	**2008(4)**	**2009(4)**	**2010(5)**	**2014**	**2015**	**2020(6)**
Forest covering (%)	44,2	46,6	47,4	48,0	48,6	50	-	-	55

Source: (1): Department of Agriculture and Rural Development of Bac Kan province, 2009.

(2): Department of Agriculture and Rural Development of Bac Kan province, 2011.

(3): Master planning of social-economic development in Bac Kan province upto 2020.

(4): Thainguyen Statistics Office, 2010.

(5): Master planning of social-economic development in Thai Nguyen province upto 2020.

(6): Institute of Agricultural Design and Planning, Report of five-year plan of Thai Nguyen (2005-2010).

In Bac Kan province, the data (Table 5.8) show that forest covering is projected to increase from 62% in 2015 to over 65% in 2020. However, according to the detailed plan for forest planting of the Bac Kan Department of Agriculture and Rural Development, more forest will be planted only until 2015, after that (over the period from 2015 to 2020) the forest area in Bac Kan province should stay approximately constant.

In Thai Nguyen province, the forest planting area mainly focuses on production forest. It was found that 5,400 hectares of new forest should be planted from 2005 to 2020. The new production forest will be developed in Vo Nhai, Dinh Hoa and Dai Tu districts in order to meet the needs of materials for paper factories, wood-processing factories, etc. within the province (*Source: Institute of Agricultural Design and Planning, Report of five-year plan of Thai Nguyen (2005-2010)*).

The detailed plan of forest planting by district (in Bac Kan province) and by forest type (in Thai Nguyen province) in the study area is indicated in Tables 5.9 and 5.10. The data are used to change the land use from bare soil and shrub areas in districts into forest land use. This land use change can affect discharge and water quality in rivers.

Table 5.9: Schedule for forest planting by district in Bac Kan province.

District	Total (ha)	Period of time			
		2008 - 2010		2011 - 2015	
		Total (ha)	Average/year (ha/year)	Total (ha)	Average/year (ha/year)
Bac Kan town	**1,000**	300	100	700	140
Bach Thong	**2,300**	500	167	1,800	360
Cho Don	**4,800**	1,700	567	3,100	620
Cho Moi	**5,450**	2,200	733	3,250	650

Table 5.10: Schedule for forest planting in Thai Nguyen province.

Forest type	2005	2010	2020	Increasing rate 2005-2010 (%/year)
Protection forest (x1000 ha)	55.60	65	66	3.17
Special forest (x1000 ha)	28.00	33	37	3.27
Production forest (x1000 ha)	81.60	82	87	0.15

Source: Institute of Agricultural Design and Planning, Report of five-year plan of Thai Nguyen (2005-2010).

5.4.2. Step 2: Identification of the key problems and main projections

In this step, the key problems which are the existing environmental problems, and the main projections for social-economic development, which can affect water quality in rivers, were identified in order to determine the priority levels for the seven factors used in step 3 of the scenario development.

As mentioned above in the part 1.1. of context of the research, the surface water of Cau River has been polluted in some river reaches. For example, BOD_5 concentration in Cau River section flowing through Bac Kan province has exceeded the Vietnamese standard of surface water quality in some locations. The observed data of BOD_5, NH_4^+, SS, etc for the current state from 2005 to 2009 can be found in Nguyen (2013). Therefore, the identification of key existing environmental problems as well as the main development projection in the future which can have impacts on future water quality is very important to deal with the water pollution problems in Cau River basin.

Key problems: Domestic wastewater and industrial wastewater

+ *Domestic wastewater*: the continuously increasing population together with the current state of untreated domestic wastewater has become a big environmental problem in the study area (DONRE Bac Kan, 2010; DONRE Thai Nguyen, 2010);

+ *Industrial wastewater* has increased over the last years due to the increasing number of factories. In Bac Kan province as well as in Thai Nguyen province, local economy will continue to expand. For example, in Thai Nguyen province, the annual average increase in the number of factories during the period from 2005 to 2009 is 22.2% (DONRE Thai Nguyen, 2010). Moreover, it was planned to continue expanding the industries in the future. Therefore, industrial wastewater also becomes a big challenges for the future environment.

Main projections: Population and industrial growth

According to the Master Plan, Bac Kan Town will become a city in 2015. Therefore, one of the main projections for social-economic development in local area is the fast future population growth for Bac Kan town. Moreover, for the other districts in Bac Kan province, according to the population projection and forecast results which are indicated in step 1 of the system analysis, Bac Kan population will increase more rapidly in the future.

The second main projection is industrial growth because the local governments plan to continue to develop the provinces' industry in order to improve the economy. In Thai Nguyen province, population will continue to increase in the future and industrial growth is also considered as one of the main key elements for projections in this province. It can be said that the two main projections for social-economic development in the river basin, which can affect water quality of the Cau River system, are the population and the industrial growth.

5.4.3. Step 3: Identification of the priority levels for factors

The identification of the priority levels for the seven factors of population, domestic wastewater, industry, livestock, agricultural fertilizer, forest, and climate change is based on the above key problems and main projections. As mentioned at the beginning of this chapter, the priority levels are divided into three groups: high, middle and low priorities. The priority levels for scenario construction for the Cau River Basin are indicated as follows:

- *High priority (or priority 1)*: includes three factors: *population, domestic wastewater* and *industry,* which are the main environmental pollution sources and the major factors for future development.
- *Middle priority (or priority 2)*: includes two factors: *livestock* and *agricultural fertilizers,* which are direct environmental pollution sources but have less impacts on water quality in rivers than the factors in the high priority group. These two factors are not the main reasons for the current environmental pollution in the study area and will not have a great influence on the watershed in the future.
- *Low priority (or priority 3)*: includes two factors: *forest* and *climate change,* which have indirect and less important impacts on water quality of the rivers than the factors in middle priority.

In order to help in scenario drafting and creation in step 4, a summary of priority levels, available data and information for each factor to develop scenarios for the Cau River Basin is presented for each province (Table 5.11).

Table 5.11: Summary of factors, priority levels, available data and information for scenario development.

Factors	Priority level (1, 2, 3)	Available data	Information on scenarios	Hypothesis and comments
Population	1	Projected values of population by district and by city in the future.	Low, medium and high values of projected population.	
Domestic wastewater	1	Treatment plants for domestic wastewater in Bac Kan town and Thai Nguyen City.	Three values of treatment plants capacity: Bac Kan province: 10,000; 20,000 and 30,000 people. Thai Nguyen province: 100,000; 150,000 and 100,000 in Thai city +10,000 people in Sonc Cong Town.	Increase of the capacity of treatment plants for several values.
Industry	1	Current and future industrial zones: location, capacity of treatment plant, contaminant concentrations.	Three values of wastewater discharges for current and future industries: Current discharge 10% increase in 2020 (5% in 2015) 20 % of increase in 2020 (10% in 2015).	All industries meet the Vietnamese standards for industrial wastewater.
Livestock	2	Annual projection in 2010-2015 and orientation for 2016-2020.	One value of increase in number of livestock.	Use of feces in nearby agricultural lands.
Agricultural fertilizer	2	Paddy fields constant and projection for productivity increase in 2010-2020. Quantity of fertilizers to increase productivity.	One value of increase in quantity of fertilizers.	Increase of fertilizers to increase productivity.
Forest	3	Changes of forest lands in the period 2010-2015 and 2016-2020.	One change of land use.	Change of land use from bare soil, and shrubs into forest.
Climate change	3	Monthly changes in temperature (ΔT) and in precipitation (ΔP) 2000-2020.	One change of ΔT and ΔP.	Use of a mean monthly value for all meteorological stations.

5.4.4. Combination of factors to draft scenarios and scenario creation

Analysis at steps 1 and 2 helped find that key problems and main projections for Bac Kan and Thai Nguyen provinces are similar. The key problems with the priority levels can therefore be considered as similar for the whole river basin. Based on results at step 3 (Table 5.11) and the priority levels of the seven factors, realistic combinations of different levels of factors were analyzed in order to obtain a matrix of combinations (Table 5.12) as results of scenario development for the whole Cau River Basin. Details for the values in Table 5.12 are indicated in Appendix 1 - Table A5.3. In order to avoid obtaining a huge number of scenarios with all possible combination, the most realistic combinations were made. A total of fourteen scenarios from S_1 to S_{14}, were therefore obtained for the Cau River Basin. Each combination is considered for a specific goal. The scenarios are divided into four groups.

Group 1: Scenarios for the 1st priority factors (priority level 1): population, domestic wastewater and industry. In this group, there are 9 scenarios. All 2nd and 3rd priority factors are assumed to be in the actual conditions (2009). The three sub-groups are:

- Sub-group 1 (3 scenarios): scenarios for population and domestic wastewater. There are three scenarios in this sub-group (S_1, S_2, and S_3). These scenarios were built to assess the impacts of future population growth and domestic wastewater on the water quality of the Cau River system.

  For example, S_1 is the combination of the low future population and the projection of domestic wastewater treatment plant for 10,000 people in Bac Kan City and 100,000 people in Thai Nguyen City. All other factors are in actual conditions.

- Sub-group 2 (3 scenarios): scenarios for industry, which were considered to assess the impacts of future industrial growth on the water quality of Cau River system. There are three scenarios in this sub-group (S_4, S_5, and S_6).

  For example S_4 is the combination of the projection for the 14 industrial zones in the future with the current factories in the actual conditions, and low projection of the population. All other factors are in actual conditions.

- Sub-group 3 (3 scenarios): scenarios of all three factors of population, domestic wastewater and industry. There are three scenarios in this sub-group (S_7, S_8, and S_9). These scenarios were developed in order to assess the impacts of future population growth, domestic wastewater and industrial growth at the same time on the water quality of Cau River system.

  For example S_7 is the combination of the projection of the 14 industrial zones in the future with the current factories in the actual conditions, low projection of the population and low capacity of the wastewater treatment plant (10,000 people in Bac Kan City and 100,000 people in Thai Nguyen City).

For the scenarios of the 1st priority factors, we assume that all the 2nd and 3rd groups factors are in reference situation.

Group 2: scenarios for the 2nd priority factors (priority level 2): livestock and agricultural fertilizer. In this group, there are two scenarios (S_{10} and S_{11}) to assess the impacts of the increase in the number of livestock and quantity of agricultural fertilizer, together with the medium scenario S_8 of the 1st priority factors, on the water quality of Cau River system.

Group 3: scenarios for the 3rd priority factors (priority level 3): forest and climate change. In this group, there are two scenarios (S_{12} and S_{13}) to assess the impacts of the increase of forest area and the changes of temperature and precipitation, together with the medium scenario S_8 of the 1st priority factors, on discharge and water quality of Cau River system.

Group 4: scenario for the combination of the 1st, 2nd and 3rd priority factors (all seven factors): population, domestic wastewater, industry, livestock, agricultural fertilizer, forest and climate change. There is only one scenario for this group (S_{14}). This scenario was developed in order to assess the impacts of future social-economic activities on the discharge and water quality of Cau River system.

Table 5.12: Matrix of combination of different levels of the seven factors for the Cau River Basin.

Priority level	Factors		Scenarios													
	Name	values	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
1st	Population	Low projection	X			X			X							
		Medium projection		X			X			X		X	X	X	X	X
		High projection			X			X			X					
	Domestic wastewater	Low capacity	X						X							
		Medium capacity		X						X		X	X	X	X	X
		High capacity			X						X					
	Industry	Current industries + projected				X			X							
		Medium increase for current					X			X		X	X	X	X	X
		High increase for current						X			X					
2nd	Livestock	Medium projection										X				X
	Agriculture	Medium projection											X			X
3rd	Forest	Medium projection												X		X
	Climate change	Medium projection													X	X

5.5 Synthesis

Through this chapter, it can be noticed that key problems and main projections of Bac Kan and Thai Nguyen provinces are similar, leading to the same priority levels of the seven factors for scenario development in the whole river basin. In order to assess the impacts of social-economic development in the Cau River Basin, we made realistic combinations of factors with different values to build scenarios from S_1 to S_{14}.

The impacts of these fourteen scenarios for the whole study area are assessed only in three selected years, which are 2009 (reference state), 2015 and 2020. In GIBSI models, it is not possible to take into consideration for a long term simulation (*e.g.* 10 years like in this study) the temporal dynamic for some input data such as land use. To simulate 10 years for one scenario, a total of 10 simulations may be necessary. This may conduct to a huge number of time consuming simulations to get the results for all 15 scenarios. Furthermore, the main objective of this study is not to determine a temporal variation in the future for water quality variables, from the reference state to 2020.

Thus, this research chose long term targets in order to determine significant variations in surface discharge and water quality in the study area. The simulation results for years 2015 and 2020 will be compared with the current state (year 2009).

- Moreover, in the master planning of social-economic development in Bac Kan and Thai Nguyen provinces, years 2015 and 2020 are the time points that the local government selected for their projections.
- Besides, in the master plan on the protection and sustainable development of the landscape and ecological environment of Cau River Basin that was approved by the decision of the Vietnamese Prime Minister on July $28^{th,}$ 2006, year 2020 was also selected as the target year when Cau River should be clean.

The fourteen scenarios for the whole study area will be assessed by taking the ideas of stakeholders, simulating the impacts of each scenario on the surface water quality of the Cau River Basin, and analysing costs comparison for scenarios. The results of these assessments are shown in the following chapter.

Chapter 6: Scenario comparison and selection

The assessment of each created scenario will be done in order to be able to select the most suitable scenarios for the local social-economic development as well as the environmental protection. This assessment includes three parts: (1) ideas of stakeholders concerning the scenarios, (2) impacts of each scenario on surface water quality in the Cau River Basin, and (3) cost/ benefit analysis for each scenario. After that, the scenario selection will be done based on the results of the three above assessment parts by using the multi-criteria method.

6.1. Ideas of stakeholders about scenarios

The role of stakeholders is very important for watershed integrated management because they have experience in local environmental management and know well what the political wishes of local governments are. Moreover, they are also the people who will apply the selected scenarios. Therefore, it is necessary to take into consideration their ideas.

This part will talk about the ideas of stakeholders regarding the developed scenarios for Cau River Basin in Bac Kan and Thai Nguyen provinces. In order to collect these ideas, a workshop was organized and a questionnaire was used (see Appendix 2, Appendix 3 and Appendix 4 for the questionnaire and pictures of the workshop).

The workshop on "Development of scenarios and water environment management for Cau River Basin in Bac Kan and Thai Nguyen provinces" was held in Thai Nguyen City on February 8th, 2012 with the objective of taking ideas from stakeholders about the developed scenarios. The scenarios created for Cau River Basin in Bac Kan and Thai Nguyen provinces were presented in this workshop along with a questionnaire to collect the ideas about these scenarios.

Three kinds of stakeholders were considered: local people community, local managers and experienced experts from different organizations. For the local people community, several interviews were made in November 2009 in Bac Kan and Thai Nguyen provinces to collect the ideas of local people about sanitation and their environmental knowledge. It was found that local people care only about nearby activities which have visible direct impacts on their life or on the environment, like neighbor livestock-breeding activities with bad odours and dust caused by the transportation near their houses are one of the greatest concerns for environmental pollution sources. These people had few or no concern for the future domestic wastewater treatment plant in Bac Kan town because they did not know the environmental benefits and the impacts that this project could have on their life. Moreover, currently, not only in Thai Nguyen province but also in other regions of the country, the environmental awareness of local people is not high and their involvement in environmental protection is limited (DONRE Thai Nguyen, 2010). So, it is difficult for them to understand these scenarios in order to give a point of view on the priority. Therefore, there were only two kinds of participants who were invited to the workshop. They were:

(1) Local managers from different organizations in Bac Kan and Thai Nguyen provinces such as the Department of Natural Resources and Environment, the Department of Agriculture and Rural Development, and the Department of Industry and Trade;

(2) Experts from different organizations such as the Ministry of Natural Resources and Environment, the Vietnamese Environment Administration, the Water Resources University, the Institute of Agricultural Environment under the Vietnam Academy of Agricultural Sciences, the Institute of Water Resources Planning under the Ministry of Agriculture and Rural Development, the Institute of universal technology and the Institute of Environmental Technology under the Vietnamese Academy of Science and Technology.

Local manager's ideas are important because they know well the local conditions and local government priorities. However, the experts are considered as important as the local managers because they may have more experience in implementing similar projects in many regions. So their ideas also contribute to identify realistic scenarios with regard to the context. Therefore, the importance levels of these two kinds of participants are considered as equal in this case.

Through the workshop, 14 questionnaires with the ideas of stakeholders have been collected, in which there are 9 ideas from experts of different organizations and 5 ideas from local managers.

The priority levels for each scenario according to the ideas of stakeholders are shown in the following table:

Table 6.1: Percentage of the ideas of experts and local managers for each priority level of each scenario for Bac Kan and Thai Nguyen.

Scenarios	Priority levels for Bac Kan province			Priority levels for Thai Nguyen province			Priority level for study area
	High	Average	Low	High	Average	Low	
Scenario S_1	11.1	11.1	77.8	20	10	70	Low
Scenario S_2	66.7	33.3	0	70	30	0	High
Scenario S_3	55.6	44.4	0	70	30	0	High
Scenario S_4	33.3	11.1	55.6	30	30	40	Low
Scenario S_5	66.7	33.3	0	100	0	0	High
Scenario S_6	33.3	55.6	11.1	40	60	0	Average
Scenario S_7	0	44.4	55.6	10	50	40	Low
Scenario S_8	55.6	44.4	0	70	30	0	High
Scenario S_9	44.4	55.6	0	50	50	0	Average
Scenario S_{10}	0	77.8	22.2	20	70	10	Average
Scenario S_{11}	22.2	22.2	55.6	0	50	50	Low
Scenario S_{12}	22.2	22.2	55.6	20	30	50	Low
Scenario S_{13}	11.1	33.3	55.6	10	30	60	Low
Scenario S_{14}	66.7	22.2	11.1	50	30	20	High

The numbers in Table 6.1 are the percentages of the ideas of stakeholders for each priority level in the total of 14 questionnaires collected. There are 3 priority levels: high, average, and low. Stakeholders arranged their priority order for each scenario for each province (Bac Kan and Thai Nguyen) according to their ideas based on two criteria: (1) the probability of happening in the future and (2) the factors in the matrix of combination which stakeholders are interested in, in order to know their impacts on surface water quality of Cau River Basin.

After we obtained the priority level results for Bac Kan and Thai Nguyen provinces, these two results were integrated into one result for each scenario (see column "Priority level for study area" in Table 6.1). We had to determine one priority level for the watershed because river water quality will be simulated for the whole watershed. For example, Scenario 1 for Bac Kan province and Scenario 1 for Thai Nguyen province are integrated into only one scenario: Scenario 1, and we will obtain only one simulation result for Scenario 1 for both Bac Kan and Thai Nguyen provinces. Simulation results will be analyzed for some river reaches to determine the impacts of future social -economic development on river water quality.

Results show that there are five scenarios with high priority, which are Scenario 2, Scenario 3, Scenario 5, Scenario 8, and Scenario 14. This result corresponded to the stakeholders' ideas. The explanation of the opinions of the stakeholders for these five scenarios considered with high priority is as follows:

- *Scenario 2, Scenario 3 and Scenario 5*: Stakeholders agreed that in the Cau River watershed, domestic and industrial wastewater are the two main types of pollution point sources and they want to know the impacts on water quality of each of these pollution point sources. Among the scenarios related to these two factors (scenarios S1, S2, S3, S4, S5, S6), scenarios S2 and S3 were considered with high priority because they want to see the impacts of the high pressure of population growth, including the population growth according to the projection (average) and the maximum forecasted population, which combines with interventions for domestic wastewater treatment. Scenario S5 was also selected with high priority because stakeholders think that the increase of 10% of current factories' discharge besides the new industrial zones is reasonable for the future (5 to 10 years).

- *Scenario 8*: Stakeholders also think it is important to know the impacts on river water quality of both main pollution point sources at the same time. Therefore, scenario 8 was chosen with high priority as it is the combination of scenarios S2 and S5.

- *Scenario 14*: Although the other factors such as livestock, agriculture, forest lands and climate change were not considered as priority factors by local governments in the future, this scenario was considered to be important by stakeholders. In fact, scenario 14 will help to know the combined impacts of all possible pollution sources and factors which can affect river water quality. It was therefore selected with high priority.

The results for the ideas of stakeholders will be combined with the results of the water quality impact assessment and the cost comparison analysis in order to select the best scenarios for the local social-economic development as well as the water environment protection of Cau River Basin in Bac Kan and Thai Nguyen provinces.

6.2. Simulation results of water quality in the Cau River Basin

This part talks about the simulation results which help determine the impacts of each scenario on river water quality and quantity. Input data prior to water quality simulation are also shown. After that, the priority level for each scenario based on the water quality improvement is given, contributing to the final scenario selection which is based on the three main results of the thesis.

6.2.1. Input data for simulation

In order to simulate river water quality in the watershed for each scenario, different types of input data are necessary: (1) point sources from domestic and industrial wastewater; (2) non point sources from population in rural areas, livestock and paddy fertilizers; and (3) forest area, and changes in climate (temperature and rainfall), which are based on collected and estimated data (see chapter 5). In the model, population in rural areas is taken into consideration as non point source of pollution and population in urban areas is taken into consideration as point source of pollution (Nguyen, 2013). During the preparation of input data for industrial wastewater point sources and future pollution point sources for domestic wastewater, there was a lack of input data for some constituents caused by the difference between the values of nitrogen and phosphorus constituents in GIBSI and in the Vietnamese standards. This problem and the way to solve the problem are shown as follows:

According to the local government policies, all the wastewater from industrial factories and domestic wastewater treatment plants should meet the Vietnamese standards for wastewater discharge (Vietnamese National Assembly, 2005). We therefore assumed that the wastewater from all the future industrial zones, as well as the current factories, and domestic wastewater treatment plants meets Vietnamese standards. Thus, the input values which were considered for all of water quality variables for future point sources in GIBSI are the concentrations indicated in the Vietnamese standards. Table 6.2 shows variables which can be simulated with GIBSI for water quality in Cau River Basin and corresponding concentrations of the variables in Vietnamese standards.

Table 6.2: Water quality variables in GIBSI for Cau River Basin and concentrations in Vietnamese standards.

Variables in GIBSI	Standard for industrial wastewater QCVN 24:2009/ BTNMT (inputs)		Standard for central domestic (municipal) wastewater treatment plants TCVN 7222:2002 (inputs)		Standard for surface water quality QCVN 08:2008/BTNMT (for comparison)		
	Variables	Values	Variables	Values	Variables	Values	
						A2[(1)]	B1[(2)]
Dissolved oxygen (DO)	-	-	-	-	DO (mg/l)	≥ 5	≥ 4
Biochemical oxygen demand (BOD5)	BOD5 (mg/l)	50	BOD5 (mg/l)	30	BOD5 (mg/l)	6	15
Organic nitrogen	-	-	-	-	-	-	-
Ammonium N-NH3	NH_4^+ (N) (mg/l)	10	-	-	NH_4^+ (N) (mg/l)	0.2	0.5
Nitrite N-NO2	Total nitrogen (mg/l)	30	Total nitrogen (mg/l)	30	Nitrite NO_2^- (N) (mg/l)	0.02	0.04
Nitrate N-NO3	-	-	-	-	Nitrate NO_3^- (N) (mg/l)	5	10
Organic phosphorus	Organic phosphorus (mg/l)	1	-	-	Organic phosphorus	0.2-0.3	0.4
Dissolved phosphorus	Total phosphorus (mg/l)	6	Total phosphorus (mg/l)	6	Phosphorate PO_4^{3-} (P) (mg/l)	0.2	0.3
Coliforms	Coliforms (MPN/100 ml)	5000	-	-	Coliforms (MPN/100 ml)	5000	7500
Suspended solids (SS)	SS (mg/l)	100	TSS (mg/l)	100	Total suspended solids TSS (mg/l)	30	50
Chlorophyl-A	-	-	-	-	-	-	-

Table 6.2 shows that there is a difference between the forms of nitrogen and phosphorus variables in GIBSI and the forms in the Vietnamese standards of industrial and domestic wastewater treatment plants. In fact, based on the cycles of nitrogen and phosphorus, GIBSI can simulate four different forms of nitrogen (organic nitrogen, ammonia, nitrite and nitrate) and two different forms of phosphorus (dissolved and organic phosphorus). However, in the Vietnamese standards, only concentrations of total

nitrogen and total phosphorus are available. Assumptions were therefore made to determine input concentrations for different forms of nitrogen and phosphorus for simulations. Table 6.3 indicates the input concentration values for future point sources in the watershed and the assumptions/references for these values.

Table 6.3: Input values of discharges and concentrations for future point sources.

Variables	Values for industrial wastewater		Input values for domestic wastewater	
	Concentration	Assumption/Reference	Concentration	Assumption/Reference
Discharge (Q)	Collected/estimated	Chapter 5 (see System analysis)	0,8 x 120 l /person/day	Vietnamese standard TCXDVN 33:2006
DO (mg/l)	5	Québec standard after treatment (available in GIBSI)	5	Québec standard after treatment (available in GIBSI)
BOD5 (mg/l)	50	Vietnamese standard QCVN 24:2009/BTNMT	30	Vietnamese standard TCVN 7222:2002
Organic nitrogen (mg/l)	0	Québec standard after treatment (available in GIBSI)	0	Québec standard after treatment (available in GIBSI)
$N\text{-}NH_3$ (mg/l)	10	Vietnamese standard QCVN 24:2009/BTNMT	26.4	$N\text{-}NH_3$, $N\text{-}NO_2$, $N\text{-}NO_3$ represent 88%, 6%, and 6% of total nitrogen respectively (Québec standard after treatment by anaerobic reservoir technology (Source: in GIBSI)
$N\text{-}NO_2$ (mg/l)	2	Maximum concentration from current factories	1.8	
$N\text{-}NO_3$ (mg/l)	18	Total nitrogen includes 4 types of nitrogen: organic, N-NH3, N-NO3, N-NO2	1.8	
Organic phosphorus (mg/l)	1	Vietnamese standard QCVN 24:2009/BTNMT	2.1-3.2	Total phosphorus includes 2 types: organic and dissolved phosphorus
Dissolved phosphorus (mg/l)	5	Total phosphorus (organic and dissolved phosphorus)	2.8	15% of 18.6 mg/l (MDDEP, 2010; Alexander *et al.* 1993)
Coliforms (MPN/100 ml)	5000	Vietnamese standard QCVN 24:2009/BTNMT	5000	Standard for industrial wastewater QCVN 24:2009/BTNMT
Suspended solids (SS) (mg/l)	100	Vietnamese standard QCVN 24:2009/BTNMT	100	Vietnamese standard TCVN 7222:2002

- Discharges, concentrations and locations of the current and future point sources has been taken into consideration for pollution point sources.
- Remaining population in urban areas without connection to domestic treatment plants were considered as point sources with variables' concentrations similar to the reference situation (Nguyen, 2013) in the watershed.
- Population in rural areas, livestock and paddy fertilizer were taken into consideration as non point sources of pollution.

- Forest areas in the future were taken into consideration by changing the land use based on the projected values in the future for hydrological simulations prior to water quality simulations. In fact, change in land use can have direct impacts on hydrology (runoff, discharges in river sections) and therefore on water quality;
- Climate change was taken into consideration by applying mean change to meteorological data (see Figure A5.3 in Appendix).

6.2.2. Simulation results of river water quality

As mentioned in section 4.3, four vairables were chosen to compare scenarios: discharge, BOD_5, NH_4^+ and SS. The impacts of the fourteen scenarios on water quality were assessed only in three selected years, which are 2009 (current state), 2015 (an intermediate year of the study period) and 2020 (the final year of the study period). For a scenario (see table 5.12), when climate change is not taken into consideration, hydrolometeorological conditions are the same in 2009, 2015 and 2020. This can help determine the effects of a specific factor or a group of factors on water quality.

For water quality results, a total of three boxplots for each scenario was obtained, because the simulation results of concentrations of three water quality variables (BOD_5, NH_4^+ and SS) were displayed by boxplot for each year of each scenario and each variable. Statistically, it is not possible to highlight a trend in the future for a water quality variable with only three years for a given scenario. Nevertheless, when mean values of a variable found in 2015 and 2020 are higher (or lower) with regard to the reference value, it can be assumed that these mean values are higher (or lower) for all the time in the future than its value for the reference scenario. Such assumption mainly helps point out for watershed managers what can probably happen in the future for water quality variables for a given scenario.

To compare scenarios, river water quality variables are shown for some selected river reaches. The concept of "priority level" was used for each scenario to make a classification of all scenarios based on the water quality improvement in these river reaches.

Selection of river reaches was made based on several criteria as follows:

- Each selected river reach should be located at a water quality monitoring station in order to take into consideration the observed data in the reference scenario.
- Each selected river reach should be at the location with an interest for cost comparison analysis in the study area such as water supply treatment plant, etc.

Based on the above criteria, the five following river reaches were selected:

- Along Cau River: there are three water quality monitoring stations in the main stream which were used in the project for river water quality model calibration (Audet, 2013; Nguyen, 2013). These monitoring stations are : Thac Rieng, Thac Buoi, and Gia Bay, which are located in Bac Kan province upstream, Thai Nguyen province in the center of the river basin, and in Thai Nguyen province at the oultet of the watershed respectively (Figure 6.1). River reaches located at these stations were therefore chosen. The three river reaches represent three different ecological regions of Cau River Basin: Thac Rieng for forest regions in mountains, Thac Buoi for agricultural regions in valleys, and Gia Bay for urban regions in plains.

- Cong River is one of the main tributaries of Cau River. Along Cong River, two river reaches were selected, one at water supply treatment plant in Song Cong town which is related to cost comparison analysis and one at Da Phuc Bridge water quality monitoring station.

These five river reaches are indicated in figure 6.1:

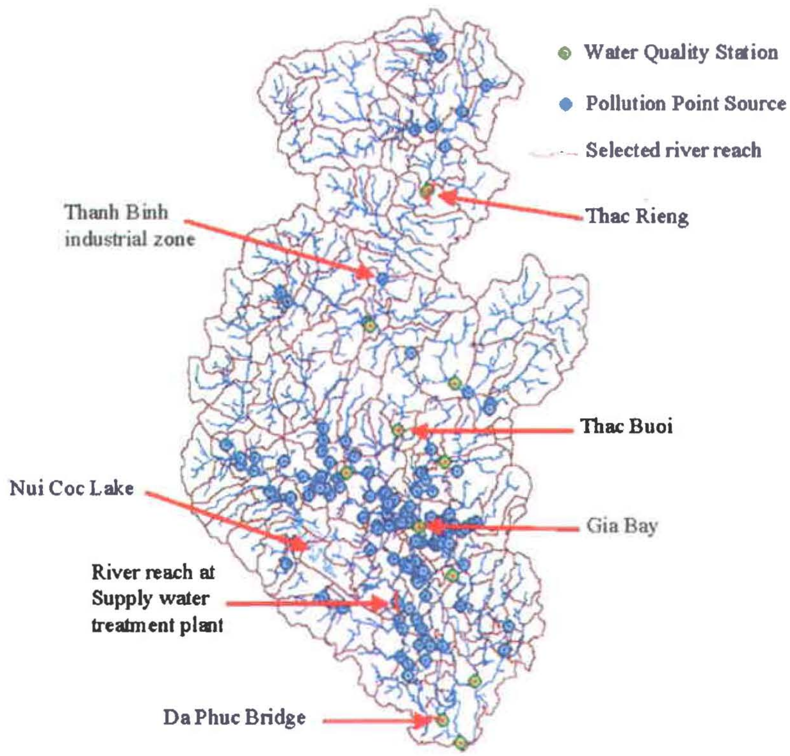


Figure 6.1: Location of the five selected river reaches and pollution point sources.

The two river reaches in Cong River sub watershed were selected for the following reasons: (1) River reach at the water supply treatment plant is related to the cost comparison analysis of water quality improvement; (2) River reach at the Da Phuc Bridge station may help analyze the impacts on water quality from some new future industrial zones and from an assumption of installing a domestic wastewater treatment plant in Song Cong town. Therefore, three river reaches in Cau River are considered to make the priority levels related to water quality improvement for the fourteen scenarios and two river reaches in Cong River are considered to make priority levels for scenarios if they are related to water quality in this river.

6.2.2.1. Simulation results in Cau River

Discharge and water quality variables are presented for each river reach and for all scenarios. The comparisons between scenarios, with the current state of the river basin, and with the Vietnamese standard for surface water quality are presented. However, we mainly focussed on the comparison of water quality changes between scenarios and with the current state (reference scenario) due to probable sources of uncertainties such as models to describe physical processes, observed data for calibration, etc.

Results of impacts of the four variables are shown: discharge, BOD_5, NH_4^+ and SS. The impacts of scenarios on discharge were determined based on the relative difference for a year and for a given scenario as follows:

$$E = \frac{\sum_{i=1}^{n}(Q_{ifuture}) - \sum_{i=1}^{n}(Q_{i2009})}{\sum_{i=1}^{n}(Q_{i2009})} * 100 \qquad \text{(Equ. 6.1)}$$

Where:

E (%) : relative difference between the reference situation and the future;

$Q_{ifuture}$ (m^3/s) is the daily discharge in the future year (2015 or 2020);

Q_{i2009} (m^3/s) is the daily discharge in 2009 (the reference situation);

n is the number of days in a year (365).

Concentrations of BOD5, NH4+ and SS are displayed by boxplot for each scenario in the future and for the reference situation. Each boxplot was represented with the 365 simulated values which correspond to 365 days in one year. The reason why we used boxplots to represent the simulation results is that in a year there may be great variations with very high and very low values of concentrations due to many reasons such as season variation, different application time of fertilizers, etc. Boxplots therefore help have an overview of the concentration values in the whole year.

In one boxplot, there is a central mark (middle line in the box) which is the median (Q2) of the data serie, indicating that 50% of the values of the data serie are under this line and 50% of the values are over it. The edges of the box are the 25th and 75th percentiles (Q1 and Q3). The whiskers extend to the adjacent values, which are the most extreme data values that are not outliers. The outliers are plotted individually if they are greater than Q3+1.5*(Q3-Q1) which is the upper whisker, or smaller than Q1-1.5*(Q3-Q1) which is the lower whisker. The median values were used to compare scenarios.

For the variables presented by boxplot, the green lines in the figures of simulation results indicate the concentrations in the Vietnamese standard for surface water quality; the lower line is the standard value for the purpose of water supply with treatment (6 mg/l for BOD_5, 0.2 mg/l for NH_4^+ and 30 mg/l for SS) and the upper line is standard value for the purpose of irrigation and other purposes (15 mg/l for BOD_5, 0.5 mg/l for NH_4^+ and 50 mg/l for SS).

The probability of exceeding standard was also calculated. It is an indicator to determine the pollution level of contaminants compared with standards and to compare scenarios. However, because of uncertainties such as model calibration, this indicator is mainly used in this research to compare scenarios betwen each other. The probability of exceeding standard in this case is the percentage of the number of days for which BOD_5 concentration exceeds the standard over one year (365 days).

There are 14 scenarios which were divided into 6 groups: a. Scenarios of population growth and domestic waste water (S1, S2 and S3); b. Scenarios of industry (S4, S5 and S6); c. Scenarios of population, domestic wastewater and industry (S7, S8 and S9); d. Scenarios of agriculture: livestock and fertilizer (S10, S11); e. Scenarios of forest and climate change (S12, S13); and f. Scenario of all factors (S14).

In order to rank scenarios in terms of water quality improvement in the future compared with reference situation, a priority level was given to each scenario for each river reach. Three priority levels were used: high, average, and low. Scenarios with "high priority level" correspond to scenarios with a positive impact on water quality compared with the reference situation and/or with other scenarios in the same group of impact, for example: group of scenarios impacted by industry S4, S5, and S6. Scenarios with "average priority level" are the scenarios in which water quality is the same as the current state and/or improved compared with low priority scenarios in the same group of impact. Scenarios with "low priority level" correspond to scenarios in which water quality is worse than the current state and/or than other scenarios in the same group of impact.

6.2.2.1.1. Thac Rieng

(1) Discharge

At Thac Rieng river reach, the impact on discharge was found to be negligible with forest planting scenario S12 (see Figure A6.1 in Appendix). The relative difference was found to be a decrease of 0.4% in the future. This decrease of river discharge at Thac Rieng as well as at other selected river reaches can be explained by the increase of forest areas in 2015 and 2020 in the river basin.

However, discharge resulting from the impacts of climate change (scenario S13) in 2015 and 2020 at this river reach showed peaks which are lower than the current state (see Figure 6.2).

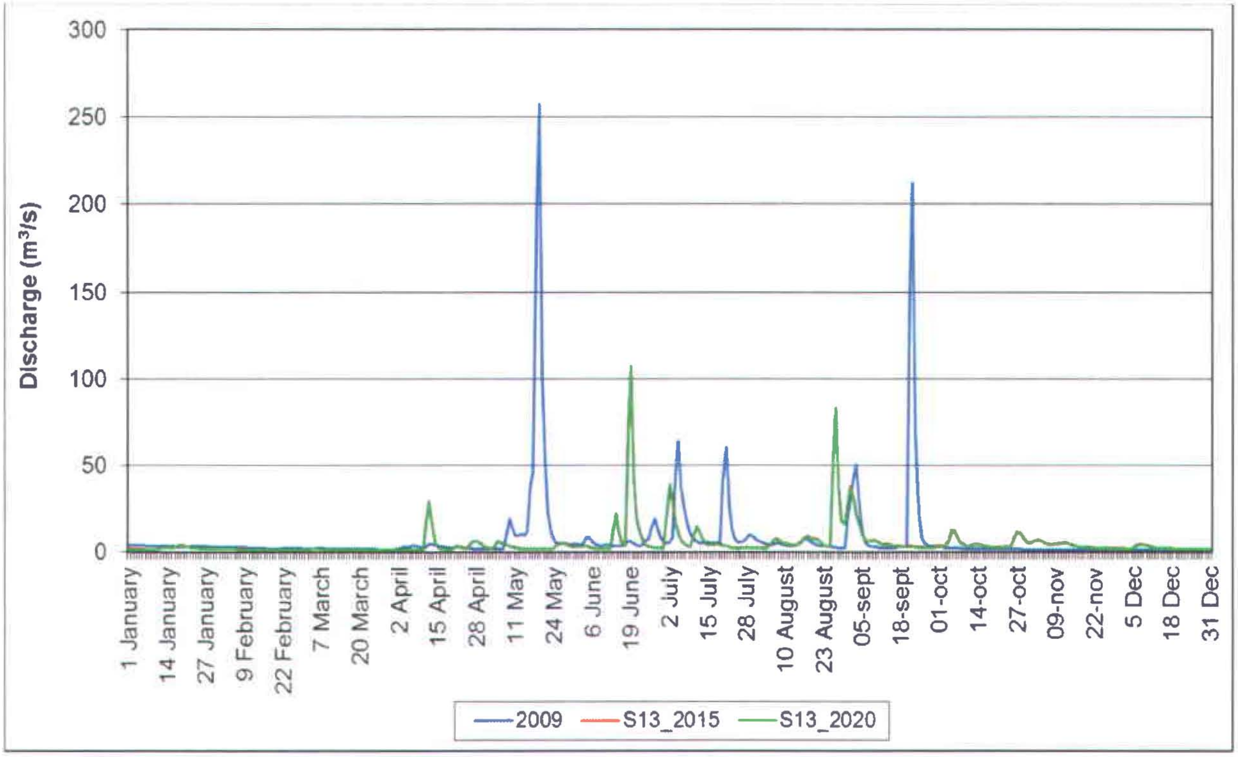


Figure 6.2. Discharge at Thac Rieng station for Scenario S13 in 2015, S13 in 2020 and current state.

On the figure 6.2, the red line for S13_2015 is overlaid by the green line for S13_2020.

Concerning the impacts of both forest planting and climate change (S14), discharge also has some peaks which are lower than in the current state (see Figure 6.3), but the total discharge shows a greater decrease with only climate change.

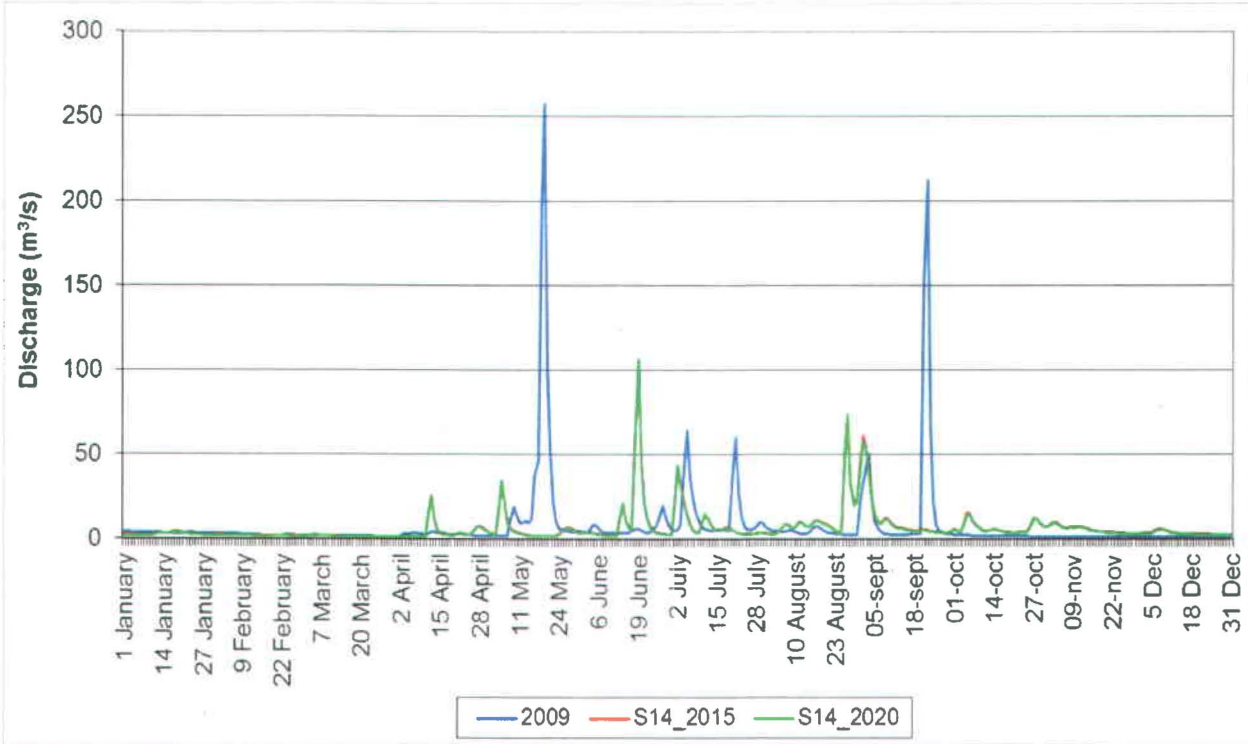
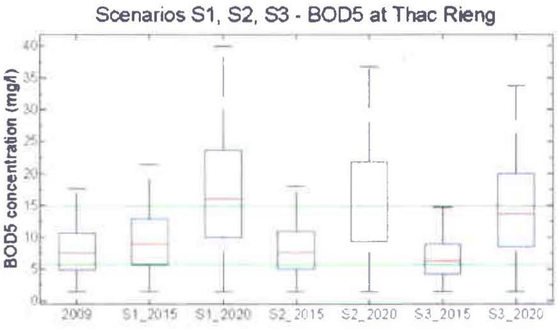


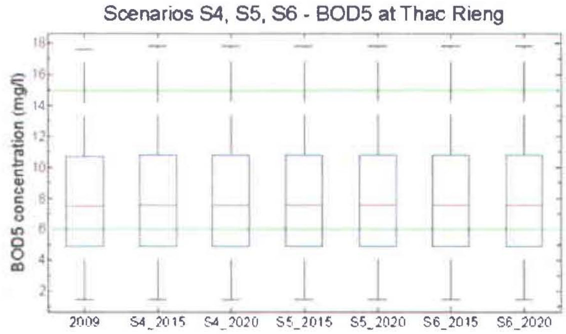
Figure 6.3. Discharge at Thac Rieng station for Scenario S14 in 2015, S14 in 2020 and current state.

On the figure 6.3, the red line which corresponds to S14_2015 is overlaid by the green line for S14_2020.

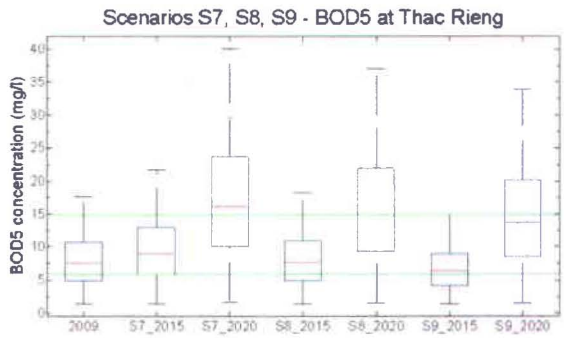
(2). BOD_5 and NH_4^+



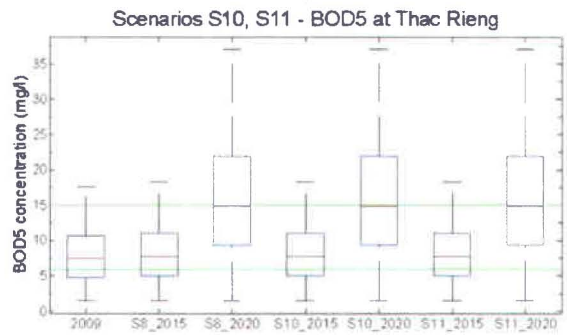
a. Scenarios of population growth and domestic wastewater (scenarios S1, S2, S3)



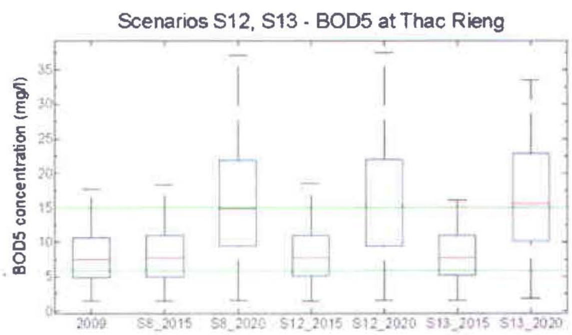
b. Scenarios of industry (scenarios S4, S5, S6)



c. Scenarios of population, domestic wastewater and industry (S7, S8, S9)



d. Scenarios of agriculture: livestock and fertilizer (scenarios S10, S11)



e. Scenarios of forest and climate change (scenarios S12, S13)

f. Scenario of all factors (scenario S14)

Figure 6.4: Simulation results of BOD_5 concentration in 2015 and 2020 at Thac Rieng.

a. Scenarios of population growth and domestic wastewater (scenarios S1, S2 and S3):

The concentration in BOD_5 for each scenario in 2015 and 2020 in the river reach at Thac Rieng station is indicated in Figure 6.4.

The simulation results of scenario S1 in 2015 (Figure 6.4a, S1_2015) showed that even if Bac Kan town installs a domestic wastewater treatment plant with a capacity of 10,000 people in 2015, the median value of BOD_5 concentration is higher than the concentration in the reference state (Figure 6.4.a). This increase can only be explained by the fast population growth in 2015 in Bac Kan town with an increase of about 18,000 more people than the reference situation, and the number of people who are not connected to the domestic wastewater treatment plant, whose domestic wastewater releases directly into the environment, is about 45,800 people. The BOD_5 concentration continues to increase in 2020 (Figure 6.4a, S1_2020) because the population in Bac Kan town continues to increase up to about 43,600 people compared with 2009 but the capacity of the domestic wastewater treatment plant remains the same as in 2015, resulting in an increase of the number of people who are not connected to the treatment plant (about 71,200 people).

The simulation result for scenario S2 in 2015 (Figure 6.4.a, see S2_2015) indicates that when we increase the capacity of the domestic wastewater treatment plant in Bac Kan town to 20,000 people in 2015, the median value of BOD_5 concentration is similar to the reference state. This can be explained by the reduction of the number of people who are not connected to the treatment plant (about 37,300 people) in Bac Kan town in 2015. However, the BOD_5 concentration still increases in 2020 because of the population growth and the increase of the number of people who are not connected to the treatment plant (about 64,700 people).

In scenario S3 (high projection for population), the simulation result shows that BOD_5 in 2015 meets the standard for other purposes and it is lower than the concentration in 2009 because the number of people who are not connected to the treatment plant Bac Kan town in 2015 is about 28,700 people. However, BOD_5 in 2020 increases due to the increase into about 58,000 people who are not connected to the treatment plant in Bac Kan town, but this concentration is still lower than in scenarios S1 and S2 in 2020.

Therefore, it can be said that among these three scenarios S1, S2 and S3, scenario S3 can be considered as the best.

The concentration of amonnium (NH_4^+) for each scenario in 2015 and 2020 in this river reach is shown in Figure 6.5.

The medians of boxplots in Figure 6.5.a show that the amonnium concentration in all three scenarios, S1, S2, and S3, tends to increase with time from 2009 to 2020. Moreover, there is nearly no differences of NH_4^+ between these three scenarios in 2015 and 2020 respectively (for example, between scenario S1 in 2015 (S1_2015) and scenario S2 in 2015 (S2_2015)). That means that even if we increase the capacity of the domestic wastewater treatment plant in Bac Kan town in scenarios S2 and S3, the water quality in this case is not improved.

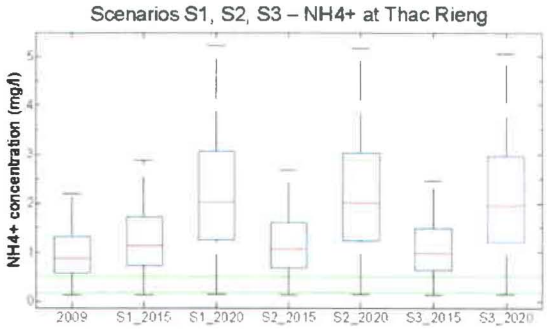
b. Scenarios of industry (scenarios S4, S5 and S6):

The simulation results in Figure 6.4.b show that this river reach does not seem to be affected by industrial activities. The BOD_5 concentrations in scenarios S4, S5, and S6 in future years are the same as in the current state. This can be explained by the fact that in the upstream area of this river reach, there is no new future industrial zone (see Figure 6.1: the only future new industrial zone in Bac Kan province - Thanh Binh industrial zone – is located downstream from this river reach), and the increase in the wastewater quantity from the current factories in this region does not have enough impacts on water quality because the contaminant concentrations in wastewater of these factories meet the standard of industrial wastewater discharge.

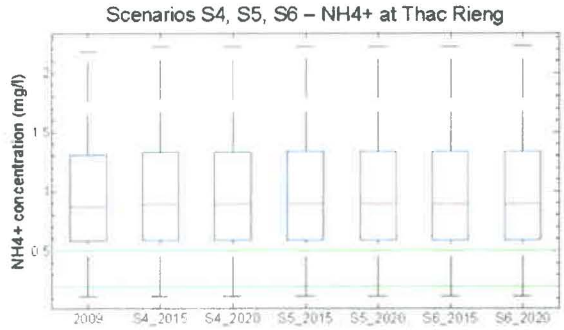
Like BOD_5 concentrations, the NH_4^+ concentrations in all three scenarios S4, S5, and S6 for both 2015 and 2020 are nearly the same as the current state in this river reach (see Figure 6.5b). It can be said that this river reach is not affected by industrial activities.

c. Scenarios of population, domestic wastewater and industry (scenarios S7, S8 and S9):

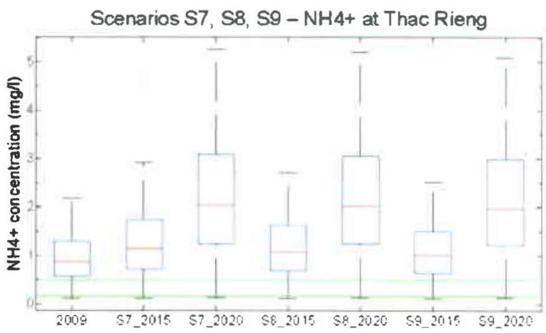
The group of scenarios S7, S8, S9 is found to be similar to the group of scenarios S1, S2, S3 (see Figure 6.4a and 6.4c) because industries have no impact on water quality in this river reach. That means that among these three scenarios S7, S8 and S9, scenario S9 is also recommended in this case because scenario S9 is similar to S3. Like in scenarios S1, S2, S3, the amonium concentration in all three scenarios S7, S8, S9 also tends to increase with time from 2009 to 2020. The differences in amonium concentrations between these three scenarios are not significant (see Figure 6.5.c).



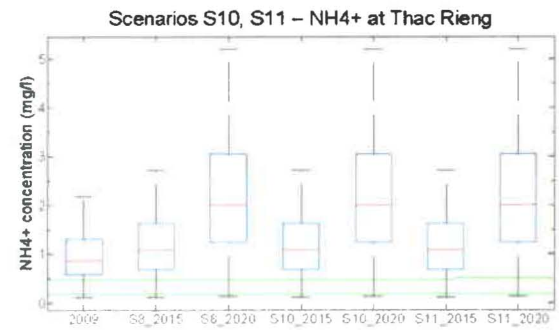
a. Scenarios of population growth and domestic wastewater (scenarios S1, S2, S3)



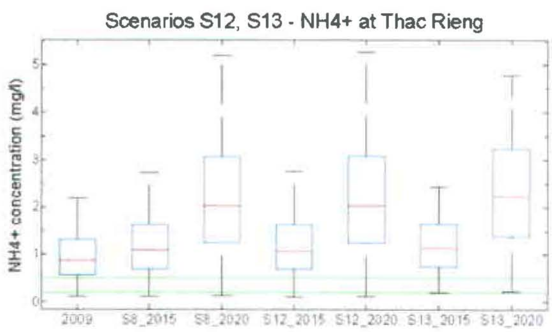
b. Scenarios of industry (scenarios S4, S5, S6)



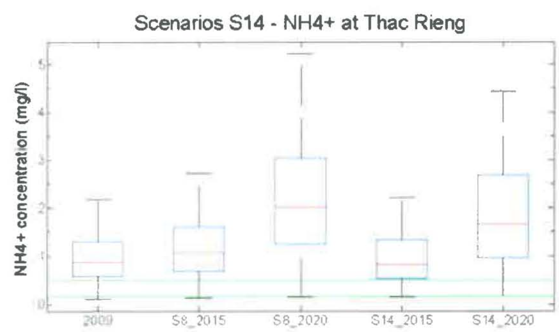
c. Scenarios of population, domestic wastewater and industry (S7, S8, S9)



d. Scenarios of agriculture: livestock and fertilizer (scenarios S10, S11)



e. Scenarios of forest and climate change (scenarios S12, S13)



f. Scenario of all factors (scenario S14)

Figure 6.5: Simulation results of NH_4^+ concentration in 2015 and 2020 at Thac Rieng.

d. Scenarios of livestock and fertilizer (scenarios S10 and S11):

As mentioned above in the Chapter 5 of scenario development, scenario S10 is the combination of scenario S8 and the changes in livestock. So in Figure 6.4d, when we compare scenario S10 in 2015 (S10_2015) and scenario S8 in 2015 (S8_2015), and between scenario S10 in 2020 (S10_2020) and scenario S8 in 2020 (S8_2020), we can see that there is no change in BOD_5 concentrations. It means that the changes of livestock numbers in the future have a negligible impact on BOD_5 concentrations.

Concerning the impact of increasing the amount of fertilizer, the simulation results of scenario S11 in 2015 (Figure 6.4d, S11_2015) and scenario S11 in 2020 (Figure 6.4d, S11_2020) also show that it seems there is no change in BOD_5 concentrations. Like BOD_5 concentrations, compared with scenario S8, it can be noticed that the NH_4^+ concentration is nearly not affected by the increase in the amount of livestock and fertilizer (see Figure 6.5d).

e. Scenarios of forest planting and climate change (scenarios S12 and S13):

Scenarios S12 and S13 are the combination of scenario S8 and the changes on forest planting and climate change respectively. The simulation result shows that BOD_5 in 2015 as well as in 2020 is not affected by forest planting (see Figure 6.4e: S12_2015 and S12_2020 compared with S8_2015 and S8_2020). However, concerning the impact of climate change (scenario S13), the number of days in 2020 in scenario S13_2020 for which the BOD_5 concentration exceeding the standard for irrigation and other purposes increases a little compared with scenario S8 in 2020 (see S8_2020). That means climate change does have an impact on BOD_5 concentration, but not much.

Figure 6.5e shows that when we compare scenarios S12 and S13 with S8, there is nearly no change in NH_4^+ concentrations in 2015 as well as in 2020 by the impacts of forest planting and climate change.

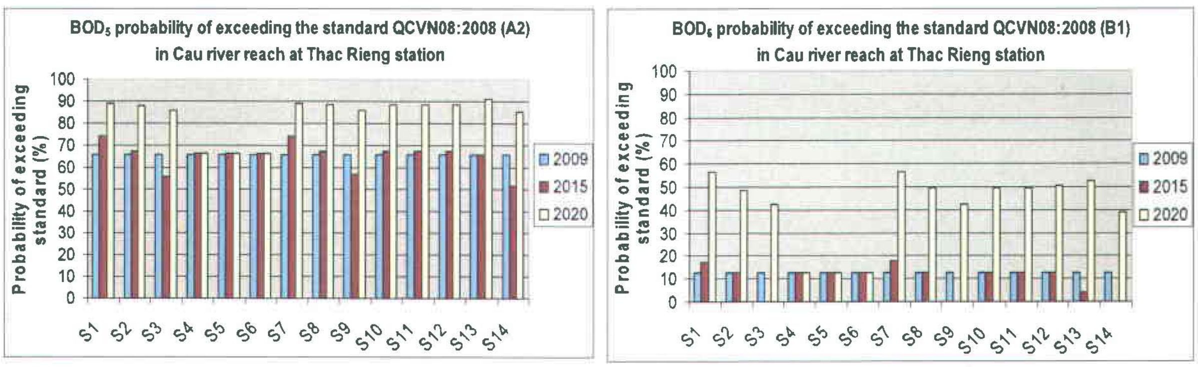
f. Scenario of all seven factors (scenario S14):

Scenario S14 is the combination of scenario S8 and the changes in livestock, fertilizer, forest planting and climate change. Therefore, in Figure 6.4f, we can see a water quality improvement in scenario S14 for both 2015 and 2020 compared with scenario S8, especially for S14 in 2015, where the BOD_5 concentration decreases compared with the current state and stays under the standard value of 15mg/l during the whole year. So scenario S14 is recommended for water quality improvement in the future in this case.

The combined impact of all seven factors makes the amonnium concentration reduce a little in 2015, but increase again in 2020 compared with the current state (see Figure 6.5f).

Probabilities of exceeding standard for all scenarios from S1 to S14 in 2015 and 2020 compared with the current state:

The probabilities of exceeding the surface water quality standard for the purpose of water supply with treatment and for irrigation and other purposes for all fourteen scenarios for BOD_5 concentrations are indicated in Figure 6.6a and Figure 6.6b respectively.



a. For the standard with purpose of water supply with treatment

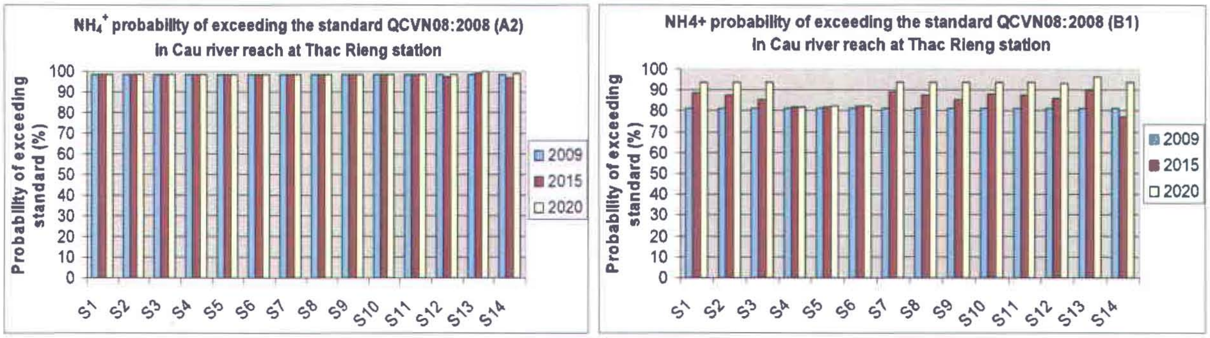
b. For the standard with purpose of irrigation and other purposes

Figure 6.6: Probabilities of exceeding standard for all scenarios for BOD_5 at Thac Rieng.

We can see in Figure 6.6 that in 2015, only three scenarios, S3, S9 and S14, have lower probabilities of exceeding standard for BOD_5 than the current state. That means that water quality is improved in 2015 for S3, S9 and S14.

However, in 2020 we can see most of fourteen scenarios (except S4, S5, S6) have much higher probabilities of exceeding standard for BOD_5 than in 2009 and 2015. This is because of the fast future population growth in Bac Kan town and the same capacity of domestic wastewater treatment plant in 2015 and 2020, as explained above.

The probability of exceeding standard in this case is the percentage of the number of days for which the NH_4^+ concentration exceeds the standard over one year (365 days). The probabilities of exceeding the surface water quality standard for the purpose of water supply with treatment application and for the purpose of irrigation and other purposes for all fourteen scenarios for NH_4^+ concentrations are indicated in Figure 6.7a and Figure 6.7b respectively.



a. For the standard with purpose of water supply with treatment

b. For the standard with purpose of irrigation and other purposes

Figure 6.7: Probabilities of exceeding standard for all scenarios for NH_4^+ at Thac Rieng.

In Figure 6.7a, we can see that the probabilities of exceeding the surface water quality standard for the purpose of water supply with treatment application for NH_4^+ concentrations in all scenarios are nearly the same. However, concerning NH_4^+ probabilities of exceeding the surface water quality standard for the purpose of irrigation and other purposes, only scenario S14 in 2015 has a lower probability of exceeding standard compared with the current state (see Figure 6.7b).

(3) SS

In the GIBSI model, suspended solid mainly comes from soil erosion. Therefore, it can change due to a variation in land use and/or meteorological conditions. Thus, like for discharge, only three scenarios, S12, S13 and S14, can have impacts on the change in suspended solid concentration. For the other scenarios from S1 to S11, there is no change in suspended solid concentration. All the results are similar, which is indicated in Figure 6.8. In this figure, the simulation results for SS concentration for three scenarios, S12, S13 and S14, in 2015, 2020 and the year 2009 are shown.

The results in Figure 6.8 show that the impacts of forest planting (scenario S12), climate change (scenario S13) and all seven factors (scenario S14) can diminish some extreme values of SS concentration in both 2015 and 2020, especially for scenario S14: SS concentration is under the standard for surface water for irrigation and other purposes in 2015 and 2020. Scenario S14 is recommended in this case.

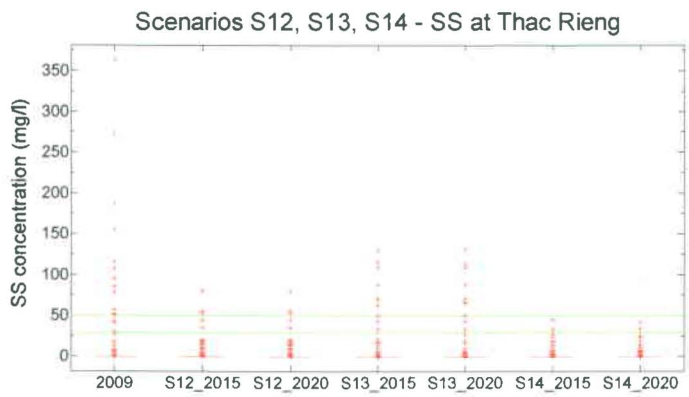


Figure 6.8: Simulation results of SS concentration in 2015 and 2020 at Thac Rieng for scenarios S12, S13, S14 compared with reference year of 2009.

The probabilities of exceeding the standard are also calculated and the results are shown on Figure 6.9. for all scenarios. It can be noted that there is nearly no difference between all scenarios.

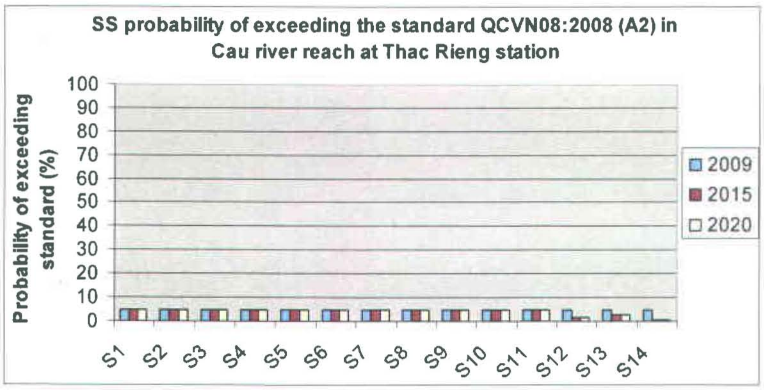


Figure 6.9: Probabilities of exceeding standard for wtater supply for all scenarios for SS in the river reach at Thac Rieng station.

(4) Comments on water quality and discharge in the river reach at Thac Rieng station

After analyzing four constituents of discharge, BOD_5, NH_4^+ and SS, several comments on quantity and water quality improvement in this river reach at Thac Rieng station are given as follows:

The resuls pointed out a minor reduction of discharge in a high amount due to climate change. Forest planting can diminish the impact of climate change by preventing the decrease of total amounts of discharge over the whole year.

- Fast future population growth in Bac Kan has significant impacts on the increase of BOD_5 and NH_4^+ concentrations in the future, especially in 2020 when the population continues to increase but the capacity of domestic wastewater treatment plant remains the same as in 2015. In 2020, an increase of 116% of the population in Bac Kan town can lead to an increase of 120% and 135% in BOD_5 and NH_4^+ concentrations respectively with a treatment plant of 10,000 people in Bac Kan town according to the projection of the local government.
- The three factors of industry, livestock and fertilizer have negligible impacts on water quality in this river reach. In the future, the increase of 10% or even 20% of discharge from the current factories seems to have negligible impacts on water quality because industries are considered to meet the standard of industrial wastewater.

In the case of livestock and agricultural fertilizers, the increases in the number of livestock and fertilizer quantity appear to have minor impact to yield a significant increase in BOD_5 and NH_4^+ concentrations; or may be due to the fact that most of the feces of livestock, which are put down into the nearby fields, are used by plants, so the excess of nitrogen and phosphorus going in the environment is not enough to affect the water quality. The process of selfcleaning along the river or dilution of contaminants concentrations can also explain the results of impacts of livestock and agricultural fertilizers.

- Forest and climate change themselves do not have much impact on BOD_5 and NH_4^+ concentrations, but if they combine with other factors (scenario S14), water quality is improved; especially in 2015, BOD_5 concentration is under the Vietnamese standard for surface water for the purpose of irrigation and other purposes. For SS, the impacts of forest and climate change can reduce some high values, and if they combine with other factors, SS concentration is also under the standard.

- Concerning water quality improvement based on three constituents of BOD_5, NH_4^+, SS, three scenarios S3, S9 and S14 can be highly recommended because of the following reasons:

  + Scenario S3: In 2015, there is a reduction in BOD_5 concentrations in scenario S3 compared with the current state as well as in scenarios S1 and S2 (see Figure 6.4a). Although the BOD_5 concentration in 2020 increases compared with 2009 because of fast future population growth, it is still lower than in scenarios S1 and S2 in 2020. Concerning NH_4^+ concentration, though it is not clear to see the water quality improvement, we can see that the probability of exceeding the NH_4^+ concentration standard in scenario S3 in 2015 is lower than S1 and S2 (see Figure 6.6.b).

  + Scenario S9: The water quality improvement in scenario S9 is the same as in scenario S3 because this river reach does not seem to be affected by future industrial development for all three constituents (see Figures 6.4.a,b,c and 6.5.a,b,c).

  + Scenario S14: Future water quality (2015) appeared to be improved compared with reference situation for the constituents of BOD_5, NH_4^+ and SS (see Figures 6.4.f, 6.5.f, and 6.8).

(5) Priority levels for the scenarios in the river reach at Thac Rieng station

Table 6.4 summarizes the priority levels related to water quality improvement of all fourteen scenarios in the river reach at Thac Rieng station based on the above results.

Table 6.4: Priority levels related to water quality improvement of fourteen scenarios in the river reach at Thac Rieng station.

Scenario	Priority level	Explanation
S1	Low	BOD_5 and NH_4^+ concentrations trend to increase from 2009 to 2020. That means the water quality is worse than in the current state.
S2	Average	BOD_5 concentration in 2015 is nearly the same as the current state, and both BOD_5 and NH_4^+ concentrations are improved compared with scenario S1.
S3	High	BOD_5 concentration in 2015 decreases compared with the current state, and both BOD_5 and NH_4^+ concentrations are improved compared with scenario S1 and S2.
S4	Average	BOD_5 and NH_4^+ concentrations in future are similar to the current state.
S5	Average	
S6	Average	
S7	Low	Like explained in scenario S1.
S8	Average	Like explained in scenario S2.
S9	High	Like explained in scenario S3.
S10	Average	The factors of livestock, fertilizer, forest planting and climate change, which correspond with scenario S10, S11, S12, S13 respectively, have negligible impacts on BOD_5, NH_4^+ and SS concentrations.
S11	Average	
S12	Average	
S13	Average	
S14	High	The water quality in 2015 is improved for BOD_5, NH_4^+ and SS, especially BOD_5 *concentration in* 2015 is under the standard of surface water for the purpose of irrigation and other purposes and SS concentrations in future are also under this standard.

6.2.2.1.2. <u>Thac Buoi</u>

(1) Discharge

The results for variations of discharge due to the impacts of forest planting, climate change and combination of the two factors are shown in Figures A6.2, A6.4 and A6.6 in Appendix. It can be found that these factors have minor effects in general on the discharge. At this river reach, all factors have negligible impacts on discharge (forest planting: maximum decrease of 1% in the future, climate change: maximum decrease of 6% of discharge and, combination of both factors: maximum decrease of 2% of the discharge).

(2) BOD_5 and NH_4^+

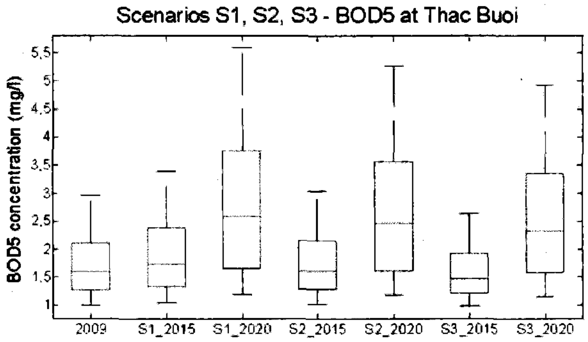
a. Scenarios of population growth and domestic wastewater (scenarios S1, S2 and S3):

BOD_5 concentration for each scenario in 2015 and 2020 in the river reach at Thac Buoi station is indicated in Figure 6.10.

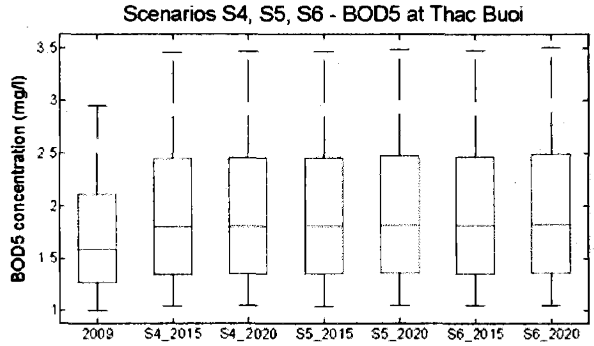
This river reach is located in the middle of Cau River Basin and in the rural area of Thai Nguyen province (see Figure 6.1). In the future, there will be no big urban area as well as no domestic wastewater treatment plant between the river reach at Thac Rieng station and this river reach. Therefore, the main pollution sources from population growth and domestic wastewater in the future probably come from the diffuse pollution of rural population due to population growth in these rural areas and domestic wastewater from upstream.

The simulation result shows that in scenario S1, BOD_5 concentration tends to increase from reference state to future (see Figure 6.10.a). For scenarios S2 and S3, BOD_5 concentrations in 2015 are nearly the same as the current state. However, in 2020, the BOD_5 concentrations increase and become higher than in the current state. This may be caused by the fast future population growth from upstream in Bac Kan town and the rural population growth in this area.

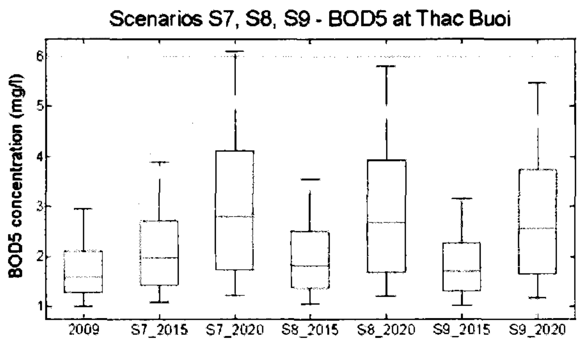
The concentration in amonnium (NH_4^+) for each scenario in the future in this river reach is shown in Figure 6.11. The median values in Figure 6.11.a shows that the amonnium concentration in all three scenarios S1, S2, S3 tends to increase with time from 2009 to 2020. Especially, the amonnium concentrations in 2020 in all three scenarios S1, S2 and S3 are much higher than in 2009. This may be caused by the effects of the fast future population growth in upstream in Bac Kan town, as well as the future rural population growth in this area. However, among these three scenarios, the amonnium concentration in scenario S3 seems to be the lowest for 2015. We can see this more clearly in Figure 6.12 for probabilities of exceeding standard.



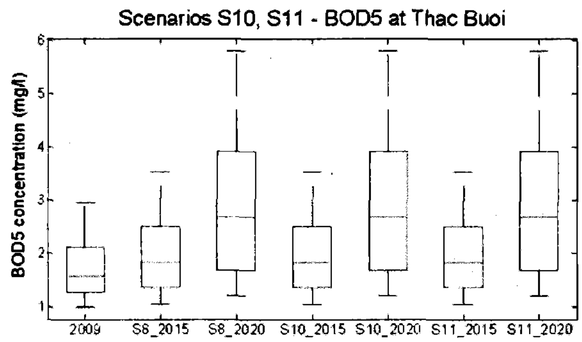
a. Scenarios of population growth and domestic wastewater (scenarios S1, S2, S3)



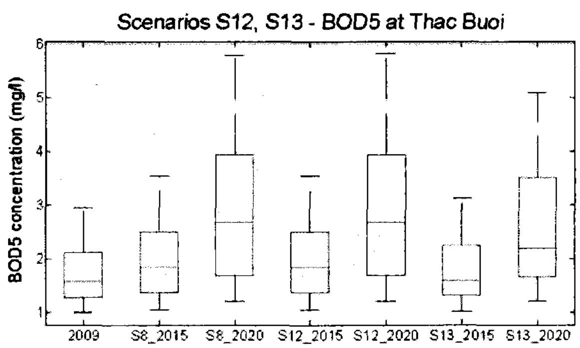
b. Scenarios of industry (scenarios S4, S5, S6)



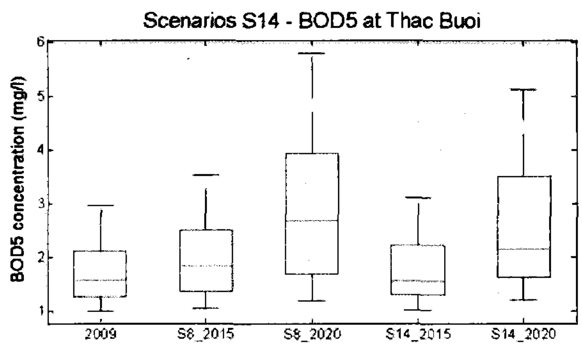
c. Scenarios of population, domestic wastewater and industry (S7, S8, S9)



d. Scenarios of agriculture: livestock and fertilizer (scenarios S10, S11)



e. Scenarios of forest and climate change (scenarios S12, S13)



f. Scenario of all factors (scenario S14)

Figure 6.10: Simulaton results of BOD_5 concentration in 2015 and 2020 at Thac Buoi.

b. Scenarios of industry (scenarios S4, S5 and S6):

The simulation results (Figure 6.10.b) show that in this river reach, industrial activities make BOD_5 concentrations increase compared with the current state. However, we can see that the values of BOD_5 stay the same in all three scenarios S4, S5, and S6 in 2015 and 2020. That means when discharges meet the Vietnamese standard of industrial wastewater, the increase of wastewater discharges of the current factories in the future has negligible impacts on river water quality. Nevertheless, the reason why BOD_5 concentrations seem to increase in the future compared with the current state is because of the installation of a new industrial zone: Thanh Binh industrial zone in Cho Moi district, Bac Kan province between Thac Rieng and Thac Buoi stations (see Figure 6.1).

Like BOD_5 concentrations, NH_4^+ concentrations in all three scenarios S4, S5 and S6 in both future years increase compared with the current state in this river reach (see Figure 6.11.b), resulting from the installation of a new industrial zone: Thanh Binh industrial zone (see Figure 6.5). NH_4^+ concentrations are also nearly the same in all three scenarios S4, S5 and S6 in the future probably because the discharges of factories meet the Vietnamese standard of industrial wastewater.

c. Scenarios of population, domestic wastewater and industry (scenarios S7, S8 and S9):

The simulation results in Figure 6.10.c show that the BOD_5 concentration increases with time from the current state in 2009 to the future in 2020. That means the impacts of all three factors of population, domestic wastewater and industry make the future water quality worse than the current state in this river reach. This increase may be mainly due to population growth and the increase of domestic wastewater because negligible impacts are found for industrial factor.

The amonnium concentration in all three scenarios S7, S8 and S9 also tends to increase with time from 2009 to 2020, and the NH_4^+ concentrations are nearly the same between these three scenarios (see Figure 6.11.c).

d. Scenarios of livestock and fertilizer (scenarios S10 and S11):

In this river reach, there is no change in BOD_5 concentrations when we increase the number of livestock or the amount of fertilizer in the future (see Figure 6.10.d: compare S10_2015, S10_2020, S11_2015, S11_2020 with S8_2015, S8_2020). It means that the changes in livestock number and fertilizer in the future have negligible impacts on BOD_5 concentration. The reason why the values of BOD_5 in the future in scenarios S10 and S11 are higher than the current state is related to the increases of three factors of population, domestic wastewater and industry in scenario S8.

Like BOD_5 concentration, NH_4^+ concentration does not change due to an increase in the amount of livestock and fertilizer (see Figure 6.11.d: compare S10_2015, S10_2020, S11_2015, S11_2020 with S8_2015, S8_2020). It means that the changes in livestock number and fertilizer in the future also have negligible impacts on NH_4^+ concentrations. However, the values of NH_4^+ in the future in scenarios S10 and S11 are higher than the current state due to the increases of three factors of population, domestic wastewater and industry in scenario S8.

e. Scenarios of forest planting and climate change (scenarios S12 and S13):

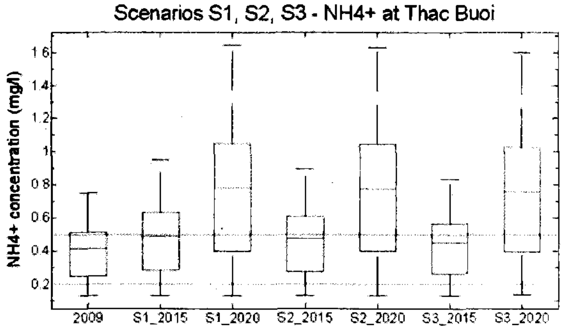
The simulation result shows that the BOD_5 concentration in the future is not affected by forest planting (see Figure 6.10.e, S12_2015 and S12_2020). However, concerning the impact of climate change (scenario S13), the BOD_5 concentration decreases a little in the future compared with scenario S8 (Figure 6.10.e).

Simulation results show that there is nearly no change in NH_4^+ concentrations in the future caused by the impacts of forest planting and climate change, excepting some extreme values affected by climate change (see Figure 6.11.e). These extreme values may be caused by an increase of rainfall for some days during the years of 2015 and 2020, resulting in an increase of runoff with contaminants.

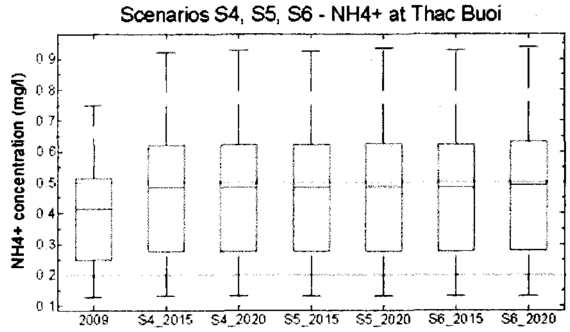
f. Scenario of all seven factors (scenario S14):

The simulation results show that the BOD_5 concentration in 2015 which is impacted by all seven factors (see Figure 6.10.f, S14_2015) remains constant compared with the current state. BOD_5 concentration in 2020 increases but it is still under the standard.

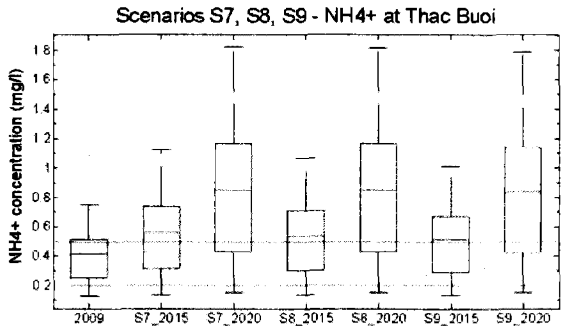
The amonnium concentration impacted by all seven factors in 2015 is nearly the same as the current state, excepting some extreme values affected by climate change (see Figure 6.11.f, S14_2015). However, NH_4^+ concentration increases in 2020 compared with 2009 due to the factors of population growth, domestic wastewater and industry.



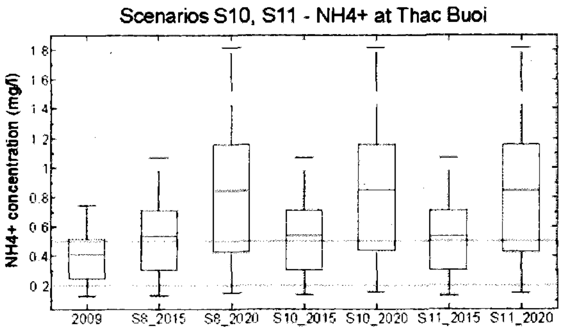
a. Scenarios of population growth and domestic wastewater (scenarios S1, S2, S3)



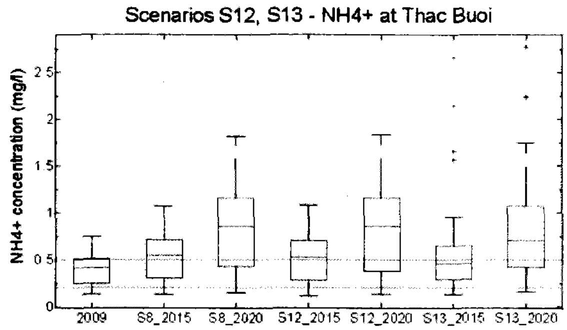
b. Scenarios of industry (scenarios S4, S5, S6)



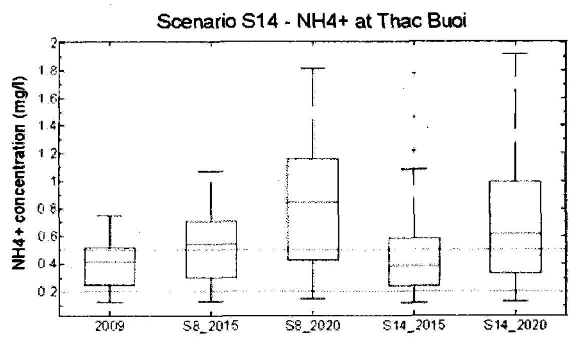
c. Scenarios of population, domestic wastewater and industry (S7, S8, S9)



d. Scenarios of agriculture: livestock and fertilizer (scenarios S10, S11)



e. Scenarios of forest and climate change (scenarios S12, S13)



f. Scenario of all factors (scenario S14)

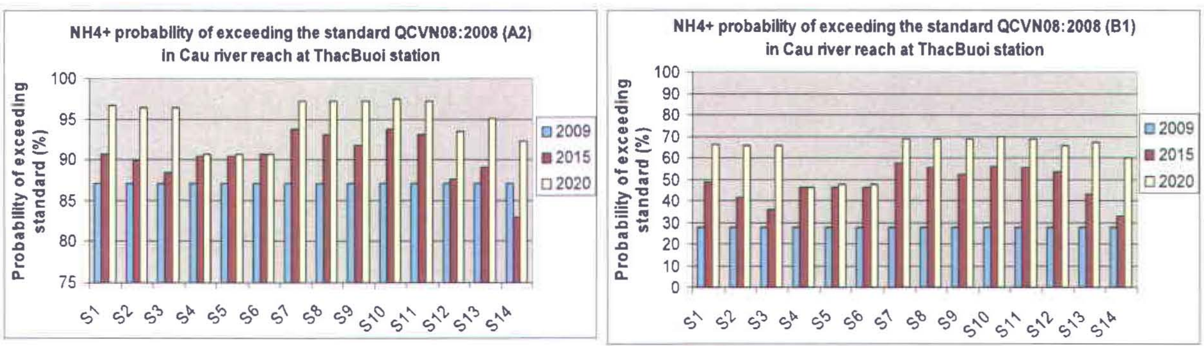
Figure 6.11: Simulation results of NH_4^+ in 2015 and 2020 at Thac Buoi.

Probabilities of exceeding standard for all scenarios from S1 to S14 in 2015 and 2020 compared with the current state:

Concerning the probability of exceeding the surface water quality standard, BOD_5 concentrations in the future in all fourteen scenarios at Thac Buoi are found to be negligible. In fact all concentrations are nearly under the standards for the purpose of water supply with treatment application, as well as the surface water quality standard for the irrigation and other purposes.

The probabilities of exceeding the surface water quality standard for the purpose of water supply with treatment application and for the purpose of irrigation and other purposes for fourteen scenarios for NH_4^+ in the river reach at Thac Buoi station are indicated in Figure 6.12.a and Figure 6.12.b respectively.

The results show that the probabilities of exceeding the surface water quality standard for the purpose of water supply with treatment application for NH_4^+ concentrations in all scenarios in both 2015 and 2020 are higher than the current state, except in scenario S14 in 2015 (Figure 6.12.a). However, concerning NH_4^+ probabilities of exceeding the surface water quality standard for the purpose of irrigation and other purposes, all the scenarios, even scenario S14 in 2015, have a higher probability of exceeding standard than the current state (see Figure 6.12.b).



a. For the standard with purpose of water supply with treatment

b. For the standard with purpose of irrigation and other purposes

Figure 6.12: Probabilities of exceeding standard for all scenarios for NH_4^+ at Thac Buoi.

(3) Comments on water quality and discharge in the river reach at Thac Buoi station

After analyzing four constituents of discharge, BOD_5, NH_4^+ and SS, several comments on quantity and water quality improvement in this river reach at Thac Buoi station are given as follows:

- The future discharge in this river reach does not change much compared with the current state due to the impacts of forest planting in Bac Kan province and climate change in this region.
- Fast future population growth upstream still has significant impacts on the increase of BOD_5 and NH_4^+ concentrations in this river reach, especially in 2020 when these concentrations are still higher than the values for the current state in 2009.
- The installation of the Thanh Binh industrial zone in 2015 is the reason why the future water quality in this river reach seems to be worse than the current state: the concentrations in BOD_5 and NH_4^+ increase of 12% and 19% respectively compared with the current state. However, if we increase of 5%, 10%, 15% or 20% the discharges of the current factories but the discharges meet the Vietnamese standard of industrial wastewater, it will not affect the water quality in this case.
- Three factors of livestock, fertilizer and forest planting have negligible impacts on river water quality. It may also be because the increases in number of livestock and fertilizer quantity according to the assumptions and local development projections in the developed scenarios for the future may not have enough impact to make a significant increase on BOD_5 and NH_4^+ concentrations; or may be due to the fact that most of the feces of livestock which are put down into the nearby fields are used by plants, so that the excess of nitrogen and phosphorus going to the environment is not important. In the case of forest planting, this river reach is located in an agricultural region, not in a mountainous region, therefore forest planting, which can reduce erosion and runoff, has negligible impacts on river water quality.
- There is nearly no change in BOD_5 and NH_4^+ concentrations in the future caused by climate change, except for some NH_4^+ outliers. However, because of the impacts of climate change, some extreme values of SS concentration are diminished and SS probabilities of exceeding standard decrease in both future years compared with the current state.

- The impact of all seven factors keep the water quality in 2015 in this river reach the same as the current state. However, the water quality in 2020 is worse than in 2009 probably because of fast future population growth in Bac Kan town.

(4) Priority levels for the scenarios in the river reach at Thac Buoi station

Table 6.5 summarizes the priority levels related to water quality improvement of the fourteen scenarios in the river reach at Thac Buoi station based on the above results.

Table 6.5: Priority levels related to water quality improvement of fourteen scenarios in the river reach at Thac Buoi station.

Scenario	Priority level	Explanation
S1	Low	BOD_5 and NH_4^+ concentrations trend to increase from 2009 to 2020. That means the water quality worse than the current state.
S2	Average	BOD_5 concentration in 2015 is nearly the same as the current state, and both BOD_5 and NH_4^+ concentrations are improved compared with scenario S1.
S3	Average	BOD_5 and NH_4^+ concentrations in 2015 are nearly the same as the current state.
S4	Low	BOD_5 and NH_4^+ concentrations in the future increase compared with the current state.
S5	Low	
S6	Low	
S7	Low	The combination impacts of three factors: population, domestic wastewater and industry make water quality worse than the current state.
S8	Low	
S9	Low	
S10	Average	These factors of livestock, fertilizer, forest planting and climate change, which correspond with scenario S10, S11, S12, S13 respectively, have negligible impact on BOD_5, NH_4^+ and SS concentrations.
S11	Average	
S12	Average	
S13	Average	
S14	Average	The water quality in 2015 is nearly the same as the current state for BOD_5, NH_4^+ and SS.

6.2.2.1.3. Gia Bay

(1) Discharge

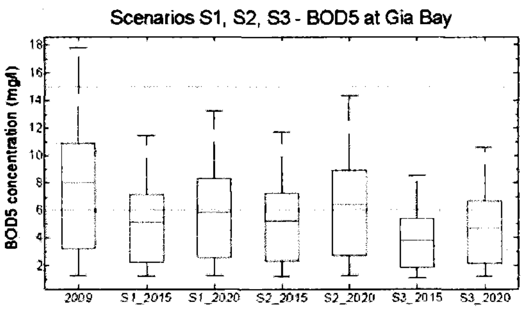
In this river reach at Gia Bay station, concerning the impact of forest planting (scenario S12), discharge also has nearly no change (see Figures A6.3 in Appendix A6). The total amount of discharge over a whole year is reduced less than 1% in the future.

Discharge resulting from the impacts of climate change (scenario S13) in 2015 and 2020 at this river reach also has some different peaks compared with the current state (see Figure A6.5 in Appendix A6), It can be said that climate change has negligible impact on discharge in the river reach at Gia Bay station.

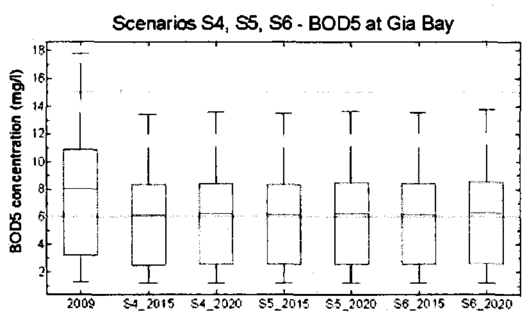
Concerning the impacts of both forest planting and climate change (S14), the future discharge also has some different peaks compared with the current state (see Figure A6.7 in Appendix A6), and the relative difference is about -4.9% for 2015 and -8% for 2020. That means the reduction of future discharge may be around 5% to 8 % compared with the current state. So it means that both forest planting and climate change have nearly no impact on discharge in this river reach.

(2) BOD_5 and NH_4^+

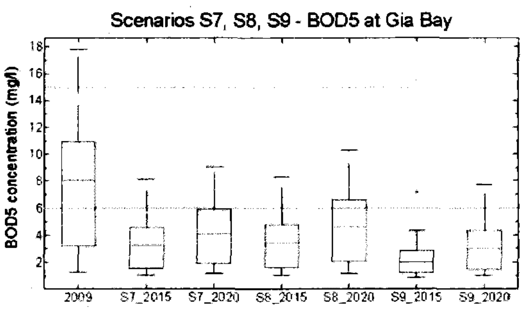
a. Scenarios of population growth and domestic wastewater (scenarios S1, S2 and S3):



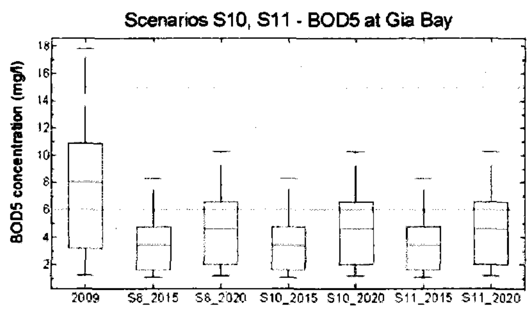
a. Scenarios of population growth and domestic wastewater (scenarios S1, S2, S3)



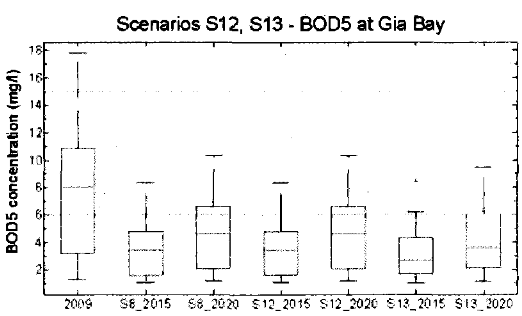
b. Scenarios of industry (scenarios S4, S5, S6)



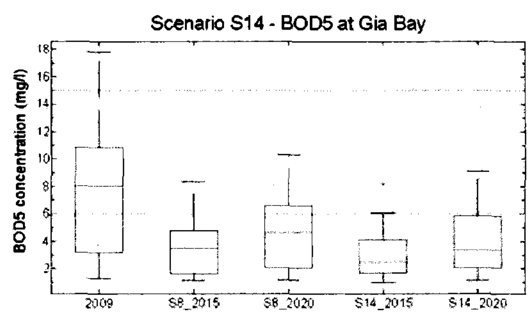
c. Scenarios of population, domestic wastewater and industry (S7, S8, S9)



d. Scenarios of agriculture: livestock and fertilizer (scenarios S10, S11)



e. Scenarios of forest and climate change (scenarios S12, S13)



f. Scenario of all factors (scenario S14)

Figure 6.13: Simulation results of BOD_5 concentration in 2015 and 2020 at Gia Bay.

Concentrations in BOD_5 for each scenario in 2015 and 2020 in the river reach at Gia Bay station are indicated in Figure 6.13.

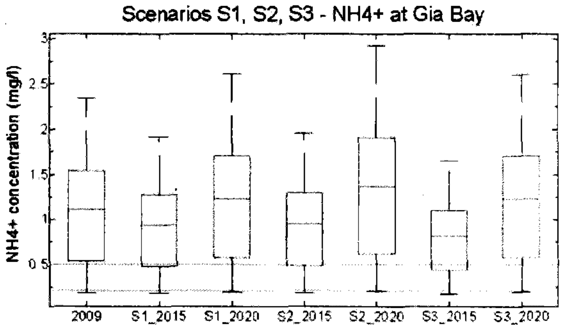
This river reach at Gia Bay station is the outlet of studied region of Cau River Basin. Upstream form Cau River to this outlet, there are two domestic wastewater treatment plants which will be installed in 2015 in Bac Kan town and Thai Nguyen City. Scenarios S1, S2 and S3 are the combination of forecasted population (low, medium, high) and the installation of these domestic wastewater treatment plants at different capacities.

The simulation results in Figure 6.13.a show that BOD_5 concentrations in all three scenarios S1, S2 and S3 in both future years decrease compared with the current state. That means the water quality is improved with the domestic wastewater treatment plants, even with the smallest capacities of two domestic wastewater treatment plants in scenario S1 (capacity of 10,000 people for treatment plant in Bac Kan town and capacity of 100,000 people for treatment plant in Thai Nguyen City). It can be said that with the smallest capacities mentioned above for two treatment plants which are projected by the local governments, if the urban population increases of around 43,600 people in Bac Kan town and 5,900 people in Thai Nguyen City in 2020 compared with the reference situation, and rural population grows at the rate of 0.57%/year in Bac Kan province and 0.19%/year in Thai Nguyen province, the median values of BOD_5 will decrease of around 26% in 2020 compared with the current state (see Figure 6.13.a: 2009 and S1_2020).

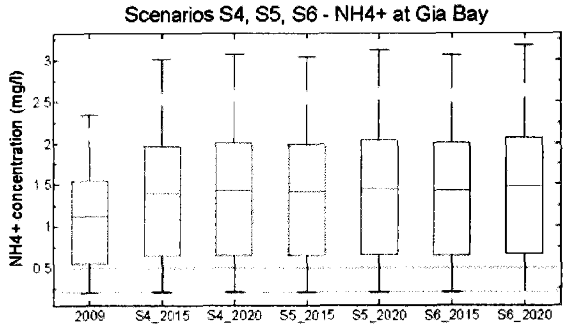
The concentrations in amonnium (NH_4^+) for each scenario in 2015 and 2020 in this river reach are shown in Figure 6.14. The green lines in the figure also tell us about the two values of NH_4^+ concentration in the Vietnamese standard for surface water quality: the standard value for the purpose of water supply with treatment application (0.2 mg/l), and the standard value for the purpose of irrigation and other purposes (0.5 mg/l).

Figure 6.14.a shows that NH_4^+ concentrations decrease in all three scenarios S1, S2, S3 in 2015, but increase in 2020 compared with the current state. That means the installation of two domestic wastewater treatment plants in Bac Kan town and Thai Nguyen City in 2015 makes NH_4^+ concentration decrease. However, in 2020, when we keep the same capacities of these two treatment plants but the population continues to increase, NH_4^+ concentration will increase like that.

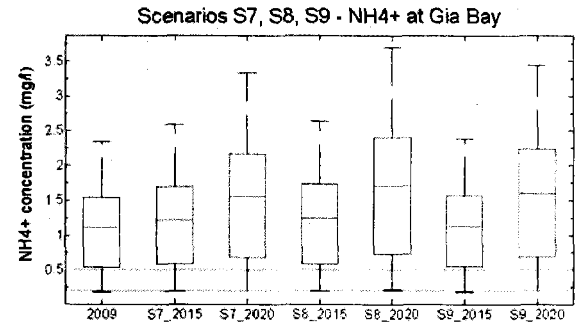
There is one thing we should pay attention to: the installation of a domestic wastewater treatment plant in Song Cong town in the scenario S2 will not affect the water quality in this river reach at Gia Bay station in Cau River because the domestic wastewater from people in Song Cong town only impacts Cong River (see Figure 6.1). Therefore, we can see in Figure 6.14.a that NH_4^+ concentrations in scenarios S1 and S2 are nearly the same, with only a little difference because of different populations. We also can see the same thing for BOD_5 concentration in Figure 6.13.a.



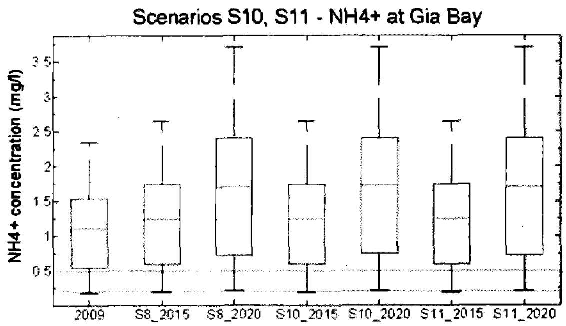
a. Scenarios of population growth and domestic wastewater (scenarios S1, S2, S3)



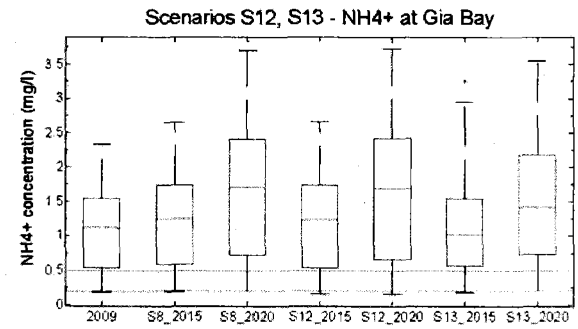
b. Scenarios of industry (scenarios S4, S5, S6)



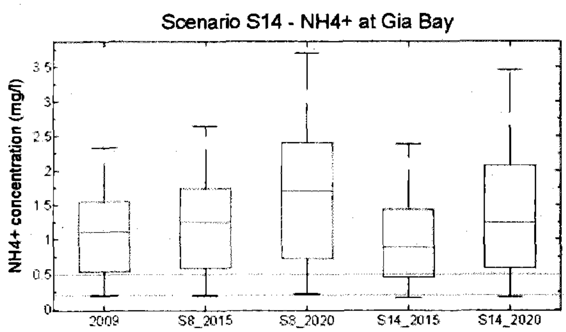
c. Scenarios of population, domestic wastewater and industry (S7, S8, S9)



d. Scenarios of agriculture: livestock and fertilizer (scenarios S10, S11)



e. Scenarios of forest and climate change (scenarios S12, S13)



f. Scenario of all factors (scenario S14)

Figure 6.14: Simulation results of NH_4^+ concentration in 2015 and 2020 at Gia Bay

b. Scenarios of industry (scenarios S4, S5 and S6):

The simulation results in Figure 6.13.b show that BOD_5 concentrations in all three scenarios S4, S5 and S6 in both future years decrease compared with the current state. This is due to the fact that in the future, all industries are supposed to meet the standard for industrial wastewater in the local development plan. We can also see in this figure that BOD_5 concentrations are nearly the same in scenarios S4, S5 and S6 in 2015 and 2020 probably because in the scenarios, all factories are supposed to meet the Vietnamese standard for industrial wastewater.

Different from BOD_5, NH_4^+ concentrations in all three scenarios S4, S5, S6 in both future years increase compared with the current state in this river reach (see Figure 6.14.b). NH_4^+ concentrations are also nearly the same in all three scenarios S4, S5, S6 in 2015 and 2020. That means although all the current and future factories apply the standard on industrial wastewater for NH_4^+ (10mg/l), the development of future industrial zones in this area still makes NH_4^+ concentration in the future increase compared with the current state.

c. Scenarios of population, domestic wastewater and industry (scenarios S7, S8 and S9):

The simulation results in Figure 6.13.c show that BOD_5 concentrations in all three scenarios S7, S8 and S9 in both future years decrease compared with the current state. That means the water quality is much improved and meets the Vietnamese standard for surface water quality for the purpose of irrigation and other purposes.

NH_4^+ concentrations in 2015 in three scenarios S7, S8, S9 are nearly the same as the current state, but still increase in 2020 because of the increase of population (see Figure 6.14.c).

d. Scenarios of livestock and fertilizer (scenarios S10 and S11):

Scenario S10 is the combination of scenario S8 and the changes in livestock. So in Figure 6.13.d, when we compare scenario S10 in 2015 (S10_2015) and scenario S8 in 2015 (S8_2015), and between scenario S10 in 2020 (S10_2020) and scenario S8 in 2020 (S8_2020), we can see that there is nearly no change in BOD_5 concentration. It means that the changes of livestock number in the future have negligible impacts on BOD_5 concentration.

The same goes for the impacts of increasing the amount of fertilizer, the simulation results of scenario S11 in 2015 (S11_2015) and scenario S11 in 2020 (S11_2020). Figure 6.13.d also shows that there is nearly no change in BOD_5 concentration.

Like BOD_5 concentration, NH_4^+ concentration is not affected by the impact of increasing the amount of livestock and fertilizer (see Figure 6.14.d). Since the outlet is not located in urban areas and not in agricultural zones, the increase of livestocks and agricultural fertilizers in lands located in upstrea may not affect this section of the river because of the selfcleaning process in the river.

e. Scenarios of forest planting and climate change (scenarios S12 and S13):

While compare with scenario S8, we can see in Figure 6.13.e that the BOD_5 concentrations in scenarios S12 and S13 are nearly the same in both future years. That means there is nearly no impact on BOD_5 concentration caused by forest planting and climate change.

Figure 6.14.e shows that there is nearly no change in NH_4^+ concentration in the future caused by the impacts of forest planting and climate change.

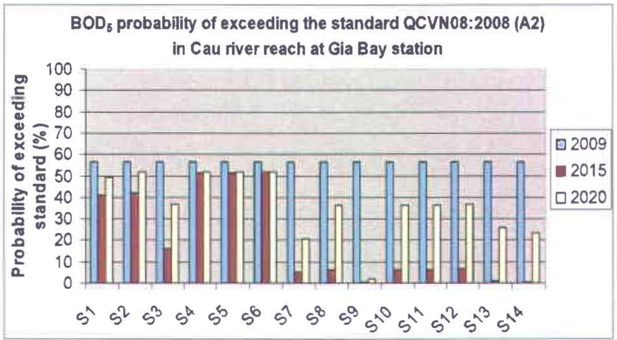
f. Scenario of all seven factors (scenario S14):

In Figure 6.13.f, we can see a water quality improvement in the scenario S14 in both future years compared with the current state; especially for S14 in 2015, where the BOD_5 concentration is nearly under the Vietnamese standard of surface water quality for the purpose of water supply with treatment application (6mg/l). This may be due to some interventions such as domestic wastewater treatment plants in Bac Kan town and Thai Nguyen City, and the compliance with Vietnamese standard of industrial wastewater by the current and future factories in the study area.

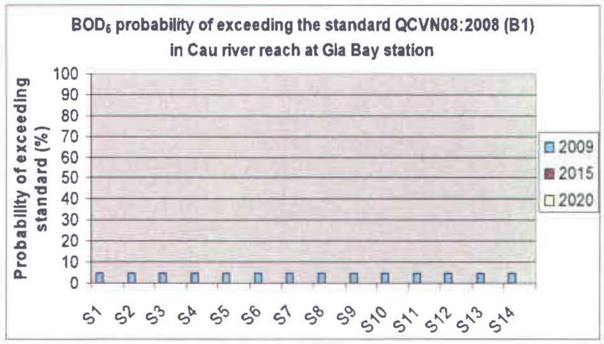
The combined impact of all seven factors makes the amonnium concentration reduce a little in 2015, but still increase a little in 2020 compared with the current state (see Figure 6.14.f).

Probabilities of exceeding standard for all scenarios from S1 to S14 in 2015 and 2020 compared with the current state:

The probabilities of exceeding the surface water quality standard for the purpose of water supply with treatment application (6mg/l) and for the purpose of irrigation and other purposes (15mg/l) for fourteen scenarios for BOD_5 in the river reach at Gia Bay station are indicated in Figure 6.15.a and Figure 6.15.b respectively.



a. For the standard with purpose of water supply with treatment

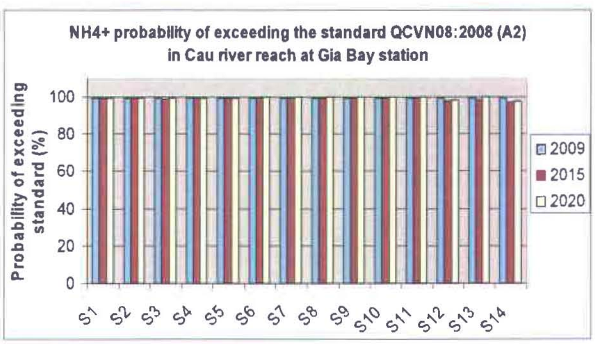


b. For the standard with purpose of irrigation and other purposes

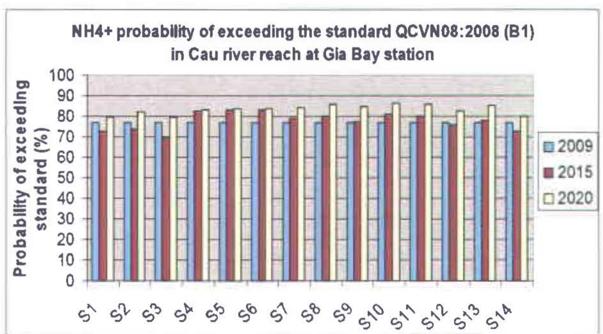
Figure 6.15: Probabilities of exceeding standard for all scenarios for BOD_5 at Gia Bay.

We can see in the above figure that the probabilities of exceeding standard decrease in all fourteen scenarios in both future years compared with the current state. Moreover, the probabilities of exceeding the standard for the purpose of irrigation and other purposes equal zero for all scenarios in the future. That means the water quality is improved in the future for all fourteen scenarios.

Probabilities of exceeding the surface water quality standard for the purpose of water supply with treatment application and for the purpose of irrigation and other purposes for fourteen scenarios for NH_4^+ are indicated in Figure 6.16.a and Figure 6.16.b respectively.



a. For the standard with purpose of water supply with treatment



b. For the standard with purpose of irrigation and other purposes

Figure 6.16: Probabilities of exceeding standard for all scenarios for NH_4^+ at Gia Bay.

In Figure 6.16.a, we can see that the probabilities of exceeding the surface water quality standard for the purpose of water supply with treatment application for NH_4^+ in all scenarios are nearly the same. However, concerning NH_4^+ probabilities of exceeding the surface water quality standard for the purpose of irrigation and other purposes, scenarios S1, S2, S3, S12 and S14 in 2015 have a lower probability of exceeding standard than the current state in 2009 (see Figure 6.16.b).

(3) SS

Only three scenarios S12 (impact of forest planting), S13 (impact of climate change) and S14 (impact of all seven factors) may have impacts on the changes in SS concentration. Negligible impacts were found for all these scenarios compared with the reference situation at this river reach. The results were found to be similar to those found at the Thac Rieng station (see figure 6.8).

(4) Comments on water quality and discharge in the river reach at Gia Bay station

After analyzing four constituents of discharge, BOD_5, NH_4^+ and SS, several comments on quantity and water quality improvement in this river reach at Gia Bay station are given as follows:

- The future discharge in this river reach does not change much compared with the current state due to the impacts of forest planting and climate change.
- In general, the water quality in this river reach is improved if two domestic wastewater treatment plants in Bac Kan town and Thai Nguyen City are installed, even with the smallest capacities in scenario S1.
- The operation of some new future industrial zones in this area makes NH_4^+ concentration in the future increase compared with the current state though all the current and future factories apply the standard on industrial wastewater for NH_4^+ (10mg/l). This may be due to the following reason: values of concentrations of NH_4^+ in industrial point sources from factories in the current state are under the standard value of industrial wastewater for NH_4^+ (Nguyen, 2013). However, BOD_5 concentration in the future impacted by industrial factor is improved compared with the current state.
- Three factors of livestock, fertilizer and forest planting have negligible impacts on water quality in this river reach. The increases in number of livestock and fertilizer quantity according to the assumptions and local development projections for the future may not

have enough impact to yield a significant increase of BOD_5 and NH_4^+ concentrations; or may be due to the fact that most of the feces of livestock which are put down into the nearby fields are used by plants, so that the excess of nitrogen and phosphorus going to the environment is not much. Regarding forest planting, this river reach is located in an urban region in a flat terrain, therefore forest planting which can reduce erosion and runoff have negligible impacts on river water quality.

- There is nearly no change in BOD_5 and NH_4^+ concentrations in the future caused by the impacts of climate change. However, because of the impact of climate change, some extreme values of SS concentration are diminished and SS probability of exceeding standard decreases in both future years compared with the current state. This may be because of a decrease of rainfall, resulting in a decrease of runoff for several days during two selected future years.
- Generally, the future water quality in this river reach is improved compared with the current state by the impact of all seven factors.

(5) Priority levels for the scenarios in the river reach at Gia Bay station

Table 6.6 summarizes the priority levels related to water quality improvement of the fourteen scenarios in the river reach at Gia Bay station based on the above results.

Table 6.6: Priority levels related to water quality improvement of fourteen scenarios in the river reach at Gia Bay station.

Scenario	Priority level	Explanation
S1	High	In general, the future water quality in this river reach is improved compared with the current state in three scenarios S1, S2, S3.
S2	High	
S3	High	
S4	Average	BOD_5 concentration decreases but NH_4^+ concentrations increases in 2015 and 2020 compared with the current state in 2009 by the industrial impact.
S5	Average	
S6	Average	
S7	High	Generally, the future water quality is improved compared with the current state in three scenarios S7, S8, S9.
S8	High	
S9	High	
S10	Average	These factors of livestock, fertilizer, forest planting and climate change, which correspond with scenario S10, S11, S12, S13 respectively, have negligible impacts on BOD_5, NH_4^+ and SS concentrations.
S11	Average	
S12	Average	
S13	Average	
S14	High	The water quality is improved in 2015 for BOD_5, NH_4^+ and SS, and in 2020 for BOD_5 and SS.

6.2.2.1.4. Water quality in 3 river reaches along Cau River

From upstream to downstream along Cau River (Thac Rieng, Thac Buoi and Gia Bay), we can see that the river reach at Thac Buoi station in midstream has the lowest probabilities of exceeding standard among three river reaches in all scenarios for BOD_5, NH_4^+ in 2009, 2015 as well as in 2020 (see figures A6.8 to A6.11 in Appendix A6). That means the water quality midstream is better than upstream and downstream along Cau River from Thac Rieng station to Gia Bay station.

For SS, differences between scenarios were found to be negligible. But scenario S12 for SS can have a good effect on SS concentration in the river reach at Thac Rieng station in the upstream of the river basin because forest will be planted in this area in the future.

6.2.2.2. Simulation results in Cong River and comments

Cong River is one of the major tributary rivers in Cau River system. It is located in the South-West of Thai Nguyen province (see Figure 3.2). The confluence of Cong and Cau Rivers is downstream from three selected river reaches of Cau River (Thac Rieng, Thac Buoi and Gia Bay) (see Figure 6.1). Therefore, the social-economic development activities in Cong River Basin as well as water quality and quantity of Cong River will not impact Cau River from upstream to the studied outlet (at Gia Bay station). Thus, as mentioned above at the beginning of section 6.2.2 of simulation results of river water quality, only three river reaches in Cau River are considered to make the priority levels related to water quality improvement for fourteen scenarios. The simulation results of water quality for the two river reaches of Cong River are analyzed in this part because the Cong River Basin is also included in the master development plan for Thai Nguyen province in the future. Therefore, the priority levels will not be given for these two river reaches in Cong River but some significant facts concerning water quality will help in selecting scenarios. For the detailed results for these river reaches, see Appendix 6.

Comments

At Song Cong town: industries have a little negative impact on water quality. However, overall the future water quality in this river reach does not vary much compared with the current state. Therefore, for this river reach, there is no remarkable factors to be considered for making the priority levels for scenarios.

At Da Phuc Bridge:

For water quality, there are two significant results which can be considered for making the priority levels for scenarios as follows:

- The operation of six new future industrial zones has a negative impact on water quality. Therefore, the industrial factor is considered as low priority in this river reach;

- The installation of a domestic wastewater treatment plant in Song Cong town has a positive effect on water quality. Thus, scenarios S2 and S8 which have the assumption of this installation are considered as high priority level in this river reach.

Along Cong River from the water supply treatment plant midstream to Da Phuc Bridge station downstream, the water quality at midstream is found to be better than downstream from Cong River.

6.2.3. Priority level for each scenario based on the water quality improvement

As mentioned above, the priority level estimation focused on three river reaches in Cau River for water quality improvement for fourteen scenarios. However, there are also two significant facts in Cong River about industry and the installation of a domestic wastewater treatment plant in Song Cong town, which should be considered in making priority levels for scenarios.

The priority levels for fourteen scenarios in three river reaches of Cau River and the combination of priority levels for the whole river basin are shown in the following table:

Table 6.7: Priority levels for water quality improvement of 14 scenarios for the whole watershed.

Scenario	Priority level			Combination of priority level
	Thac Rieng	Thac Buoi	Gia Bay	
S1	Low	Low	High	Low
S2	Average	Average	High	High
S3	High	Average	High	High
S4*	Average	Low	Average	Low
S5*	Average	Low	Average	Low
S6*	Average	Low	Average	Low
S7	Low	Low	High	Low
S8*	Average	Low	High	High
S9	High	Low	High	High
S10	Average	Average	Average	Average
S11	Average	Average	Average	Average
S12	Average	Average	Average	Average
S13	Average	Average	Average	Average
S14	High	Average	High	High

*Note: *: The significant results in Cong River were considered in the combination of priority levels for scenarios S4, S5, S6, and S8.*

The explanation of the combination priority levels in Table 6.7 for each scenario is given as follows:

- ***Scenario S1***: the future water quality is improved but only in the river reach at Gia Bay station. Two other river reaches at Thac Rieng and Thac Buoi stations have a future water quality worse than the current state. Therefore, the combination priority level for whole river basin for scenario S1 is low priority level.

- ***Scenario S2***: the future water quality is improved in the river reach at Gia Bay station and stays the same as the current state in two river reaches at Thac Rieng and Thac Buoi stations. That means along Cau River, the future water quality is improved at least in one river reach downstream. Moreover, scenario S2 is considered as high priority according to the significant fact of Cong River. Therefore, the combination priority level for the whole river basin for scenario S2 is high priority level.

- ***Scenario S3***: the future water quality is improved in two among three river reaches, at Thac Rieng and Gia Bay stations, and stays the same as the current state in the river reach at Thac

Buoi station in midstream. Therefore, the combination priority level for the whole river basin for scenario S3 is high priority level.

- ***Scenarios S4, S5, S6***: the future water quality is not improved, it is even worse than the current state in the river reach at Thac Buoi station in midstream. Moreover, these scenarios are the scenarios impacted by industrial activities, so they are considered as low priority according to the significant fact found for Cong River. Therefore, the combination priority levels for the whole river basin for scenarios S4, S5, S6 are low priority levels.

- ***Scenario S7***: like scenario S1, the future water quality in scenario S7 is improved but only in the river reach at Gia Bay station. Two other river reaches at Thac Rieng and Thac Buoi stations have a future water quality worse than the current state. Therefore, the combination priority level for the whole river basin for scenario S7 is low priority level.

- ***Scenario S8***: in three river reaches in Cau River, the priority level related to water quality improvement of scenario S8 in Thac Rieng is average priority level, in Thac Buoi it is low priority level, and in Gia Bay it is high priority level. Normally, we would consider that the combination priority level for the whole river basin for scenario S8 is average priority level. However, according to the significant fact found for Cong River, scenario S8 is considered as high priority level. Therefore, finally the combination priority level for the whole river basin for scenario S8 is high priority level.

- ***Scenario S9***: although the priority level of scenario S9 in the river reach at Thac Buoi station is low priority, the future water quality is still improved in two among three river reaches: at Thac Rieng and Gia Bay stations. Therefore, the combination priority level for the whole river basin for scenario S9 is high priority level.

- ***Scenarios S10, S11, S12, S13***: as analyzed above, four factors of livestock, fertilizer, forest planting and climate change in scenarios S10, S11, S12 and S13 respectively have nearly no impact on water quality in all selected river reaches. Therefore, the future water quality in these scenarios is nearly the same as the current state. Thus, the combination priority levels for the whole river basin for scenarios S10, S11, S12 and S13 are average priority levels.

- ***Scenario S14***: concerning the impact of all seven factors in scenario S14, the future water quality is improved in two among three river reaches of Cau River: at Thac Rieng and Gia Bay stations, and stays the same as the current state in the river reach at Thac Buoi station. Therefore, the combination priority level for the whole river basin for scenario S14 is high priority level.

6.3. Cost comparison for scenarios

As mentioned above in the Methodology section (part 4.4 of cost/benefit analysis), this study aims to estimate monetary benefits related to: (1) water-based recreational activities and (2) the reduction of treatment cost for domestic water, and the monetary costs of different interventions for improving water quality such as the installation of a wastewater treatment system. However, this target could not be attained due to lack of data. Therefore, this section mainly focused on the qualitative analysis of costs based on the comparison of different interventions between the scenarios in order to give priority levels for scenarios. Benefit in this case can be taken into consideration through water quality improvement. Scenarios with better water quality will have more benefit for public health, ecological system, water uses for different purposes.

Concerning benefit analysis, this part will mention several kinds of benefits people can obtain from the improvement of surface water quality and explain why this study cannot estimate the monetary benefits. Regarding cost analysis, this part will talk about the comparison between the scenarios of the cost for scenario implementation in order to make the priority levels for each scenario.

6.3.1. Benefit analysis

Changes in water quality primarily results from human activities, and those changes in water quality also affect human benefit. Human health is the most important issue relevant to water quality. In developing countries, it is estimated that every year, about three million people die of water-related diseases such as diarrhea or cholera, and most of them are children under the age of five (DFID *et al.*, 2002). Therefore, the first important benefit which people can obtain from water quality improvement is public health.

Besides the health benefit, the benefit of biodiversity conservation in fresh-water systems is also important because fresh-water systems may degrade in a short time due to pollution, overuse, etc., which can reduce biodiversity or exceed a certain threshold of tolerance (DFID *et al.*, 2002).

Withdrawal benefit includes agricultural withdrawal required by irrigation purpose, industrial withdrawal, and withdrawal for domestic water supply:

- Irrigation without proper water quality will reduce crop production, and may result in disease (Koteen *et al.*, 2002).

- Industrial withdrawal is the input water used in a production process, such as cooling, condensation, washing, and moving materials (Koteen *et al.*, 2002). For example: the pulp and paper industry uses water to cool equipment such as steam-generating machines, as well as for the pulping process. Water can also be incorporated into products. In the case that water is used for human consumption or for boiler feed, water quality improvement is very important (Koteen *et al.*, 2002).
- Concerning municipalities' water supply, water quality improvement can reduce the cost for water treatment and equipment replacement. For instance, water with low concentrations of total suspended solids may be treated only by filtration; other treatments such as sedimentation can be eliminated (Koteen *et al.*, 2002). Therefore, it can be said that low levels of total suspended solids in the public water supply is one of the important benefits of water quality improvement.

Water-based recreation is also affected by the water quality of rivers or lakes in recreational areas. This effect depends on the recreational activity. Direct water contact recreation, such as swimming, requires higher water quality than boating, hunting, etc. Wildlife viewing is also one of the water-based recreational activities affected by water quality. Water quality improvement restores wildlife habitat and enhances the wildlife viewing experience. Therefore, water-based recreational activities are also one of the benefits which people can get if water quality improves.

It can be said that there are many kinds of benefits people can obtain from the improvement of surface water quality. However, in the case of this doctoral study, as mentioned above in the Methodology section, we only focus on the benefits related to the water-based recreational activities and the reduction of treatment costs for domestic water supply.

- *For water-based recreational activities*: In the study area, the water-based recreational activities are tourism activities which take place in Nui Coc Lake. However, according to the benefit analysis method of Salvano *et al.* which is used in this study, we need the simulation results of water quality in Nui Coc Lake to estimate the monetary benefit related to the water-based recreational activities. In this case, we do not have the simulation results of water quality for Nui Coc Lake because the GIBSI model, which is calibrated for the Cau River Basin, can only simulate surface water quality in rivers. So we cannot evaluate the benefits related to tourism activities.

- *For domestic water supply*: In the study area, there are two kinds of supply water sources: (1) underground water, and (2) surface water. In this case, only the surface water source for domestic water supply in the Cau River Basin is considered.

There are 3 domestic water supply factories which use the surface water source in the study area. However, 2 of those water supply factories could not be considered in this case because there are no simulation results for water quality in Nui Coc Lake. So only the domestic water supply factory in Song Cong town may be taken into consideration for the benefit analysis.

In order to evaluate the monetary benefit related to the reduction of treatment costs for domestic water supply, the data of unit cost for treatment and simulation results of water quality improvement in the river reach in Cong River at the supply water treatment plant in Song Cong town are needed. However, we lack the data of unit cost for treatment, so it is impossible to calculate the monetary benefit. Moreover, as analyzed in section 6.2 of simulation results of water quality for the river reach at the supply water treatment plant, the future water quality in this river reach does not vary much compared with the current state. That means there is no big difference about water quality between the scenarios themselves as well as between the scenarios and the current state. Therefore, the benefits from water quality improvement in Cau River Basin are not considered to make the priority levels for scenarios.

6.3.2. Costs comparison

In this part, the costs of different interventions which the local governments have to pay for improving water quality such as the installation of domestic wastewater treatment systems, etc. will be mentioned. However, because of lack of data to estimate the monetary costs for the interventions of water quality improvement, together with the non-consideration of benefits from water quality improvement in making priority levels for scenarios as mentioned above, we mainly focus on the cost comparison between the scenarios in each scenario group in order to determine the priority levels for each scenario.

* *Cost comparison between the scenarios of population growth and domestic wastewater (scenarios S1, S2 and S3):*

In this scenario group, there are three interventions for improving water quality. Those are:

(1) Installation of two domestic wastewater treatment plants for Bac Kan town (capacity of 10,000 people) and for Thai Nguyen City (capacity of 100,000 people) according to the projections of local governments in scenario S1.

(2) Increasing the capacity to 20,000 people for the domestic wastewater treatment plant in Bac Kan town; keeping the same capacity of 100,000 people for the treatment plant in Thai Nguyen City; and installing a treatment plant for Song Cong town (capacity of 10,000 people) in scenario S2.

(3) Increasing the capacity to 30,000 people for the domestic wastewater treatment plant in Bac Kan town; and increasing the capacity to 150,000 people for the treatment plant in Thai Nguyen City in scenario S3.

Based on three above interventions, the cost differences between scenarios S1, S2 and S3 are compared as follows:

- Scenario S1 has the lowest cost among scenarios S1, S2, S3 because the capacities of two treatment plants are lower.
- Scenario S2 has the average cost among three scenarios because the cost is higher than scenario S1 but lower than scenario S3. The reason why the cost of S2 is lower than S3 is that besides the higher cost due to the increase of capacity to 30,000 people for the treatment plant in Bac Kan town, the cost for increasing and operating the treatment capacity of more 50,000 people for plant in Thai Nguyen City in scenario S3 is also higher than the cost for installing and operating the treatment plant for Song Cong town with a capacity of 10,000 people in scenario S2.
- Scenario S3 has the highest cost among three scenarios S1, S2, and S3.

It can be said that there are three different levels of cost which are given for three scenarios: low cost for scenario S1, average cost for S2, and high cost for S3. Therefore, scenario S1 will have a high priority level, S2 is average priority level, and S3 is low priority level.

** Cost comparison between the scenarios of industry (scenarios S4, S5 and S6):*

The differences between scenarios S4, S5 and S6 are the increases in the future of discharges from current factories. In scenario S4, the discharge of current factories stays the same in the future. In scenario S5, the discharge from current factories increases by 5% in 2015 and 10% in

2020. In scenario S6, the discharge from current factories increases by 10% in 2015 and 20% in 2020.

There is a significant fact that in all of these three scenarios, we assume that all the discharges from industrial factories in the future meet the Vietnamese standard for industrial wastewater because the industrial wastewater is obligated to meet standard before being discharged into the environment according to the Vietnamese law on environment (Vietnamese National Assembly, 2005). So the water quality shows nearly no difference between scenarios S4, S5 and S6 as mentioned in Section 6.2 of simulation results for surface water quality for the Cau River Basin. However, it is not sure that all the industrial factories in the future will often operate their wastewater treatment plants in order to make their discharge meet the standard because even in the current state, some of the current enterprises usually stop operating their wastewater treatment systems and run them only when there is an inspection of the local environmental managers (JICA and MONRE, 2009). Therefore, there may be a risk of water quality degradation which can cause a risk for public health, ecosystems or other activities using the polluted water source if the industrial wastewater does not meet the standard.

The different levels of risks for public health and ecosystems, etc., are considered between three scenarios, S4, S5 and S6, to compare the different levels of costs which the local government will have to pay to solve the problem if the risk happens.

- Scenario S4 has the lowest level of risk among the three scenarios because the industrial discharge in this scenario is lower than in the two others. Therefore, this scenario has the lowest level of cost among three scenarios.
- Scenario S5 has the average level of risk among the three scenarios because the industrial discharge in this scenario is higher than in S4 but lower than in S6. Therefore, this scenario has the average level of cost among the three scenarios.
- Scenario S6 has the highest level of risk among the three scenarios because the industrial discharge in this scenario is higher than in the two others. Therefore, this scenario has the highest level of cost among the three scenarios.

As a result, scenario S4 will have a high priority level, S5 is average priority level, and S6 is low priority level.

* *Cost comparison between the scenarios of population, domestic wastewater and industry (scenarios S7, S8 and S9):*

In fact, scenario S7 is the combination of scenarios S1 and S4, so scenario S7 will have a high priority level because both S1 and S4 have high priority levels.

Scenario S8 is the combination of scenarios S2 and S5. Thus, scenario S8 will have an average priority level because both S2 and S5 have average priority levels.

As for S7 and S8, scenario S9 is the combination of scenarios S3 and S6. Therefore, it will have a low priority level because both S3 and S6 have low priority levels.

* *Cost analyses for the scenarios S10, S11, S12, S13 and S14:*

Scenarios S10, S11, S12, S13, and S14 are the combination of scenario S8 and the changes of livestock, fertilizer, forest planting, climate change, and all four above factors respectively. There is no alternative concerning the impacts of livestock, fertilizer, forest planting and climate change in order to make the cost comparison. Therefore, the priority levels of these five scenarios will follow the priority level of scenario S8: average priority level.

6.3.3. Scenario priority level related to cost comparison analysis

Based on the above analyses, scenario priority levels related to cost comparison analysis are summarized in Table 6.8:

Table 6.8: Priority levels related to cost comparison analysis for 14 scenarios.

Scenario	Priority level related to cost comparison
S1	High
S2	Average
S3	Low
S4	High
S5	Average
S6	Low
S7	High
S8	Average
S9	Low
S10	Average
S11	Average
S12	Average
S13	Average
S14	Average

6.4. Scenario comparison and selection

By using the multi-criteria method, the scenario comparison and selection are done based on the results of scenario priority levels for the three assessment parts: (1) ideas of stakeholders about scenarios, (2) simulation results for surface water quality in Cau River Basin for each scenario, and (3) cost/ benefit analyses for each scenario.

Based on the formula mentioned in the Multi-criteria method section, the final score for each scenario is estimated based on the score and the importance of each of three results, in which the score is given based on three priority levels: 1 for low priority, 2 for average priority, and 3 for high priority, and the importance of water quality and ideas of experts and stakeholders is considered as 2 times while cost comparison has 1 time of importance. The results of estimating final score for each scenario are indicated in Table 6.9:

Table 6.9: Final score for 14 scenarios.

Scenario	Ideas of experts and stakeholders			Water quality			Cost comparison			Final score
	Priority	Score	Importance	Priority	Score	Importance	Priority	Score	Importance	
S1	Low	1	2	Low	1	2	High	3	1	7
S2	High	3	2	High	3	2	Average	2	1	14
S3	High	3	2	High	3	2	Low	1	1	13
S4	Low	1	2	Low	1	2	High	3	1	7
S5	High	3	2	Low	1	2	Average	2	1	10
S6	Average	2	2	Low	1	2	Low	1	1	7
S7	Low	1	2	Low	1	2	High	3	1	7
S8	High	3	2	High	3	2	Average	2	1	14
S9	Average	2	2	High	3	2	Low	1	1	11
S10	Average	2	2	Average	2	2	Average	2	1	10
S11	Low	1	2	Average	2	2	Average	2	1	8
S12	Low	1	2	Average	2	2	Average	2	1	8
S13	Low	1	2	Average	2	2	Average	2	1	8
S14	High	3	2	High	3	2	Average	2	1	14

In order to make it easier to select the scenarios with high score, fourteen scenarios are rearranged according to the score from high to low. This rearrangement is shown in Table 6.10.

Table 6.10: Scenario arrangement from high to low score.

Score	14	14	14	13	11	10	10	8	8	8	7	7	7	7
Scenario	S2	S8	S14	S3	S9	S5	S10	S11	S12	S13	S1	S4	S6	S7

We can see in Table 6.10 that there are three scenarios, S2, S8 and S14, which have the highest score among the fourteen scenarios. Therefore, three scenarios, S2, S8 and S14, are selected. *Scenario S2* is the combination of the average future population and the assumption of increasing the capacity of the domestic wastewater treatment plant to 20,000 people in Bac Kan town, installing a treatment plant in Song Cong town for 10,000 people (like the capacity of the projected treatment plant in Bac Kan town) together with keeping the projection of the domestic wastewater treatment plant for 100,000 people in Thai Nguyen City. *Scenario S8* is the combination of the projection of 14 industrial zones and increasing by 10% the discharge of the current factories in 2020 (in 2015: increasing by 5%), the average future population, and increasing the capacity of the domestic wastewater treatment plant to 20,000 people in Bac Kan town, installing a treatment plant in Song Cong town for 10,000 people (like the capacity of the projected treatment plant in Bac Kan town) together with keeping the projection of the domestic wastewater treatment plant for 100,000 people in Thai Nguyen City. *Scenario S14* is the combination of scenario S_8, which is the average scenario of three factors of population, industry and domestic wastewater in high priority level, and the changes of livestock, agricultural fertilizer, forest and climate change. Scenario S14 can be considered to be the most realistic one among the 3 scenarios with highest score because it takes into consideration all factors at medium values. The two others are more theoretical scenarios or analysis scenarios than realistic scenarios because they do not take into consideration changes in some factors.

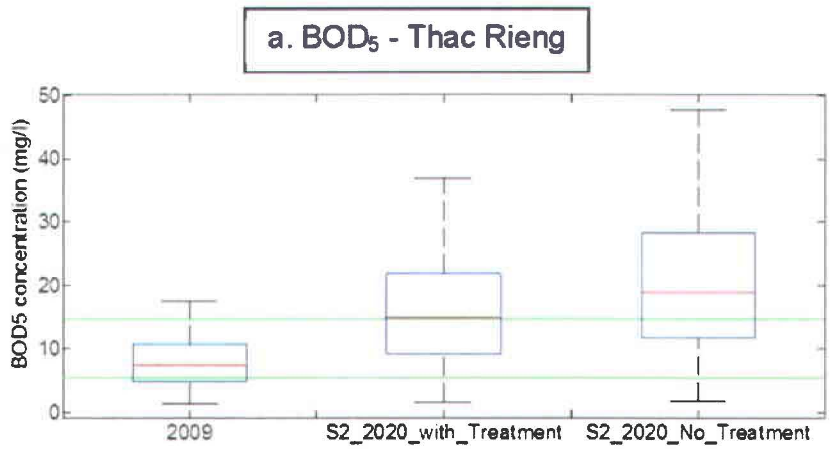
In all of these three selected scenarios, the interventions for improving the water quality of the Cau River Basin are the same. Those are: (1)- increasing the capacity of the domestic wastewater treatment plant in Bac Kan town to 20,000 people (corresponding to around 35% of the forecasted average population in 2015 in Bac Kan town) rather than 10,000 people like in the local projection (corresponding to around 18% of the forecasted minimum population in 2015 in Bac Kan town); (2)- keeping the projection of domestic wastewater treatment plant for

100,000 people in Thai Nguyen City (corresponding to around 67% of a half of the forecasted average population in 2015 in Thai Nguyen City since only the northern half of the population in Thai Nguyen City are considered in the study area); and (3)- installing a treatment plant in Song Cong town for 10,000 people (corresponding to around 19% of the forecasted average population in 2015 in Song Cong town). So these interventions are recommended to improve the surface water quality of the Cau River Basin.

6.5. Discussion

Some interventions for water quality improvement were integrated into development of scenarios. For example, domestic wastewater treatment plants were integrated in scenarios S1, S2, S3 with the projected capacity or industrial wastewater treatment plants were applied for all factories in scenarios S4, S5, S6, etc. The results of water quality may change if such interventions are not done in the future. Therefore, in order to understand the importance of these interventions or to investigate the response of the watershed without such interventions, several simulations without interventions were made and results of variation of one variable (BOD5) were analyzed.

- *Domestic wastewater*:



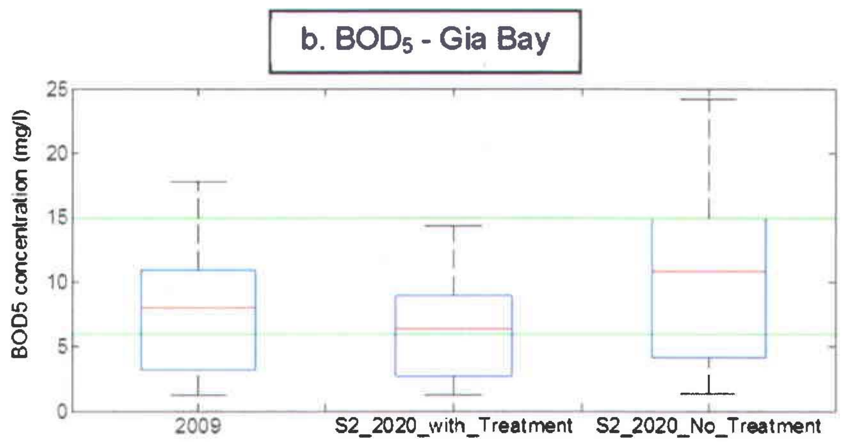


Figure 6.17: BOD_5 comparison in 2020 between with and without domestic wastewater treatment at Thac Rieng and Gia Bay.

BOD_5 concentration without domestic wastewater treatment plant was investigated in 2020 (Figure 6.17, a&b, S2_2020_No_Treatment). It was found that BOD_5 concentration increases around 27% at Thac Rieng (upstream) and 69% at Gia Bay (downstream) compared with the scenario of treatment plant, for the same increase of average population in 2020 (Figure 6.17, a&b, S2_2020_No_Treatment & S2_2020_with_Treatment). Besides, the results in figure 6.17 also show that BOD_5 in 2020 without treatment plant increases more than 138% at Thac Rieng and 38% at Gia Bay compared with the current state because of the population increase in upstream of each point (around 125% in Bac Kan town and 10% in Thai Nguyen city). Based on the BOD5, this result highlights what may happen in the future with no domestic treatment plant. It is therefore very important to install and operate the domestic wastewater treatment plants in Bac Kan town and Thai Nguyen city in order to improve water quality in Cau River Basin. In other words, the objective of water quality improvement by 2020 may not be achieved with no treatment plant or treatment plants with lower capacities.

- *<u>Industry</u>*: BOD_5 at Gia Bay

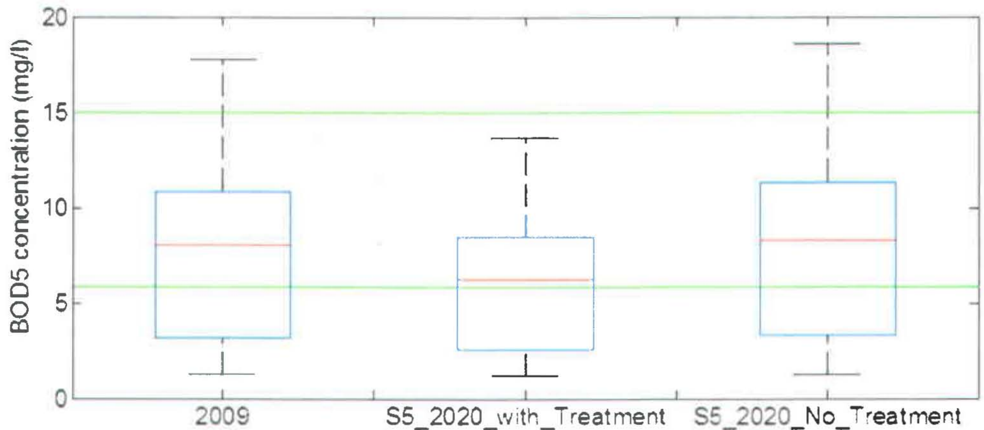


Figure 6.18: BOD_5 comparison in 2020 between scenarios with and without industrial wastewater treatment of current factories at Gia Bay.

Another hypothesis was made for the investigations. It is related to industrial wastewater. In this simulation, the wastewater of all current factories was considered to be released into the environment with no treatment while the future industrial zones' wastewater meets the standard. Figure 6.18 shows the simulation results of BOD_5 concentration at Gia Bay in 2020 in the present case. BOD_5 concentration without treatment increases more than 34% compared with treatment in 2020 (Figure 6.18, S5_2020_No_Treatment & S5_2020_with_Treatment). Besides, the simulation results also show that BOD_5 in 2020 without treatment is nearly the same as in the current state, which is higher than one of the values indicated by the standards (Figure 6.18, see lower value indicated by green lines). It can therefore be said that with no treatment plant in the future, discharge from current factories may not help to improve water quality. The situation should be worst with no treatment for all factories, including the new industrial zones. It can finally become a challenge for governments to achieve the target of water quality improvement by 2020.

In this study, a negligible impact of increase of livestock and agricultural fertilizer was found in Cau River. In fact, the simulation results at three selected river reaches: Thac Rieng, Thac Buoi and Gia Bay showed that these factors have negligible impacts on water quality of Cau River. This may be explained by the fact that these river reaches are not nearby agricultural lands where feces and fertilizers are distributed by the model prior to simulation. Therefore, results of some other river reaches in Cau River show that the increase of fertilizer quantity in the future has nearly no impact on BOD_5 and NH_4^+ concentrations. This can be explained by the low increase of quantity of fertilizers in the future compared with the reference state. However, the increase of number of livestock lead to an increase of NH_4^+ concentration in several days in the rainy season from May to September, but this increase is not significant (the maximum increase of NH_4^+ is found to be 0.014 mg/l in 2020). Regarding the load of NH_4^+, the increase of total load in 2020 is around 22.25 kg/year (increase of 2.7%) compared with the reference situation and the maximum increase of NH_4^+ load for a day is around 2.35 kg/day (increase of 4.2%) in 2020 compared with the current state.

In this study, we used the comparison method to give priority levels of scenarios based on each of three main results of water quality, cost comparison and ideas of stakeholders. However, it is possible to use another method to compare and select scenarios. For example, we can analyse two results of water quality and cost at the same time in order to give priority levels for scenarios, such as the scenario which water quality meets standard and with lower cost should be in higher priority. Different methods of scenario comparison and selection may conduct to different results of scenario selection. In fact for a given scenario which meets the standard with a given cost for implementation, it can be considered that another scenario with better water quality should conduct to a lower priority level because since the target is to meet surface water quality standards.

Chapter 7: Conclusions, uncertainties, recommendations and perspectives

Conclusions

The surface water in the Cau River Basin, located in the Norh of Vietnam, has become polluted, and the environmental improvement of this river basin is one of the priorities and important tasks of the Vietnamese government. In 2006, this priority was seriously taken into consideration in order to make Cau River clean by 2020. In order to contribute to the water quality improvement of the Cau River Basin, a co-operation project for the integrated management of the Cau River Basin between INRS and VAST began in 2007 and this doctoral study is a part of this project.

The principal objective of this doctoral research is therefore to build a methodology for scenario development in order to identify the best interventions for improving the water quality of Cau River, helping the decision-makers select the optimal interventions to "make Cau River clean" by 2020. The approach of integrated watershed management, which can help taking into consideration both aspects of social-economic development and environmental protection in order to go towards a sustainable development, is applied in order to achieve this objective. The main tasks of this research are to develop future scenarios based on the social-economic development plans and compare and select the best scenarios by using a multi-criteria method. The multi-criteria method used three criteria: (1) ideas of stakeholders about the scenarios, (2) impacts of each scenario on surface water quality in the Cau River Basin, and (3) cost/ benefit for each scenario.

This doctoral thesis built fourteen future scenarios of social - economic development and interventions for water quality improvement in the Cau River Basin in Bac Kan and Thai Nguyen provinces in Vietnam in the context of few available data in the study area. These fourteen scenarios are different combinations of seven factors: population, domestic wastewater, industry, livestock, agricultural fertilizer, forest, and climate change which are associated with the social - economic development plans of local goverments and can cause direct or indirect impacts on the discharge and water quality of the river system. It is possible to build more than fourteen scenarios when we combine these seven factors, but the fourteen scenarios created are considered more relevant and the most probable scenarios because they are built by taking into consideration several projections of the local governments for social - economic development and environmental protection, and based on realistic hypotheses.

In order to reduce the number of possible scenarios, and analyze the relevant and most probable scenarios in the context of this watershed, the scenarios were developed according to three different priority levels considered for the seven factors: the high priority level for three factors: population, domestic wastewater, and industry; the middle priority level for two factors: livestock and agricultural fertilizer; and the low priority level also includes two factors: forest and climate change. The priority levels help taking into consideration the importance level of each factor in the development plan of the local governments. The group of scenarios S1, S2, S3 is the combination of two factors: population and domestic wastewater. The group of scenarios S4, S5, S6 is the combination of two factors: population and industry. The group of scenarios S7, S8, S9 is the combination of three factors: population, domestic wastewater, and industry. Scenarios S10, S11, S12, and S13 are the combination of scenario S8, which is the average scenario of the three factors (population, domestic wastewater, industry) in high priority level, and the changes in livestock, agricultural fertilizer, forest, and climate change respectively. Scenario S14 is the combination of scenario S8 and the changes in livestock, agricultural fertilizer, forest and climate change at the same time.

This research used a river basin integrated management computer tool named GIBSI (Villeneuve *et al.* 1998). It helps simulating water quality variables for each scenario. A scenario called "reference scenario", in which the conditions of the watershed such as hydro-meteorological conditions, population, pollution sources, etc. are in the reference situation, is considered to compare water quality in future scenarios with the present situation. Four water quality variables are considered to compare the impacts of the scenarios on water quality: discharge, BOD_5, NH_4^+, and SS. Through the simulation results in three selected river reaches in Cau River and two in Cong River (one of the main branches in Thai Nguyen province), there are some significant facts related to the impacts of the seven factors on water quantity and quality as follows:

- *Population*: Through the release of domestic wastewater, population growth has a huge impact on water quality in this river basin, especially in Cau River. The fast future population growth in Bac Kan town may lead to an increase in BOD_5 and NH_4^+ concentrations in the upstream (Thac Rieng and Thac Buoi stations) in the future compared with the reference situation and even with a domestic wastewater treatment plant put in service in 2015 in Bac Kan town. So population control is very important for water quality improvement in the study area, especially for the immigrants in Bac Kan town in the period of time from 2016 to 2020 after Bac Kan town becomes a city.

- *Domestic wastewater treatment plant*: The local projection for the installation of a domestic wastewater treatment plant in Bac Kan town in 2015 with a capacity of 10,000 people, representing about 17.9% of Bac Kan town's forecasted low population in 2015 and 12.3% in 2020, connected to the treatment plant, is not efficient enough for water quality improvement due to the fast future population growth in Bac Kan town. However, increasing the capacity of this treatment plant to 20,000 or 30,000 people can improve the water quality in the upstream of Cau River in 2015. For the downstream and the outlet at Gia Bay station of Cau River, the water quality will improve in the future if two domestic wastewater treatment plants in Bac Kan town and Thai Nguyen City are installed, even at the smallest capacities projected by the local governments. In Cong River, the installation of a domestic wastewater treatment plant at Song Cong town in Cong River sub-watershed with a capacity of 10,000 people, representing about 19% of Song Cong town's forecasted medium population in 2015 and 18% in 2020, connected to the treatment plant, has a positive effect on water quality downstream of Cong River.

- *Industry*: The operation of new future industrial zones in the study area seems to have negative impacts on water quality though we assume that all the current and future industrial discharges meet the Vietnamese standard of industrial wastewater. Only BOD_5 concentration in the river reach at Gia Bay station in the future is improved compared with the current state. However, an increase of discharges of the current factories does not affect the water quality in the river since discharges meet the Vietnamese standard for industrial wastewater. This can also be explained by the fact that we assume in this research that all the discharges from industrial factories in the future meet the Vietnamese standard for industrial wastewater because the industrial wastewater is obligated to meet standard before discharged into the environment according to the Vietnamese law on environment (Vietnamese National Assembly, 2005). But it is not sure that all the industrial factories in the future will often operate their wastewater treatment plants in order to make their discharge meet the standard because even in the current state, some of the current enterprises usually stop operating their wastewater treatment systems and run them only when there is an inspection of the local environmental managers (JICA and MONRE, 2009), which may lead to a risk of water quality degradation, causing a risk for public health, ecosystems or other activities using the polluted water source. Therefore, the control of the conformity to the Vietnamese law on environment of factories is important to improve water quality in the study area.

- *Livestock and agricultural fertilizer*: The changes in livestock and fertilizer have negligible impacts on the future water quality in all five selected river reaches. This may be due to the fact that the increase in the numbers of livestock and fertilizer quantity according to the assumptions and local development projections for the future may not have enough impact to make a significant increase on BOD_5 and NH_4^+ concentrations; or maybe due to the fact that most of the feces of livestock which are put down into the nearby fields are used by plants, so that the excess of nitrogen and phosphorus going to the environment is not much.

- *Forest and climate change*: Only these two factors may have minor effects on river discharge. The simulation results show that the future discharge in 2015 and 2020 does not change much compared with the current state. Forest planting and climate change do not have much impact on BOD_5 and NH_4^+ concentrations in all five selected river reaches because there is nearly no effects on runoff and discharge. Only some extreme values of SS concentration in the future are diminished by these factors. This may be due to a short studied period of time (only until 2020). Climate change impacts would probably be more visible in long term simulations.

The simulation results (Chapter 6) indicate that population and domestic wastewater are factors which may have visible impacts on water quality in the study area. Four other factors, livestock, agricultural fertilizer, forest, and climate change have nearly no impact on water quality. Therefore, identifying the priority levels for seven factors based on the current key problems for environmental management and the main projections for social-economic development of the local government in order to build future scenarios in Chapter 5, which identified that three factors (population, domestic wastewater and industry) are in high priority level and can be considered as reasonable.

Besides the assessment of the impacts of fourteen scenarios on the water quality of the Cau River system, a cost comparison analysis and the ideas of experts and stakeholders regarding these scenarios are also taken into consideration. For the cost comparison analysis, the target of estimating monetary benefits and costs could not be achieved due to the lack of data. Thus, this study only mentioned some kinds of benefits people can obtain from the improvement of surface water quality and mainly focused on a qualitative analysis of costs based on the comparison of different interventions between the scenarios in order to give priority levels for scenarios.

The role of experts and stakeholders is also very important for the watershed integrated management because they have experience with local environmental management and know well about the political wishes of local governments. Moreover, they are also the people who will apply the selected scenarios. As a result, the priority levels for each scenario, according to the ideas of stakeholders, were collected.

In order to make a classification of scenarios, this doctoral research elaborated a complete method for scenario selection based on the bottom-up approach of multi-criteria analysis. A framework of criteria and indicators was developed. There are three main results for scenario selection related to three criteria: water quality, cost comparison, and scenarios (ideas of experts and stakeholders). The priority levels (high, average and low) for each scenario are given after analyzing the indicators for each criterion, and then the score for each scenario of each result is calculated based on the priority levels. The final score for each scenario is estimated based on the score and the importance of each result.

There are three scenarios, S2, S8 and S14, that have the highest final score which means the highest priority level among fourteen scenarios. Therefore, three scenarios, S2, S8 and S14, can be selected as the best scenarios for social-economic development with water quality improvement.

Scenario S2 is the combination of the medium future population and increasing the capacity of the domestic wastewater treatment plant to 20,000 people in Bac Kan town, a treatment plant in Song Cong town for 10,000 people together with the domestic wastewater treatment plant for 100,000 people in Thai Nguyen City.

Scenario S8 is the combination of S2 and the projection of 14 industrial zones and increasing 10% of the discharge of current factories in 2020.

Scenario S14 is the medium scenario comprising all factors at medium values.

This research really contributes to an evaluation of the impacts of future social-economic development on surface water quality in the Cau River Basin in Bac Kan and Thai Nguyen provinces, and identifying the best interventions for water quality improvement in the future in the context of scarce data in the study area.

Uncertainties

Uncertainties are the conditions which may cause differences between the estimated values and the true values (*Source*: http://www.thefreedictionary.com/uncertainty). There are several uncertainties which may happen during the implementation of this research such as uncertainties due to lack of data, uncertainties in the local projections, and model uncertainties even though they are physically based models.

In order to deal with the uncertainties due to the lack of data, several assumptions were given based on the foreign and Vietnamese guideline documents and experience in order to complete the data set needed to develop scenarios and for the input data in GIBSI. For example, there is a lack of data on industrial wastewater discharges from the current and future factories. It would be better if an emission inventory with detailed information of each factory was implemented. However, time and resources are the major limiting factors to carry out such inventory. Thus, the industrial discharges were estimated based on the experiential values of water supply and discharge for industry. For another example, this study aimed at estimating monetary costs and benefits for water quality improvement. However, this target could not be achieved due to the lack of data. Therefore, this research only does a qualitative analysis of cost based on the comparison of different interventions between the scenarios to give priority levels.

Concerning the uncertainties in the data collected from local projections, the solution is that besides the projection data to calculate the future forecast and develop future scenarios, other probabilities based on statistic data in the past are also considered in this research. For example, in order to calculate the future population, besides the projection data of local governments, the higher and lower future populations are also estimated based on the statistic data of population in the past ten years.

The probable sources of model uncertainties may be the models themselves to describe physical processes, the observed data for calibration, the calibration process, etc., which may have impacts on the simulation results of water quality. In order to avoid this kind of model uncertainties, the scenario comparison in this study mainly focuses on the comparison of water quality changes between scenarios and with the current state (reference scenario) because all the scenarios may have the same uncertainties. Therefore, this kind of uncertainties may not affect the comparison between scenarios.

The proposal of different levels of importance for three criteria such as water quality, cost comparison and scenarios (ideas of experts and stakeholders) is also considered as a kind of uncertainty because the changes in the weight of these three criteria may affect the final score and scenario selection. Three tests were carried out in order to see the effects of criteria weight changes on the results. It has been shown that the changes in levels of importance for the three criteria will affect the results of this research.

All these uncertainties may have impacts on the results of this study. We therefore should consider the results as guidelines for local decision makers, representing a trend in the future rather than the exact results.

Recommendations and perspectives

There are two factors (population and industry) which must be controlled in order to improve the water quality for the study area. Those are as follows:

- *Population*: The fast future population growth in Bac Kan town is the reason why the BOD_5 and NH_4^+ concentrations in the river reaches at Thac Rieng and Thac Buoi stations increase a lot in the future. Therefore, besides the installation of a domestic wastewater treatment plant with a capacity of 20,000 people in 2015, population growth in Bac Kan town should be controlled from 2016 to 2020 after it becomes a city. If this control of population growth can not be done, the capacity of domestic wastewater treatment plant in Bac Kan town should be increased more than the level of 30,000 people because the simulation results showed that the water quality in 2020 in the upstream of Cau River is worse than the current state even with the high capacity of 30,000 people.

- *Industry*: The operation of industrial wastewater treatment plants by all the current and future factories must be strictly controlled to ensure that their discharges meet the Vietnamese standard of industrial wastewater, in order to avoid the risk of water quality degradation in case the industrial wastewater does not meet the standard.

Concerning climate change, it has minor effects on water quality in the study area. In the framework of this research, the studied period of time is only until 2020, which may be a short period of time to study the impacts of climate change on water quality. Therefore, studies about this issue for longer term impacts should be conducted (*e.g.* 30 years).

The context of few available data in the study area, which may lead to uncertainties in the thesis results, is a challenge for us. There are several ways to deal with the uncertainties as mentioned above in the part of uncertainties in this chapter. However, it is better to have these data than to make hypotheses, helping us to improve the accuracy of the results of the study. For example, for industry, an inventory should be carried out to update the number of traditional village and industrial pollution sources, their locations, type of industry in the study area, and to collect the wastewater discharge, pollutants' concentrations in wastewater, etc. For cost/benefit analysis, a survey should be implemented to collect the data about technology and cost for treatment of water supply plants and domestic wastewater treatment plants in the study area.

Besides, also because of the lack of data and because the land use map in GIBSI could not distinguish between different crop plants, this study only assessed the impact of fertilizer increase for paddy on water quality in the study area. The other kinds of plants such as maize, tea, fruit-tree, etc. as well as pesticides which may have an effect on water quality were not considered in this research. Therefore, more studies of the impacts of agricultural fertilizers and pesticides should be carried out.

This study did not take into consideration the impacts of heavy metals and pollution from traditional villages because of lack of observed data to calibrate the model. Future studies for heavy metals and pollution from traditional villages should also be taken into consideration.

This research could not take into consideration the part of Cau River south of Thai Nguyen province from Gia Bay monitoring station because the models in GIBSI has not been calibrated for this river segment due to the effect of tide from downstream. Therefore, calibration of this segment in GIBSI by integration of a model of tide regime should be implemented in order to be able to assess the combination impacts of Cau and Cong sub-watersheds in Bac Kan and Thai Nguyen provinces on surface water quality of the Cau River system.

This research proposed a methodology of integrated management for the Cau River Basin to be able to select the best interventions for both aspects of social-economic development and environmental protection in order to go towards a sustainable development. This may be a valuable methodology for watershed integrated management which can be applied for other river basins in Vietnam and also elsewhere.

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APPENDIX 1- FIGURES AND TABLES

APPENDIX A1 TO A6

Appendix A1: Chapter 1

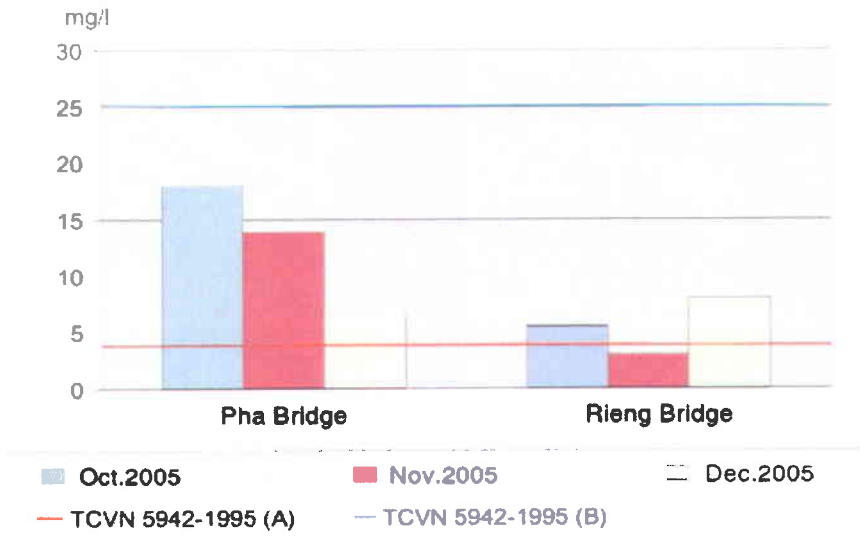


Figure A1.1: The BOD_5 content in Cau river section flowing through Bac Kan province.

Source: VEPA in Environment Report of Vietnam, 2006.

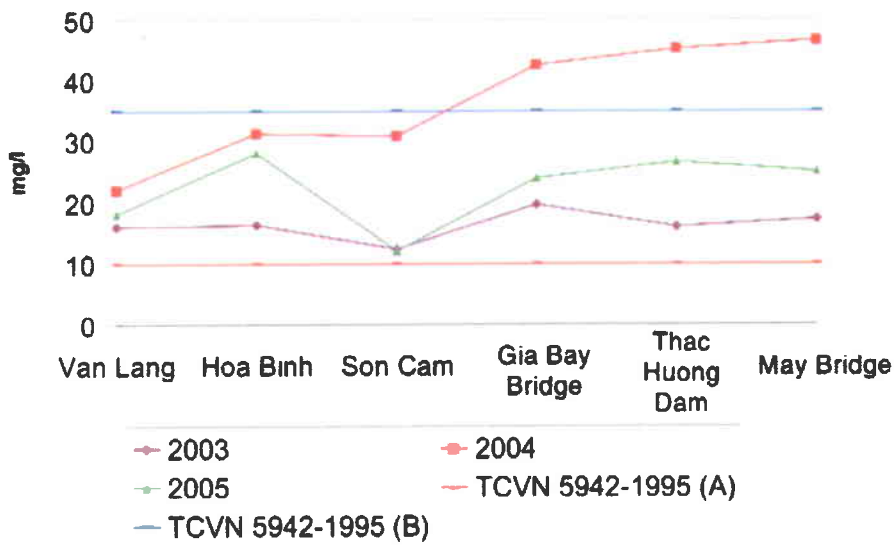


Figure A1.2 : COD concentration in Cau river segment flowing through Thai Nguyen province.

Source: Thai Nguyen DONRE, 2006 in Environment Report of Vietnam, 2006.

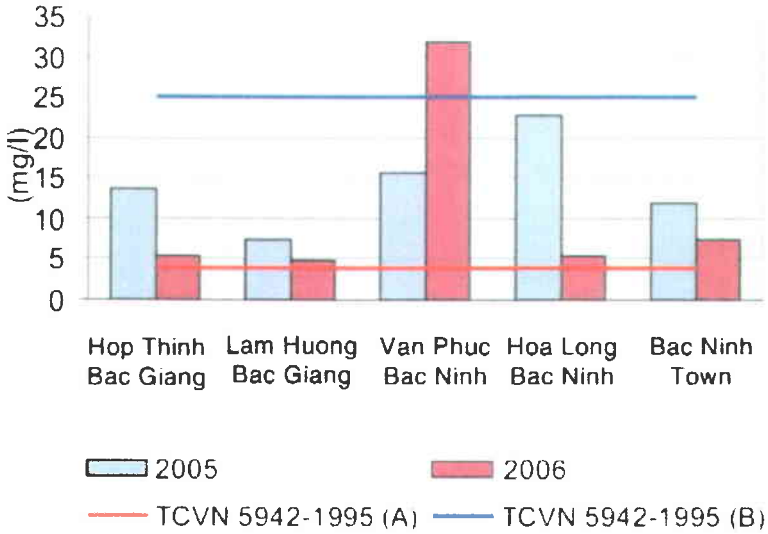


Figure A1.3: Variation of BOD_5 concentration at Cau river segment flowing through Bac Giang and Bac Ninh provinces.

<u>Source</u>: VEPA, 2006 in Environment Report of Vietnam, 2006.

Appendix A2: Chapter 2

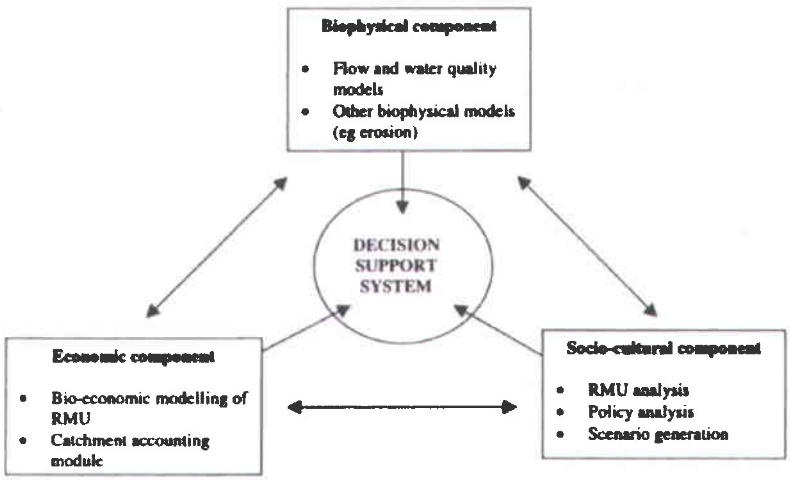


Figure A2.1: Linkages between the four components (from Scoccimarro *et al.* 1999).

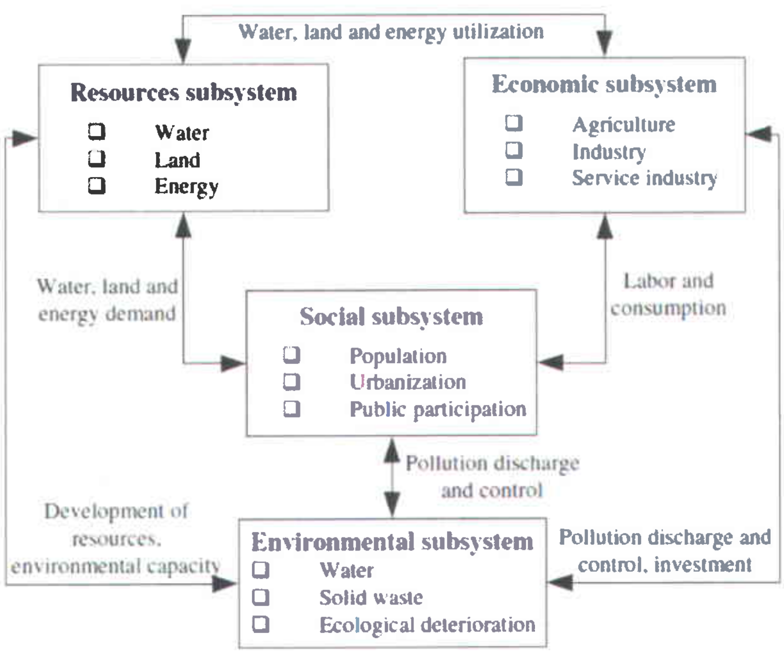


Figure A2.2: The subsystems and relationships for watershed management (from Liu *et al.* 2007).

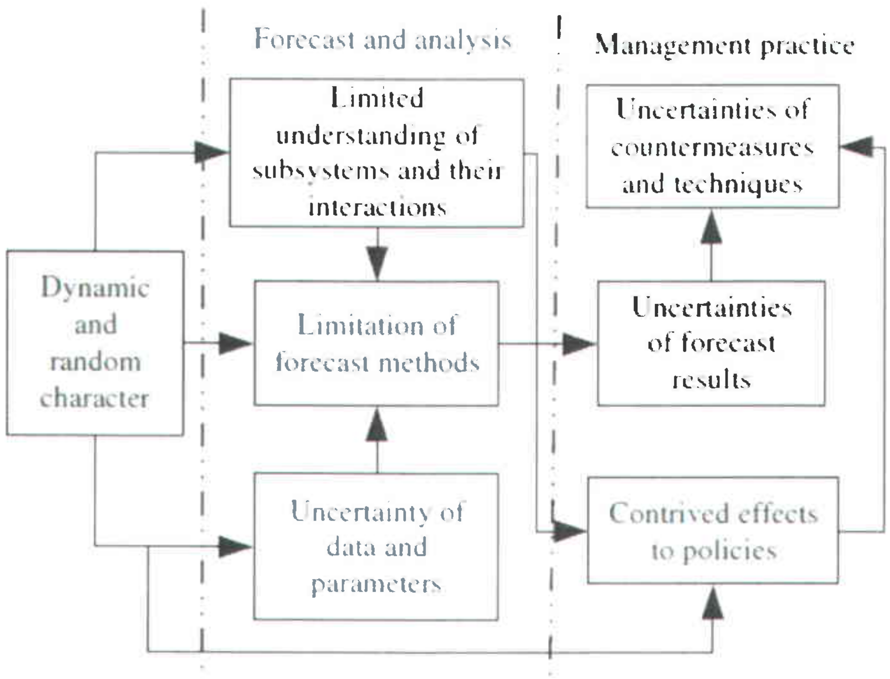


Figure A2.3: The uncertainties of the different stages in watershed management (from Liu *et al.* 2007).

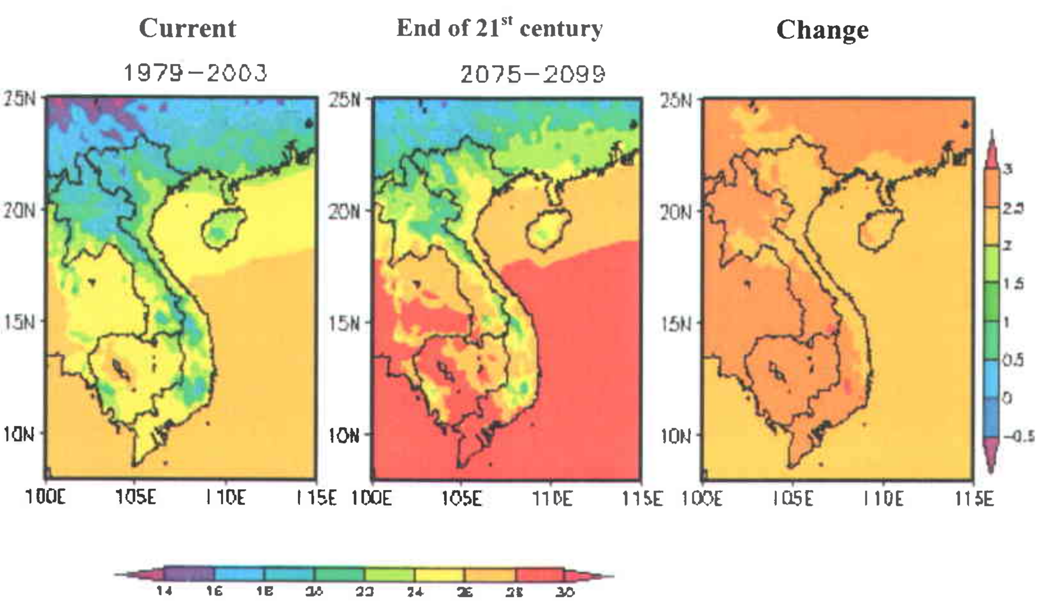


Figure A2.4: Temperature simulation results of MRI-AGCM model for the area of Vietnam (MONRE, 2009).

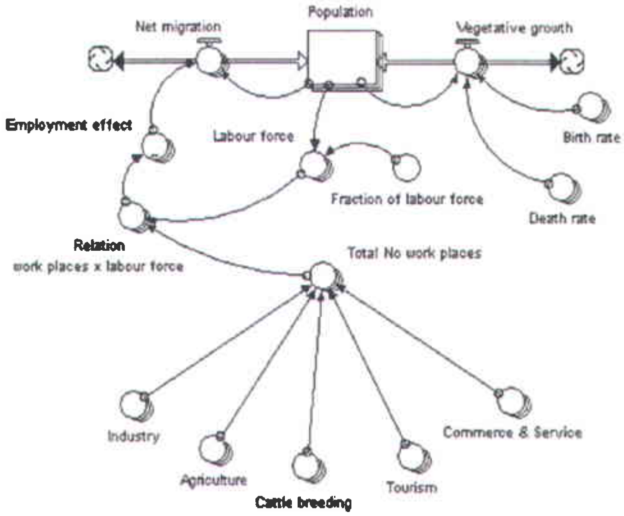


Figure A2.5: Dynamic model for the Population sector (from Leal-Neto *et al.*, 2006).

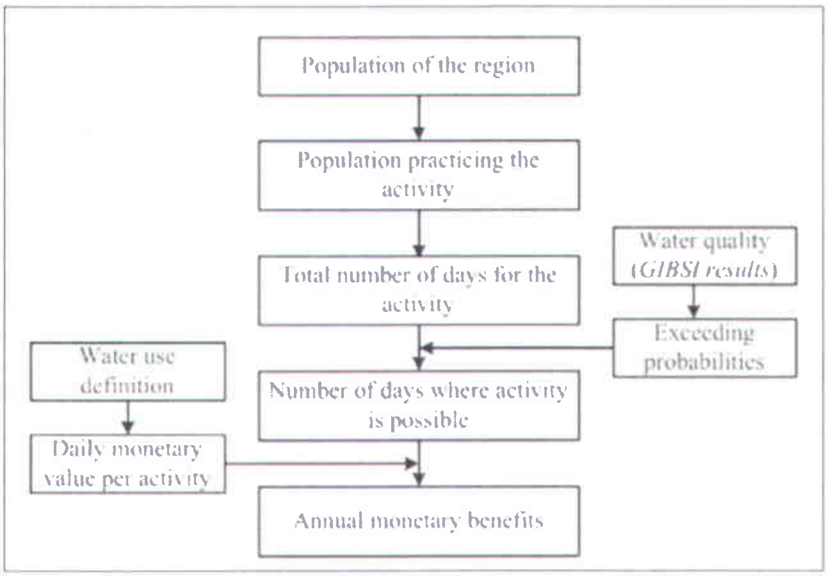


Figure A2.6: Estimation of monetary benefits of water-based recreational activities (from Salvano *et al.*, 2006).

Appendix A3: Chapter 3

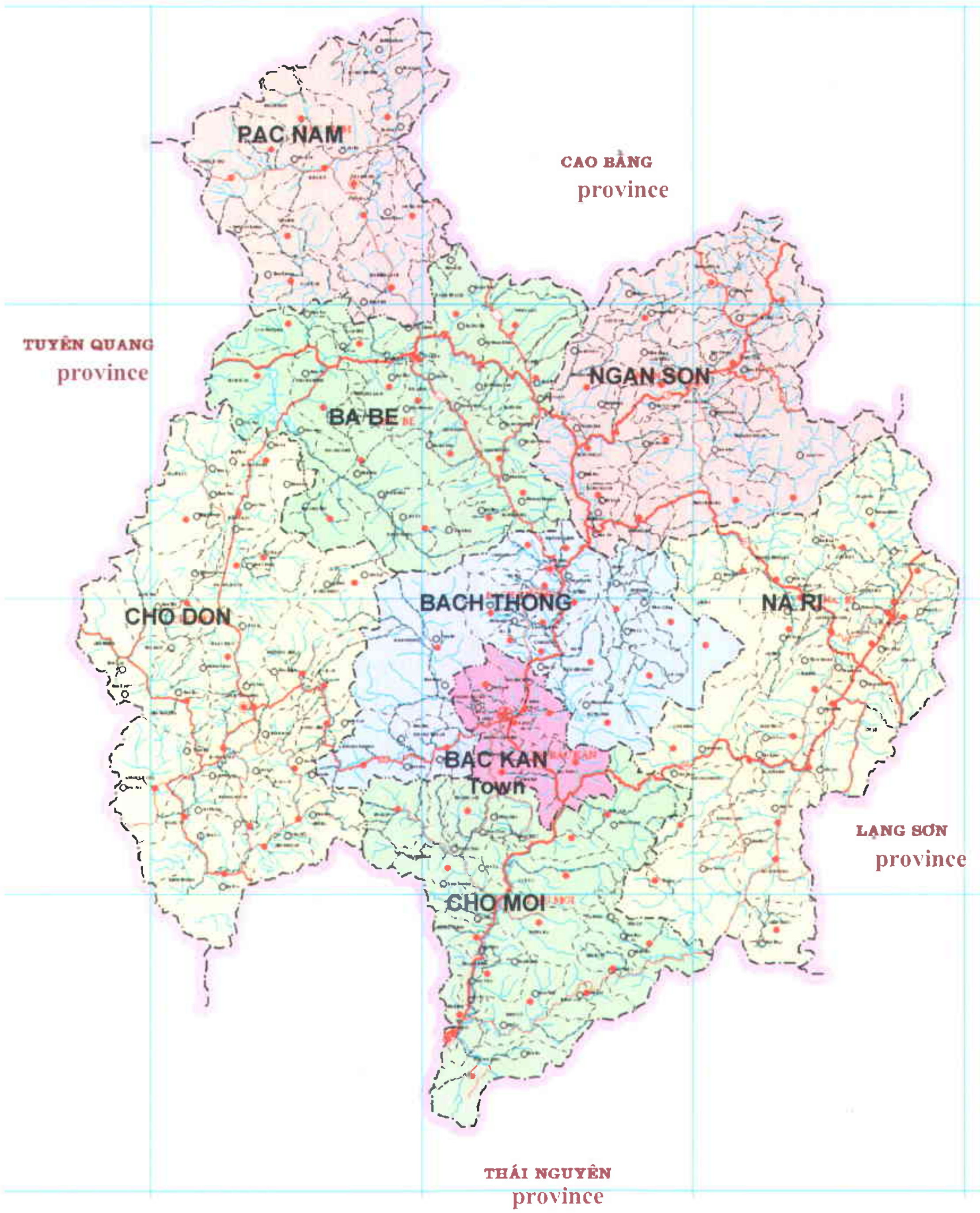


Figure A.3.1: Administrative map of Bac Kan province.

TT	ĐƠN VỊ HÀNH CHÍNH	DIỆN TÍCH (Km²)	DÂN SỐ (Người)	MẬT ĐỘ (Người / km²)
1	TP. Thái Nguyên	177,1	217 500	1 228
2	TX. Sông Công	83,7	41 200	493
3	H. Đại Từ	577,9	160 300	277
4	H. Định Hóa	520,8	87 300	168
5	H. Đồng Hỷ	461,8	117 000	253
6	H. Phổ Yên	256,7	129 300	504
7	H. Phú Bình	249,4	133 000	533
8	H. Phú Lương	368,8	101 500	275
9	H. Võ Nhai	845,1	61 700	73
	Toàn tỉnh	3 541,1	1 048 800	296

Figure A3.2: Administrative map of Thai Nguyen province.

Table A3.1: Area and Population in 2009 of Bac Kan province by district

District	Area (km^2)	Population in 2009 (persons)
Bac Kan town	137.08	37,585
Ba Be	685.35	46,719
Pac Nam	477.44	30,071
Ngan Son	646.96	28,482
Cho Don	913.17	48,207
Na Ri	854.07	37,240
Bach Thong	547.18	30,228
Cho Moi	607.16	36,764
Total	**4,868.41**	**295,296**

Source: Backan Statistics Office, 2010.

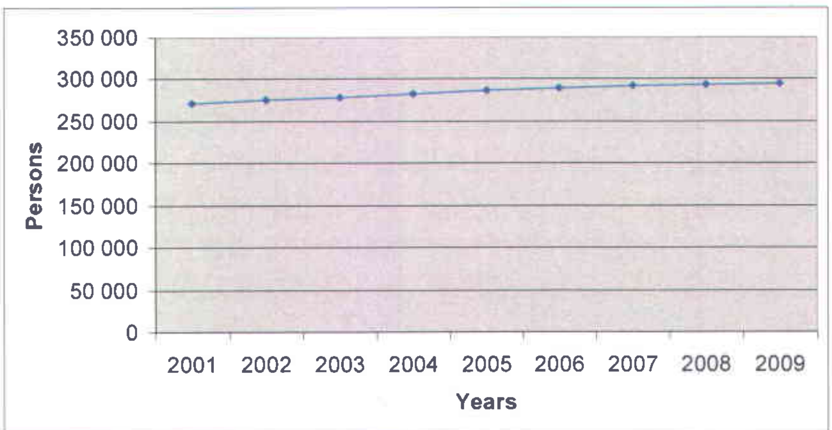


Figure A3.3: Variation of population in Bac Kan province from 2001 to 2009.

Source: Backan Statistics Office, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010.

Table A3.2: Area and Population in 2009 of Thai Nguyen province by district.

District	Area (km^2)	Population in 2009 (persons)
Thai Nguyen City	189.70	279,710
Song Cong town	83.64	50,000
Dinh Hoa	511.09	86,200
Vo Nhai	840.10	63,950
Phu Luong	369.33	105,250
Dong Hy	457.75	112,970
Dai Tu	568.55	158,700
Phu Binh	249.36	133,500
Pho Yen	256.68	137,150
Total	**3,526.20**	**1,127,430**

Source: *Thainguyen Statistics Office, 2010.*

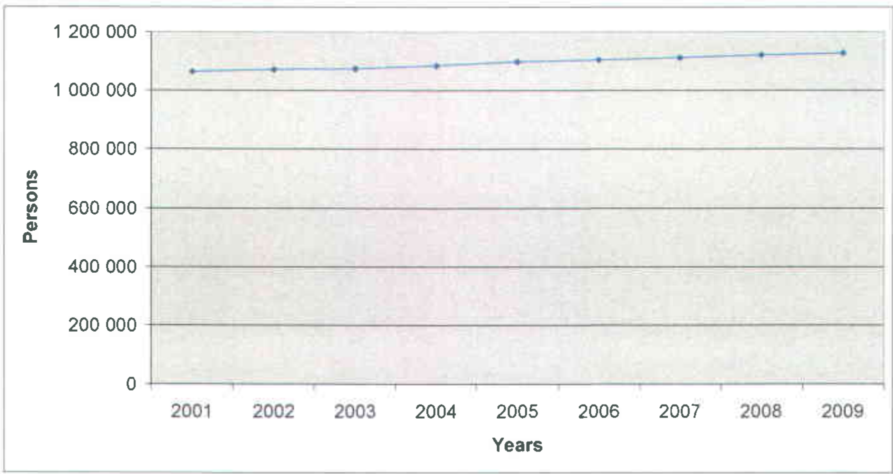


Figure A3.4: Variation of population in Thai Nguyen province from 2001 to 2009.

Source: *Thainguyen Statistics Office, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010.*

Table A3.3: Trend of social-economic development.

Items		Case	Thai Nguyen province				Bac Kan province			
			2008	2012	2015	2020	2008	2012	2015	2020
Population [persons]		Base:	100%	104%	106%	111%	100%	105%	109%	114%
Industrial Turnover [million VND]		High:	100%	183%	274%	534%	100%	182%	303%	719%
		Base:	100%	174%	251%	463%	100%	163%	241%	471%
		Low:	100%	165%	230%	400%	100%	145%	191%	303%
Number of livestock [heads]	Cattle	Base:	100%	110%	122%	148%	100%	198%	233%	292%
	Pigs	Base:	100%	147%	170%	208%	100%	161%	189%	236%
Land use area [ha]	Urban	Base:	100%	157%	174%	204%	100%	165%	198%	255%
	Agriculture	Base:	100%	110%	108%	108%	100%	114%	122%	135%
	Forest	Base:	100%	104%	104%	104%	100%	113%	116%	120%

Source: JICA and MONRE, 2009.

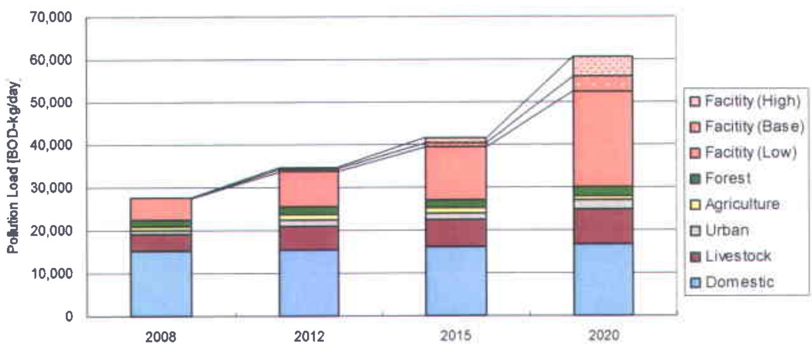


Figure A3.5: Future pollution load (BOD) of the scenarios (from JICA and MONRE, 2009).

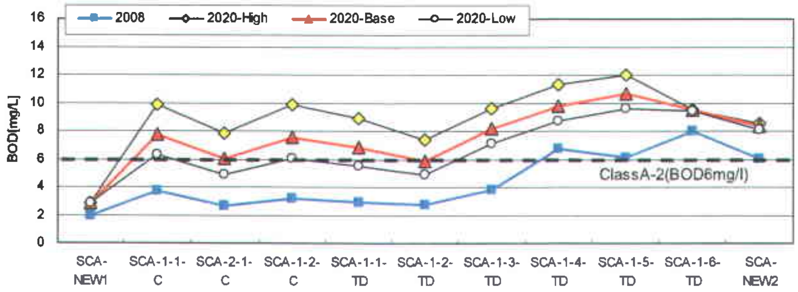


Figure A3.6: Future water quality (BOD) of the three scenarios in 2020 (from JICA and MONRE, 2009).

Appendix A5: Chapter 5

Table A5.1: The current livestock of Cau River basin in Bac Kan and Thai Nguyen provinces.

Districts	Buffaloes	Cattles	Pigs	Poultry
Bac Kan province:				
Bac Kan town	2,070	187	12,875	67,170
Cho Don	2,529	598	5,425	39,832
Bach Thong	7,323	1,500	25,601	143,499
Cho Moi	7,446	1,922	24,943	146,094
Total (Cau RB in Bac Kan)	**19,368**	**4,206**	**68,843**	**396,595**
Thai Nguyen province:				
Thai Nguyen City	6,532	3,439	59,485	704,000
Song Cong town	4,853	1,980	18,728	323,000
Dinh Hoa district	11,490	2,655	41,767	447,000
Vo Nhai district	7,401	1,515	20,897	222,443
Phu Luong district	7,992	903	51,547	558,000
Dong Hy district	12,377	2,564	61,834	565,000
Dai Tu district	16,892	1,728	65,310	873,000
Phu Binh district	11,716	16,442	127,408	1,421,000
Pho Yen district	13,364	11,685	101,432	830,000
Total (Cau RB in Thai Nguyen)	**92,617**	**42,911**	**548,408**	**5,943,443**

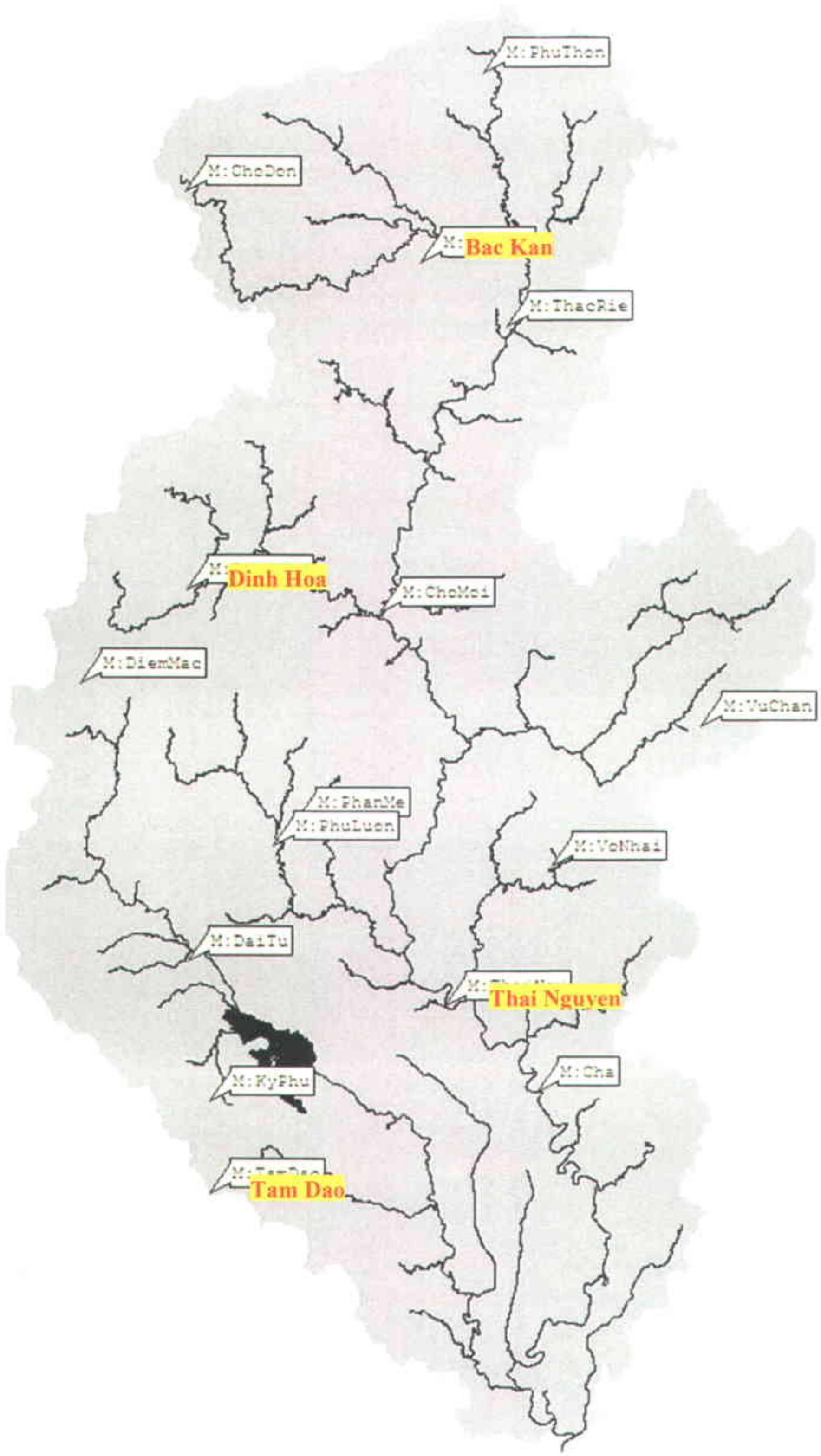


Figure A5.1: Meteorological stations in the study area.

(The names of the stations considered for the climate change scenarios appear in red).

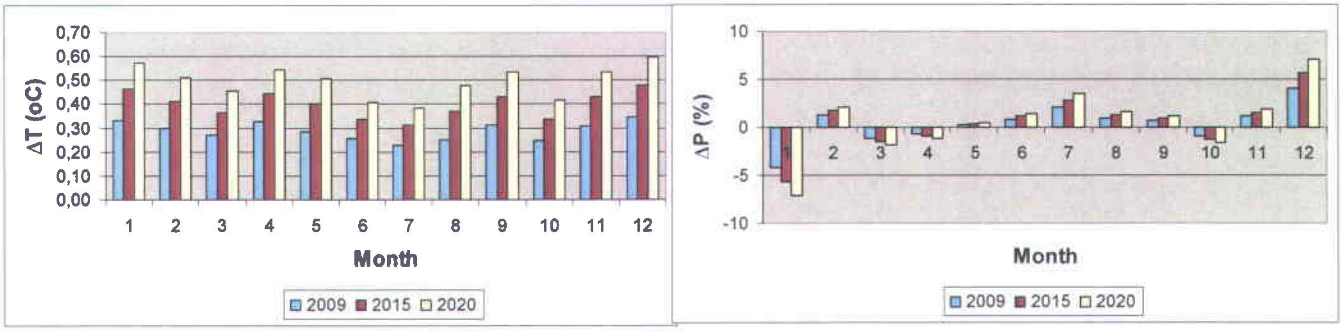


Figure A5.2: Average projected ΔT and ΔP for Cau river basin meteorological stations.

Table A5.2: Main information of the future industrial zones in the Cau River basin.

Name of Industrial zone	Area (ha)	% Area in use	Type of industry	Discharge (m^3/s)		Note
				2015	2020	
Thanh Binh	154-500		mechanical assembling, processing agricultural and forestry products, etc.	0.022	0.044	-
Sông Công I (1) (Current state : 25% in use)	220	-	-	0.0224	0.0448	Large scale
Sông Công II (1)	250	-	Construction material, electricity, textile, heath instruments, agricultural product, etc,	0.0255	0.0509	Large scale
Nam Phổ yên (1)	200	-	Car assembling, electricity, mechanic, food and beverage processing, livestock slaughter	0.0204	0.0407	Large scale
Tây Phổ Yên (1)	200	-	High-tech industries, production of car parts	0.0204	0.0407	Large scale
Quyết Thắng (1)	200	-	Production of electronic facilities, information technology, etc,	0.0204	0.0407	Large scale
Điềm Thuy (1)	350	-	Mechanic, metallurgy, construction material, electronics industry, etc,	0.0356	0.0713	Large scale
Vân Thượng (2)	47	50% (in 2015)	Construction material, steel production, etc,	0.0048	0.0096	Small scale
Kim Sơn (2)	20	60% (in 2013)	Construction material, mechanic,electric facility	0.0024	0.0041	Small scale
Quang Trung - Chí Son(2)	45	80% (in 2015)	Construction material, mineral, etc	0.0073	0.0092	Small scale
Quang Sơn 2 (2)	50	60% (in 2015)	Construction material, mechanic, mineral, etc	0.0061	0.0102	Small scale
Phú Lạc 2 (2)	40	50% (in 2015)	Construction material, mineral, etc	0.0041	0.0081	Small scale
Sơn Cẩm 2 (2)	50	70% (in 2015)	Metallurgy, electric facility, pharmaceutical chemistry, construction material, mineral, etc	0.0071	0.0102	Small scale
Xuân Phương-Kha Sơn(2)	75	-	Textile, leather, pulp and paper, etc	0.0076	0.0153	Small scale

Sources: (1): Management Board of industrial zones in Thai Nguyen, 2011.
(2): People Committee of Thai Nguyen province, 2010.
- : No information → assuming that 50% of the planning area of industrial zone will be in use in 2015.

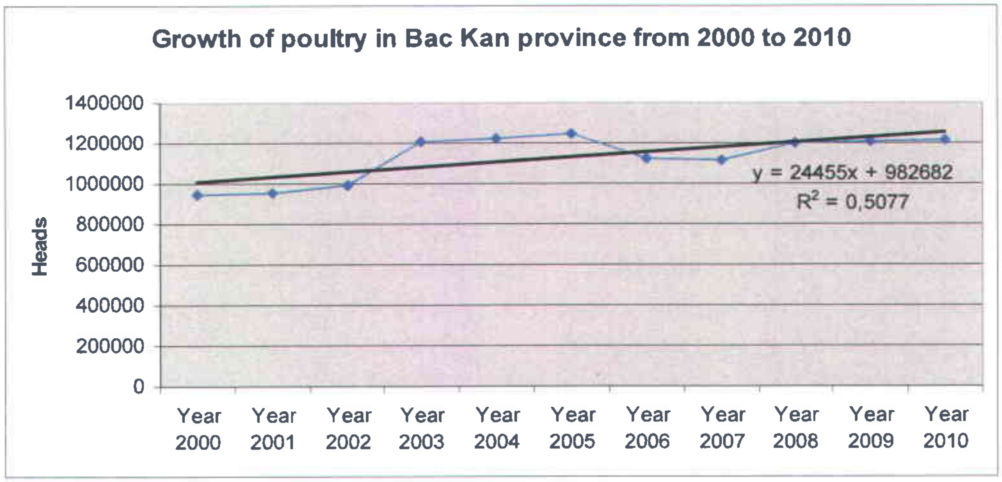


Figure A5.3: Linear regression function to forecaste the future poultry of Bac Kan province.

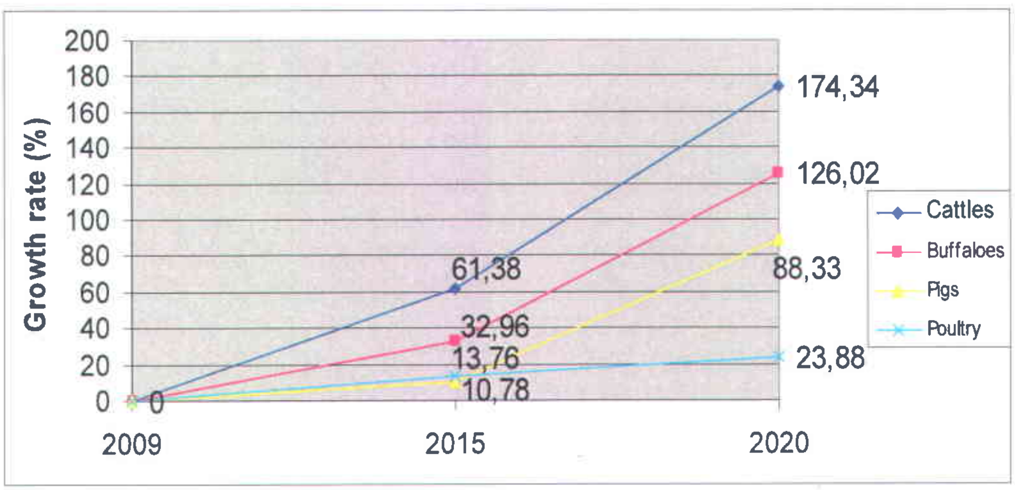


Figure A5.4: Futute livestock growth rates compared with current state (%) for Cau River Basin in Bac Kan province.

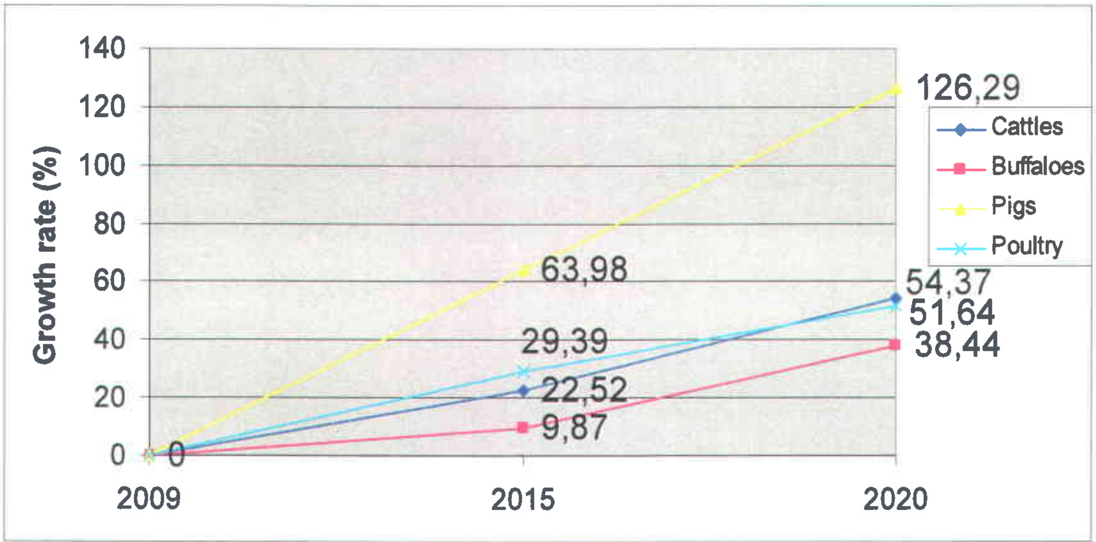


Figure A5.5: Future livestock growth rates compared with current state (%) for Cau River Basin in Thai Nguyen province.

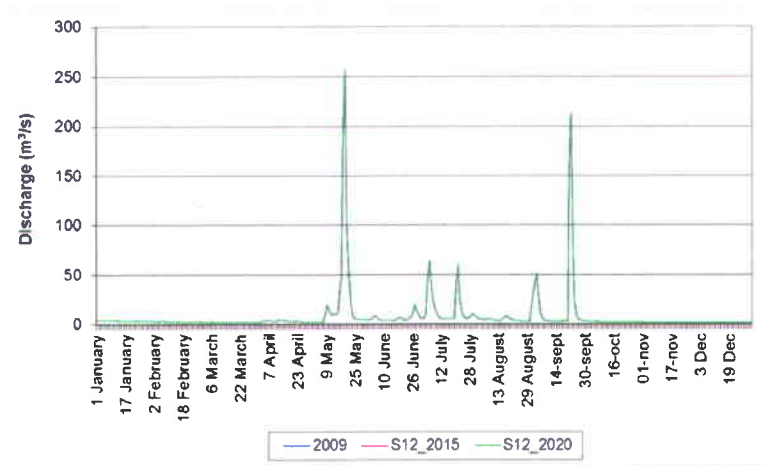
Table A5.3: Details for the values of the matrix of factor combination to develop scenarios.

Factors	Values	Explanation
Population	Low projection	Low population growth in Bac Kan and Thai Nguyen.
	Medium projection	Based on the projections of local governments.
	High projection	High population growth in Bac Kan and Thai Nguyen.
Domestic wastewater	Low capacity	- *Bac Kan town*: 10,000 people. - *Thai Nguyen city*: 100,000 people.
	Medium capacity	- *Bac Kan town*: increase capacity to 20,000 people. - *Thai Nguyen city*: 100,000 people. - *Song Cong town*: installing a treatment plant for Song Cong town for 10,000 people.
	High capacity	- Bac Kan town: increase capacity to 30,000 people. - Thai Nguyen city: increase capacity to 150,000 people.
Industry	Current industries + projected	- *Current factories*: keeping current discharge. - 14 future industrial zones.
	Medium increase for current	- *Current factories*: increase 10% of the discharge in 2020 (in 2015: increasing 5%). - 14 future industrial zones.
	High increase for current	- *Current factories*: increase 20% of the discharge in 2020 (in 2015: increasing 10%). - 14 future industrial zones.
Livestock	Medium projection	Increase of future livestock calculated based on local projections.
Agriculture	Medium projection	Increase of quantity of fertilizers for paddy fields.
Forest	Medium projection	Projected forest planting.
Climate change	Medium projection	Changes of future temperature and precipitation.

Appendix A6: Chapter 6

1. Impacts of forest planting on water discharge

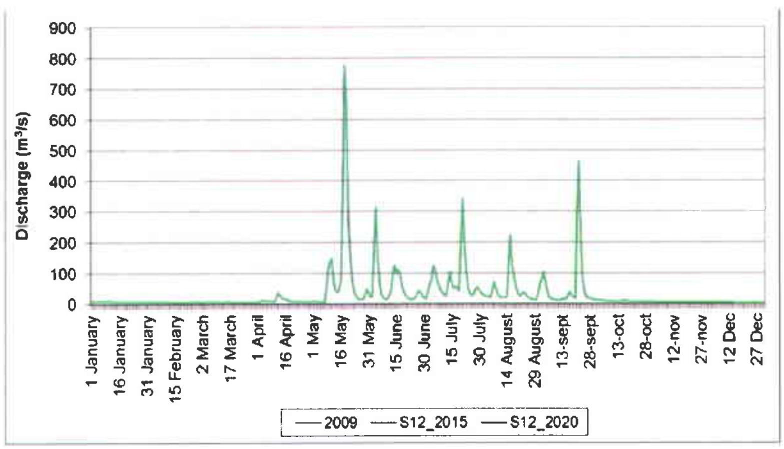
River reach at Thac Rieng station



(*Note*: The blue and red lines for 2009 and S12_2015 are overlaid by the green line for S12_2020 in the figure).

Figure A6.1. Impact of forest planting on discharge in the river reach at Thac Rieng station: the changes in discharge between Scenario S12 in 2015, S12 in 2020 and 2009 (current state).

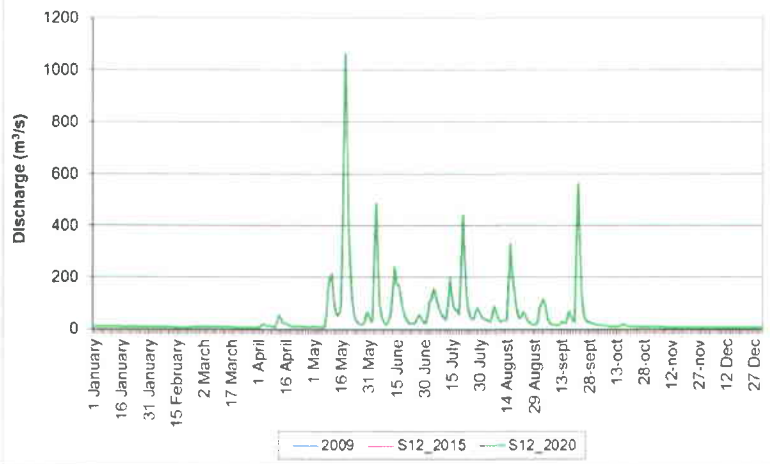
River reach at Thac Buoi station



(*Note*: The blue and red lines for 2009 and S12_2015 are overlaid by the green line for S12_2020 in the figure).

Figure A6.2. Impact of forest planting on discharge in the river reach at Thac Buoi station: the changes in discharge between Scenario S12 in 2015, S12 in 2020 and 2009 (current state).

River reach at Gia Bay station

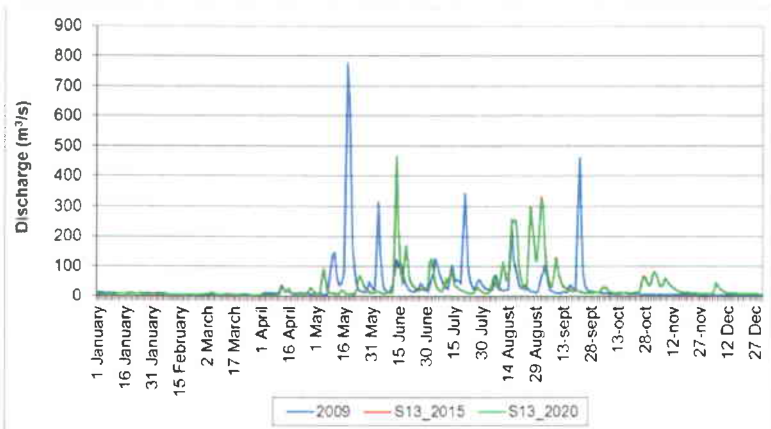


(*Note*: The blue and red lines for 2009 and S12_2015 are overlaid by the green line for S12_2020 in the figure).

Figure A6.3. Impact of forest planting on discharge in the river reach at Gia Bay station: the changes in discharge between Scenario S12 in 2015, S12 in 2020 and 2009 (current state).

2. Impacts of climate change on water discharge

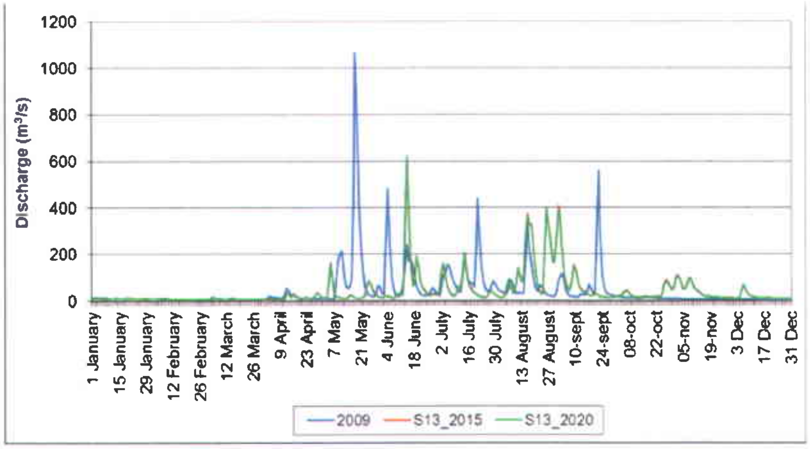
River reach at Thac Buoi station



(*Note*: The red line for S13_2015 is overlaid by the green line for S13_2020 in the figure).

Figure A6.4. Impact of climate change on discharge in the river reach at Thac Buoi station: the changes in discharge between Scenario S13 in 2015, S13 in 2020 and the current state in 2009.

River reach at Gia Bay station

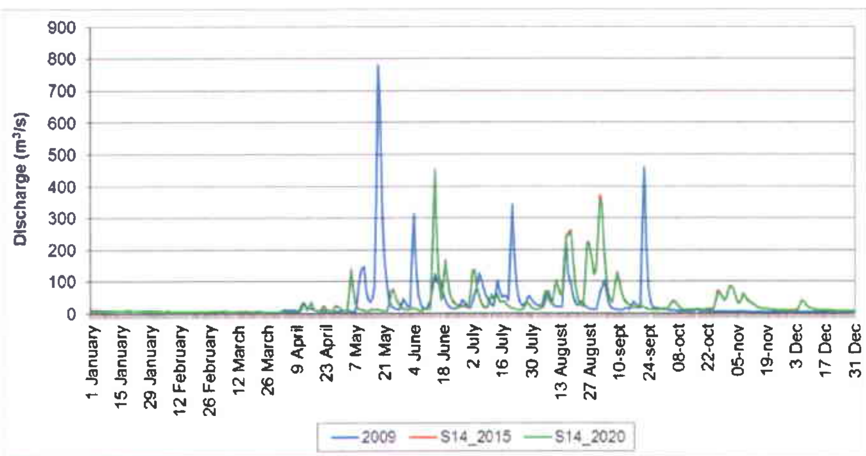


(*Note*: The red line for S13_2015 is overlaid by the green line for S13_2020 in the figure).

Figure A6.5. Impact of climate change on discharge in the river reach at Gia Bay station: the changes in discharge between Scenario S13 in 2015, S13 in 2020 and 2009 (current state).

3. Impacts of forest planting and climate change on water discharge

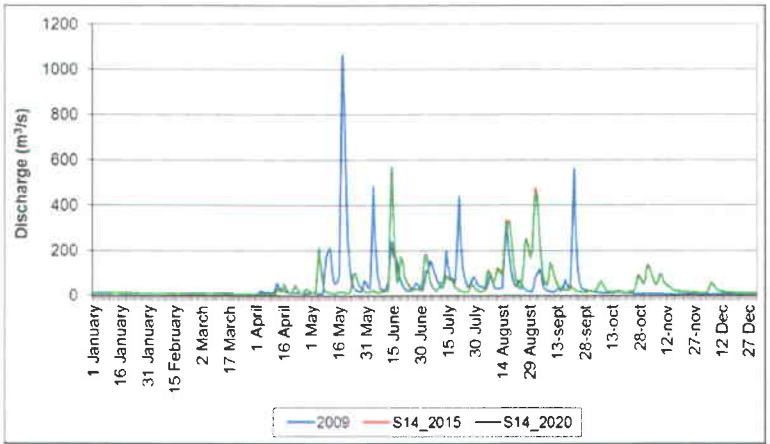
River reach at Thac Buoi station



(*Note*: The red line for S14_2015 is overlaid by the green line for S14_2020 in the figure).

Figure A6.6. Impact of both forest planting and climate change on discharge in the river reach at Thac Buoi station: the changes in discharge between Scenario S14 in 2015, S14 in 2020 and the current state in 2009.

River reach at Gia Bay station

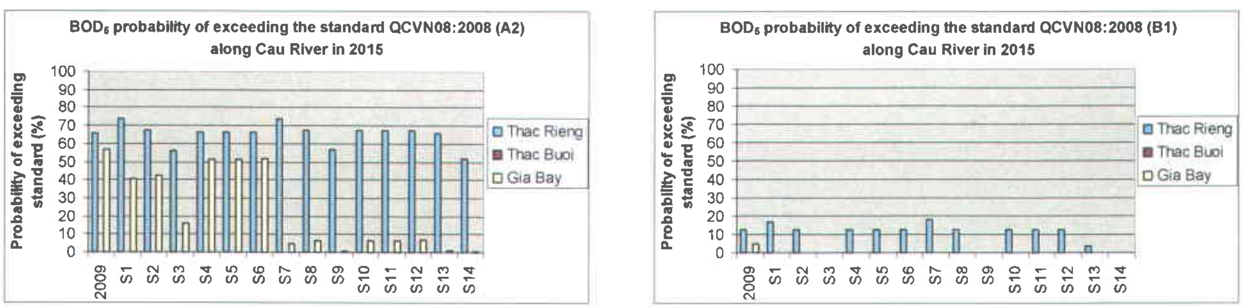


(*Note*: The red line for S14_2015 is overlaid by the green line for S14_2020 in the figure).

Figure A6.7 Impact of both forest planting and climate change on discharge in the river reach at Gia Bay station: the changes in discharge between Scenario S14 in 2015, S14 in 2020 and the current state in 2009.

4- Probabilities of exceeding standard in the 3 river reaches along Cau River from upstream to downstream

1. BOD_5 in 2015

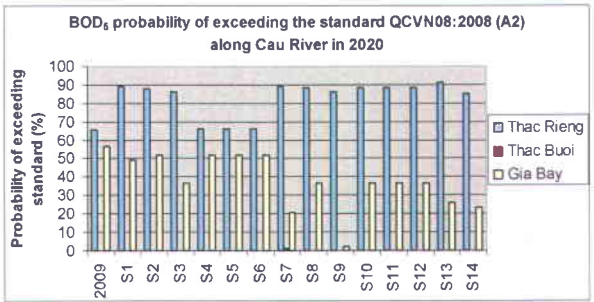


a. QCVN08:2008/BTNMT - Column A2 for the purpose of water supply with treatment application

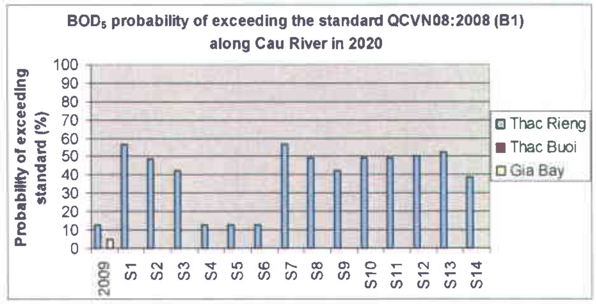
b. QCVN08:2008/BTNMT - Column B1 for the purpose of irrigation and other purposes

Figure A6.8: Probabilities of exceeding standard for BOD_5 in 2015 in 3 river reaches from upstream to downstream along Cau river.

2. BOD_5 in 2020



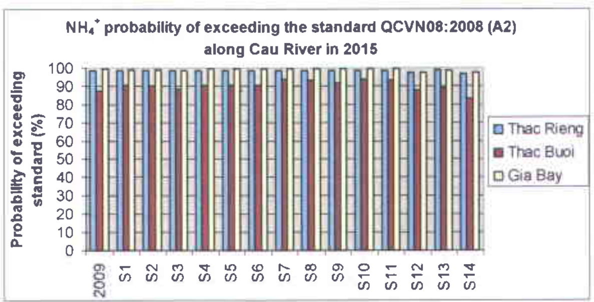
a. QCVN08:2008/BTNMT - Column A2 for the purpose of water supply with treatment application



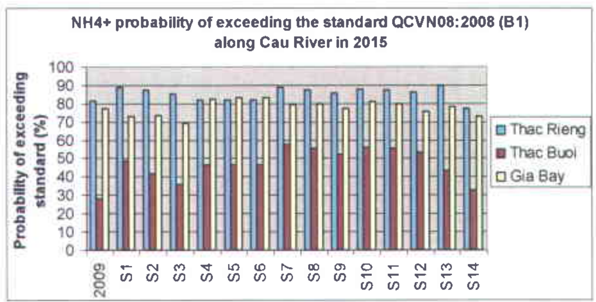
b. QCVN08:2008/BTNMT - Column B1 for the purpose of irrigation and other purposes

Figure A6.9: Probabilities of exceeding standard for BOD_5 in 2020 in 3 river reaches from upstream to downstream along Cau river.

3. NH_4^+ in 2015



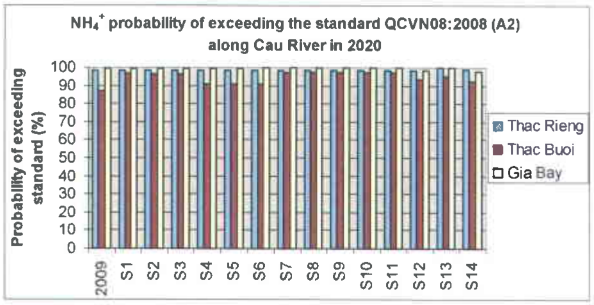
a. QCVN08:2008/BTNMT - Column A2 for the purpose of water supply with treatment application



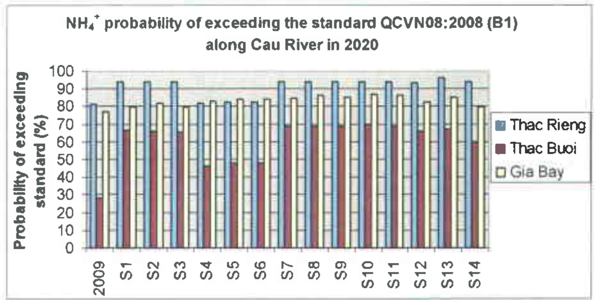
b. QCVN08:2008/BTNMT - Column B1 for the purpose of irrigation and other purposes

Figure A6.10: Probabilities of exceeding standard for NH_4^+ in 2015 in 3 river reaches from upstream to downstream along Cau river.

4. NH4+ in 2020



a. QCVN08:2008/BTNMT - Column A2 for the purpose of water supply with treatment application



b. QCVN08:2008/BTNMT - Column B1 for the purpose of irrigation and other purposes

Figure A6.11: Probabilities of exceeding standard for NH_4^+ in 2020 in 3 river reaches from upstream to downstream along Cau river.

APPENDIX 2: QUESTIONNAIRE OF DEVELOPMENT SCENARIOS FOR CAU RIVER BASIN IN BAC KAN PROVINCE

(For the workshop to take the ideas of stakeholders)

Questionnaire of development scenarios for Bac Kan province:

(1) Do you correct or supplement the information for 7 factors in the part of system analyses?

- Population:
- Domestic wastewater:
- Industry:
- Livestock:
- Agricultural land use:
- Forest:
- Climate change:

(2) Ideas about the parameters indicated in the matrix of combination of factors:

- Do you think the parameters of each factor given in the matrix are reasonable? (Yes/ No):
- If No, please give your ideas:
- Which parameters have high capacity of happening in the future (please arrange in priority order for the parameters of each factor in the following tables, there are 3 levels: **high** priority, **average** priority, and **low** priority):

+ *For population:*

Factor	Priority	Comments
Min		
Average		
Max		

+ *For domestic wastewater:*

Parameters	Priority	Comments
Treatment system for 10.000 people in Bac Kan town.		
Treatment system for 20.000 people in Bac Kan town.		
Treatment system for 30.000 people in Bac Kan town.		

+ *For industry:*

Parameters	Priority	Comments
Keep the discharges of current factories and take Thanh Binh industrial zone into account.		
Increase 10% of water discharges from current factories and take Thanh Binh industrial zone into account.		
Increase 20% of water discharges from current factories and take Thanh Binh industrial zone into account.		

- Do you have any idea else for these parameters?

(3). Ideas about scenarios:

- Do you think the way to create scenarios is reasonable? (Yes/ No):
- If No, please give your ideas:

- Please arrange in priority order for 14 scenarios in the following table (there are 3 levels: **high** priority, **average** priority, and **low** priority):

Scenarios	Priority	Comments
S_1		
S_2		
S_3		
S_4		
S_5		
S_6		
S_7		
S_8		
S_9		
S_{10}		
S_{11}		
S_{12}		
S_{13}		
S_{14}		

- Do you have any idea else for these scenarios?

APPENDIX 3: QUESTIONNAIRE OF DEVELOPMENT SCENARIOS FOR CAU RIVER BASIN IN THAI NGUYEN PROVINCE

Questionnaire of development scenarios for Thai Nguyen province:

(1). Do you correct or supplement the information for 7 factors in the part of system analyses?

- Population:
- Domestic wastewater:
- Industry:
- Livestock:
- Agricultural land use:
- Forest:
- Climate change:

(2). Ideas about the parameters indicated in the matrix of combination of factors:

- Do you think the parameters of each factor given in the matrix are reasonable? (Yes/ No):
- If No, please give your ideas:
- Which parameters have high capacity of happening in the future (please arrange in priority order for the parameters of each factor in the following tables, there are 3 levels: **high** priority, **average** priority, and **low** priority):

+ *For population:*

Parameters	Priority	Comments
Min		
Average		
Max		

+ *For domestic wastewater:*

Parameters	Priority	Comments
Treatment system for 100.000 people in Thai Nguyen City		
Treatment system for 100.000 people in Thai Nguyen City, and installation of a treatment system for 10.000 people in Song Cong town		
Increase the capacity into 150.000 people for the treatment system in Thai Nguyen City		

+ *For industry:*

Parameters	Priority	Comments
Keep the discharges of current factories and take 13 new industrial zones into account.		
Increase 10% of water discharges from current factories and take 13 new industrial zones into account.		
Increase 20% of water discharges from current factories and take 13 new industrial zones into account.		

- Do you have any idea else for these parameters?

(3). Ideas about scenarios (reference to the scenarios for Thai Nguyen in Appendix 2, page PL-10)***:***

- Do you think the way to create scenarios is reasonable? (Yes/ No):
- If No, please give your ideas:
- Please arrange in priority order for 14 scenarios in the following table (there are 3 levels: **high** priority, **average** priority, and **low** priority):

Scenarios	**Priority**	**Comments**
S_1		
S_2		
S_3		
S_4		
S_5		
S_6		
S_7		
S_8		
S_9		
S_{10}		
S_{11}		
S_{12}		
S_{13}		
S_{14}		

- Do you have any idea else for these scenarios?

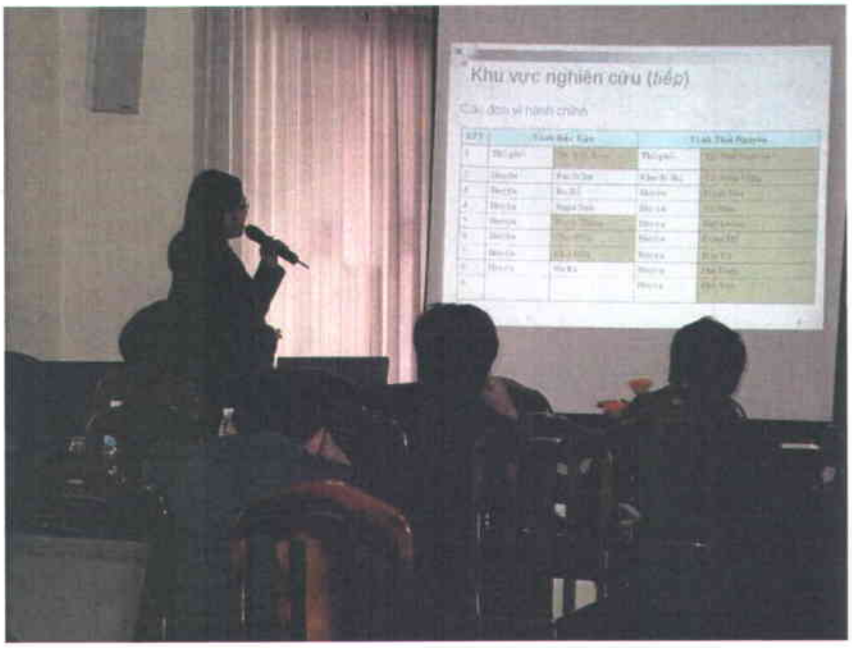
APPENDIX 4: PICTURES OF THE WORKSHOP TO TAKE THE IDEAS FROM STAKEHOLDERS

Workshop openning

Workshop participants

Workshop participants

Presentation of Mr. Nomessi Kokutse (INRS) on the integrated management of Cau river watershed with a computer system



Presentation of Ms. Pham Thi Thu Ha (PhD. student in INRS - the author of this thesis report) on the development scenarios for Cau River basin in Bac Kan and Thai Nguyen provinces based on GIBSI model of decision-making support

Presentation of Ms. Tran Thi Huong (Vice Director, Thai Nguyen Sub-Department of Environment Protection) on the current state and future action plan of environmental management for Cau River basin in Thai Nguyen province

Participants contributed their ideas in the workshop

Participants contributed with their ideas

APPENDIX 5: PROJECTED AND OBSERVED TOTAL ANNUAL RUNOFF IN 2009

Climate change (CC) was taken into consideration as one of the factors based on variations of temperature ΔT and rainfall ΔP in the future (baseline: 1980-1999; Projection period: 2000-2019). For hydrological simulations in the future, daily rainfall and temperature values were calculated for the period 2010-2019 based on the general expressions: $T_{future} = T_{ref} + \Delta T$ and $P_{future} = P_{ref} + \Delta P$; Where: T_{future} is the temperature for a day in the future, T_{ref} is the temperature for a day in the reference year, ΔT is the corresponding increase of the temperature, P_{future} is the rainfall in the future for a day in future, ΔP is the corresponding increase of the rainfall. 1999 (the last year of the period of baseline) was considered as the reference year and projected values of *T* and *P* were calculated for the period 2000-2019.

Observed data used for hydrological model calibration covered the period 1998-2009. The last year of this period (2009) was considered as the reference for scenario building and analysis. Uncertainties in climate change projections may conduct to a difference between the total run off simulated with observed *T* and *P* in 2009 and total run off simulated with projected *T* and *P* in 2009. Results of the values of total monthly run off simulated are summarized in the following table:

Month	Run off with projected values of T and P (m3)	Run off with observed values of T and P (m3)
January	5.20E+07	4.91E+07
February	3.24E+07	3.02E+07
March	2.88E+07	2.96E+07
April	5.63E+07	5.32E+07
May	1.15E+08	5.16E+08
June	2.31E+08	2.99E+08
July	1.64E+08	3.13E+08
August	4.03E+08	1.64E+08
September	2.31E+08	2.58E+08
October	9.47E+07	4.19E+07
November	1.21E+08	2.23E+07
December	5.26E+07	1.69E+07
Total	1.58E+09	1.79E+09

The relative difference between both values of total annual run off with regard to the observed values is found to be around 12%, which may conduct to underestimation of the observed total run off in 2009.

APPENDIX 6: SIMULATION RESULTS IN CONG RIVER

River reach at the supply water treatment plant in Song Cong town

(1) Discharge

In this river reach at the supply water treatment plant in Cong River, concerning the impact of forest planting (scenario S12), there is nearly no change for discharge. Discharge resulting from the impact of climate change (scenario S13) pointed out negligible variations in the future compared with the current state. The combination of the two factors in scenario 14 have minor effects on the discharge.

(2) BOD_5, NH_4^+, and SS

Generally, water quality in Cong River is better than in Cau river. Especially, water quality in this river reach at supply water treatment plant is the best among five selected river reaches in Cau river basin because this river reach is less impacted by the future social-economic activities than other river reaches.

The simulation results of BOD_5 and NH_4^+ showed that only industry has the impact on water quality in this river reach. BOD_5 and NH_4^+ concentrations trend to increase in the future compared with the current state, but the increase can be considered as minor. The reason of this little increase is because there are six new future industrial zones linked to Cong River system, but only one industrial zone is located in the upstream of this river reach.

Beside the impact of industry, climate change also has a little effect on NH_4^+ and SS concentrations. Some high values of NH_4^+ and SS concentrations are found to diminish in scenarios S13 and S14 in both future years compared with the current situation.

River reach at Da Phuc Bridge

(1) Discharge

In this river reach at Da Phuc Bridge station in Cong River, concerning the impact of forest planting (scenario S12), discharge also has nearly no change. Discharge resulting from the impact of climate change (scenario S13) in 2015 and 2020 at this river reach also has found to decrease a little compared with the current state.

(2) BOD_5, NH_4^+, and SS

This river reach at Da Phuc Bridge station locates in the downstream of Cong River. So it will be affected by all of six new future industrial zones located in Cong River system (Phu Lac 2, Song Cong 1, Song Cong 2, Van Thuong, Tay Pho Yen, Nam Pho Yen). The simulation results show that BOD_5 and NH_4^+ concentrations impacted by industry in the future increase compared with the current state.

The water quality in this river reach is also affeted by the installation of a domestic wastewater treatment plant in Song Cong town. It was found that BOD_5 concentration in scenario S2 in 2015 and 2020 decreases compared with the current state. That means the installation of a domestic wastewater treatment plant in Song Cong town has a positive effect on water quality in this river reach. Like the river reach at Supply water treatment plant, climate change also has no effect on NH_4^+ and SS concentrations.

The other factors such as livestock, fertilizer, forest planting have negligible impacts on water quality in this river reach. This may be because the increases of number of livestock and fertilizer quantity according to the assumptions and local development projections for the future may not have enough impact to make a significant increase on BOD_5 and NH_4^+ concentrations; or may be due to most of the feces of livestock which are put down into the nearby fields are used by plants, so that the excess of nitrogen and phosphorus going to the environment is not much. Forest planting which can reduce erosion and runoff has negligible impacts on water quality in this river reach in particular and in Cong River in general probably because only a part of Cong River from Nui Coc Lake to the confluence of Cong and Cau Rivers is taken into consideration in this research, but the projected forest is planted in three districts of Thai Nguyen province: Dai Tu, Dinh Hoa, Vo Nhai where forest planting may not have effect on this part of Cong River.