Data and water balance estimation approaches for an agriculturally developing ungauged catchment: towards improved groundwater management

by

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Declaration

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Co-authorship

I, Hai M. Vu, am the first author of all manuscript in this thesis. All the other co-authors provided their intellectual authorship.

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Summary

Groundwater is of fundamental importance as a fresh water resource for drinking water supply and irrigation. Groundwater is spatially and temporally variable and is in a dynamic (dis-)equilibrium with recharge, evapotranspiration, base-flow and abstractions for anthropogenic use. A number of factors, including natural variability and human activities, influence these flow components. Therefore, information and knowledge about these components is crucial for informing the sustainable use and development of groundwater resources, especially for agricultural catchments in developing countries. In many of these countries, groundwater demand is high, while technical and management expertise is lacking. Failure to appropriately manage groundwater resources based on data and scientifically tested methods often leads to groundwater depletion, pollution and ecological degradation of groundwater-dependent ecosystems.

This study aims to develop methods for understanding the groundwater budget in relation to its controlling factors in the context of a tropical agricultural headwater basin in the developing conditions of Vietnam. The methods developed for estimating the groundwater budget have to be commensurate with the ungauged conditions of this basin. Specifically, this study aims to (1) estimate the influence of the strong seasonal tropical climate and anthropogenic groundwater abstraction on the fluctuations of groundwater base-flow to streams; (2) develop a multi-method approach for estimation of groundwater abstraction for ungauged catchments; and (3) examine the response of the groundwater system to different scenarios of agricultural development, in which both crop patterns and groundwater demand and extraction vary.

The used methods and data consist of analysis tools, simulation models, literature (databases), as well as for this thesis field collected data. The data have been used to build a number of simulation models, more specifically a 2D cross-sectional unsaturated-saturated zone model, a spatially distributed monthly water balance model and a 3D saturated zone groundwater flow model.

The main results are:

1. 2D cross-sectional models have been developed for simulating the exchange fluxes between groundwater and surface water at three transects located upstream, midstream and downstream in the catchment. Variations of precipitation and anthropogenic groundwater abstraction were reflected by the changes in both groundwater and in-channel water levels as inputs for the models. Simulated fluxes

varied both spatially and temporally: in addition to increasing from upstream to downstream, fluxes are high during the rainy season and decrease in the dry season. Groundwater discharges to streams most of the time, with exceptional losing conditions during intensive rainfall. The results indicate the strong influence of the seasonal pattern on precipitation for base-flow generation to the river, while groundwater abstractions have a smaller influence on the base-flow.

2. For an ungauged catchment, two approaches were developed for indirect quantification of groundwater abstraction based on 'soft data' from local knowledge and satellite-based land use data. In the first approach, the catchment's average groundwater abstraction was estimated based on a qualitative field survey of groundwater level fluctuations, supplemented with information from the base-flow estimation of Chapter 2 and geographical and hydrogeological data for the catchment. In the second approach, distributed groundwater abstraction for the whole catchment was mapped based on land use data combined with local knowledge on cropping and irrigation practices, obtained by field surveys. The uncertainties associated with each approach were discussed and recommendations were made for low-cost management options to reduce possible uncertainties when estimating groundwater abstractions. The advantages and simplicity of these approaches make them attractive for application in other ungauged catchments.
3. For understanding the influences of land use change and climatic variability on catchment groundwater budgets, 12 potential land use scenarios were developed from the base scenario of current (2016) land use of the agriculturally dominant La Vi catchment. Three climatic conditions (i.e., dry, average and wet) were categorised from a 30-year time series of annual precipitation. A multi-model approach was used for testing 18 combinations of climate and land use conditions, comprising three climatic conditions and six land use scenarios (selected from those developed), including base scenarios. The WetSpass-M model was used for simulating spatial recharge and the MODFLOW 3D finite-difference groundwater flow model was employed for simulating a groundwater flow system, with recharge data taken from the WetSpass-M output. Results from the models showed significant modifications, ranging from a 39% reduction to up to a 44% increase in the groundwater storage during the eight-month dry period for the selected land use scenarios. Seasonal climatic variation also causes a significant change in groundwater storage and base-flow to streams during the four-month

wet season. Specifically, groundwater storage varies between -44% and a 45%, while base-flow to streams varies between -71% and 192%. The results show that 15 of the 18 developed scenarios have to be classified as overexploited, as their groundwater abstraction ratio (i.e., proportion of abstraction to recharge) is higher than a sustainable ratio of groundwater abstraction of 0.35.

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Chapter 1. Introduction

1.1 Problem statement

Groundwater accounts for approximately one-third of worldwide freshwater consumption, with more than two-fifths of that used for agriculture (Taylor *et al.*, 2013). Groundwater resources are spatially and temporal variable, and form a continuum with surface water and atmospheric water in a dynamic equilibrium as a part of the global water cycle. This is referred to as the groundwater balance or groundwater budget (Theis, 1940; Bredehoeft *et al.*, 1982). For shallow unconfined aquifers, the components of the groundwater budget include recharge (from precipitation) as a source; evapotranspiration and base-flow to springs/streams as a sink; and changes in storage as the difference between inflow and outflows (Wittenberg & Sivapalan, 1999). If rivers are losing, groundwater is recharged by surface water infiltration. If groundwater abstractions occur, discharge to the wells derives from either increasing the inflow, decreasing the outflows, changes in groundwater storages or a combination of these until a new balanced condition is achieved (Theis, 1940; Brown, 1963).

As groundwater is in a dynamic (dis-)equilibrium with its sinks and sources, a full understanding of the groundwater balance is therefore required for effective management (Wittenberg & Sivapalan, 1999). Depletion in groundwater resources caused by mismanagement leads to many problems, including food scarcity (Brown, 2007). Sustainable groundwater development (i.e., determination of the sustainable yield for a specific region) depends for a great deal on being able to estimate the relation between the components of the groundwater budget (i.e., recharges and discharges) (Kinzelbach *et al.*, 2003; Vrba *et al.*, 2007; Henriksen *et al.*, 2008). Weiskel *et al.* (2007) stated that sustainable use of water resources by humans has been a growing concern in recent years. There has also been ongoing debate among scientists about how to determine sustainable yield of groundwater abstractions in relation to the components of the groundwater balance. As summarised in Bredehoeft *et al.* (1982), it is often believed that the virgin equilibrium of an aquifer will be maintained sustainably if the total groundwater development (i.e., the yield of the productive wells) does not exceed the magnitude of groundwater recharge. However, Bredehoeft *et al.* (1982) argued that this is ‘a most common misconception’, as groundwater development is not decided by the recharge but is limited by the ‘capture’, which is the amount of change in the virgin recharge and discharge in response to groundwater pumping. Sustainable pumping is generally dependent on the capacity of the aquifer, and hence aquifer parameters, to capture the natural discharge, in terms of time and magnitude (Bredehoeft *et al.*, 1982).

In the last decades, numerous problems have been caused by unsustainable groundwater use as a result of unplanned development. In the case that water managers implement groundwater development, they often do not have a proper understanding of the groundwater balance (Weiskel *et al.*, 2007; Giordano, 2009). Many parts of the world have been experiencing strong reductions in groundwater levels, which negatively effects groundwater-dependent ecosystems, including a reduction in base-flow to rivers, drying up of wetlands, seawater intrusion in coastal aquifers and land subsidence. Over-exploitation also brings a higher risk of contamination to groundwater (Giordano, 2009). Many of these groundwater-related problems, especially over-exploitation of aquifers and consequent depletion of groundwater levels, have been reported to be associated with the failures of water managers, due to their poor understanding of groundwater budgets (Kinzelbach *et al.*, 2003; Aeschbach-Hertig & Gleeson, 2012).

Groundwater budgets and the associated processes of recharge, evapotranspiration, base-flow as well as groundwater abstractions are influenced by natural hydro(geo)logical conditions and human activities. Healy (2010) addressed that variation in groundwater recharge is mainly a consequence of differences in precipitation regimes, and to a lesser extent is determined by geology, topography and land cover. Spatial variability in soils, surface topography and vegetation influence the processes of both infiltration and surface runoff. As described in Allen *et al.* (1998), climate and land use conditions are the main factors controlling the process of evapotranspiration. The climate parameters of temperature, humidity, radiation and wind speed influence evaporation, while crop parameters of stomatal resistance, height, roughness, reflection, ground cover (leaf area index) and root characteristics are additional factors determining transpiration. Another component of the groundwater budget is subsurface flow, which is determined by the complex relation between groundwater and connected surface water bodies (e.g., rivers and lakes) and highly dependent on subsurface conditions and topography (Wong, 2012).

Along with the natural factors, land use and anthropogenic abstraction practices are the main factors associated with human activities influencing groundwater dynamics. Change in land use has been recognised as one of the growing problems of the last decades, with implications for different components of water balance at different scales (DeFries &

Eshleman, 2004). Recent studies have shown the consequences of land use change on both groundwater and surface water resources due to modification of flow components such as infiltration, evapotranspiration, base-flow and in-channel flow (Siriwardena *et al.*, 2006; Li *et al.*, 2007; Li *et al.*, 2009; Wijesekara *et al.*, 2012; Kalantari *et al.*, 2014; Gashaw *et al.*, 2018). The effects of land use change are connected with both surface and subsurface water resources, but it takes much longer for groundwater systems to recover compared to surface water systems (Cuthbert *et al.*, 2019). Moreover, in addition to modifying water resources directly (e.g., by recharge) land use change also has an indirect impact by altering the demand for or abstraction of water resources (for irrigation) (Mehta *et al.*, 2013). However, a review of the literature showed very little attention to the problems associated with water extraction (Döll *et al.*, 2012). This shows the need for more research on the combined influence on groundwater resources of land use change, via modified flow components (i.e., recharge and subsurface runoff) and altered water abstraction practices, for water management in a changing environment (Zomlot *et al.*, 2015).

As many of these problems of unstainable use of groundwater are related to recent expansion in agriculture and land use change (Giordano, 2009), they seem to be intensified in developing countries. In such countries, expansion in agriculture is mainly a result of the need to meet high demand for food and improve the living standards of a strongly growing population (DeFries & Eshleman, 2004). For example, about one-quarter of food crop production in India is at risk due to inadequate groundwater management (Seckler *et al.*, 1999); one-half of the wheat production in North China is threatened due to degradation of aquifers as simultaneously estimated by Brown and Halweil (1998) and Foster and Chilton (2003); and about 10% of China's food production will face problems when groundwater in the Hai River basin is depleted (Brown, 2007). Southeast Asia, including Vietnam, has recently been experiencing a rapid expansion of agricultural land (Barbier, 2004), which could bring problems associated with water resources in general and groundwater resources in particular.

Data paucity is an additional challenge typically faced in developing countries due to the high costs for setting up and maintaining infrastructure for data collection. Groundwater resource components, such as groundwater recharge and abstraction, are often ungauged, as they are difficult to measure or estimate accurately (Siebert *et al.*, 2010). The data paucity issue strongly limits water managers from understanding groundwater systems.

The use of ‘soft data’ has been considered as an alternative to compensate for data paucity. In particular, remote sensing and model approaches (Cheema *et al.*, 2014) and statistical relations based on inventory data (Siebert *et al.*, 2010) have been used to provide soft data (Seibert & McDonnell, 2002), in lieu of direct measurements, to assist in the sustainable management of groundwater resources.

To summarise, knowledge and information about the groundwater budget is needed for sustainable groundwater development. A number of natural and anthropogenic factors influence groundwater budgets. Estimating the budget components requires a variety of methods, which all need appropriate data. Failure to provide this data has resulted in poor management of groundwater development practices. Providing this data and the associated knowledge gap should no longer be overlooked in planning groundwater developments. This is particularly important for agricultural areas, with their high demand for groundwater for irrigation, especially in developing countries, for which the required data is often lacking. To address this issue, methods for obtaining alternative data are required, as are approaches for estimating components of the groundwater budget that are appropriate for the data that is available. These methods and approaches should have high value for areas in which groundwater conditions are ungauged.

1.2 Research aims and questions

The main research aim of this study was to develop detailed information and methods for understanding the groundwater budget in relation to its controlling factors under conditions of a strongly seasonal humid tropical climate and a developing agricultural sector. Specifically, the thesis aimed to answer the following questions:

(1) How does the strongly variable seasonal tropical climate influence the components of the groundwater budget?

(2) How do the human practices of groundwater abstraction impact the catchment groundwater resources as a system?

(3) Is it possible to develop agriculture while simultaneously increasing the sustainability of the groundwater resources?

The small headwater catchment of the La Vi River located in south central Vietnam was selected as the study area for illustrating research methods for answering the above-mentioned questions in a specific catchment. The catchment is dominated by agriculture, covering more than 75% of its land use (see Chapter 3 for more details). The survey performed for this study showed that agriculture in this catchment heavily relies on groundwater abstraction for irrigation. The river is intermittent with only limited use for small-scale irrigation in the downstream part of the catchment. The area is developing, and the catchment is fully ungauged without any traditional monitoring systems constructed for both groundwater and surface water.

The first and second question will be dealt with in Chapter 2 (paper 1; for base-flow and how it is influenced by extraction) and Chapter 4 (paper 3; for recharge). The third question will be answered in Chapter 4 (paper 3). Chapter 3 (paper 2) outlines a method for estimating groundwater abstraction for ungauged catchments, which is often the case in developing countries. The outcomes of Chapter 3 (paper 2) serve as inputs for Chapter 4 (paper 3) for answering the second and third questions.

1.3 Contribution of this PhD

To my knowledge, this PhD is the first in the global literature to investigate how the strongly seasonal pattern of a humid tropical climate combined with anthropogenic groundwater abstractions affects the groundwater system by modifying the fluxes between groundwater and surface water to reveal how this determines the intermittent flow regime of the stream. The findings from this examination show that the seasonal pattern of base-flow to streams from groundwater is strongly influenced by the seasonal variation in precipitation in this tropical climate. Local groundwater abstractions by small wells typically located more than 50 m away from the river do not strongly influence the variation in base-flow. The research also shows how a combination of natural processes and human practices can modify the flow components as well as the demand (extraction) of a groundwater system as a whole.

This examination was conducted using a relatively unique combination of models applied to a set of land use change scenarios. The result of this work illustrates how human activities, particularly changing land cover, influence a groundwater system through a combination of modified flow components and changing water demand/groundwater pumping. This understanding will be most helpful for planning and implementing groundwater development in agriculturally developing catchments, where irrigation is the biggest consumer. Moreover, it provides a multiple-approaches method for estimating groundwater abstraction for ungauged catchments, which has high applicability in other parts of the world where no data on groundwater abstractions are available.

Chapter 2. Flux dynamics at the groundwater-surface water interface in a tropical catchment[1]

Abstract

Seasonal shifts between wet and dry seasons cause marked changes in river flow regimes and therefore exchanges with the streambed surface. This seasonal variation is particularly apparent in tropical climates, which are characterized by strong differences between wet and dry seasons. However, fluxes between surface water and groundwater and the impacts of these interactions on streambed dynamics are rarely investigated in tropical climates, where few surface water-groundwater field investigations have been performed. In this study, an intermittent river in south coastal Vietnam was investigated to better understand links between seasonal hydrologic shifts, human use of water resources, and streambed dynamics. Three transects along the main tributary were instrumented with water level and streambed temperature sensors to examine both spatial and temporal variability in stream-aquifer dynamics. Calibrated models estimated increasing streambed fluxes along the length of the river, with highly variable fluxes up to 1.6 $m^2 h^{-1}$ upstream and 0.2 $m^2 h^{-1}$ downstream during the rainy season (i.e., the rate of the total amount of water exchanged per meter of river length) decreasing to low fluxes of 1.0 $m^2 h^{-1}$ upstream and 0.15 $m^2 h^{-1}$ downstream in the dry season before flow ceased. During the wet and into the dry season the river was gaining (i.e., flux from the aquifer into the river) at all times and all locations with the notable exception of fluxes into the streambed only at the upstream and downstream sites during peak flow of the largest captured rain event (550 mm in 164 hours). Based on 30 years of precipitation data, this suggests that water is pushed from the stream into the streambed approximately three times per year. Groundwater withdrawal by households near the cross-sections was found to have a comparatively small effect on streambed fluxes, reducing the flux by up to 3% during dry conditions, although this pumping did cause a reversal in the gradient to the stream for a short period (less than 12 hours) on one occasion during the dry season.

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2.1 Introduction

Intermittent streams constitute more than half of the world's river networks, and some of the most vibrant ecosystems (Larned *et al.*, 2010; Datry *et al.*, 2014). Intermittent streams are inherently variable, with flows typically changing rapidly in response to rain events (Nolte *et al.*, 1997), and can therefore be difficult to adequately characterize. Perennial streams have historically received greater attention than intermittent streams (Boulton & Suter, 1986; Williams, 1988), although recently more attention has been given to the importance of meteorological, geological, and land-cover controls on flows in intermittent streams (Costigan *et al.*, 2016). Notwithstanding this previous research, it is clear that our understanding of the hydrological processes controlling flow permanence and interactions between streamflow and aquifer recharge in intermittent river systems needs further improvement (Costigan *et al.*, 2016).

This knowledge gap is even more significant for tropical regions, where climate patterns are typically highly dynamic with distinct wet and dry seasons which strongly influence both surface flows and groundwater levels (Nolte *et al.*, 1997; Costigan *et al.*, 2016). The lack of information on intermittent stream dynamics is acute in these tropical areas, as rainfall data is missing or does not capture the high spatial variability because many catchments are ungauged, and no long-term hydrological datasets are available (Klemes, 1993). Climate model predictions suggest a future reduction of flow in tropical catchments in response to changes in air temperature and precipitation due to greenhouse gas emissions (Nijssen *et al.*, 2001). Given the importance of these tropical intermittent river systems for surface and groundwater resources as well as for connected ecosystems, a more thorough understanding of these systems is imperative (Abrantes & Sheaves, 2010).

Recently, research on interaction between groundwater and surface water has shifted from large-scale to smaller scale, and an increasing number of modelling studies focus on field or laboratory data to elucidate exchange dynamics and associated biogeochemical processes of groundwater-surface water (GW-SW) interaction (Fleckenstein *et al.*, 2010). For tropical systems, there is limited scientific understanding of GW-SW interaction due to a lack of detailed field studies.

This research aims to study a tropical, intermediate-sized intermittent stream in South Central Vietnam, with the objective of understanding how the flow at the interface between the river and the aquifer spatially and temporally changes as a function of seasonal forcing and human impact by groundwater extraction. Three cross-sections were instrumented to capture groundwater levels and streamflow during precipitation events and during the transition into the dry season. The influences of both local groundwater pumping and precipitation events were modelled to understand flow dynamics within the streambed.

2.2 Study area

The La Vi River is a small tributary of the Kon Ha Thanh River system located in Binh Dinh, a south central coastal province of Vietnam (Figure 2.1). Upstream in the catchment, two small tributaries converge and form the La Vi River, which has a length of about 15 km. The La Vi is an intermittent river, which flows around 8 months per year (typically from September until April). There are no discharge estimates or statistics for the river available as it is ungauged.

The catchment area of the La Vi River comprises approximately 100 km^2. Approximately 35,000 people live within the river basin, primarily in three communes. Roughly 75% of the river basin is covered by agricultural land, of which 30% is irrigated and 40% is rainfed; the remaining land is broadleaved evergreen forest (10%) and shrubland (20%) (Tran, 2016). Field observations show that most of the irrigation in the catchment is from groundwater wells.

The entire river sits within a shallow aquifer of sandy alluvial deposits (Do, 1987). The terrain of the catchment is quite flat with the slope ranging from 0.5% downstream to about 1% upstream; the elevation ranges from 10 m to 50 m (above mean sea level). There is limited climatic and hydrogeological information for this basin available (e.g. Do, 1987; Nguyen, 2005). No previous studies have investigated the GW-SW interaction in this area.

Climate in the La Vi River catchment belongs to the Wet-Dry Tropical climatic subtype (Chang & Lau, 1993) with the wet seasons lasting for approximately 4 months from September to December and during which precipitation is higher than evapotranspiration. January to August is typically considered the dry season, with higher temperatures and inconsistent, low rainfall. Climate data from An Nhon and Phu Cat station for 1977-2007 shows that the annual precipitation ranges between 1,300 and 2,600 mm with nearly 75% of this falling during the wet season (data obtained from Centre for Meteorology and Hydrology of South-Central Region of Vietnam). Average yearly evapotranspiration is between 1,200 and 1,400 mm/year. To measure how strongly the precipitation and temperature varies seasonally, the seasonality index (Dingman, 2015) can be used. The index is approximately 0.6 and 0.7 for precipitation and temperature, respectively, indicating a significant shift between wet and dry seasons. Recently, a project funded by the Australian Centre for International Agricultural Research (ACIAR) has established two weather and stream gauging stations that have been collecting river stage and meteorological data since 10 November, 2015.

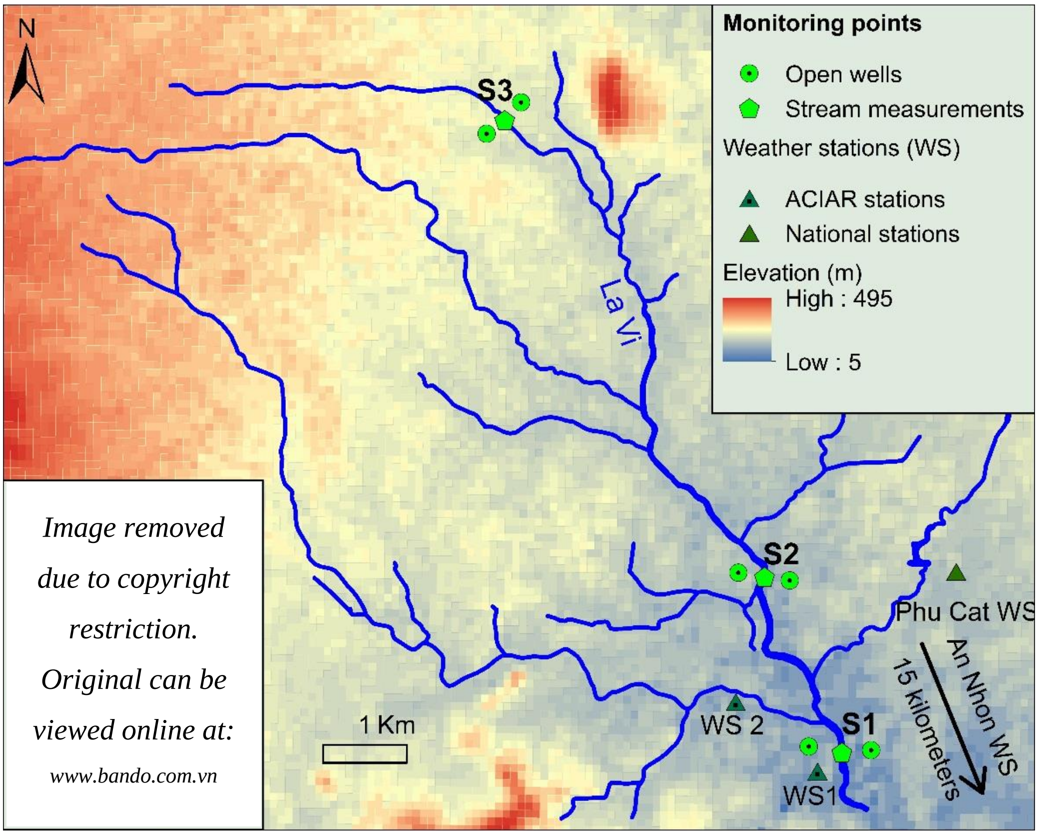

Figure 2.1: Map of the La Vi River Basin in Binh Dinh Province, Vietnam. The inset shows a map of Vietnam with the Binh Dinh Province shaded and the location of the La Vi Basin marked with an orange dot (Source: Vietnam Publishing House of Natural Resources, Environment and Cartography). The three study sites (S1, S2, and S3) with well and stream water level locations as well as weather stations are indicated.

2.3 Methods

2.3.1 Field and laboratory methods

Three cross-sections were selected to investigate hydrological conditions along the upstream, midstream, and downstream sections of the La Vi River (labelled S3, S2, and S1, respectively; Figure 2.1). Each cross-section was instrumented with one or two 0.016 m solid polyvinyl chloride (PVC) rods containing five iButton© temperature sensors (accuracy ±0.5°C, precision ±0.0625°C, Maxim Integrated, San Jose, USA) at depths of

0, 0.15, 0.3, 0.6 and 0.9 m below the streambed surface to measure the temperature at 20-minute intervals. The iButtons© were accurately installed to the desired depths beneath the river bed by insertion of the PVC rod into a hollow metal pipe, which was then gently pushed into the river bed. A metal tip was temporally connected to the metal pipe during insertion of the rods; the metal pipe was then removed, and the rods were left in the river bed. These PVC rods were oriented perpendicular to the interface between river bed and surface water. Re-insertion was necessary approximately every two months due to logger memory limits. Due to sensor failure at the beginning of the study period, temperature data at each cross-section was collected from the end of December 2015 until the end of March 2016 from one rod in each transect.

Both surface water level at the river and groundwater levels on each side of the river were measured using Aqua TROLL water level loggers (In-Situ Inc, Fort Collins, USA; 1 mm accuracy). A 0.05 m diameter PVC pipe was vertically installed into the river in each transect, with 0.5 m screen near the bottom of the pipe. The loggers were put into the PVC pipe at the level of the river bed. Pressures were compensated using barometric measurements collected nearby (Baro TROLL, In-Situ Inc, Fort Collins, USA). Additional loggers were placed in existing open wells located as close to the cross-section as possible (typically 200 m from each stream bank) to capture groundwater temperature and level. The diameter of these open wells is 0.8-1.0 m with depths of 4.0-6.0 m. These wells are permeable along their full depth and were observed to react to groundwater changes at the same speed as 0.06 m diameter piezometers later drilled nearby. Further, the sandy aquifer has a calculated hydraulic conductivity on the order of 10^{-5} m s^{-1}. Therefore, the water level measured in these larger open wells is considered to accurately represent the groundwater conditions of the aquifer. All pressure transducers collected data at 20-minute intervals, for the period from the middle of rainy season (November 2015) to the middle of March 2016, when the river ceased to flow in the dry season. The relative elevations of the wells and surface water station at each site were surveyed to relate the water level in the wells to the streambed cross-sections.

Undisturbed soil samples representative of all four soil types of the area were collected in December 2015 to determine soil hydraulic conductivities. Shallow wells drilled near study sites showed relatively homogeneous soil profiles with depth (sandy throughout), but there has been little soil characterization in this area. Therefore, shallow samples were collected to give initial estimates from which to begin model calibration. The locations of the soil samples were selected based on the soil map produced by National Institute of Agricultural Planning and Projection of Vietnam (NIAPP) in 2006 (NIAPP, 2006). All sampling sites were in agricultural fields, which represent 70% of catchment land use. Samples were collected using an auger setup that pushed a 0.05 m diameter; 0.05 m deep metal collection cylinder into the soil at a depth of 0.20 m, and the cylinder was capped and analysed in the laboratory. Hydraulic conductivities were calculated for each sample from constant head experiments (Baker, 2001). The samples were first saturated with fresh water, then a constant head of 0.05 m of water was maintained until steady-state outflow was measured. The grain size distributions of the soils were also determined in order to estimate the hydraulic conductivities (Cronican & Gribb, 2004), using Zunker's empirical equation (SizePerm, EasySolve Software LLC, Tehachapi, USA). All available meteorological data was collected to analyze seasonal change, including: rainfall data from Phu Cat station; evaporation, humidity, atmospheric pressure, and temperature from An Nhon station (Central Regional Hydro-meteorological Center); and precipitation from the two ACIAR stations.

2.3.2 Modelling methods

A two-dimensional (2D), variably saturated model was built for each of the three cross-sections using VS2DH (Lappala *et al.*, 1987; Healy & Ronan, 1996) based on surveyed data. VS2DH uses the finite-difference method to simulate variably-saturated water flow and energy transport. The domains of the models were drawn based on streambed surveys, with the lateral limits of the models determined by the locations of open wells monitored for groundwater level and temperature (Figure 2.2). The downstream and middle reach cross-sectional models were 15 m deep, while the model for the upstream cross-section was 10 m deep. These depths were determined to be the approximate interface between alluvium sandy soil and the bed rock based on data from wells drilled nearby (Do, 1987). Water levels in the open wells from November 2015 - March 2016 and stream gauging station data were used for assigning variable total head boundary conditions at both sides of the model domain and along the river water level segments (Figure 2.2). The parts of the river banks above the highest observed water level were treated as possible seepage faces. No flow boundary conditions were assigned to the bottom edge of the model domain and the surfaces of the model adjacent to the river, because evapotranspiration recorded at the meteorological stations was very low at this time of the year and the contribution of direct infiltration in the surrounding catchment was captured by measured changes in the groundwater level. Soil hydraulic parameters were taken from the column experiment (Baker, 2001) and particle-size analyses on soil samples (Cronican & Gribb, 2004). Soil thermal properties were obtained from the literature (Naranjo *et al.*, 2012).

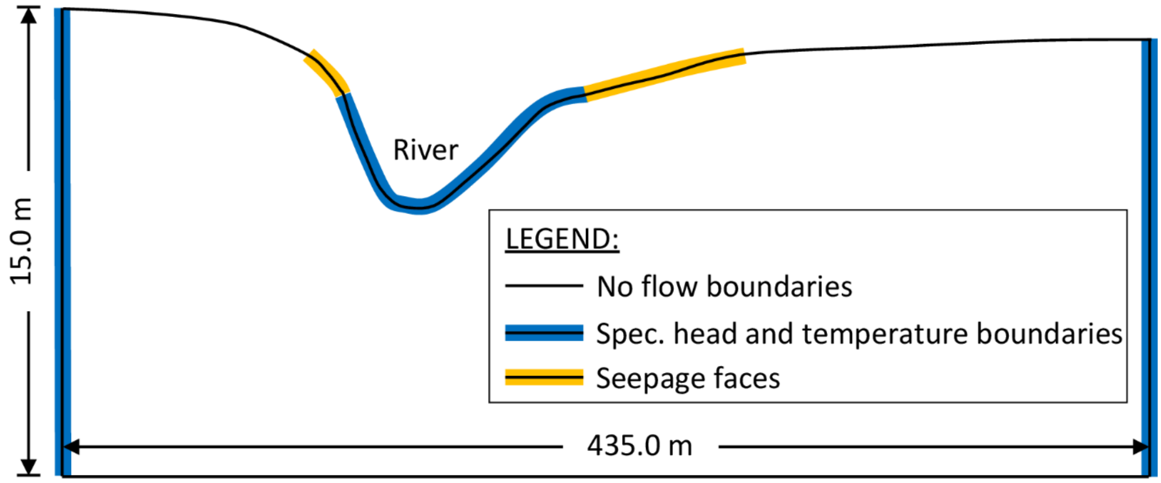

Figure 2.2: Model setup for the downstream cross-section (S1). Boundary conditions for the other cross-sections were the same, but the shape of the cross-section was slightly different (based on the survey data).

The three models were calibrated manually by adjusting the hydraulic conductivity values until a minimum error between simulated and observed streambed temperatures was obtained. The base-flow period at the beginning of dry season was selected for the model calibration because during this time there was no recharge from precipitation and only a gradual water level decline in the groundwater and river levels. Therefore, the flow and energy transport were mainly influenced by the hydraulic conductivities during this period. First, the model was run with constant head values for 10 days to achieve steady-state for the initial conditions. Ten days of observed temperature at 20-minute time steps were then used for calibration, from the end of December 2015 until 10 January 2016.

Because the porous medium of each cross-section was assumed to be homogeneous, only the hydraulic conductivity was calibrated at each site. Thermal conductivity was not varied, since model results have been shown to be less sensitive to this parameter, and its range is much smaller than that of hydraulic conductivity (Healy & Essaid, 2012). Therefore, thermal conductivity and other parameters, including the transport properties, remained unchanged in the calibration. The boundary condition was also fixed. The calibrated values for the hydraulic conductivity and other soil parameters for all three sites are presented in Table 2.1.

Table 2.1. Model input parameters. Hydraulic conductivity values were calibrated for each model, while default VS2DH values for 'fine sand' were used for specific storage and water retention parameters based on observed field conditions. Thermal parameters were taken from Naranjo *et al.* (2012).

Parameters	**Unit**	**Initial values**	**Site**		
			S1 (Downstream)	**S2** (Midstream)	**S3** (Upstream)
Flow parameters					
Hydraulic conductivity (K_{hh})	m s^{-1}	2 10^{-5}	1 10^{-3}	2 10^{-4}	2 10^{-4}
Anisotropy (K_{hh}/K_{zz})	-	1.0	1.0	1.0	1.0
Specific storage (S_s)	-	1 10^{-4}	1 10^{-4}	1 10^{-4}	1 10^{-4}
Water retention parameters					
Porosity (n)	-	0.377	0.377	0.377	0.377
Residual moisture content (RMC)	-	0.072	0.072	0.072	0.072
van Genuchten α	m^{-1}	1.04	1.04	1.04	1.04
van Genuchten β	-	6.9	6.9	6.9	6.9
Thermal parameters					
Long. disp. (αL)	m	0.5	0.5	0.5	0.5
Trans. Disp. (βL)	m	0.1	0.1	0.1	0.1
Heat capacity - dry (Cs)	J m^{-3} ^{0}C	2.5 10^6	2.5 10^6	2.5 10^6	2.5 10^6
Thermal conductivity	W m^{-1} ^{0}C	1.0	1.0	1.0	1.0
Heat capacity – water (C_W)	J m^{-3} ^{0}C	4.5 10^6	4.5 10^6	4.5 10^6	4.5 10^6

The calibrated hydraulic conductivities were then used to do a forward run of the model to calculate exchanges between the groundwater and the stream for the whole period, from the middle of the rainy season (November) to the time that water in the river ceased to flow (mid- March) under two different scenarios. This modelling was done with two goals; to understand groundwater-surface water exchanges during dynamic streamflow events and to understand the effects of local groundwater pumping on groundwater fluxes to the river. Therefore, the first model ignored the measured influences of pumping on the groundwater levels by manually filtering the data to include only the long-term trends and changes due to precipitation events. In this data set, spikes and drops greater than 0.2 m (within a 20-minute interval) were removed as they were considered to be caused by groundwater pumping. The second model used measured data for the whole time series. This data was subjected to a 12-hour moving average filter to remove sudden, extreme shifts in levels, but still maintain the daily observed groundwater depletion and recovery due to pumping. In order to ensure that the trends of water fluctuation were accurately simulated, while avoiding convergence issues caused by steep and sudden jumps in water levels (i.e., due to pumping at the observation well), the time steps of all forward models were set to 1 hour during the wet period and 12 hours during the base-flow period. The validity of this model for capturing measured dynamics was tested using unfiltered, measured data from the downstream cross-section (S1) for comparison to the filtered model result of this site.

2.4 Results

Four precipitation events, with up 20 mm of rainfall per hour (8 to 560 mm cumulative precipitation over the event) were captured. Both groundwater levels and river stage started to increase within 5 – 12 hours of the onset of intense rainfall, while the peaks occurred near the ends of the events (8 to 164 hours from the onset), and were followed by steep receding limbs. These responses were similar for surface and subsurface water levels at each particular site in terms of the trends and the peak moments, but the magnitude of the changes were different from site to site and varied between storm events and between river and groundwater (Figure 2.3). The overall trend is an increase in amplitude of changes in water levels from upstream to downstream; from slight to heavy storm events; and from groundwater to surface water. The downstream site shows higher amplitudes of change in water level of 0.35-1.3 m compared to 0.2-0.6 m at the upstream river cross-section. The heavy storm event of 550 mm rainfall caused a change of up to 1.30 m in river stage and 1.05 m in groundwater level, while the change resulting from a small storm event of 30.2 mm rainfall was only 0.20 m in river and 0.15 m in groundwater level. The highest fluctuations were usually seen in surface water levels (0.15-1.30 m) rather than in either river bank water level (0.05-1.05 m). The measured water levels showed overall decreasing trends from wet to dry seasons.

In addition to the seasonal changes in hydrology, daily changes of up to 1.5 m in groundwater level were observed due to localized pumping of the open bores. However, the bores recovered within 1 - 2 hours after pumping stopped, as they are situated in a sandy aquifer with high permeability. When groundwater level declines caused by pumping were removed from the time series, the groundwater level at both sides of the river was always higher than the river level, even during peak moments of surface water level at every site (Figure 2.3).

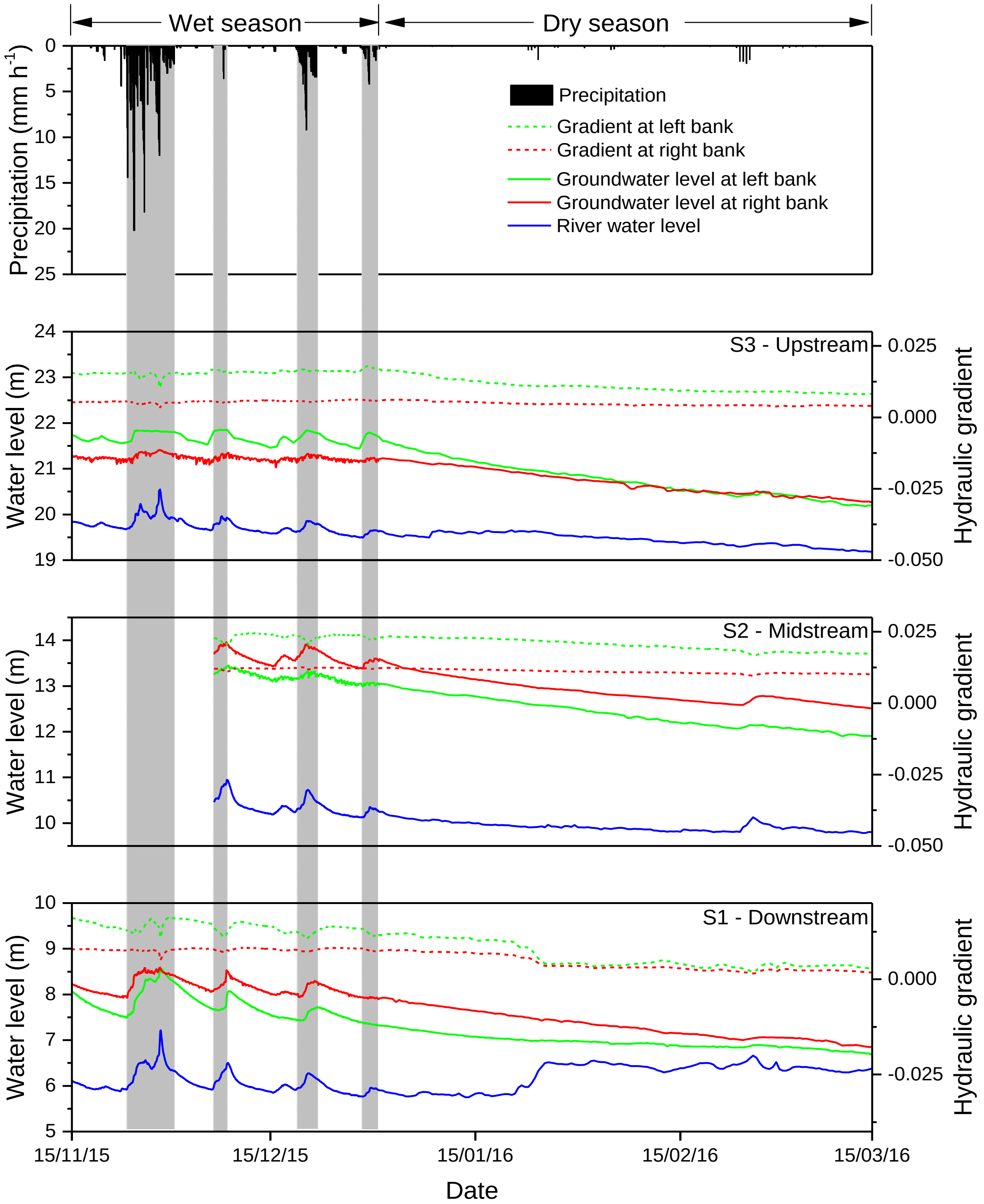

Figure 2.3: Local precipitation (top) and measured water levels and gradients in the three cross-sections from 15 November, 2015 until 15 March 2016. Grey shaded periods show the days of storm events.

Diurnal temperature fluctuation was approximately 3-6°C in the river and decreased with depth to 0.5°C at a depth of 0.3 m (Figure 2.4); below this depth the water temperature remained constant. For S1 and S3, the simulated values accurately matched the magnitude, trend and amplitude of the measured temperatures; however, for S2 the simulated temperature at all depths under the river bed were slightly higher than observed, with differences between observed and modelled temperatures of 1.0-1.5 °C. Nevertheless, the trend and amplitude were well captured by the model for this site

(Figure 2.4). The lowest value of the root mean square error (RMSE) between observed and modelled temperatures for all four fitted depths over a period of five days was 0.16 °C at S1 using a hydraulic conductivity value of 1 x 10^{-3} m s^{-1}. An RMSE of 0.07 °C was obtained at S3 using a hydraulic conductivity of 2 x 10^{-4} m s^{-1}. For S2, the best fit in terms of trend and amplitude was obtained with a hydraulic conductivity of 2 x 10^{-4} m s^{-1}. The conductivities from the constant head and particle-size analyses provided a good starting point for model calibration, although they were 1-2 orders of magnitude lower than the calibrated values at 1.5 – 8.5 x 10^{-5} m s^{-1} and 1.5 x 10^{-7} - 3 x 10^{-6} m s^{-1}, respectively.

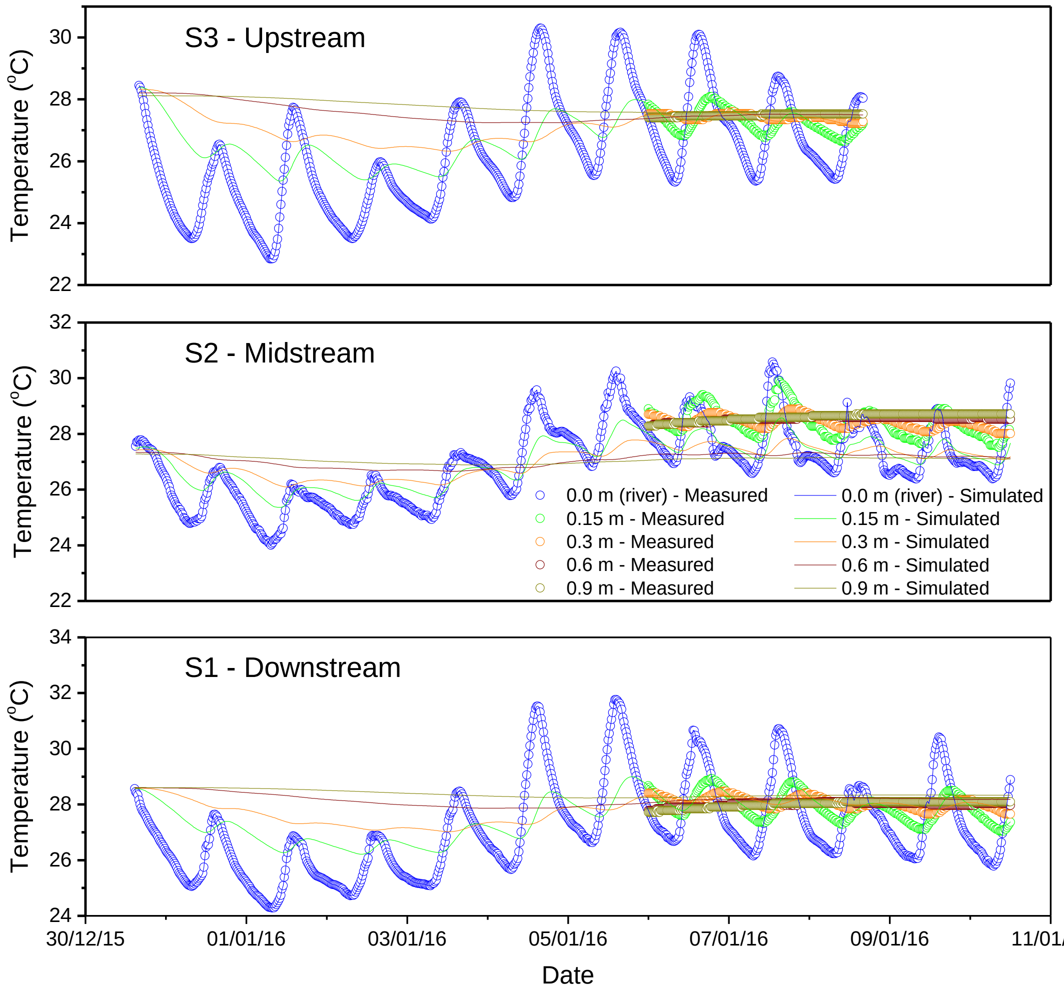

Figure 2.4: Comparison of measured and simulated temperatures in the river at 0.15, 0.3, 0.6 and 0.9 m in the river bed for the three simulated sites over the calibration period. Temperature measurements in the river bed start 6/1/2016.

2.4.1 Seasonal and spatial influences on GW-SW interactions

The total flux of groundwater discharge to the river estimated by the calibrated model increased from upstream to downstream (Figure 2.5). The flux at S1 was three and six times higher than at S2 and S3, respectively. Also, the amplitude of the flux downstream is up to approximately two and five times higher than at midstream and upstream. The average exchange velocity at S1 (0.005 m h^{-1}) was nearly two times higher than that at S3 and the wetted cross-section downstream (98.5 m) was approximately three times the cross-section upstream (37.0 m). Temporally, the flux reduced from the wet to the dry season. Fluxes at all three sites decreased suddenly from the onset of the precipitation, when the river stage started to increase; reached a minimum before the river stage peaked; and increased again when the river stage began to drop. In general, the total fluxes at all three sites showed highly variable fluxes during the rainy season, then steadily decreased to low fluxes into the beginning of the dry season before flow ceased. Expressed as the total amount of water exchanged at the GW-SW interface along the full wet cross-section per meter of river length, fluxes of up to 1.6 m^2 h^{-1} and 0.2 m^2 h^{-1} were estimated for the wet season in the upstream and downstream sections, respectively, while during the dry season the fluxes were only 1.0 m^2 h^{-1} upstream and 0.15 m^2 h^{-1} downstream (Figure 2.5). S1 was an exception and showed a higher rate of decrease at the end of the study period; however, this was due to anthropogenic causes (downstream dam operation) and not normal river flow (Figure 2.3).

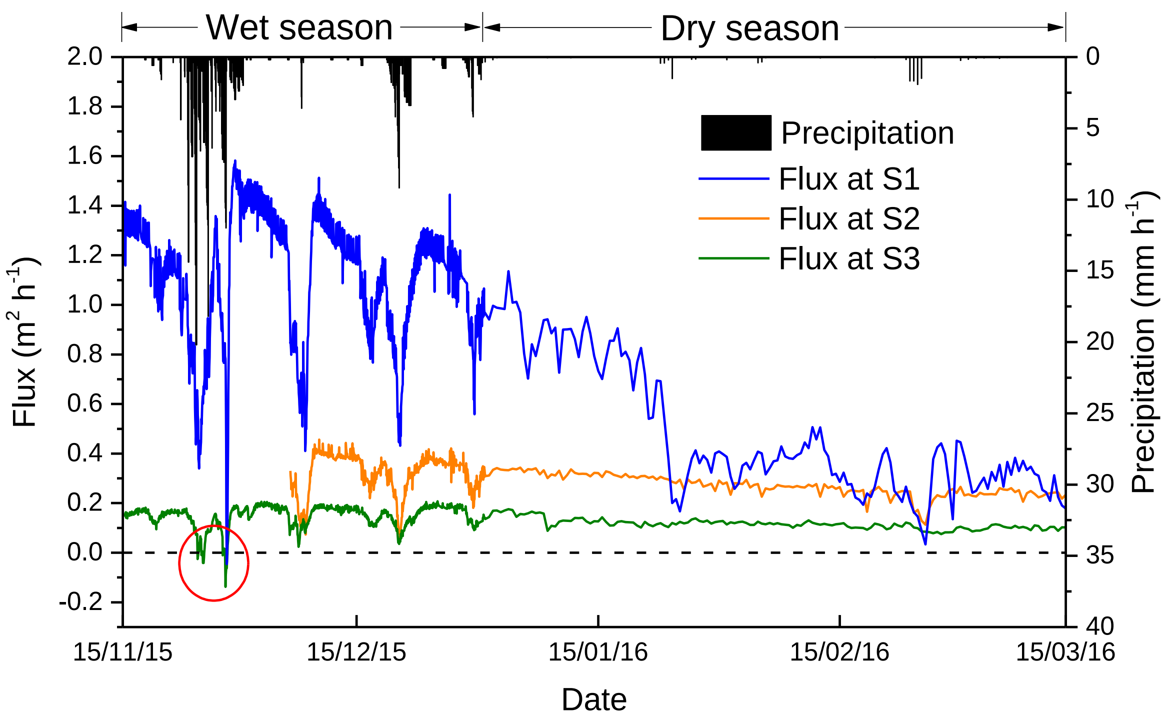

Figure 2.5: Modelled flux of groundwater discharge to the river at the three sites using groundwater level long-term trends (pumping effects removed). Modelled flux reversed from discharge to the river to infiltration into the banks (marked in the red circle) at the upstream and downstream sites (S3 and S1) during a large storm event on 28 November, 2015. The flux is given in m^2 h^{-1}, i.e., as the total amount of water exchanged at the GW-SW interface along the full wet cross-section per meter of river length.

With pumping effects removed, modelled flux at all three study sites was generally gaining, i.e., discharge from groundwater to the river. The only exception to the gaining conditions is at the moment of peak flow during the first (biggest) storm event, a flux from surface water to groundwater was observed before the peak in river stage. This flux reversal was maintained for approximately 2-4 hours, after which the interaction returned to normal condition of groundwater flux to the river. Upstream, three reversals were observed compared to only one downstream.

2.4.2 Groundwater extraction influences on GW-SW interactions

Figure 6 shows the simulated GW-SW interaction fluxes using the observed data and the 12-hour moving average filtered data. The fluxes closely parallel one another, with the biggest differences observed during sudden jumps in water levels. The changes induced by groundwater extraction caused small changes in groundwater discharge to the river in terms of magnitude, and a brief (observed for one time step) reversal in the direction of modelled GW-SW interaction at the river on February 25 in S1 (Figure 2.6c; not seen in Figure 2.5 when pumping effects are removed from the data). Comparing the results of the two model scenarios, which did not include the groundwater levels affected by pumping, showed that the groundwater pumping reduced the cumulative flux on average by 0.6%. This translates to 0.45% at the end of wet season and up to approximately 3.0% halfway through the dry season (15 March).

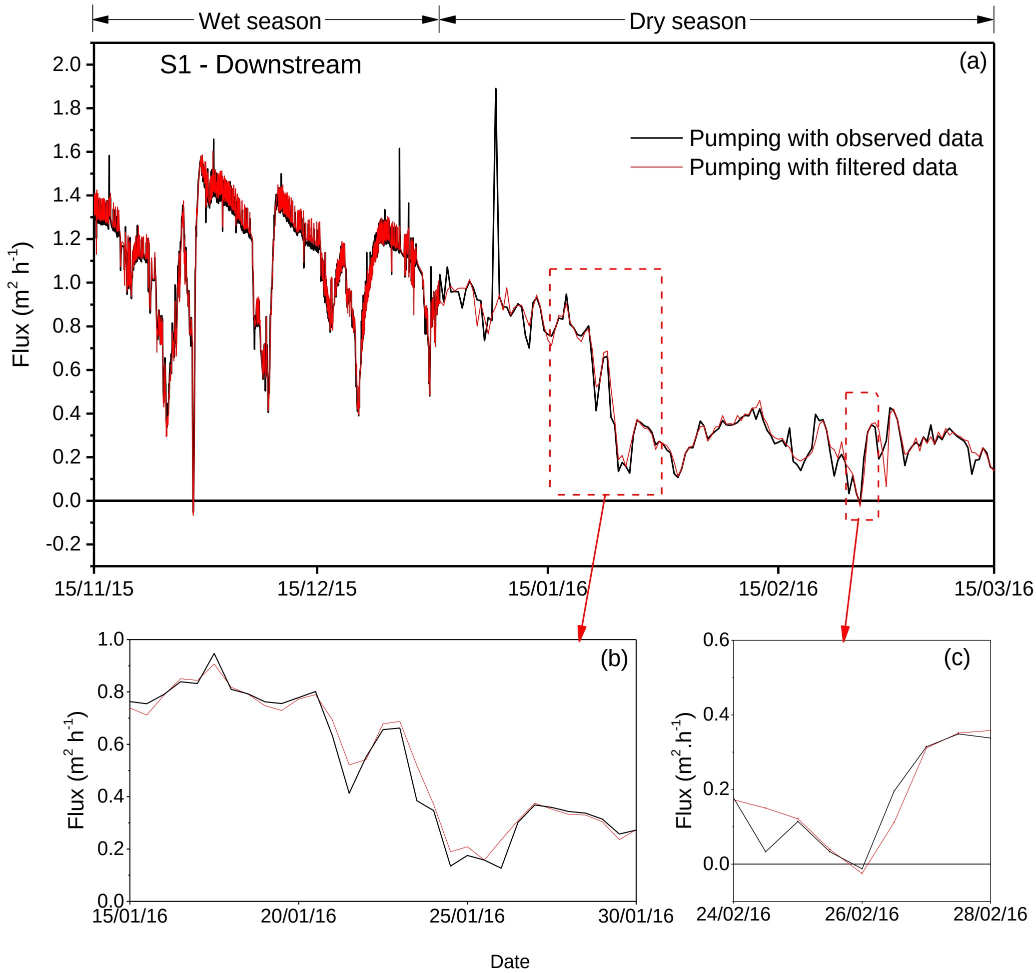

Figure 2.6: Simulated fluxes from groundwater to the river with pumping included, using observed data and data filtered with 12-hour moving average for the whole period of simulation (a); focused in to show the period at the beginning of the dry season when pumping is intensive (b), and the flow reversal on 26 February (c).

2.5 Discussion

Fluxes of water into the streambed and banks have been shown to have long-lasting consequences (McCallum & Shanafield, 2016) and can be important for biogeochemical cycling within the streambed, which in turn influences in-stream water quality (Boulton *et al.*, 2010; Bencala *et al.*, 2011). As summarized in Figure 2.7a, in the La Vi, fluxes at all sites are normally outflow from the banks to the stream (gaining) and have generally decreasing trends from the wet to the dry season. However, a reversal in flux both upstream and downstream occurred during the precipitation event from 22 to 29 November 2015, when 560 mm of rain fell in 164 hours, leading to a change in hydraulic gradient, which pushed river water into the streambed. This process is explained in Figure 2.7b. Examination of long-term precipitation data from the An Nhon station suggested that the frequency of such precipitation events is 2-3 times per year, normally occurring between October and December, but occasionally in September. Hence, major flow reversals are expected to occur with the same frequency.

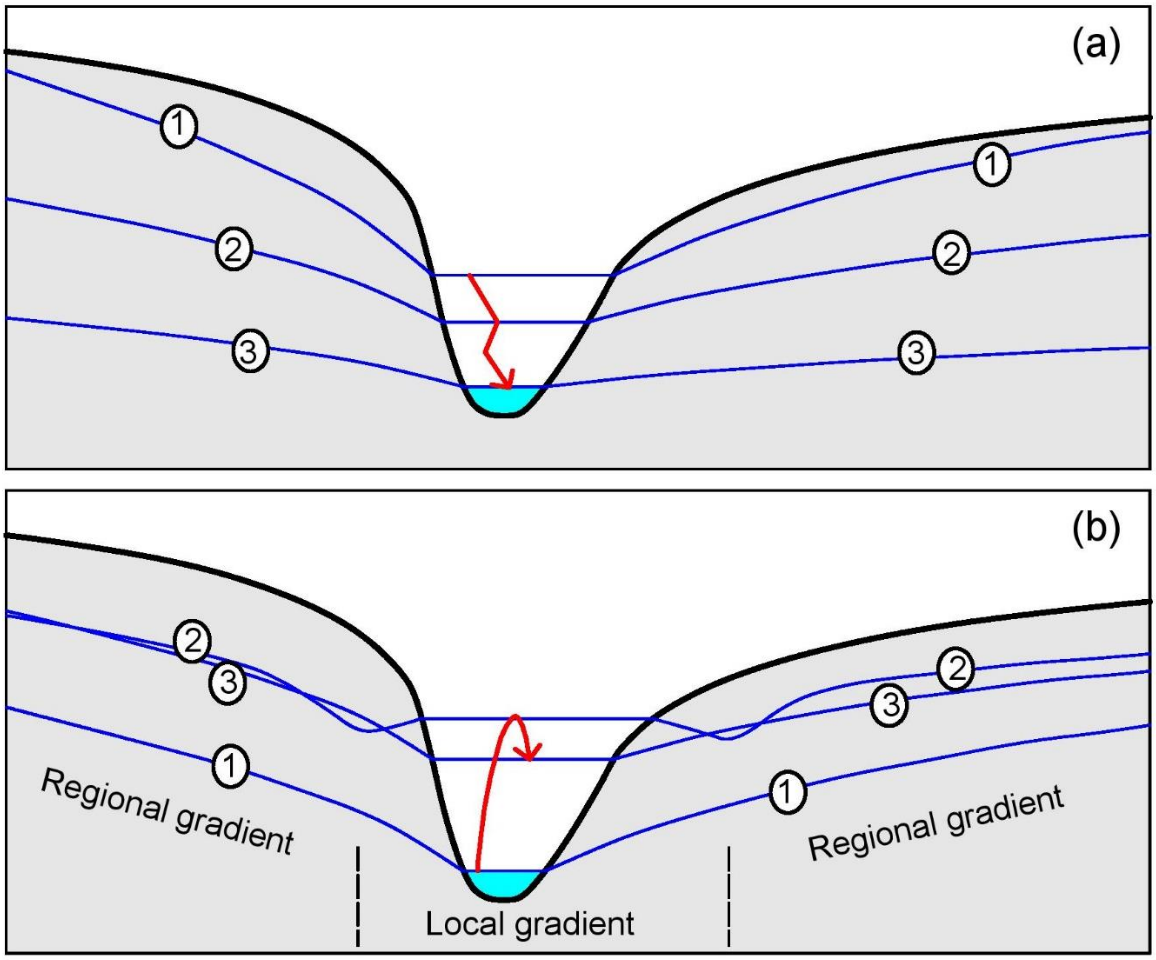

Figure 2.7: Summary of seasonal and storm influences on the GW-SW interaction dynamics for the tropical study site.

- *(a) Change in the GW-SW interaction dynamics from wet season to dry season (1-3): the groundwater discharge to the river decreases steadily, simply due to the decrease in the gradient from wet to dry seasons.*
- *(b) GW-SW dynamics due to large storm events:*
  - *(1) Base-flow conditions during rainy season. Flow is from the surrounding aquifer to the river (gaining) due to the high regional groundwater level gradient;*
  - *(2) During the rising limb of a big storm event, the water level in both the subsurface and the river rise quickly; however, high rainfall intensity during large storm events causes the river water level to rise faster than the groundwater and a flow reversal develops from the river into the streambanks for a brief period;*
  - *(3) Shortly after the storm peaks, the groundwater depression in the river banks disappears because of the high aquifer transmissivity, and the flow direction is again towards the river (gaining).*

Similar to the results of this study, Bartsch *et al.* (2014) show that in the case of a monsoonal catchment in South Korea, the river changes from gaining flow from the adjacent aquifer into the river before a storm event to losing, groundwater recharge through the river bed after a storm event. However, our results show a change from discharge into the river to inflow to the banks for only a very short time of 2-4 hours before the moment of peak river stage. In addition, Bartsch *et al.* (2014) indicated that vertical flow is dominant, whereas the La Vi modelling suggested more lateral flux into the river at the banks than vertical flow at the river bed. These results highlight the highly variable temporal and spatial aspects of riverbed fluxes (e.g. Conant, 2004; Schmidt *et al.*, 2006; Anibas *et al.*, 2009) .

Human activities such as groundwater abstraction and dam operation have been shown to have effects on water exchange between rivers and nearby sediments (Nyholm *et al.*, 2003; Francis *et al.*, 2010). In the case of the La Vi River, the dam operation at S1 downstream caused an increase of river stage, which reduced the hydraulic gradient resulting in a decrease of outflow to the river during the dry period. The modelling, as summarized by Figure 2.8, has shown that the influence of groundwater extraction on the flux between surface and subsurface was quite small due to the quick recovery in groundwater levels of sandy soil aquifers.

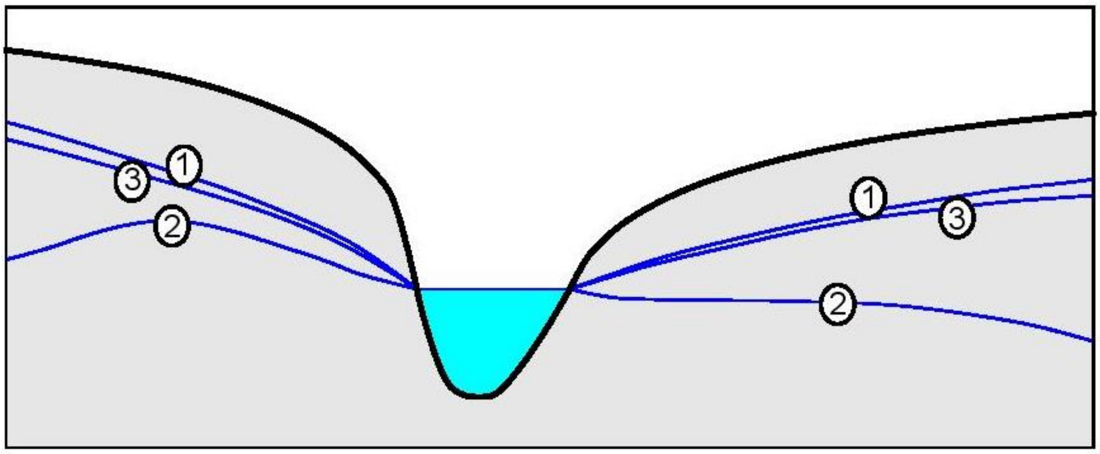

Figure 2.8: The influence of groundwater abstraction on the GW-SW interaction dynamics: 1) before the abstraction, the flow is from groundwater to the river (i.e., gaining). 2) Onset of pumping causes a drop in groundwater level, which in turn causes a decreased the gradient to the river. Therefore, the groundwater discharge to the river is decreased. Under some pumping conditions a reversal of flow into the banks occurs. 3) However, due to high aquifer transmissivity, the groundwater level recovers very quickly (1-2 hours after pumping ceases) and the flow returns to normal.

Even though groundwater extraction was found to cause a change in the direction of streambed flux, the influence from groundwater extraction was quite small compared to the change driven by seasonal climate shifts. However, if the rate of water extraction increases to meet future higher water demands, greater impacts on streambed dynamics may be observed (Baalousha, 2016). Increased extraction will cause a reduction of water entering the stream and hence will alter the stream flow regime and continuity, which consequently will impact the river and its surrounding wetland ecosystems (Costigan *et al.*, 2016), particularly during base-flow periods.

This study showed that La Vi River flow is controlled primarily by recharge throughout the catchment and not by direct runoff during storm events. This differs from much of the literature on intermittent and ephemeral streams, which are often thought of as the primary groundwater recharge areas for their catchments (Shentsis & Rosenthal, 2003); however, most of those studies are from arid regions. Our results may be more typical of tropical intermittent streams, especially in sandy coastal regions where aquifer transmissivity in high. The understanding of the flow permanence of intermittent river systems has been recognized to be important, but is still overlooked (Costigan *et al.*, 2016). This example of discharge of groundwater to a stream in a tropical, agriculture-based catchment in Vietnam has pointed out that flow permanence in this environment is heavily dependent on the local climatic setting (i.e., diffuse catchment recharge during rain events), the hydrogeological characteristics of high permeable sandy soils, and the human activities of groundwater extraction and dam operation.

The limitation of this study is that the recharge to groundwater from precipitation, evapotranspiration and also return flow from irrigation were not directly measured and simulated. However, these effects were included in the observed changes in the groundwater levels, which were used as modelled boundary conditions (Healy & Cook, 2002). Although the lateral width of the cross-sectional models was small, this limitation might have reduced the accuracy of simulated change in the flux of groundwater to the stream. The influence of groundwater extraction appeared to be small in terms of effect on GW-SW interaction quantity, but the possible impacts on groundwater and surface water quality have not been explored.

The results of this study suggest further study of water quality conditions and processes in the catchment as it is influenced by fluxes between GW and SW. The results showed that GW-SW interaction is very sensitive to dynamic water levels, which represented in this study the effect of vertical recharge from precipitation, and probably from return flow from irrigation to groundwater. Because the La Vi River is gaining over its full length, with high fluxes during the wet season, there is potential for significant stream pollution from agricultural activities. Several studies have shown that agricultural based activities, including use of fertilizers and pesticides, are considered to be the most important pollution sources for groundwater and surface water (Ongley, 1996; Waibel, 2010). However, water cycling in river beds and banks during storms also has the possibly to drive nutrient cycling and nitrate removal from riverbed processes (Rahimi *et al.*, 2015; McCallum & Shanafield, 2016). These processes might function differently for intermittent compared to perennial river systems (Datry *et al.*, 2014; Costigan *et al.*, 2016). This suggests that further investigation of water quality response to precipitation events, regular groundwater pumping and the relation to the dynamics of the GW-SW interaction is warranted.

2.6 Conclusion

This study used a transient heat and water flow model to examine the changes in the fluxes in a tropical streambed by simulating the field-measured time series data of heat and water levels in surface and subsurface water. The general conclusion is that the results showed significant impact on the flux due to influencing factors as shifts between wet and dry seasons and regional groundwater extraction. Specific conclusions are:

- Surface and subsurface water levels are very sensitive to the regional precipitation, which in turn causes changes in fluxes between groundwater and river water. Although the river was found to be primarily gaining water from the aquifer at all three cross-sections, a decrease in the groundwater discharge to the river and sometimes a change from discharge to recharge was seen as the result of rapid increase in river water level in response to storm events.
- Local groundwater extractions are apparent as a result of high water demand for agriculture in the dry season; however, the impact of these activities on the exchange flux was estimated to be still quite small compared to the impact from the seasonal shift in the climate.
- This example of a tropical, agriculture-based catchment in Vietnam with an intermittent gaining stream has shown that the flow regime strongly depends on the local climate, the hydrogeology and the human alterations of the groundwater and surface water levels.

Chapter 3. Mapping catchment scale unmonitored groundwater abstractions: approaches based on soft data[2]

Abstract

In many parts of the world, groundwater abstraction for food and industrial production is strongly increasing. This causes severe stress on groundwater resources and often on the connected ecosystems. Therefore, understanding the extent of abstractions in catchments is essential. In many countries, monitoring of abstraction is poorly organised, resulting in a huge paucity of data, particularly in developing regions where it is not feasible to install expensive infrastructure and coordinate basin-wide monitoring. Therefore, alternative approaches to estimating groundwater withdrawals are necessary. In this study, two soft-data approaches for indirect catchment-scale groundwater abstraction are developed using: (1) local knowledge through a qualitative field survey of groundwater level fluctuations and groundwater withdrawals, and (2) land use data combined with local knowledge on cropping practices. The approaches are tested and applied for the ungauged, agriculturally dominated La Vi River Basin, Vietnam, for the 2016 dry season. The qualitative field survey of 77 farms showed that groundwater withdrawals from the shallow, sandy aquifer are mainly used to irrigate crops and that 85% of the annual abstraction was used for irrigation, particularly from January to April. The remaining groundwater abstraction was used for domestic use and small private livestock farming system. The first approach resulted in a total estimated abstraction of 31.07×10^6 m^3 during the dry season. The advantage of the second approach is the spatial distribution of the estimated groundwater abstraction, aligning highly intensive abstractions with intensive agricultural areas. The total abstraction of 36.19×10^6 m^3 is just slightly higher than in the first approach. The advantage of using multiple approaches is to provide the possibility for crosschecking, and the consistency of results observed in this study provides greater confidence in the groundwater abstraction estimations. However, recommendations are also made for low-cost management options to reduce possible uncertainties in the estimation of abstractions.

Keywords: groundwater abstraction, soft data, irrigation, domestic consumption

[2] *Published as:* Vu, H. M., et al. (2020). Mapping catchment-scale unmonitored groundwater abstractions: Approaches based on soft data. *Journal of Hydrology: Regional Studies, 30,* 100695

3.1 Introduction

Aquifers contain the world's biggest storage of high-quality fresh water. The use of groundwater is estimated to account for one-third of total global water consumption. Agricultural, domestic and industrial use of fresh water is sourced from groundwater at rates of 42%, 36% and 27%, respectively (Taylor *et al.*, 2013). Globally, there has been a significant expansion in groundwater abstraction, and in some areas strong over-abstraction to satisfy water demand and food security for the growing population (Llamas & Martínez-Santos, 2005; Wada *et al.*, 2010; Qureshi, 2011; Rasul, 2016). Llamas and Martínez-Santos (2005) documented a global shift from surface water resources to groundwater abstraction to meet agricultural demands, fuelled by the immediate benefits to farmers and largely without governmental regulation. The resulting consequences include declining groundwater tables, degradation in groundwater quality due to pollution from use of fertilisers and pesticides in agriculture and induced seawater intrusion in coastal aquifers (Llamas & Martínez-Santos, 2005; Giordano, 2009; von Rohden *et al.*, 2010; Nazemi & Wheater, 2015). It has also been recognised that climate change will intensify these problems further. The consequences should be appropriately managed considering the long time frame that groundwater systems need to adjust to changes (Cuthbert *et al.*, 2019).

To manage groundwater resources, we need information on groundwater budgets (i.e., aquifer recharge and discharge) in general, and groundwater abstraction data, in particular, is essential for groundwater management and development (Qureshi *et al.*, 2010; Cheema *et al.*, 2014; Rasul, 2016). Under natural long-term equilibrium conditions, the volume of water recharged to the aquifer is equal to the volume of water discharged from the aquifer by base-flow to rivers and transpiration from groundwater. When aquifer abstraction occurs, this natural equilibrium is changed, ultimately leading to either a reduced discharge or induced recharge or a combination of both (Bredehoeft *et al.*, 1982; Bredehoeft, 2002; von Rohden *et al.*, 2010; Stewardson *et al.*, 2017; Fetter, 2018). Understanding these effects of abstractions is important for sustainable systems, even more so as groundwater resources come under increasing global stress. Hence, managing groundwater abstractions should no longer be overlooked by governmental water agencies (Llamas & Martínez-Santos, 2005) and sustainable groundwater use must be a high priority for water policymakers (Bastiaanssen & Feddes, 2005).

Although important to water management, groundwater abstractions are often unmonitored and difficult to estimate accurately, especially in developing countries (Giordano, 2009; Siebert *et al.*, 2010). Spatial variation in land use, along with changing irrigation practices, result in complicated patterns of groundwater abstraction (Giordano, 2009). Moreover, in many areas, the change in land use from natural landscapes to farmland or urban areas often results in strongly exploited groundwater systems. The International Groundwater Resources Assessment Centre (IGRAC) has initiated the Global Groundwater Information System (IGRAC, 2015) to address the availability and paucity of data. However, groundwater abstractions are not included, as they are mostly unmonitored (Shah *et al.*, 2007; Giordano, 2009).

While groundwater abstraction data are needed for modelling studies of regional aquifers, often these data are not (sufficiently) available. However, there are options for methods using alternative data to fill this gap. Also called ‘soft’ data, this includes ‘local’ knowledge of environmental parameters and land use practices, qualitative field surveys or upscaled statistical data (Seibert & McDonnell, 2002). Studies that use soft data are often a response to the problem of unavailability of required data, especially in the developing world where there is insufficient or an absence of traditional monitoring infrastructure.

Soft data lessens the lack of traditional data but there are typically many assumptions, some of which might be strong. For example, Maréchal *et al.* (2006) used land use data in combination with a determined consumption rate (i.e., amount of water irrigated for a unit area) for estimating the amount of groundwater extracted for irrigation on paddy rice at a pilot watershed (Andhra Pradesh State, India). This method helps to overcome missing groundwater abstraction data by the availability of land use data. However, the authors assumed the absence of base-flow to the streams and agriculture to be the unique consumer when estimating groundwater abstraction. Qureshi *et al.* (2003) estimated unrecorded groundwater abstractions for the whole of Pakistan by upscaling the relationship between energy consumption from investigated wells and pumped volumes, noting that it is important to include the utilisation factors (e.g., electric or diesel) while estimating groundwater abstraction. The method was successful in estimating unmeasured groundwater pumping by relating it to a measured factor of energy consumption as determined from sampled wells, with the assumption that they were representative of the whole study area.

Besides soft data, widely available remote sensing data offer huge opportunities to reduce the limitations of the lack of data from observational hydrological networks. Cheema *et al.* (2014) used a combination of remotely sensed data and the Soil and Water Assessment Tool (SWAT) model to estimate groundwater abstractions in the Indus basin (covering parts of four countries of Afghanistan, China, India and Pakistan). Remotely sensed evapotranspiration was used by Bastiaanssen *et al.* (2012) to calibrate the SWAT model. From the evapotranspiration, precipitation and simulated water balance components, groundwater abstraction was estimated by solving the groundwater balance equation.

Few studies take advantage of the many non-traditional sources of information. Hence, there is wide scope for using 'local' knowledge, especially in the developing world where the population is expanding and understanding groundwater availability is paramount. Using multiple approaches provide opportunities for comparing results and will make uncertainties in the estimates evident that can help to evaluate assumptions that must be made when using alternative data. Therefore, the goal of this study is to develop and test different methodologies for estimating catchment-scale groundwater abstractions based on soft data for areas severely constrained by data availability. Two approaches, (a) a groundwater balance and (b) a land use-based method, were developed from local knowledge extracted from farmer surveys, agricultural practices and geographical data. For demonstration of the advantages and limitations of these two approaches, we applied them to the La Vi catchment in South Central Coastal Vietnam for the dry season of 2016, as the dry season is the period critical for the groundwater system to supply irrigation water. The catchment is essentially ungauged (i.e., there is no surface or groundwater monitoring), while its agriculture relies on extensive irrigation from groundwater. This study aims to show the advantage of using local knowledge and information in multiple approaches for estimating groundwater abstractions in ungauged catchments in function of hydro(geo)logical and water resources studies and in support of agricultural development.

3.2 Study area

The La Vi catchment is located in the central coastal province of Binh Dinh, Vietnam (see Figure 3.1). It covers an area of almost 100 km^2 and has an elevation ranging from 4 to 395 m. The main river in the catchment is the La Vi, with an approximate length of 12 km. The upstream part of the La Vi and its tributaries are intermittent and typically flow from September to April (Vu *et al.*, 2018). The downstream part of the La Vi River is perennial, albeit the weir located approximately 500 m downstream of the outlet of the catchment reduces the risk of the river from drying out. Only the downstream part of the river is used for surface water irrigation of rice crops in riparian fields.

There are five administrative communities within the catchment: the small town of Ngo May, large parts of the two communes Cat Hiep and Cat Trinh and small parts of the Cat Hanh and Binh Thuan communes (Vu *et al.*, 2018). Different estimates on the population in the catchment resulted in approximately 37,500 to 51,000 people (see Results for more detail).

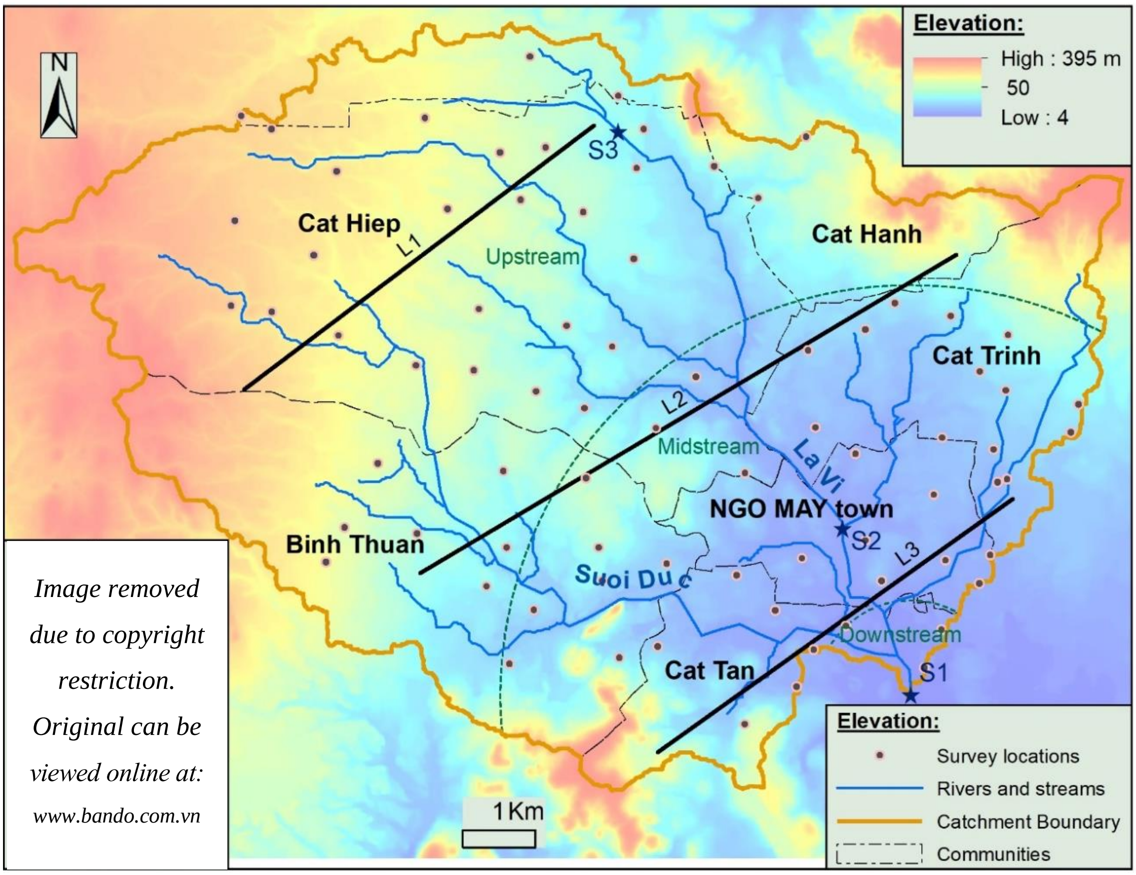

Figure 3.1. La Vi catchment showing elevation and administrative communities. The digital elevation model (DEM) is based on the 10-m DEM for Binh Dinh province by Binh Dinh DONRE (2015). The small town of Ngo May is the only semi-urban area, other communities are rural. The dots show the locations where farmers were surveyed for local knowledge on groundwater table fluctuations and pumping routines. The inset shows the map of Vietnam (Source: Vietnam Publishing House of Natural Resources, Environment and Cartography) with indication of Binh Dinh province and La Vi catchment marked as an orange dot. The black lines L1–L3 indicate the location of the hydrogeological cross-sections of Figure 3.4. S1, S2 and S3, indicated by stars, are respectively the downstream, midstream and upstream locations where base-flow has been estimated. The green semi-circles indicate the boundaries between downstream, midstream and upstream regions. A weir is located (not indicated on the figure) approximately 500 m downstream of the outlet S1.

A land use map (Tran *et al.*, 2018) shows that the area is dominated by agriculture (78%), while urban (residential) land accounts for 3.7% of the catchment area; other classes, including forest, bare land and water body cover 15.3%, 3.4% and 0.2%, respectively (see Figure 3.2). The typical crops cultivated in the catchment are annual crops of rice, peanut, cassava and vegetables and perennial crops of mango, acacia and coconut (Hoang *et al.*, 2015).

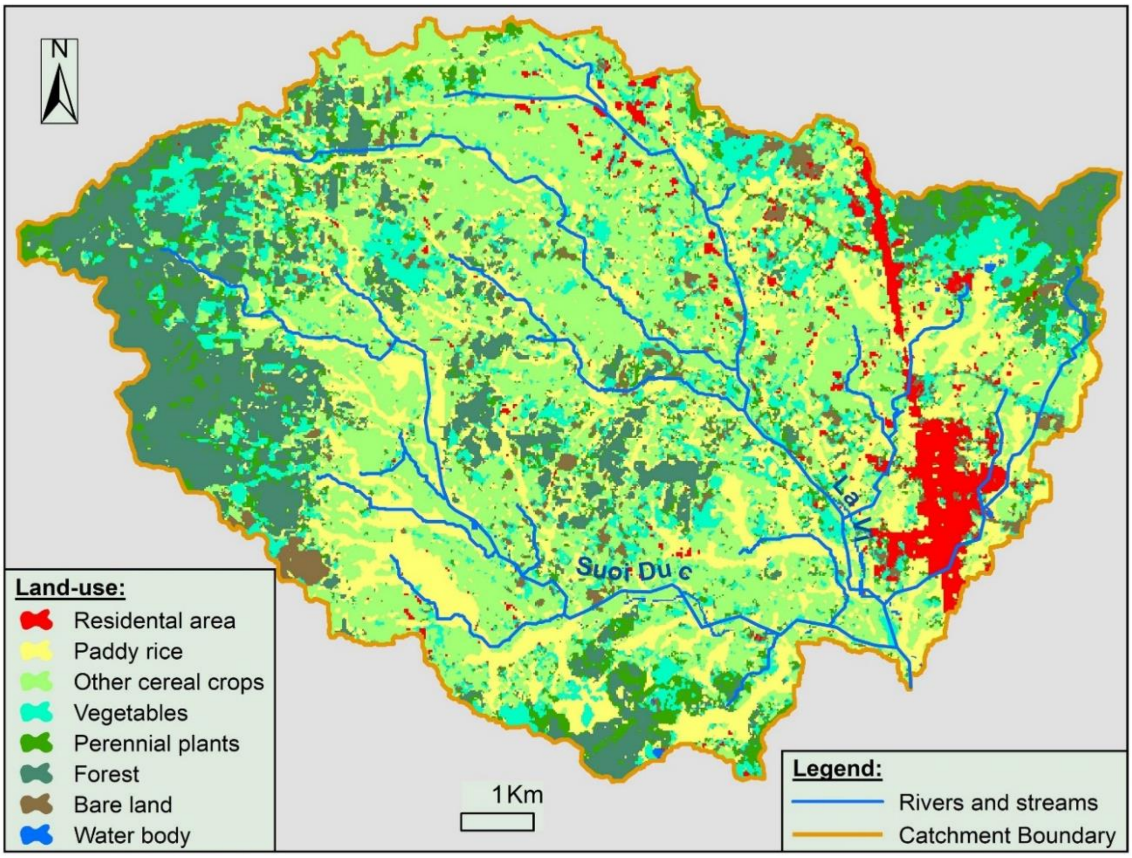

Figure 3.2. Land use for 2016 for the La Vi catchment (Tran et al., 2018), showing the dominance of agricultural lands (i.e., paddy rice, other cereal crops of peanut and cassava, vegetables and perennial plants of mango and coconut) covering 78% of the catchment area, followed by the forest (15%). The residential area occurs mainly in the small town of Ngo May in the south-east corner of the catchment and covers 4% of the total area. The remaining areas belong to bare land (2%) and water bodies (<1%).

The soil types for the whole Binh Dinh province, including the La Vi catchment, has been mapped in 2005 by the National Institute of Agricultural Planning and Projection (NIAPP) (NIAPP, 2006). For this study, an update of the soil classification was performed (see Materials and Methods). Seven soil types were recognised within the catchment (see Figure 3.3). Among these, the greyed (Xa) and the greyed degraded (Ba) soils, derived from weathered acid magmatic rocks and sandstones, are dominant in the catchment, covering 50% and 37% respectively. The reddish-yellow soil (Fa), a product of acid magmatic rocks, covers 8% of the catchment area. The deluvial deposited soil (D) and the yellowish-brown soil derived from old alluvium (Fp) cover approximately 2% each, while the eroded skeletal soil (E) and the red and yellow patched alluvial soil (Pf) account each for around 0.2%.

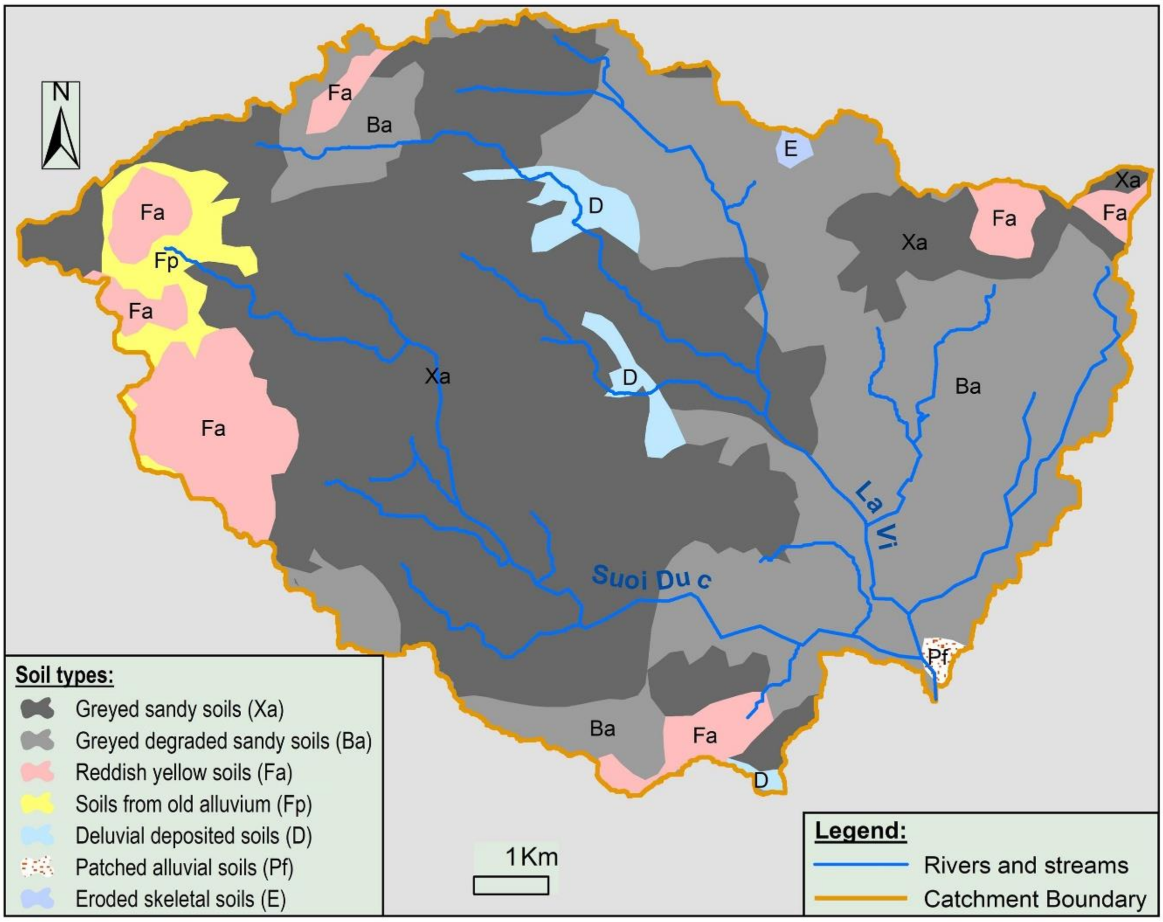

Figure 3.3. The soil map of the La Vi catchment with seven soil types mapped (NIAPP, 2006). The dominant soils are the greyed (Xa) and greyed degraded (Ba) sandy soils, covering 50% and 37% of the catchment, respectively, followed by reddish-yellow soils contributing to 8% of the catchment. The other four soil types each cover small areas (0.25–2.5%) of the catchment.

A shallow, unconfined sandy aquifer with a thickness ranging between 0 m (at bedrock outcrops) and 40 m (typically 5–20 m thick) is underlain by a granitic basement rock located beneath the whole catchment (Do, 1987) (see Figure 3.4).

The catchment has a tropical climate with an annual rainfall varying between 1,300 and 2,600 mm for the period 1986–2015 (Vu *et al.*, 2018). Its strong seasonal distribution produces large fluctuations in groundwater levels (Do, 1987), with the highest groundwater table at the end of the rainy season (December) and lowest at the end of dry season (August). Groundwater is extracted from thousands of private, shallow dug wells distributed throughout the catchment. It serves as the main source of water for satisfying the needs of irrigation, domestic water use and small livestock farming system. The La Vi River and its tributaries drain the aquifer and discharge excess surface runoff during high-precipitation events. There are no monitoring wells in this catchment or long-term river gauging stations.

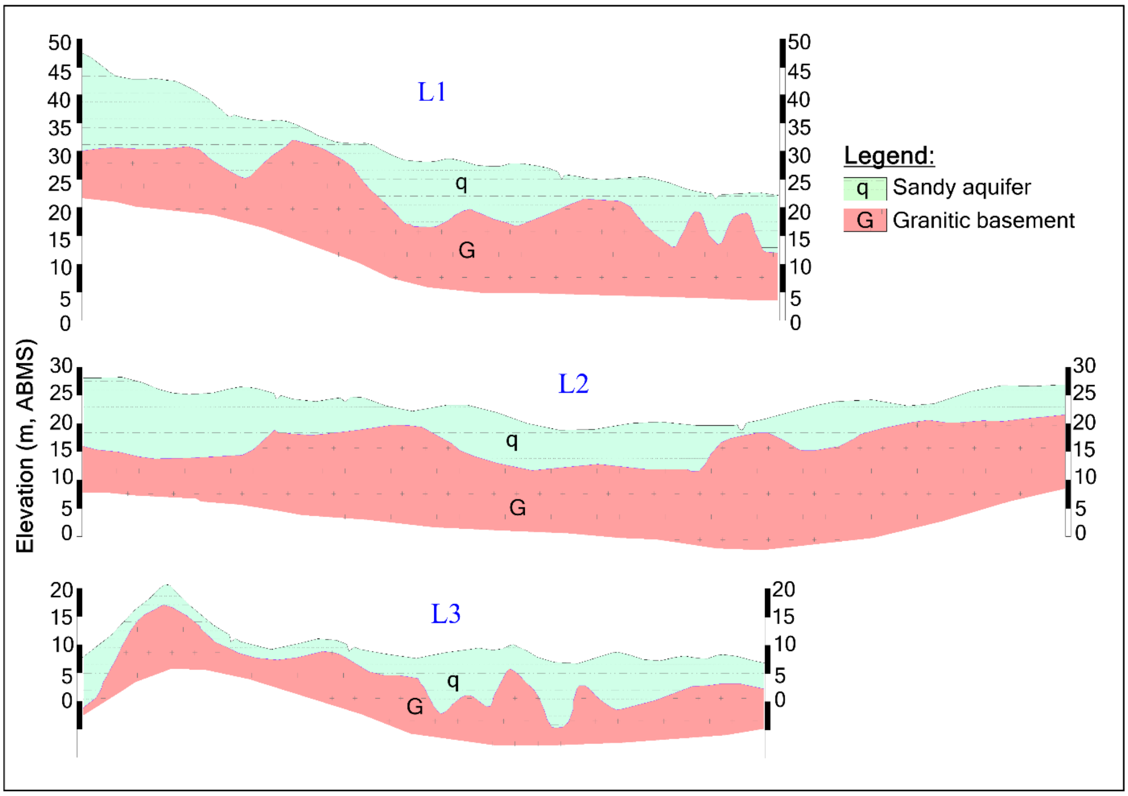

Figure 3.4. Hydrogeological cross-sections L1–L3 as indicated in Figure 1, showing the variation in the thickness of a sandy aquifer (q), which is underlain by the granitic basement rock (G) (based on Do, 1987).

3.3 Materials and methods

3.3.1 Qualitative field survey

A qualitative field survey at 77 farms located throughout the study area (see Figure 3.1) using a questionnaire (SI 3) was conducted between 20 and 25 October 2015. Farmers were asked what the purpose of their wells was, and to estimate the minimum and maximum groundwater depths in their wells and the typical month of occurrence of the corresponding depths. From general knowledge of the area and first results of the survey, it was obvious that the minimum and maximum groundwater depths occur respectively in December at the end of the wet season, and in August at the end of the dry season. The depth to groundwater was also directly measured on the day the survey was taken.

For understanding groundwater abstraction and use on a monthly basis, the farmers were also asked to approximately judge the daily average duration of pumping for each month of the year, while the pumping rate was measured during the survey. Moreover, farmers were surveyed on their area of land irrigated and the applied cropping patterns (i.e., single crop or crop rotation) connected to the well in question. The irrigation rate (i.e., amount of water consumed by each unit area, Ra-irr (m)) of crop was calculated by dividing the total amount of groundwater abstracted by the area irrigated.

For understanding groundwater use for domestic purposes, the number of persons per farming household was surveyed, the average per person domestic use (R_c) (m^3/day) and the percentage of water consumption provided by groundwater (P_{gw}). The number of livestock per farm was also surveyed.

3.3.2 Groundwater balance-based approach

The groundwater balance-based approach aimed at estimating catchment-scale groundwater abstractions for the dry season, as in this period, cropping and irrigation are critically dependent on the capacity of the groundwater system to supply water. This approach (see Figure 3.5a) derives the total abstraction as the rest term from a catchment groundwater balance equation, after all other components of the groundwater balance have been estimated. The first step was to develop maps of maximum (Step 1) and minimum (Step 2) phreatic groundwater levels based on the results of the qualitative survey.

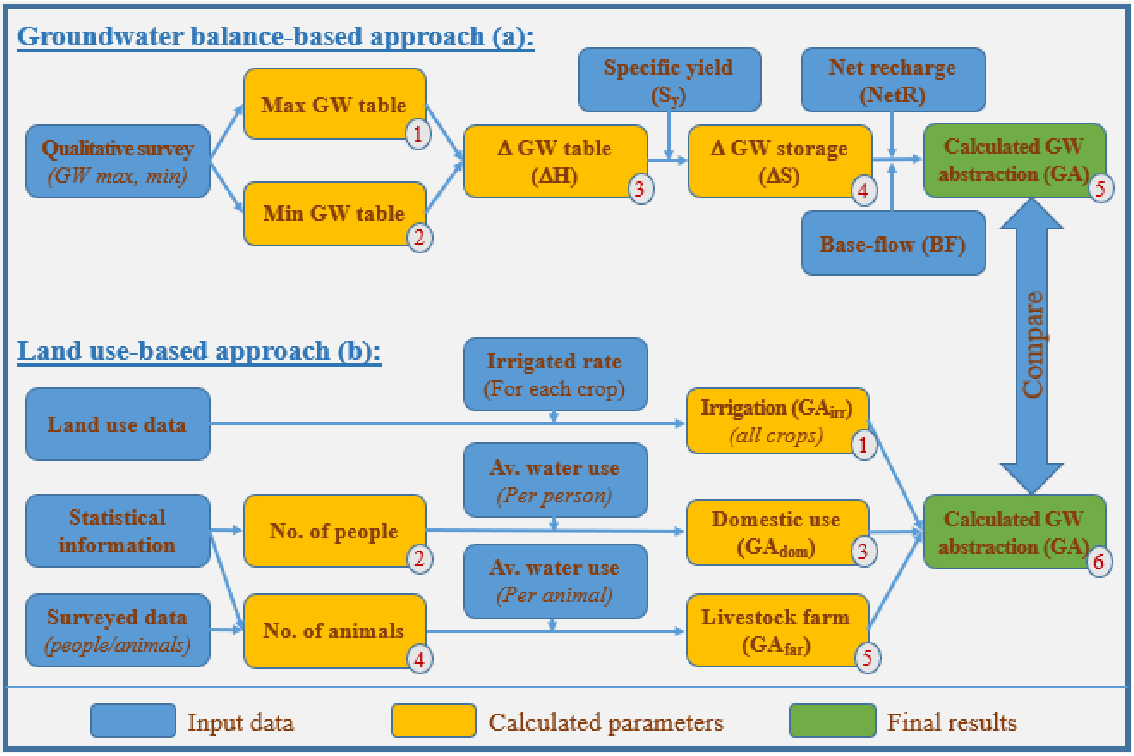

Figure 3.5. Schematic flowchart for the two approaches for estimating groundwater abstraction during the dry season. (a) Groundwater balance-based approach in which groundwater abstraction is estimated as the rest term of a groundwater balance equation, while all other components, including recharge, change in groundwater storage and groundwater base-flow to streams were estimated by a combination of soft–hard data and modelling. (b) Land use-based approach in which groundwater abstraction is calculated for irrigation, domestic use and livestock farming based on land use, population and other auxiliary data. The difference between the results from the two approaches was evaluated.

In processing the surveyed data, the first step was to subtract the surveyed maximum and minimum depth to groundwater from the elevation (extracted from digital elevation model (DEM)) for obtaining referenced values of minimum and maximum groundwater levels. Next, these levels were interpolated, using radial basis functions, as implemented in the Python package Scipy (Virtanen *et al.*, 2020). Subtracting from the interpolated maximum and minimum groundwater levels, we obtained a spatially distributed estimate of the change in the groundwater level (ΔH) (Step 3) from the wet to the dry season.

In Step 4, the change in aquifer storage (ΔS) was estimated by multiplying the change in the groundwater level (obtained from Step 3) with the specific yield of the aquifer. The soil map extended with field soil surveys and sampling resulted in the classification of seven soil types. Porosity and field capacity were experimentally estimated for soil samples from 11 locations. Specific yield was then calculated as the difference between the porosity and field capacity (Johnson, 1967).

The groundwater balance-based approach also requires an estimate of the net recharge to groundwater and base-flow to streams. Monthly net recharge for the whole catchment area was estimated by using the raster-based, water balance model WetSpass-M (Abdollahi *et al.*, 2017). WetSpass-M uses distributed data on land use, soil texture, depth to groundwater, topography and monthly climatic data (i.e., rainfall, potential evapotranspiration, number of rainy days, wind speed and average temperature) as inputs. Land use data of (Tran *et al.*, 2018) was used (see Figure 3.2) and soil texture was based on the soil map (see Figure 3.3) (Nguyen & Thach, 2018). Maps of average conditions of monthly depth to groundwater table were derived by using two temporal linear functions interpolating between the minimum and maximum obtained groundwater levels and, consequently, determining groundwater depths by subtracting from the DEM. For some remote hilly terrain areas of no investigation where interpolated groundwater level dropped down below aquifer bottom (see Figure 3.8), the artificial of 2.5 m depth to groundwater level was assigned (bellow the maximum root depth of all local crops) to ensure that there is no evapotranspiration accounted for these areas as there is no groundwater there.

Monthly climatic data, required for WetSpass-M, were estimated by averaging the daily measured data for 2016 from the An Nhon national weather station located approximately 15 km away from the catchment. WetSpass-M simulated for 2016 the monthly distributed net recharge, surface runoff and actual evapotranspiration. As the actual evapotranspiration transpiration includes transpiration from groundwater, WetSpass-M provides net recharge.

Vu *et al.* (2018) simulated (monthly) groundwater discharge to the La Vi River at a downstream (S1), midstream (S2) and upstream (S3) cross-section for November 2015 to March 2016 (see Figure 3.1). To estimate the catchment-wide dry season (January to August 2016) base-flow, the linear trend of decreasing flux at each cross-section for the simulation period was extrapolated until the end of the dry season (April to August). Next, the sum of the dry season base-flow (January to August) was assigned as the flux rate for each cross-section. Next, each segment of the river network was assigned an upstream, midstream or downstream flux rate based on its relative location to the modelled cross-sections. For determining the downstream, midstream and upstream areas, two semi-circles were defined with their centre at the location of the S1 cross-section and their radiuses the distance between S1 and the middle points between the S2 and S3 cross-sections, respectively (see Figure 3.1). Finally, the total base-flow was obtained by summing up the product of the length and assigned flux rate of all the stream segments, which was then divided by the catchment area to obtain a specific base-flow.

All estimated water balance components were used to estimate groundwater abstraction (Step 5, see Figure 3.5). In the case of a closed watershed, the groundwater balance equates the sources (positive net recharge), sinks (groundwater base-flow to rivers, actual evapotranspiration or negative net recharge and groundwater abstraction) and changes in groundwater storage. Arranging the groundwater balance equation to estimate groundwater abstraction yields:

$$-\Delta \mathrm{H} * \mathrm{S}_y + \mathrm{NetR} - \mathrm{BF} = \mathrm{GA} \tag{3.1}$$

where ΔH is change in groundwater level, S_y is specific yield, NetR is net recharge to groundwater, BF is groundwater base-flow to streams and GA is groundwater abstraction for anthropogenic purposes; all the terms are expressed as depths of water [L]. ΔH, S_y and NetR are distributed estimates, while BF is a catchment average value. Hence, the calculated GA is a catchment average result.

ModelBuilder, a special tool included in ArcGIS for building workflows with multiple data layers and functions, was used for developing and processing the multiple steps of this approach (see Figure 3.5). The built application brought all the inputs and GIS functions into a single framework, feeding outputs of one function as inputs to another in a consequent sequence. The automatic procedures ensured consistency in processing the original inputs, through to intermediate results to the final outputs. Most spatial analyses were done on raster maps with a resolution of 10 m.

3.3.3 Land use-based approach

The land use-based approach aimed at estimating, on the basis of the type of land use, the groundwater abstractions for the dry season for the three main groundwater users in the catchment: irrigation, domestic and livestock farming. The amount of groundwater used for irrigation was estimated (Step 1, see Figure 3.5) on basis of the land use map (see Figure 3.1) and the rate of irrigation ($R_{a\text{-}irr}$). For evaluation of uncertainty in the estimated results, the irrigation rates of each crop was estimated based on data from two separated sources: (1) qualitative survey and (2) estimated by the Agricultural Science Institute for

Southern Coastal of Vietnam (ASISOV) using FAO56 guidelines from the Food and Agriculture Organization (FAO) (Allen *et al.*, 1998) and experiments of water requirements of local crops for each stage after planting. Determined crop rotation cycles for each land use class (Nguyen, 2017) allowed detailed irrigation rates from both sources for each land use as the amount of water consumed by the type of crop planted in that land use for each month.

Two possible approaches were employed for developing the map of population density of the catchment (Step 2, see Figure 3.5), based on (1) an online source of global data on population distribution and (2) a Google Earth image of the area. In the first approach, the worldwide 250 m resolution grid data of population for the year 2015 was used (https://www.prepdata.org/explore). For the second approach, a point map indicating the distribution of households over the area was created based on Google Maps. The point map was converted to a raster (250 m resolution) population distribution map by multiplying the number of households in each cell with the average number of people in each household (i.e., household's size) as resulting from the survey. Both population density maps were downscaled to 10 m grid resolution for compatibility with other data in this study and application in Eq. 3.2 using the resample tool in ArcGIS (bilinear interpolation). A spatially distributed raster map of groundwater abstractions for domestic use (GA_{dom} (m), Step 3, see Figure 3.5) was estimated from a population density map (Pop_{den}, number of persons per raster cell of 10 by 10 m) and the average groundwater consumption rate per person per area ($R_{a\text{-}dom}$, (m)).

$$\mathrm{GA}_{dom} = \mathrm{Pop}_{\mathrm{den}} * \mathrm{R}_{\mathrm{a-dom}} \tag{3.2}$$

The amount of groundwater abstracted on average per person per unit area for domestic use ($R_{a\text{-}dom}$) was calculated based on the average volume of water consumed per person (R_c, (m^3)) and the percentage of water provided by groundwater (P_{gw}) as obtained from the survey,

$$\mathrm{R}_{\mathrm{a-dom}} = \frac{\mathrm{R_c} * \mathrm{P_{gw}}}{\mathrm{A}} \tag{3.3}$$

where A is the area of a raster cell of 10 by 10 m. This areal consumption rate was differentiated for (1) Ngo May town and (2) all other villages, as ancillary and survey data allowed estimating the percentage of people using groundwater.

Similar to groundwater use for domestic purposes, the spatial distribution (raster) of groundwater abstracted for use by livestock animals (GA_{far} (m), Step 5, see Figure 3.5) was estimated based on the density of animals (N_{ani}, number of animals per raster cell of 10 by 10 m) and the average consumption rate of each animal (R_{a-far} (m)),

$$\mathrm{GA}_{far} = \mathrm{N_{ani}} * \mathrm{R_{a-far}} \tag{3.4}$$

The total number of people and livestock per farm surveyed and using groundwater was used to determine the ratio of people to animals in each community. This ratio was then applied for converting the population density maps to a livestock density map (N_{ani}) (Step 4, see Figure 3.5). For examining all possibilities, both population data from two sources as described above were used, resulting in two maps of animals' density for the catchment estimated. The results from the qualitative survey showed that the areal consumption rate per animal was the same as the rate consumed per person for their domestic use. The survey also showed that the amount of water used for domestic purposes and livestock farming reduces towards the end of the dry season because some productive wells dry out. Based on the survey, a decrease during the dry season was considered in the groundwater consumption for domestic needs (Step 3, see Figure 3.5) and animals for livestock farming (Step 5, see Figure 3.5).

Finally, total groundwater consumption (GA) was calculated (Step 6, see Figure 3.5) by summing up the abstractions for irrigation (GA_{irr}), domestic use (GA_{dom}) and livestock farming (GA_{far}).

$$\mathrm{GA}_{irr} + \mathrm{GA}_{dom} + \mathrm{GA_{far}} = \mathrm{GA} \tag{3.5}$$

The calculation of groundwater abstraction in this approach was done on the basis of raster maps for the whole catchment. Similar to the groundwater balance-based approach, ModelBuilder was used to automate the calculation process.

3.3.4 Uncertainty and error propagation

Uncertainties and errors enter the results from errors associated with the original input data and are propagated through the calculation processes. Errors associated with inputs resulting from measurements, estimation and determination processes or a combination of them, were estimated either in absolute form as its possible discrepancy or in relative form as the proportion of the determined values, depending on how each input was estimated (e.g., directly measured or modelled). The errors of the inputs directly measured or estimated (e.g., groundwater levels) were assigned absolute values of potential errors of each particular measurement or estimation. Modelled inputs (e.g., recharge and base-flow) were assigned errors equivalent to the relative percentage of the estimated values. Categorial input errors of crop irrigation rates were estimated as the difference between the value of each crop with the maximum and minimum of the others crops that would be confused as the estimated one (e.g., peanut would be confused by cassava and some kinds of vegetables when classifying land use and determining its irrigation rate). For population and irrigation rates, which have more than one possible value, the most reasonable value (i.e., agreed well with other data and information) was selected as the determined value, while other possible values were used for determining the errors. The error of the specific yield was based on the possible range as reported in literature. In practice, if an input has more than one method for determining its error (e.g., irrigation rates), the largest error was used. All the inputs were considered normally distributed, and the error introduced was equally representative for both sides of the distribution.

The error propagation toolbox included in ArcGIS (Heuvelink *et al.*, 1999; Miller, 2015) was used for estimating how the errors would propagate through the calculation process to result in a final error estimate. The error propagation toolbox includes four tools for every single calculation of addition, subtraction, multiplication and division of each time two parameters. To apply these tools, any complex calculation should be broken down into multiple two parameter functions. The tool is able to not only calculate the result but also to estimate the errors associated with the result, which is propagated from errors introduced to the inputs. The propagated errors are calculated using standard equations for propagation of error as described in Taylor (1997).

Results from the error propagation tools applied in ArcGIS provided the absolute errors that were propagated from errors associated with inputs through calculation processes to the final outputs. Relative errors were then calculated by dividing the absolute errors to their estimated values. The result from the first approach (groundwater balance based) was a catchment average value. Therefore, the error was also estimated as an average value for the whole catchment. For the second method, errors were examined in both spatial distribution and the catchment average values.

3.4 Results

3.4.1 Groundwater abstraction of the surveyed wells

Owners of 77 wells reported their pumping routines regarding the amount, time and purposes of extracted groundwater. The information was not specific for a particular year but rather indicative of typical average year conditions. Generally, intensive groundwater abstraction was reported during the dry season (from January to August), particularly for the main cropping period from the end of December to the beginning of April, accounting for up to 70% of total annual abstraction. Surveyed farms showed much lower irrigation during the wet season, and some of the domestic water demand was covered by rainwater. The amount of water extracted varied from well to well and from month to month. Smaller abstractions were observed at wells used for domestic demand only, with 5–10 m^3 of water pumped per month, while larger abstractions were reported for wells for irrigation and multiple purposes. Monthly average abstractions slowly increased from about 65 m^3 up to 175 m^3 during the wet season (September to December) and increased significantly at the beginning of the dry season (January to March) for crop irrigation up to about 330 m^3 per month (see Figure 3.6). In the second half of the dry season (May to August), the surveyed abstractions dropped significantly. Even though total water use for domestic purposes and livestock farming was constant with time, the amount of groundwater used for these purposes dropped at the end of the dry season (June to August) (see Figure 3.7), as some wells dried out and water use was satisfied by other sources (e.g., surface water and bottled water).

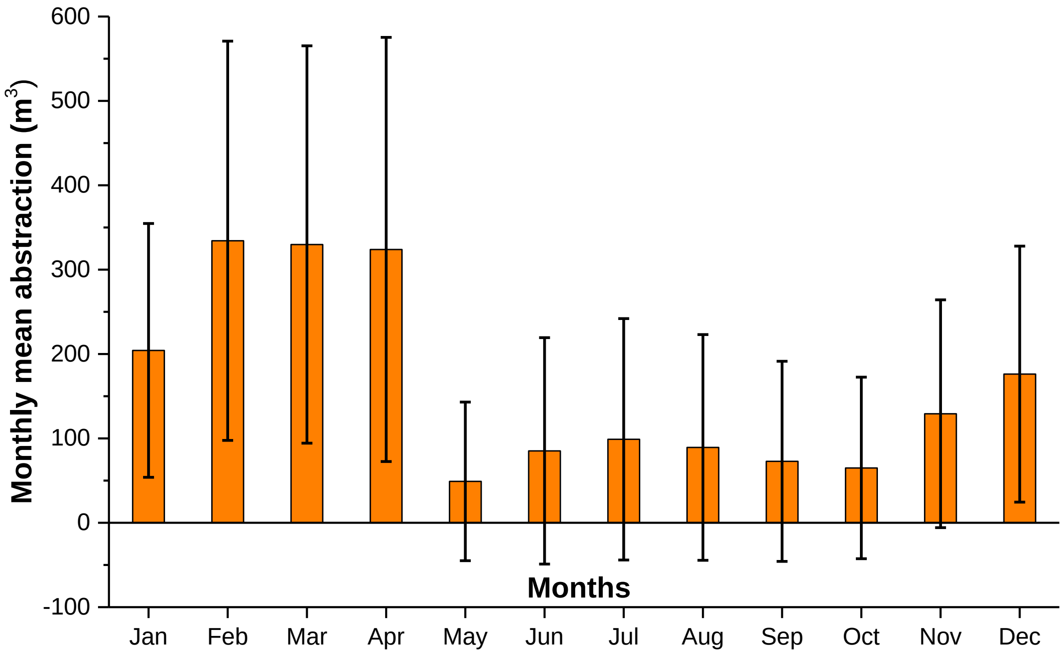

Figure 3.6. Monthly mean abstraction per well for the 77 surveyed wells. The error bars exhibit the standard deviation.

Summation of the results of the 77 surveyed farmer wells showed a total groundwater abstraction of 137,775 m^3/yr or 1,800 m^3/yr per well for satisfying the demands of water for domestic use, livestock farming and irrigation. Irrigation was the dominant water user with 84% of the total annual abstraction, while domestic use and livestock farming (e.g., cows and pigs) consumed 11% and 5% of the total, respectively (see Figure 3.7).

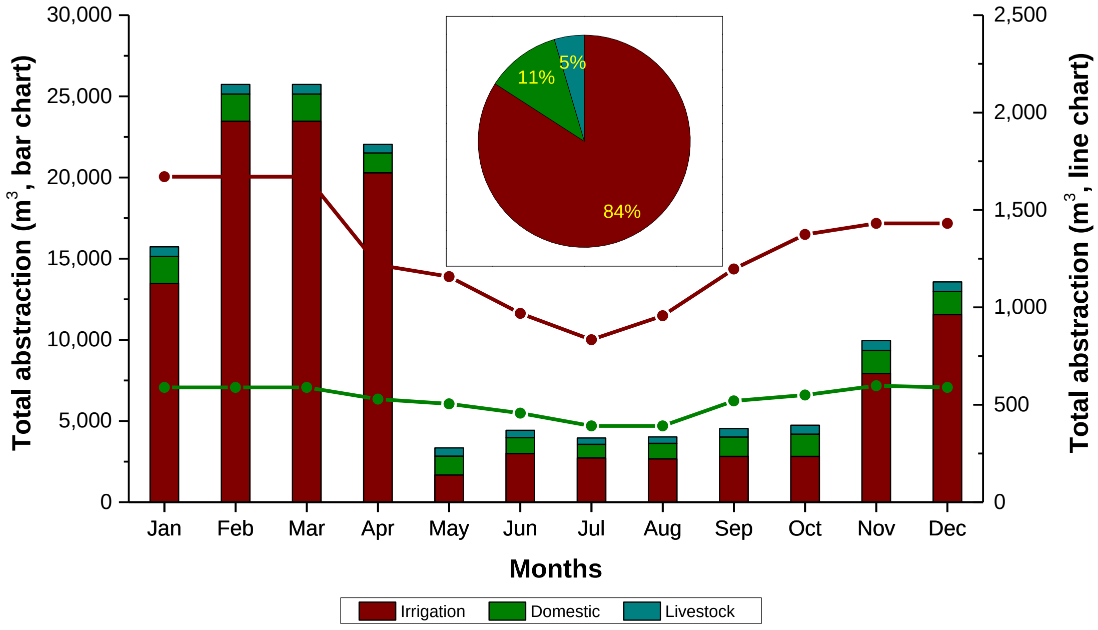

Figure 3.7. Monthly total groundwater abstracted for irrigation, domestic and livestock use from 77 surveyed wells. The bar chart shows the abstraction of the three uses, the line chart shows the usages for domestic and livestock separately. The inset pie chart exhibits the contribution of the three different uses to the total yearly abstraction.

3.4.2 Groundwater balance-based abstraction

The survey shows that the highest groundwater table typically occurred at the end of the rainy season in December, with the groundwater depths spatially varying up to a maximum 1.4 m below-ground surface. The groundwater level dropped to its lowest level at the end of dry season in August, with a 1.6–9.8 m drop observed. Larger variations were typically observed in upland areas close to the water divide, rather than in the valleys.

Both interpolated minimum and maximum groundwater levels mimicked the surface topography, as groundwater gradients are from the high elevation at the watershed divide to the low elevations along the river, and from upstream to downstream. At the end of the rainy season (in December), the groundwater level was maximum with its absolute elevation spatially varying between almost 6 m (near the outlet of the catchment) up to about 49 m (north-west corner of the catchment) above mean sea level. At the end of the dry season in August, the groundwater table dropped to its lowest level, spatially ranging from about 4 m to 42 m above mean sea level. In mountainous areas, there were no observations of groundwater depths from the survey. This resulted in poor interpolation of the groundwater table in some areas with elevations lower than the aquifer bottom. Hence, for about 15% of the area (mostly remote hilly terrain), the elevation of the groundwater table could not be determined and was treated as no data.The largest variations in groundwater level (about 13 m) were observed in the mountainous area at the north-west edge of the catchment. Some agricultural land areas close to the north-western edge and centre of the catchment and at the small town of Phu Cat (south-east corner) exhibited a medium variation of 5–7 m. Conversely, a small variation of 1.5 m approximately was observed in parts of the lowlands near the stream network (see Figure 3.8).

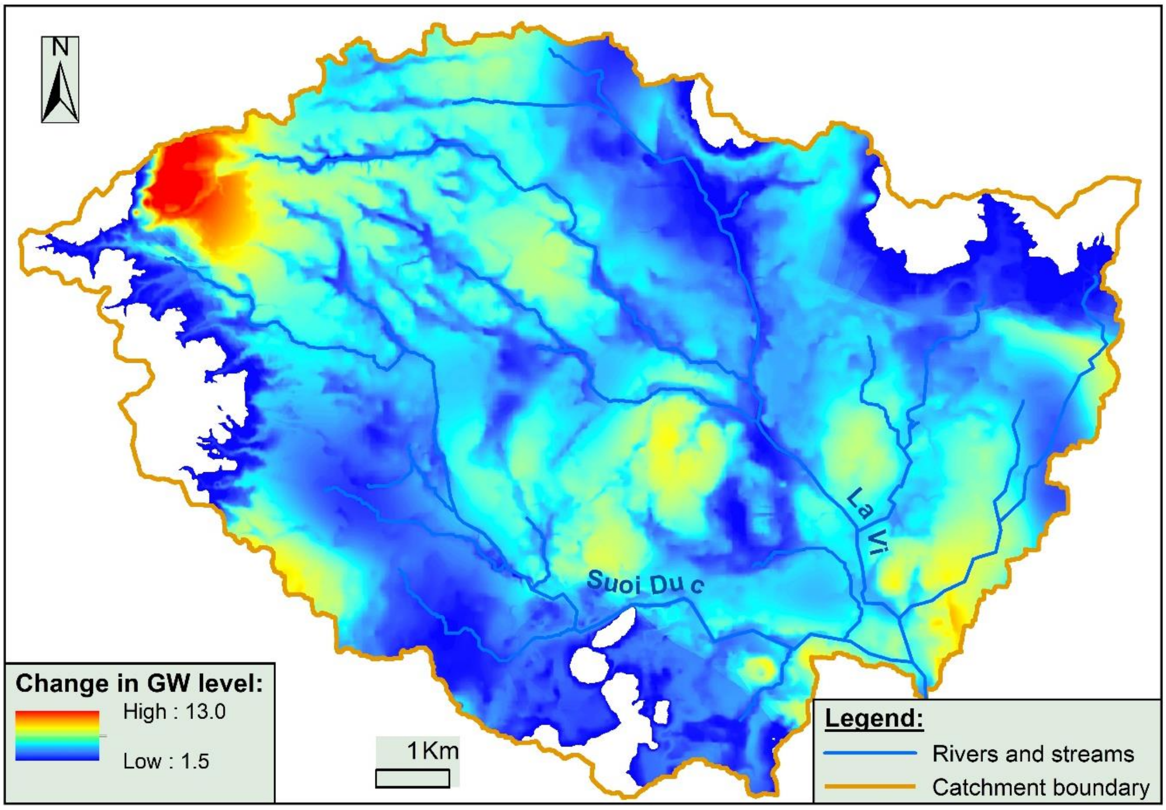

Figure 3.8. Reduction in groundwater level from December to August, based on differences in the interpolated maximum and minimum groundwater levels as resulting from the farmer surveys. The white areas are zones where the interpolated groundwater levels fell below the bottom of the aquifer, hence no significant groundwater resource was assumed.

Given the values of calculated specific yield of all the soils throughout the whole catchment varied, though small, in the range of 0.26–0.29 (standard deviation of 0.01), the pattern of change in groundwater storage (0.0–2.65 m) was much the same as the variation in groundwater table elevation.

As simulated by the WetSpass-M model, the total net recharge for the dry season from January to August (2016) was mostly negative (i.e., actual evapotranspiration from groundwater), as the 365 mm precipitation for the dry season is only 14% of the annual rainfall. The spatial recharge pattern (see Figure 3.9) showed relatively high evapotranspiration in the central part of the catchment between the two main tributaries, particularly for the lowland areas along these streams, as here groundwater tables are shallow, and evapotranspiration is high. In contrast, actual recharge (positive values) were observed in the upland areas in the west and north-east where groundwater is depth and little evapotranspiration occurred.

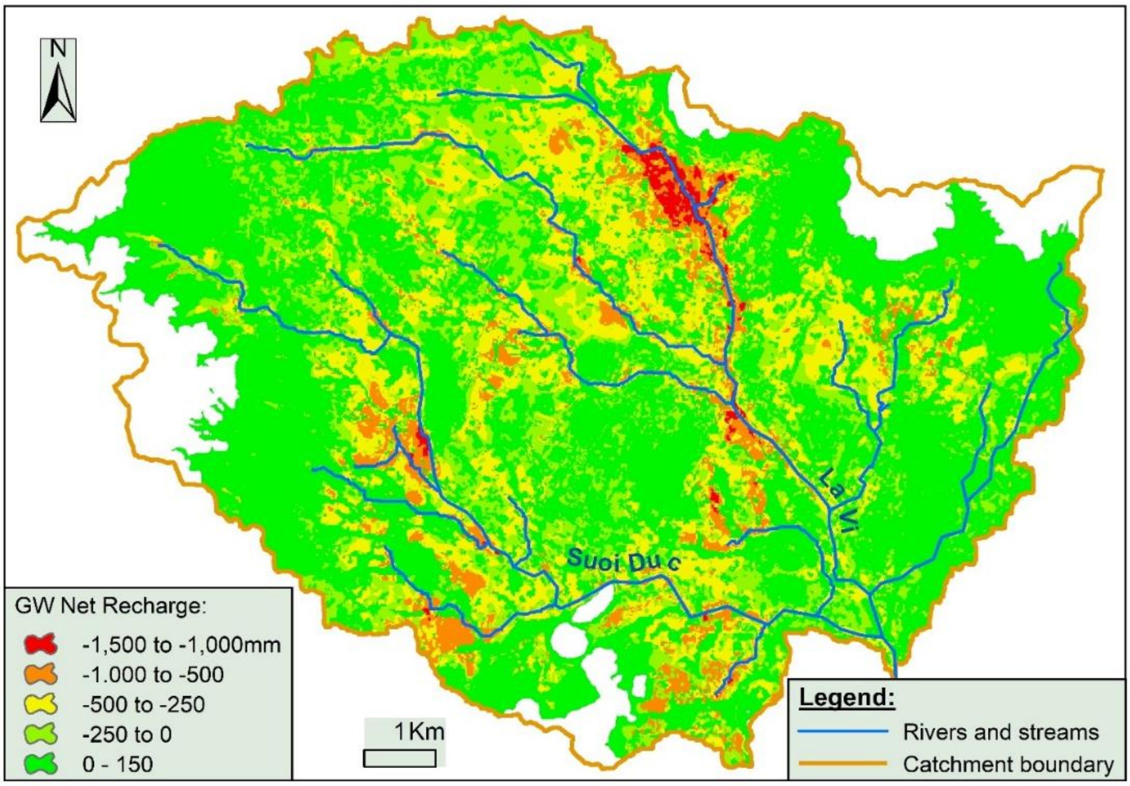

Figure 3.9. Net recharge to groundwater as simulated by WetSpass-M for the dry season from January to August 2016. The white areas are zones where the interpolated groundwater levels are below the bottom of the aquifer, hence no significant groundwater resource and recharge was assumed.

Groundwater base-flow to the river was another component of the change in groundwater storage. As estimated by Vu *et al.* (2018), the flux to the river varies both spatially and temporally. Generally, the base-flow increased from upstream to downstream, and decreased from the rainy to the dry season and it ceased around five months after the end of the intensive rainfalls in May (see Table S.1). Summing up the fluxes for the base-flow active months from January to August resulted in a total flux downstream (S1), midstream (S2) and upstream (S3) of 1,007, 644 and 281 m^2, respectively (i.e., the specific flux - the volume of flux per metre of river length). These fluxes scaled up to a total flux of approximately 35×10^6 m^3 for the whole catchment, which is equivalent to a specific discharge of 35 mm (the catchment area is slightly over 99 km^2).

3.4.2.1 *Catchment average groundwater abstraction from groundwater balance-based approach*

The groundwater balance was calculated for the active cells (not including the no-data zones where the interpolated groundwater levels fell below the bottom of the aquifer in Figure 3.8) of the catchment for the dry season from January to August (see Table 3.1). The results show that during the dry season groundwater abstraction, base-flow to the river and evapotranspiration were the groundwater sinks of the whole catchment, of which groundwater abstraction was largest, contributing to nearly half (43%) of the total. Base-flow to the river and evapotranspiration contributed to the other half with their portions of 43% and 14%, respectively. As the rainfall in the dry season was low and recharge from rainfall was smaller than evapotranspiration from groundwater, all the sinks, including groundwater withdrawal were sourced by the decrease in groundwater storage.

Table 3.1. Catchment-based groundwater balance for the dry season, from January to August

Component	**Unit**	**Type**	**Value**	**Proportion (%)**
Change in groundwater storage	10^6 m^3	Sources	73.13	100
Evapotranspiration (negative net recharge)	10^6 m^3	Sinks	10.30	14
Groundwater flow to the river (Base-flow)	10^6 m^3		31.76	43
Calculated groundwater abstraction	10^6 m^3		**31.07**	43

3.4.3 Land use-based groundwater abstraction

3.4.3.1 *Groundwater abstractions for irrigation purposes*

The typical type of crops grown in the La Vi River catchment are peanut, cassava, paddy rice and vegetables (i.e., cucumber and pepper chilli) as annual crops, along with the perennial plants of coconut, mango and acacia. Crops are either planted separately or in combination with others. For instance, cassava can be mixed with peanut and paddy rice. These complicated cultivation practices have resulted in 11 detailed agricultural land use classes along with four other classes. These land use classes and their areal coverage are listed in Table S 3.2. Urban land is mainly located in the small town of Ngo May in the south-east corner of the catchment and further small villages occur throughout the catchment. Only the agricultural land and urban land use classes use groundwater for irrigation, domestic use and livestock farming.

Groundwater consumed by irrigation differs from one crop to another in amount and scheduling. For each type of crop, farmers' irrigation practices vary by experience and groundwater availability in their own wells. The surveyed results (see Table 3.2) showed that the maximum consumption rate was for vegetables (e.g., cucumber and chilli), with rates of 11,625 m^3/ha annually, as they are seasonally planted in rotation and normally require irrigation the whole year. Seventy-five per cent (8,732 m^3/ha) of this amount was consumed during the dry season (January to August). Conversely, mango required the least water for irrigation, needing only 3,303 m^3/ha annually (all consumed in the dry season), as it requires water for only five months (typically from January to May). Other types of crops exhibited rates between these values. Annual crops of peanut, vegetables, paddy rice and perennial crop coconut are watered not only during the dry season (January to August), but also to a lesser extent in the rainy season. Cassava does not require irrigation during the rainy season. Intensive irrigation occurs during the dry season, contributing to at least 75% of annual groundwater extraction. Acacia, forest and the cassava are non-extractive classes that do not require any groundwater abstraction for irrigation.

The irrigation estimates by ASISOV based on the FAO56 guidelines were significantly smaller than the estimates from the surveyed results (see Table 3.2). This may be because farmers tend to use more water than is really required by the crops based on their poor understanding and lack of irrigation techniques. The exception was cassava, as the survey showed that it is a low-income crop that farmers normally plant in remote hilly areas or in rotation with other crops without irrigation applied to the cassava. The estimates also showed that mango required the least water for irrigation with a rate of only 3,303 m^3/ha, as mango only requires irrigation for a short period from January to May. None of the crops was expected to consume water during the wet season from September to December. Again, acacia and forest plants were considered to not use groundwater for irrigation.

The areal consumption rates of each land use class for the dry season was based on their cultivation practices (i.e., the crop pattern of each land use class for every month and its irrigation practice) (see Table S 3.2).

Table 3.2. Groundwater consumption rates for each land use class for the La Vi catchment, calculated based on irrigation rates resulting from the survey and FAO56 guidelines. The rates for the perennial plants class were obtained as the average of surveyed rate for coconut and FAO56 rate for mango.

Land use class	**Dry season (m^3/ha)**		**Wet season (m^3/ha)**		**Annual (m^3/ha)**	
	Survey	**FAO56**	**Survey**	**FAO56**	**Survey**	**FAO56**
Paddy rice (single)	0	0	0	0	0	0
Paddy rice (double)	0	1,499	0	0	0	1,499
Paddy rice (triple)	3,614	3,866	0	0	3,614	3,866
Cassava	0	4,665	0	0	4,665	0
Paddy rice, cassava	0	4,665	0	0	4,665	0
Peanut, cassava	6,553	4,661	902	0	7,455	4,661
Paddy rice, peanut, cassava	7,510	5,076	0	0	7,510	5,076
Peanut	6,553	1,359	902	0	7,455	1,359
Paddy rice, peanut	7,510	1,010	0	0	7,510	1,010
Other annual plants	8,732	3,591	2,920	0	11,652	3,591
Perennial plants	4,672		0		4,672	

The dry season groundwater abstraction for irrigation, obtained from land use data and irrigation rates of crops from the qualitative survey, was spatially highly variable. Generally, intensive irrigation was observed in the centre of the valley where it is mostly covered by agricultural land. Conversely, there was no groundwater abstraction for irrigation purposes in the forest and bare land mostly at the edges of the catchment and at the intensive residential area of Ngo May town (south-east edge of the catchment). Highest consumption rates of 873 mm (8,732 m^3/ha) were observed at places where other annual plants (vegetables) are planted. Low abstractions of 361 mm (3,614 m^3/ha) were observed at places where paddy rice is planted three times per year (irrigation is applied only for the second season of the year, from June to August). A total estimated 35.33×10^6 m^3 of groundwater was extracted for irrigation for the whole catchment.

The spatial pattern of groundwater abstraction for irrigation, based on the irrigation rate of crops estimated by ASISOV (FAO56 method), was similar to the one from the qualitative survey of intensive irrigation central in the catchment. However, the amounts of groundwater abstractions were different. The highest abstraction rate of 467 mm (4,672 m^3/ha) was observed where perennial plants (mango and coconut) were planted, while lower abstractions of 101 mm (1,010 m^3/ha) were estimated when paddy rice was planted together with peanut. The discrepancy of the abstractions rates estimated based on the FAO56 guideline and the qualitative survey is attributed to poor irrigation practices of local farmers, which was mainly limited by groundwater availabilities in their wells. Cassava and paddy rice were mostly planted in the highland areas where limited groundwater is available and hence no irrigation was applied. In contrast, vegetables, peanut and mango are usually grown in the central valley where groundwater is available for irrigation. A total estimated 23.51×10^6 m^3 of groundwater was extracted for irrigation for the whole catchment. This was 33% lower than the amount based on the land use data and irrigation rates of crops from the qualitative survey described above.

3.4.3.2 Groundwater abstractions for domestic and livestock purposes

Population data from the two used sources showed a large range of 50 to 2,500 persons/km^2 for the rural areas. The sub-urban area of the small town of Ngo May exhibited a higher population density of 5,000 to 10,000 persons/km^2. The population distribution from both sources was similar. However, data converted from the house map of the catchment along with the average number of people per household (see Figure 3.10) resulted in a total of 37,475 people, while this was 51,590 people according to the global population data for 2015 - a difference of approximately 40%.

The qualitative survey showed that livestock density in the rural communities was 2.5 times lower than people density, while the number of animals for the small town of Ngo May was assumed zero.

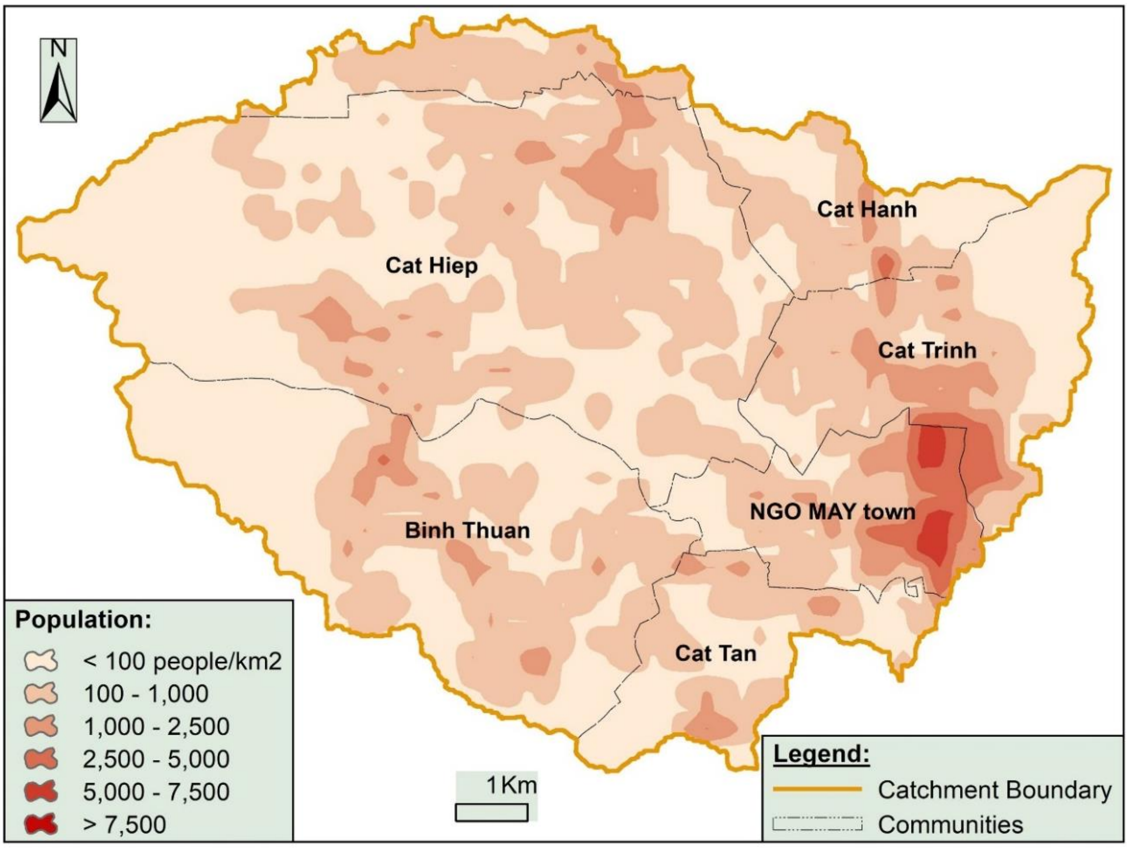

Figure 3.10. Population density map of La Vi catchment, derived from houses identified on a Google Earth image and using an average of five persons per household as obtained from the field survey. The largest residential area is the small town of Ngo May in the south-east corner of the catchment with more than 7,500 persons/km^2, while most other rural areas have lower densities of up to 1,000 persons/km^2.

The qualitative survey showed a spatially constant per capita water consumption of 0.1 m^3/day for both people and livestock animals. However, the percentage of water supplied from groundwater (P_{gw}) was spatially variable. All the water consumption for domestic use in the rural communities of the catchment was supplied by groundwater, as there was no tap water supply system (P_{gw} = 100%). There was no information about the percentage of groundwater contribution for domestic use at the small town of Ngo May. Hence, the rough estimation of P_{gw} = 50% was used for this area, as the water consumed by people and animals was not supplied for groundwater or tap water (from external water sources). Moreover, groundwater consumption for domestic use and livestock farming was estimated to drop to around 50–70% in the second half of the dry season due to the unavailability of groundwater in some areas.

As it is mainly controlled by the population distribution, the spatial pattern of groundwater consumed for domestic use and livestock farming was similar to the population distribution. If the population data converted from the house map was used, the total amount of groundwater extracted for domestic use was 0.69×10^6 m^3 for dry season. The highest abstractions of 100–130 mm (100,000–130,000 m^3/day.km^2) were observed at the Ngo May town, while much lower rates of just 10–50 mm (10,000-50,000 m^3/day.km^2) were observed in rural areas. When the downscaled global population data were used, the total domestic use was 0.95×10^6 m^3, which is 38% higher than the use based on the house map. The rates for livestock farming consumption that were based on the survey were a factor 2.5 lower than the rates for domestic use, except the Ngo May town where no farming system was applied.

3.4.3.3 Total groundwater abstractions land use-based approach

Summing up the groundwater abstractions for irrigation, domestic and livestock use provides the total for the whole catchment. However, as two approaches were pursued for both the irrigation rate and population estimation, there are four outcomes for the total groundwater withdrawn during the dry season (see Table 3.3).

Table 3.3. Total catchment dry season 2016 groundwater abstractions based on the land use approach with estimates based on two different inputs for irrigation rates (columns) and two options for population data (rows).

Irrigation rate / **Population**	**As surveyed**	**Per FAO56 guideline**
Converted from house map	36.19×10^6 m^3	24.37×10^6 m^3
Downscaled from global population data	36.39×10^6 m^3	24.57×10^6 m^3

The groundwater abstraction with the irrigation rate as surveyed and population based on the house map (see Figure 3.11) was spatially heterogeneous but had a strong imprint of the land use distribution in the catchment. In general, high abstraction rates of approximately 1,000 mm (10,000 m^3/ha) were observed in the valleys in the centre of the catchment where agricultural land is dominant. Conversely, intensive residential areas around Ngo May town exhibited a lower rate. Mountainous areas showed no abstraction, as they are forested and have no associated abstractions.

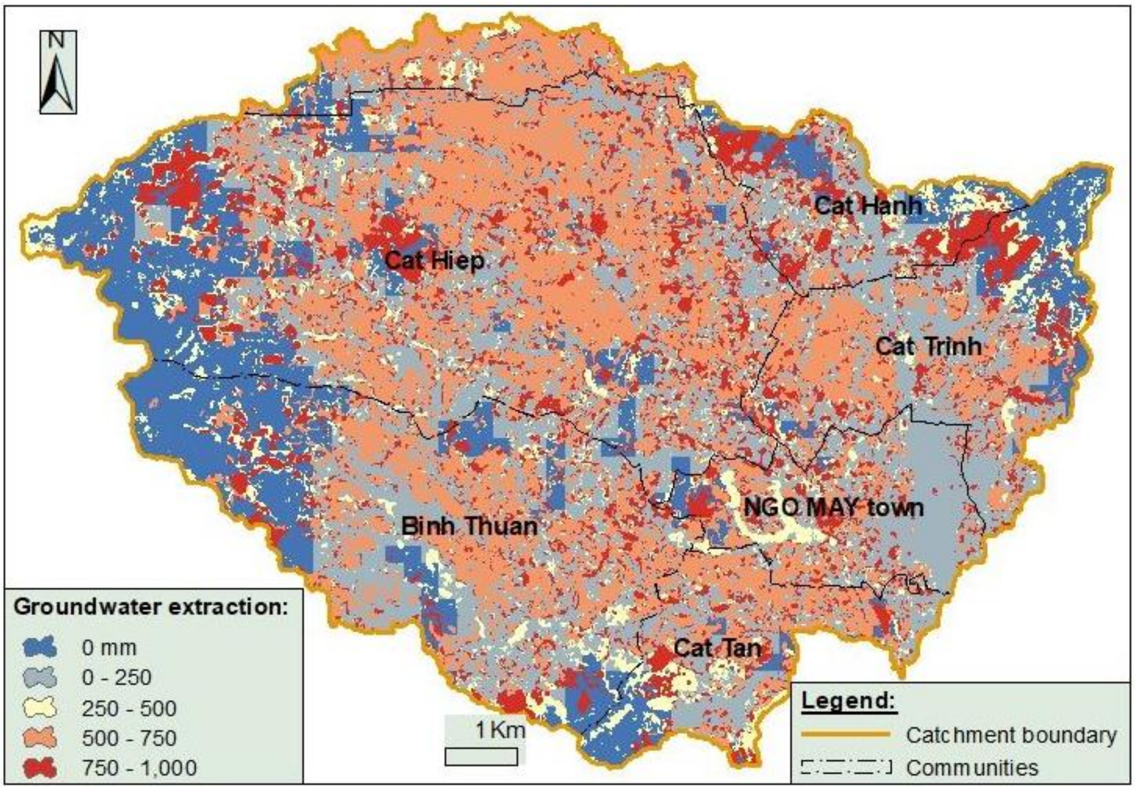

Figure 3.11. Map of groundwater abstraction for the La Vi River catchment for the 2016 dry season estimated following the land use-based approach, with irrigation rates as surveyed and population based on house map.

3.4.4 Uncertainty assessment

Estimated errors associated with every single input of each method are summarised in Table 3.4 and are propagated through the groundwater abstraction calculation process.

Table 3.4. Inputs for estimating groundwater abstraction and their associated errors.

No.	Input	Source of data	Source of errors	Value	Notes
I. GW balance-based approach					
I.1	Max GW level	Estimated by farmers	Wrong in estimation	Up to 1 m	Not above the ground surface
I.2	Min GW level	Estimated by farmers	Wrong in estimation	Up to 1 m	Not below the aquifer bottom
I.3	Specific yield	Experimental	Wrong in experiment	0.1	Based on the possible range of S_y for sandy soils from the literature
I.4	Net recharge	Modelled	Modelling	10%	
I.5	Base-flow	Modelled and calculation	Modelling	10%	
II. Land use-based approach					
II.1.	Irrigation rate	Surveyed	Wrong in estimation and confusion in crop type	20% or max difference	Differences between rate of a crop with its confusion ones, or between the rates estimated by surveyed and FAO's guidelines
II.2	Number of people	Internet	Wrong in survey and interpolation	40%	Difference between population data converted from the map of households and downscaled from the global population data
II.3	Rate for domestic use	Surveyed	Wrong in estimation	10%	
II.4	Relation between people and animal	Surveyed	Wrong in estimation	10%	

Note. FAO: Food and Agriculture Organization of the United Nations; GW: groundwater; S_y: specific yield.

For the groundwater balance-based approach, an absolute error of 42.65×10^6 m^3 was calculated, equalling a relative error of 137% of the estimate. This error, together with the estimated groundwater abstraction of 31.07×10^6 m^3, resulted in a potential range of $0\text{-}73.72\times10^6$ m^3 of groundwater abstraction for the whole catchment.

For the land use-based approach, spatially distributed errors of 0–873 mm (0–8,732 m^3/ha) were estimated. In general, lower errors of less than 200 mm (2,000 m^3/ha) were observed in residential areas where the water was extracted only for domestic use and livestock farming. In contrast, for agricultural land, the errors were high, up to 873 mm (8,732 m^3/ha). The average estimated relative error was 176%, with 6%, 74% and 100% of the catchment area having relative errors smaller than 50%, 100% and 250%, respectively. As the used groundwater abstraction for error estimation was 36.19×10^6 m^3, a resulting range of 0–99.90×10^6 m^3 was obtained for the groundwater abstraction for the land use-based approach. This range was larger and entirely covered the range for the groundwater balance-based approach (0-73.72×10^6 m^3).

3.5 Discussion

Using soft data in hydrology in place of the often-lacking 'hard data' (i.e., the direct measurements) for estimating groundwater abstractions is obviously useful (Seibert & McDonnell, 2002). The La Vi River catchment is ungauged in terms of groundwater abstraction, similar to many other catchments in developing countries (Giordano, 2009; Siebert *et al.*, 2010). Thousands of small, private open boreholes and wells exploit groundwater in the catchment. The absence of abstraction monitoring means that it is impossible to record the amount of groundwater withdrawn from all the wells throughout the catchment. It also means that due to this lack of groundwater management, there are serious risks of over-abstraction, groundwater depletion and decline of ecological values of groundwater-dependent ecosystems (Wada *et al.*, 2012; Gleeson & Richter, 2018). Conversely, 'soft data' for estimating groundwater abstraction might either already be available or can be relatively easily obtained by field surveys or from data sources available over the internet (e.g., remotely sensed data). Here, we tested the applicability of soft data for a groundwater balance and a land use-based approach for estimating groundwater abstractions in the La Vi catchment.

The groundwater balance-based approach estimated the groundwater abstraction as the rest term of the balance equation, as the other terms could be estimated on the basis of soft or hard data. However, this approach provides only a single catchment average value for the groundwater abstraction, as the required base-flow cannot be estimated in a distributed manner. The uncertainty in the result of this approach is due to the difficulty in accurately determining the specific yield and change in groundwater level and, hence, the product of change in groundwater storage (Healy & Cook, 2002). Inaccuracy in interpolation of the groundwater level from point data, especially where points were limited or not well distributed throughout the catchment, contributed significantly to the error. As the relative error in the change in groundwater level was estimated to be 137% compared to the relative error of 38% in the specific yield, it is obvious that this method is highly dependent on the accuracy of the groundwater level estimation.

The direct link between the land use and abstraction makes the land use-based approach extremely useful in scenarios analyses, supporting decision-making processes regarding water allocation problems (Letcher *et al.*, 2007). However, the uncertainties of this approach depends on the accuracy of the data and methods for land use mapping (Letcher *et al.*, 2007), and mixed land use and seasonal changes that make remote sensing image classification difficult (Hurtt *et al.*, 2006). The uncertainties are also highly determined by the accuracy of water consumption rates, which are hard to quantify, both for crop irrigation rates (Zwart & Bastiaanssen, 2004) and for residential water demand (Arbués *et al.*, 2003). The variation in the estimated irrigation rate for each crop and between crops, possibly occurring within the classified land use class, created the most uncertainty in this method, with estimated relative errors of up to 180%. Another source of uncertainty in this approach was that the variation in population density from two different sources showed a difference of up to 40%. A 1999 population estimation (Wikipedia, 2017, 2018a, 2018b, 2018c) of the area showed 33,821 inhabitants. As the population growth rate in Vietnam since 1999 is about 1%, this aligns closer with the population estimated on the basis of the house map than on the basis of the global downscaled data. However, as the abstraction in the dry season for domestic use and livestock farming was small (2.5%) compared to irrigation (97.5%), the error in the population estimate will have a relatively small effect on the total error. The combination of two options for estimating the irrigation rate and two options for the population density resulted in four spatially distributed abstraction results. As for both the irrigation rate and the population estimates, the local or surveyed data appears more reliable. Most confidence is given to the total dry season abstraction estimation of 36.19×10^6 m^3 (see Table 3.3 and Figure 3.11).

Comparing the total dry season abstraction estimates of both approaches, the results compared well to each other, with a discrepancy of approximately 15%. However, the discrepancy would be larger if some of the other land use-based results were used or if groundwater level data were available for some upstream areas. The discrepancy between the methods would be huge if they were applied to other areas due to differences in the circumstances of data availability. This large uncertainty is normally connected to the 'soft data'. Hence, it is important to use multiple soft-data approaches, as consistency in results will provide confidence.

In terms of the applicability of each approach, the land use-based approach has the advantage of providing spatially distributed results, as it takes into account spatial information and knowledge on irrigation and domestic and livestock consumers when estimating groundwater abstractions. Therefore, this method would be appropriate when land use change scenarios would be analysed. In addition, its spatially distributed result makes it more suitable for using in a groundwater flow model. Comparing the two methods in terms of uncertainty, the land use-based approach has a smaller range of possible outcomes than does the groundwater balance-based approach.

Even though studies using 'soft data' are limited in the literature, there have been some other catchment groundwater abstraction estimation approaches, such as using a model or utilisation factors. Cheema *et al.* (2014) used a SWAT model with remotely sensed precipitation data that was calibrated based on remotely sensed evapotranspiration data to build a 1 km resolution map of groundwater abstraction for the Indus basin, India. Maupin (1999) used historical pumping data to correlate water consumption with power consumption and total head at different pumping sites of the Snake River, United States, for estimating total irrigation water withdrawals from recorded power consumption data. Although benefits of 'soft data' are clear, some disadvantages and uncertainties are noted, including the limited available measurements (Cheema *et al.*, 2014) for setting up and calibrating the model or that some utilisation factors are influenced by other factors than by the amount of water withdrawal.

The indirect data approaches used in this study for estimating groundwater abstraction are mostly constrained by uncertainties in establishing land use data (Hurtt *et al.*, 2006), estimating (ground)water consumption rates for irrigated crops (Zwart & Bastiaanssen, 2004) and domestic use (Arbués *et al.*, 2003) and inaccuracy in interpolating groundwater level data (Peeters *et al.*, 2010). Using the ModelBuilder tool included in ArcGIS for working with spatial data, this study has shown the tool to be advantageous in its consistency to produce results due to estimation automation (i.e., easily updated versions can be produced and compared). The utility of the tool increases further when land use scenarios would be tested in terms of their effect on groundwater abstraction.

Considering the global pressure on groundwater resources due to agriculture, especially in developing areas, there is a high need for approaches for estimation and monitoring of groundwater abstractions supporting improved and more sustainable groundwater use. Approaches need to support water managers and be commensurate with the financial, social and organisational constraints of a region. From this study, it follows that approaches based on remotely sensed land use have considerable advantages. To reduce uncertainties, it is highly recommended to have regular groundtruthing of land uses (e.g., types of crops and rotation), more detailed stratified sampling of farmers' irrigation practices (e.g., number and type of wells, irrigation scheduling and techniques used) and, based on this, automated groundwater level and discharge monitoring for limited but representative practices.

3.6 Conclusion

This study examined two soft-data approaches for estimating groundwater abstraction based on local knowledge and information on groundwater levels and land use data based on remotely sensed information. These data sources were able to help in overcoming the issues of unlicensed or non-recorded groundwater abstraction currently facing many regions. The tested approaches add to the variety of methods for estimating groundwater abstraction known from the literature. The specific conclusions are:

- The groundwater balance-based approach estimated groundwater abstraction as the rest term of the groundwater balance equation. However, the method is only able to provide one catchment average abstraction value. Therefore, it likely serves more as a check on other more local or regionalised approaches.
- The land use-based approach examined the spatial distribution of groundwater abstraction. Hence, this is highly beneficial if groundwater abstractions are localised, and useful for examining the consequence of land use changes to groundwater resources.
- Using more than one method for estimating groundwater abstraction in one single study allows for crosschecking estimated results. Uncertainty analyses are another crucial issue when using soft data, as it allows estimating most critical parameters and data to be updated by monitoring programs, surveys or other targeted measurements.

Supplementary information (SI)

SI 3.1. Base-flow calculation

Table S 3.1. Calculations of base-flow to the river

Time duration	**Specific flux (per unit length of stream segment) at each cross section, m^3/m or m^2**			**Notes about estimations**
	S1 – Downstream	**S2 – Midstream**	**S3 - Upstream**	
January	533	230	98	Simulated (Vu *et al.*, 2018)
February	225	170	75	
March	154	126	56	
April	83	81	36	Extrapolated from the linear decrease of the simulated months
May	12	37	16	
June	0	0	0	The flux to the river ceases
July	0	0	0	
August	0	0	0	
Total specific flux	***1,007***	***644***	***281***	*Sum January to August*
Total stream length (m)	*2,459*	*32,963*	*39,306*	*Measured from the map of stream network*
Volumetric flux (m^3)	*2,745,142*	*21,244,072*	*11,041,319*	*Total specific flux times total stream length*
Total flux or base-flow (m^3)	*34,760,534*			*Sum of all the segments down-, mid-, upstream*
Catchment area (m^2)	*99,201,900*			*Estimated from DEM*
Specific base-flow (m)	**0.35**			Base-flow divided by catchment area

SI 3.2. Land use classes and cropping patterns information

Table S 3.2. Information about cropping pattern and coverage of land use classes

No.	**Land use class**	**Area (ha)**	**Description of crop types and their cultivated/irrigated periods**
1	Paddy rice (single)	1,131	Rice crop planted once per year, from December to April, un-irrigated.
2	Paddy rice (double)	364	Rice crop planted twice per year continuously, from December to June, un-irrigated.
3	Paddy rice (triple)	143	Rice crop planted triple times per year continuously, from December to June. Irrigation applied only on the third season, from June to September.
4	Cassava	594	Cassava planted from March to November, un-irrigated
5	Paddy rice, Cassava	333	Paddy rice (December to March) and cassava (March to November) are planted together, un-irrigated.
6	Peanut, Cassava	1,783	Peanut (January to April) and cassava (February to November) are planted together, irrigation applied on peanut from January to April.
7	Paddy rice, Peanut, Cassava	122	Paddy rice (December to March), peanut (March to June) and cassava (April to November) are planted together, irrigation applied on peanut from March to June.
8	Peanut	1,148	Peanut are planted from January to April, irrigated.
9	Paddy rice, Peanut	176	Rice (December to March) and peanut (April to June) are planted together, irrigation applied on peanut from April to June.
10	Other annual plants	1,169	Vegetables (cucumber, pepper chili, etc.), planted all the year, irrigated.
11	Perennial plants	714	Mainly mango and coconut, irrigated from January to May
12	Bare land	334	Bare land (no crops)
13	Built-up land	368	Residential areas
14	Forest	1,885	Acacia and brush forest, un-irrigated
15	Water body	24	Water

SI 3.3. Qualitative survey data

SI 3.3.1. The survey questionnaire form

CENTRAL DIVISION FOR WATER RESOURCES
PLANNING AND INVESTIGATION

AUSTRALIA-VIETNAM
COOPERATION PROGRAM

GROUNWATER EXPLOITATION AND USAGE INVESTIGATION FORM

1. General Information:

Project: *"Integrated soil, water and nutrient management for sustainable agriculture system in South Central Coastal Vietnam"*

Investigation date: _ _/_ _/_ _ _ _

2. Well ID: ______ ; Type: ☐ Well; ☐ Borehole

3. Owner(s): ______ Start date: _ _/_ _ _ _

4. Location and Coordinates:

Village: ______ Commune: ______ District: ______

Coordinates: X: ______ Y: ______

5. Usage purposes:

☐ Households *(Description)*:
<Description about No. of users, frequencies of usage and seasonal change in discharge, including the reasons not to use water for particular time>

☐ Irrigation *(Description)*:
<Description about types of crops, frequencies of usage and seasonal change in discharge, including the reasons not to use water for particular time>

☐ Others *(Description)*:
<Description about usage purposes, frequencies of usage and seasonal change in discharge, including the reasons not to use water for particular time>

Yearly usage calendar

Time	Wet? (Y/N)	DTW (m)	Discharge (m^3/d)			
			Dom.	Irr.	Far.	*Sum*
Jan						
Feb						
Mar						
Apr						
May						
Jun						
Jul						
Aug						
Sep						
Oct						
Nov						
Dec						
Sum						

6. Exploitation methods

☐ Pumping: Type of pump: .... Capacity (HP): ....; ☐ Other: ....

7. Salinization and water treatment:

8. Water quality:

Colour: ______ Smell: ______ Tasty: ______

Further description:

Owner **Authority** **Investigator**

Signature: ____________________
Name: ______________________

Signature: ____________________
Name: ______________________

9. Information about well and aquifer[1]:

Aquifer: | | Depth (m): | | DWL (m): | | Max (m): | | Min (m): | |

Further description:

WELL'S STRUCTURE AND STRATA

Scale (m)	Layer depth (m)	Thickness (m)	Strata	Soil description	Well's structure

PHOTOS AREA

[1] Some information about well and aquifer can be achieved by real measurement while some others are optional and can be achieved by other methods, like interviewing or observing during investigation campaign

SI 3.3.2. Examples of the survey results

LIÊN ĐOÀN QUY HOẠCH VÀ ĐIỀU TRA
TÀI NGUYÊN NƯỚC MIỀN TRUNG

DỰ ÁN HỢP TÁC PHÁT
TRIỂN VIỆT NAM – ÚC

PHIẾU ĐIỀU TRA HIỆN TRẠNG KHAI THÁC VÀ SỬ DỤNG NƯỚC DƯỚI ĐẤT

1. Thông tin chung:

Dự án: *"Quản lý tổng hợp đất, nước và dinh dưỡng phục vụ hệ thống nông nghiệp bền vững khu vực Nam Trung Bộ Việt Nam"*

Ngày khảo sát: 20 / 10 / 2015

2. SH giếng: BĐ06 Loại: Giếng đào/Giếng khoan

3. Chủ sử dụng: Nguyễn Thị Chữ | Ngày bắt đầu: __ / __ / 1976

4. Vị trí và tọa độ:

Thôn: Thuận Hạnh Xã: Bình Thuận Huyện: Tây Sơn

Tọa độ (Hệ: VN-2000) Y: 284624 X: 1546677

5. Mục đích sử dụng:

Ăn uống, sinh hoạt:

Giếng dùng cho ăn uống sinh hoạt (5 người)

Tưới tiêu nông nghiệp:

Tưới cho diện tích lúa (bao) từ T6 – T9.

Mục đích khác:

Giếng dùng cho (5 con heo)

Thời gian biểu sử dụng nước					
T.gian (tháng)	Nước? (Có/Kh)	CSMN (m)	Lưu lượng (m³/d)		
			SH	Tưới	Khác
Th.1	Có	/	0,5	0	0,3
Th.2	Có	/	0,5	0	0,3
Th.3	Có	/	0,5	0	0,3
Th.4	Có	/	0,5	0	0,3
Th.5	Có	/	0,5	0	0,3
Th.6	Có	/	0,5	12	0,3
Th.7	Có	/	0,5	12	0,3
Th.8	Có	0,4	0,5	12	0,3
Th.9	Có	/	0,5	12	0,3
Th.10	Có	1,37	0,5	0	0,3
Th.11	Có	/	0,5	0	0,3
Th.12	Có	/	0,5	0	0,3

6. Phương pháp lấy (khai thác) nước:

Bơm: Loại bơm: bơm nổ Công suất (HP): 80 Khác: ....

7. Hiện trạng VS và PP xử lý nước: giếng đào không che đậy nước. Nước được sử dụng không qua xử lý

8. Chất lượng nước:

Màu: không Mùi: không Vị: không

Các mô tả khác: pH 7,72 EC 678 DO: 0,73

Chủ sử dụng
Ngày...... tháng.........
Họ tên
Nguyễn Thị Chữ

Xác nhận của địa phương
KT CHỦ TỊCH
PHÓ CHỦ TỊCH
Nguyễn Tiến Dũng

Người khảo sát
Ngày......tháng......
Họ tên
Đặng Văn Quyết

9. Thông tin về giếng và tầng chứa nước:

TCN: CS giếng (m): 3,50 CSMN hiện tại (m): 1,37

Các mô tả khác:

ĐỊA TẦNG VÀ CẤU TRÚC GIẾNG

Tỷ lệ (m)	Chiều sâu lớp (m)	Bề dày (m)	Địa tầng	Mô tả đất đá	Cấu trúc giếng
	0,65	0,65		Đất phủ	0,72
	2,95	2,30		Cát hạt thô màu xám trắng	
	3,50	0,55		Sét màu xám nâu, xám đen	

HÌNH ẢNH MINH HỌA

SI 3.3.3. Summary of the survey results

Table S 3.3. Summary of survey results

No.	Parameter	Unit	Count	Median	Mean	Max	Min	Std
1	Depth to groundwater level when surveyed	m	77	3.10	3.40	8.03	1.40	1.39
2	Depth to max. groundwater level in December	m	77	0.00	0.32	1.40	0.00	0.41
3	Depth to min. groundwater level in August	m	77	4.74	4.82	9.82	2.20	1.63
4	Discharge for irrigation - Q_{irr}	m^3/day						
4.1	Q_{irr} in Jan		64	467.10	7.30	25.00	0.00	4.57
4.2	Q_{irr} in Feb		64	794.50	12.41	30.00	0.00	7.10
4.3	Q_{irr} in Mar		64	794.50	12.41	30.00	0.00	7.12
4.4	Q_{irr} in Apr		59	680.50	11.53	30.00	0.00	7.94
4.5	Q_{irr} in May		55	60.10	1.09	20.00	0.00	3.35
4.6	Q_{irr} in Jun		43	104.00	2.42	20.00	0.00	4.72
4.7	Q_{irr} in Jul		35	95.00	2.71	20.00	0.00	4.99
4.8	Q_{irr} in Aug		38	93.10	2.45	20.00	0.00	4.77
4.9	Q_{irr} in Sep		50	98.10	1.96	20.00	0.00	4.30
4.10	Q_{irr} in Oct		60	98.10	1.64	20.00	0.00	3.84
4.11	Q_{irr} in Nov		64	268.10	4.19	20.00	0.00	4.65
4.12	Q_{irr} in Dec		64	389.10	6.08	25.00	0.00	4.92
5	Discharge for domestic - Q_{dom}	m^3/day						
5.1	Q_{dom} in Jan		76	47.70	0.63	8.00	0.20	0.92
5.2	Q_{dom} in Feb		76	47.70	0.63	8.00	0.20	0.92
5.3	Q_{dom} in Mar		76	47.70	0.63	8.00	0.20	0.92
5.4	Q_{dom} in Apr		68	40.60	0.60	8.00	0.20	0.92
5.5	Q_{dom} in May		63	38.60	0.61	8.00	0.20	0.95
5.6	Q_{dom} in Jun		47	31.80	0.68	8.00	0.20	1.10
5.7	Q_{dom} in Jul		39	27.80	0.71	8.00	0.30	1.20
5.8	Q_{dom} in Aug		43	31.90	0.74	8.00	0.30	1.19
5.9	Q_{dom} in Sep		61	40.40	0.66	8.00	0.20	1.02
5.10	Q_{dom} in Oct		72	45.80	0.64	8.00	0.20	0.94
5.11	Q_{dom} in Nov		76	47.70	0.63	8.00	0.20	0.92
5.12	Q_{dom} in Dec		76	47.70	0.63	8.00	0.20	0.92
6	Discharge for livestock farming - Q_{far}	m^3/day						
6.1	Q_{far} in Jan		44	13.23	0.30	1.00	0.10	0.16
6.2	Q_{far} in Feb		44	13.23	0.30	1.00	0.10	0.16

No.	Parameter	Unit	Count	Median	Mean	Max	Min	Std
6.3	Q_{far} in Mar		44	13.23	0.30	1.00	0.10	0.16
6.4	Q_{far} in Apr		40	11.83	0.30	1.00	0.10	0.17
6.5	Q_{far} in May		38	11.03	0.29	1.00	0.10	0.17
6.6	Q_{far} in Jun		29	8.93	0.31	1.00	0.10	0.19
6.7	Q_{far} in Jul		24	7.05	0.29	0.80	0.10	0.14
6.8	Q_{far} in Aug		25	6.65	0.27	0.50	0.10	0.10
6.9	Q_{far} in Sep		35	10.33	0.30	1.00	0.10	0.16
6.10	Q_{far} in Oct		40	11.63	0.29	1.00	0.10	0.15
6.11	Q_{far} in Nov		44	13.23	0.30	1.00	0.10	0.16
6.12	Q_{far} in Dec		44	13.23	0.30	1.00	0.10	0.16
7	Number of people	people	76	404	5.3	28	3	3.6
8	Number of animals per farm	animals	44	156	3.5	10	1	1.5
9	Proportion of animals to people	-			0.4			
10	Area of irrigated paddy rice per farm	ha	2		0.35	0.40	0.30	0.05
11	Area of irrigated peanut per farm	ha	42		0.41	1.80	0.03	0.33
12	Area of irrigated vegetation per farm	ha	9		0.18	0.30	0.03	0.08
13	Area of irrigated perennial coconut per farm	ha	7		0.17	0.30	0.05	0.00

Note: Descriptive data (e.g., water quality, soil description) from the survey were not summarised as they were not used in this study

Chapter 4. Quantifying groundwater resource responses to changes in land use/land cover in a developing agricultural catchment[3]

Abstract

Strong changes have been observed in land use/land cover and variation in climate, which need to be studied for their impacts on groundwater resources. The drivers and impacts of change are often stronger in the case of developing regions and in humid tropical climates. In this study, a multi-model approach was used to test the influences of land use change and climate variability on the groundwater budget components of recharge, evapotranspiration, groundwater storage, base-flow and anthropogenic groundwater abstractions. This study was applied in the humid tropical climate, La Vi catchment, Vietnam, an area of agricultural development. Twelve potential land use scenarios were developed for the catchment from a base scenario of current land use (in 2016). These land use scenarios identified the variation in groundwater extraction for irrigation, from a 58% reduction to a 30% increase compared to the base scenario. Three climatic conditions representing dry, average and wet conditions, were determined from a 30-year time series of precipitation for the region. Six of the land use change scenarios, including the base scenario, covering the range of groundwater abstractions, were tested in combination with the three climatic conditions for their influences on the groundwater budget components. The results showed the significant impact of land use change on groundwater storage, producing from a 39% reduction to a 44% increase in groundwater storage during the dry season compared to the base scenario. Variations in groundwater abstraction for irrigation by land use scenario showed small (positive or negative) impact on recharge to groundwater, but are mainly expressed in modified actual evapotranspiration. Variability of climatic conditions caused strong changes in groundwater storage and base-flow during the wet period. Results show groundwater storage to vary between a 44% decrease and a 45% increase, and base-flow to vary between a 71% reduction and a 192% increase during the wet period. Fifteen of the 18 combinations were classified as overexploited groundwater systems based on the ratio of abstraction over recharge being higher than the sustainable ratio.

Key words: Land use change, agricultural, abstraction, flow components.

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[3] To be submitted to the *Journal of Hydrology: Regional Studies*

4.1 Introduction

Land cover has been changing globally as a consequence of rapidly growing populations and an increasing standard of living (DeFries & Eshleman, 2004). The main trend in global land cover change is the expansion of human modified lands (e.g., agricultural land and urban areas) to the detriment of natural land covers (e.g., forest and wetland) (Lambin *et al.*, 2003; DeFries & Eshleman, 2004). Globally, humid tropical forests decreased at an average rate of 4.9 10^6 ha per year over the last decades, due to their conversion to agricultural and urban land (Lambin *et al.*, 2003). As population growth is such an important driver of land cover change, the most extensive changes are observed in developing regions, including Southeast Asia (Lambin *et al.*, 2003; Barbier, 2004). For the city of Daqing, China, Yu *et al.* (2011) identified an increase in urban and agricultural land of more than 1.5 times between 1997 and 2007, which came at the cost of losing half of the city's total area of forest and wetland. Gashaw *et al.* (2018) estimated that in a headstream catchment of the Blue Nile, Ethiopia, cultivated land increased from 62.7% to 76.8% between 1985 and 2015, while the total area of shrub- and grasslands reduced from 33.8% to 20.2%.

Changes in land cover have negatively impacted bio-physical systems at various scales (DeFries & Eshleman, 2004). The primary consequences of land cover change are (1) loss of natural habitats for flora and fauna (Mattison & Norris, 2005) and (2) contributing to climate change (Houghton, 1995; Bonan, 1997). The second consequence is explained by the fact that land cover and climate change are bi-directionally linked. Changes in land cover modify the energy exchange between land surface and atmosphere (Bonan, 1997), while changing temperatures, precipitation and CO_2 concentrations affect the occurrence, growth and resilience of plant species.

Land use alteration also impacts on the different water balance fluxes at spatial scales varying from the catchment to the global level (DeFries & Eshleman, 2004). Modified hydrology as a result of land use change refers to (1) changes in flow components (infiltration, evapotranspiration, runoff, base-flow and in-channel flow) (Siriwardena *et al.*, 2006; Li *et al.*, 2007; Li *et al.*, 2009; Wijesekara *et al.*, 2012; Kalantari *et al.*, 2014; Gashaw *et al.*, 2018); (2) degradation of water quality (Bhaduri *et al.*, 2000; Tong & Chen, 2002); and (3) variation in water demand (for irrigation and domestic use) (Mehta *et al.*, 2013). Both surface water and groundwater systems are affected (Wijesekara *et al.*, 2012). Changes in groundwater systems are intensified by climate change and normally take a longer to recover compared to surface water systems (Cuthbert *et al.*, 2019). Therefore, studies focusing on the influences of changes in land cover on groundwater systems in terms of altered net recharge, subsurface runoff and anthropogenic extraction are needed for improving water management in a changing environment (Zomlot *et al.*, 2015). A review of the current literature indicated a focus on the consequences of land use change for water resource quantity and quality, while the relationship with water demand received relatively little attention. This is reflected in the limited information on the development of groundwater extractions (Döll *et al.*, 2012).

Recent studies suggest the advantages of integrated modelling approaches as a tool for quantifying the consequences of land use change on hydro(geo)logical systems (Bormann *et al.*, 2007; Wijesekara *et al.*, 2012). Future land use changes have been addressed by developing change models (e.g., Cellular Automata, CLUE-s and ProLand) (Bormann *et al.*, 2007; Chen *et al.*, 2009; Wijesekara *et al.*, 2012) or by scenario analysis (Kalantari *et al.*, 2014). Generally, these land use predictions are then used as inputs for physical-based models for examining/quantifying their influences on water resources. Tested models for assessing the change in surface water and/or the connected groundwater system include HEC-HMS (Chen *et al.*, 2009), MIKE-SHE/MIKE-11 (Wijesekara *et al.*, 2012; Kalantari *et al.*, 2014), SWAT, TOPLATS and WASIM (Bormann *et al.*, 2007; Li *et al.*, 2009). While, many models have a high data demand, WetSpass (Batelaan & De Smedt, 2007) and WetSpass-M (Abdollahi *et al.*, 2017) have proven to be spatially distributed water balance models commensurate with conditions hampered by limited data availability. Batelaan *et al.* (2003) showed that, coupled with a groundwater model, evaluation of land use change scenarios is feasible.

This study addresses the need for greater understanding of the impact on groundwater resources of land cover change, including variation in anthropogenic extractions (for irrigation) and climatic variability, by examining the groundwater response to different scenarios of land use change in a tropical, agriculturally developing catchment. A multi-model approach is used, for which scenarios of future cropping patterns were developed. Six land use scenarios, including the base scenario of current land use, are simulated for dry, average and wet conditions of climatic inputs, and their impact on the groundwater system is evaluated and discussed. The resulting trends in groundwater resources are interpreted, and conclusions are drawn with respect to the sustainability and management of the system.

4.2 Materials and methods

4.2.1 Study area

The La Vi River Basin is located in the central coastal province of Binh Dinh, Vietnam, and encompasses approximately 100 km^2 (see Figure 4.1). A 2016 land use map for the catchment showed the dominance of agricultural lands, which cover approximately 77% of the catchment area. The agricultural lands are almost exclusively composed of small family plots with areas of 0.5 to 2.5 ha, but on average smaller than 1.0 ha. There are some residential areas, including the small town of Ngo May in the south-east of the catchment, and along the main road in the region.

A shallow sandy quaternary aquifer, which covers a granitic basement rock, extends throughout the catchment. It serves as the main source of water for irrigation of cropped land, as well as water for domestic consumption for local residents and family-based livestock farming (as surveyed by the Central Division of Water Resources Planning and Investigation in Vietnam on 21 to 25 October 2015). The sandy soils of the area allow high infiltration, making diffuse recharge from precipitation the main process of aquifer replenishment (Do, 1987). The sinks for the groundwater system are base-flow to the stream network, evapotranspiration from shallow groundwater tables and anthropogenic abstractions for irrigation and domestic use. Due to the strong seasonal precipitation the La Vi River and its tributaries flow intermittently; they only provide irrigation water for rice crops during the beginning of the dry season. Hence, during the long (eight-month) dry season from January to August, farming is strongly dependent on irrigation from groundwater.

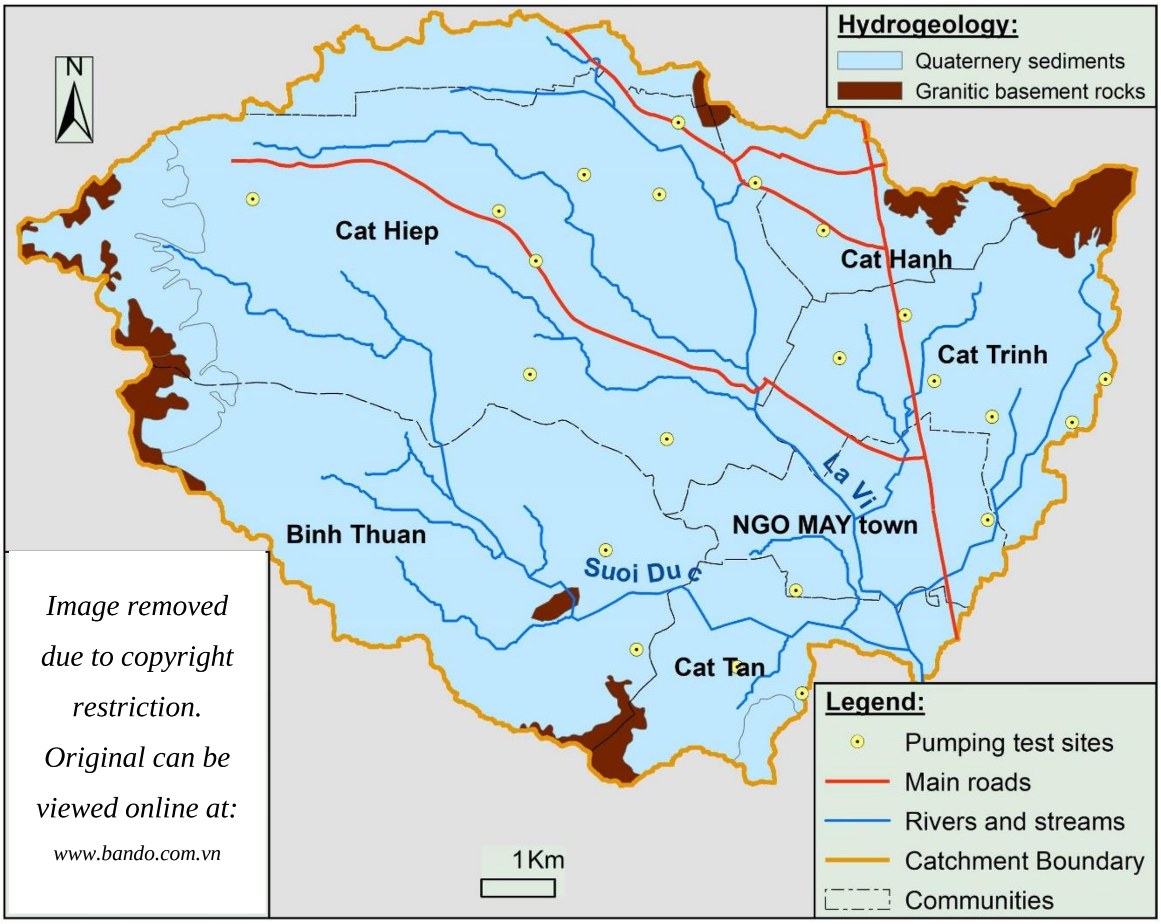

Figure 4.1. La Vi River catchment, quaternary sandy sediments and granitic basement rocks. The yellow dots represent locations selected for pumping tests to determine aquifer properties. The inset shows Vietnam, with the location of the La Vi catchment marked as an orange dot within the green shaded area of Binh Dinh province (Source: Vietnam Publishing House of Natural Resources, Environment and Cartography).

4.2.2 Historical land use data

Land use maps for the catchment for 2005, 2010 and 2016 were established based on classification of Sentinel-2A and LANDSAT 4/5 satellite images (see Table 4.1). A multiple-step supervised maximum likelihood classification with post-classification correction was employed to produce the three land maps (Tran *et al.*, 2018). For 2010 and 2016, there were two images available per year, which allowed examination of the seasonal changes in land use patterns (see Table 4.1).

Table 4.1. Collected satellite images used for classification of land use data

Satellite/sensor	Date of images	Resolution
Sentinel-2A	13 February and 9 October 2016	10 m
LANDSAT 4-5TM	4 February and 30 July 2010; 16 July 2005	30 m

For 2016, the high spatial resolution of the Sentinel imagery made it possible to use a detailed classification system (15 classes, Table 4.2). Conversely, for 2005 and 2010, a more generalised classification (11 classes) had to be used due to the lack of ground truth data and the lower spatial and spectral resolution of the imagery (see Table 4.2). The detailed classification of 2016 was also generalised for the purpose of analysing land use changes between 2005, 2010 and 2016.

Table 4.2. Detailed (2016) and generalised (2005 and 2010) land use classes used in the supervised classifications

Detailed classification		**Generalised classification**	
No.	***Land use class***	***No.***	***Land use class***
1	Built-up	1	Built-up
2	Bare land	2	Bare land
3	Paddy rice (single)	3	Paddy rice
4	Paddy rice (double)		
5	Paddy rice (triple)		
6	Paddy rice, peanut	4	Other annual plants
7	Paddy rice, peanut, cassava		
8	Paddy rice, cassava		
9	Peanut		
10	Peanut, cassava		
11	Cassava		
12	Other annual plants		
13	Perennial plants	5	Perennial plants
14	Forest	6	Forest
15	Water body	7	Water body

Historical changes in land cover between the different years were examined to understand the trends in the changes and their potential drivers. Transition probability matrices were created by calculating the proportion of each land use type that either stayed the same or was converted to another class for the two compared periods of 2005 to 2010 and 2010 to 2016. Socio-economic information on the area was obtained from a range of sources, including government policies, development plans and the adoption of new modern irrigation techniques, to explain the potential driving factors triggering changes in land cover.

4.2.3 Land use change scenarios

Based on the analysis of the historical changes in land cover as well as the socio-economic information for the catchment, scenarios of future land cover were developed. The scenarios take into account the following likely future developments: (1) new irrigation techniques for saving water consumption to various degrees; (2) the replacement of some water-intensive crops by more water-efficient crops; (3) continued conversion of barren land into cropped land; and (4) the increasing market for vegetables and fruits.

For the first development, land use/irrigation scenarios were created by either only reducing the irrigation rate (on the selected crops of mango and peanuts) or combining this reduction with the conversion of some crops to save water for irrigation. To address the second development, the less water-intensive crop of maize replaced paddy rice. The third future development was included in the first two, as bare land was converted into either a water-intensive crop (e.g., peanut) or water-efficient crop (e.g., cassava). The fourth development encouraged the expansion of seasonal vegetables and fruits crops, replacing perennial plants. Scenarios were developed in which particular land use classes were converted to other classes, by using location and class-based rules in ArcGIS. The land use scenarios were then used as input for calculating: (1) groundwater abstraction based on the methodology developed in Chapter 3; and (2) recharge by WetSpass-M.

4.2.4 Land use to groundwater extraction

The Modelbuilder tool in ArcGIS was used to develop a procedure to calculate the distributed groundwater abstractions based on land cover maps (see Chapter 3 of this thesis for more details). Total abstraction is the amount of groundwater used by irrigation, domestic use and livestock farming. For irrigation, this amount was calculated by multiplying the area of each land use class with the irrigation rate for that class. To calculate groundwater abstraction, the following data is needed: a land use and population map, the average number of people per household, irrigation rates and domestic and livestock water use. A qualitative survey at 77 farms, conducted in October 2015, also provided important information.

4.2.5 Assessment of precipitation variability

To evaluate the land cover scenarios under dry, average and wet conditions, an assessment of long-term precipitation variability was required. For this, a rainfall time series of 30 years (1987–2007) from the An Nhon weather station, approximately 15 km southeast of the catchment, was analysed. Annual rainfall values were sorted from low to high. The percentile for each year was obtained as the proportion of the number of years having an amount of rainfall less than or equal to that of the calculated year to the total number of years. Every year was then categorised into three groups of wet, normal/average and dry circumstances based on the threshold percentiles of 10%, 45–55% and 90% of historical distribution, respectively, as suggested by Knapp *et al.* (2015).

4.2.6 Recharge and actual ET estimations

The six land cover scenarios, including the current land use scenario for 2016 as the reference, in combination with the three precipitation regimes, produced 18 combinations for simulating recharge and actual evapotranspiration (ET) with the monthly water balance model WetSpass-M (Abdollahi *et al.*, 2017). The simulated recharges were compared to the amount of groundwater abstraction to analyse the sustainability of the groundwater abstraction.

WetSpass-M is a spatially distributed water balance model that simulates interception, actual ET (the total actual ET from vegetated, open water, bare soil and impervious surfaces; calculated from potential evaporation and vegetation data) and surface runoff, then estimates recharge as the rest term of the water budget (Abdollahi *et al.*, 2017). The data used as inputs into WetSpass-M included (1) a 10 by 10 m resolution DEM created by the local government of Binh Dinh (Binh Dinh DONRE, 2015); (2) an updated soil map (Nguyen & Thach, 2018); (3) land use data for different land use scenarios as described above (Tran *et al.*, 2018); and (4) climatic data representative of wet, normal and dry conditions, determined by averaging the measured parameters at the An Nhon station for the years of three conditions. The total amount of groundwater abstraction, including 97.5% for irrigation and 2.5% for domestic use and livestock, which is directly released to the field after use, is added to the actual precipitation as an input for the recharge and actual ET calculations by the WetSpass-M model.

The monthly WetSpass-M model was run for a one-year simulation period for each land cover and precipitation combination. Spatially distributed recharge to groundwater as the output of WetSpass-M served as the net recharge for the groundwater flow models (MODFLOW); that is, they were used to parameterise the RECHARGE package. Evapotranspiration was not parameterised (in the groundwater flow models), as it was already included in the simulated net recharge.

4.2.7 Groundwater model

The 3D finite-difference groundwater model code MODFLOW-NWT (Harbaugh, 2005) was selected for simulating groundwater flow and assessment of the groundwater balance. Running and post-processing of model outputs was carried out with the Python package Flopy in Python 2.7. The model extent was defined by the catchment boundary and set as a no flow boundary. A one-layer flow model was set up, representing an unconfined aquifer on top of the bedrock, which is considered an aquiclude. The model top was defined by the 10 by 10 m resolution of the local DEM, and the aquifer thickness was interpolated from a set of electrical resistivity tomographies together with locations of bedrock outcrops. The horizontal discretisation of the model was 100 by 100 m. The hydraulic conductivities of the aquifer were obtained from the set of 22 pumping tests, located throughout the catchment (see Figure 4.1), while specific yield values were based on a soil map parameterised by Nguyen and Thach (2018).

The main La Vi River running along the centre of the catchment was treated in MODFLOW as a river boundary condition (RIV), with its bottom elevation 0.5 m below the surface of the river cells. Surface water levels monitored at three stations from upstream to downstream locations were interpolated and extrapolated to all river cells. The tributaries of the La Vi River were conceptualised with the drain package (DRN) with its level assigned equal to the ground surface, which acts as a sink and prevent heads from building up above the land surface.

The actual recharge to groundwater was estimated by the WetSpass-M model, including recharge from natural precipitation and return flow from irrigation. To do that, a map of irrigated water (for each month) was converted from the land use map for each scenario, based on the cropping pattern and rates of irrigation for different crops. Then, rainfall precipitation was added to the irrigated water map as a 'precipitation' input for the WetSpass-M simulation. The MODFLOW recharge package (RCH) was activated with the WetSpass-M calculated recharge. As the input recharge could be negative (i.e., dominated by evapotranspiration), care was taken to ensure that negative recharge was not applied to cells where there was not enough water to match the forcing.

For calibration purposes, a monthly transient model was established for the year 2017, which represented the most data-rich period. Time series data were collected for the year 2017, monitored by pressure transducer loggers at 14 wells located throughout the catchment area. These were then converted to the groundwater levels by subtracting them from the DEM values of the wells. The model calibration was carried out using the parameter-estimation software PEST (http://www.pesthomepage.org/). PEST was used in estimation mode, adjusting parameters for hydraulic conductivity and specific yield spread out across 152 pilot points across the catchment. This produced 304 adjustable parameters. The initial values for hydraulic conductivity at the pilot points were obtained through radial basis function interpolation from measured K values across the catchment. Values of K at each of the pilot points was allowed to vary between 90% of the minimum measured K and 110% of the maximum measured K, thus constraining the K values to measured values only, with a small margin of error allowed.

4.2.8 Model scenarios

Calibrated values of hydraulic conductivities and specific yield and existing parameters of all boundary conditions were used to establish the MODFLOW models with inputs of simulated recharge and groundwater extractions associated with each land use scenario. One-year monthly transient model simulations were created for each combination of climate and land use condition. The scenario models had a four-year warm-up with identical forcing over each of those years. The main goal of these scenario models was to examine the annual variation of groundwater budget components for each scenario of land use and climate combination, as well as to quantify the influences of land use changes and climatic variation on the sustainability of the groundwater resources. Monthly simulated values of the groundwater budget components of recharge, base-flow to streams and anthropogenic extraction from each scenario were compared to one another, particularly to the base-model with actual land use data, to quantify the changes caused by each scenario of land use change and climate variability.

4.3 Results

4.3.1 Model calibrated results

The calibration of hydraulic groundwater head from the 14 observation wells yielded a fit with model efficiency of 0.98, a percentage bias of -2.53%, and a root mean squared error of 1.41 m. Given the uncertainty associated with the groundwater level data, the fit was deemed sufficient. The fit is shown below in **Error! Reference source not found.**. The calibrated values of hydraulic conductivity (K) ranged from 0.1 to 30.0 m/d and closely followed the pattern of those measured in the field. The final specific yield ranged from 0.232 to 0.296. Compared to the initial values, hydraulic conductivities exhibited significant changes with an average factor of about 3 times observed, whereas specific yield showed small changes of 10% approximately, both increase and decrease.

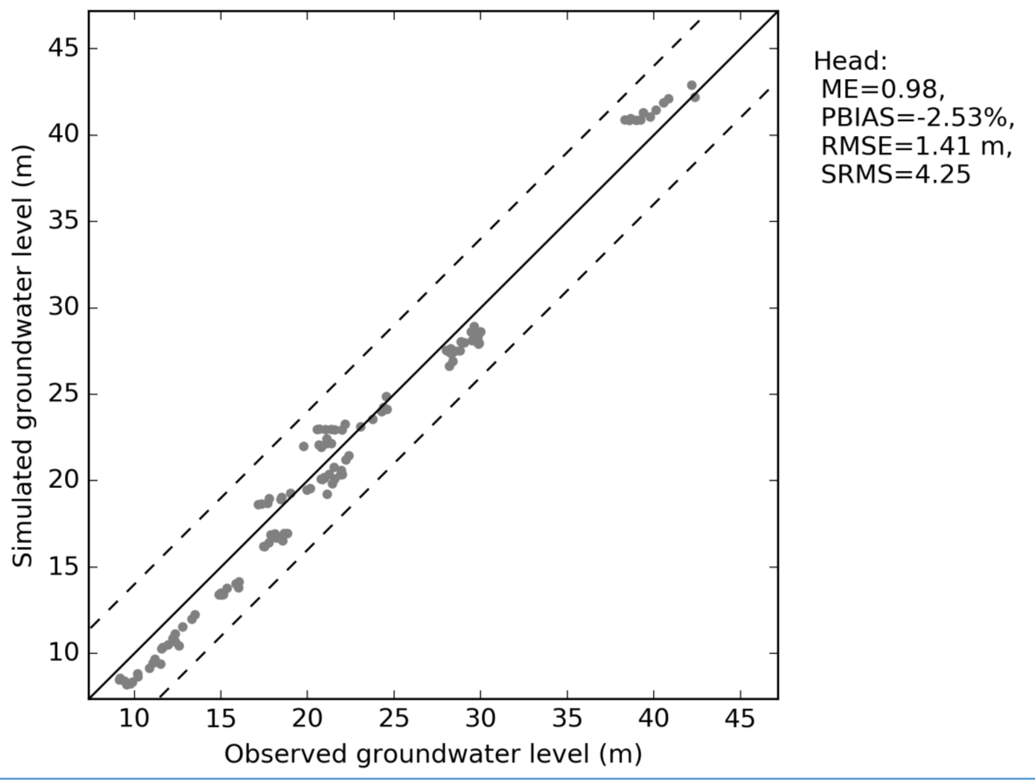

Figure 4.2. Observed versus simulated groundwater levels at 14 monitored wells for all time steps of the calibrated model (for the year 2017). Dashed lines represent a standard error of 2 m assuming the errors are normally distributed.

4.3.2 Historical land use changes

Land cover maps were developed for the years of 2005, 2010 and 2016, with seven land cover types classified (see Figure 4.3). Land cover change analysis between these years showed the significant conversion of bare land to agricultural lands and to built-up land (urban) to a lesser extent. Specifically, bare land decreased significantly from 4,144 ha (41.8% of the catchment area) in 2005 to 2.508 ha (25.3%) in 2010 and 334 ha (3.4%) in 2016. In response, other annual plants with a coverage of 897 ha (9.0%) in 2005 increased more than five times to 3.273 ha (33.0%) in 2010 and 4.695 ha (47.3%) in 2016. Built-up land slightly expanded from 226 ha (2.3%) in 2005 to 319 ha (3.2%) and 368 ha (3.7%) in 2010 and 2016, respectively. Forest and water body cover remained stable, contributing 13–15% and approximately 1% of the total catchment area, respectively. Rice and perennial plants fluctuated. Paddy rice decreased from 3.106 ha (31.3%) in 2005 to 1.284 ha (12.9%) in 2010, before increasing to 2.269 ha (22.9%) in 2016. Conversely, perennial plants increased substantially from 111 ha (1.1%) to 1.070 ha (10.8%) between 2005 and 2010, then slightly decreased to 714 ha (7.2%) in 2016. The details of the land use changes from 2005 to 2010 and from 2010 to 2016 are presented in the land cover conversion matrices (see Table 4.3 and Table 4.4).

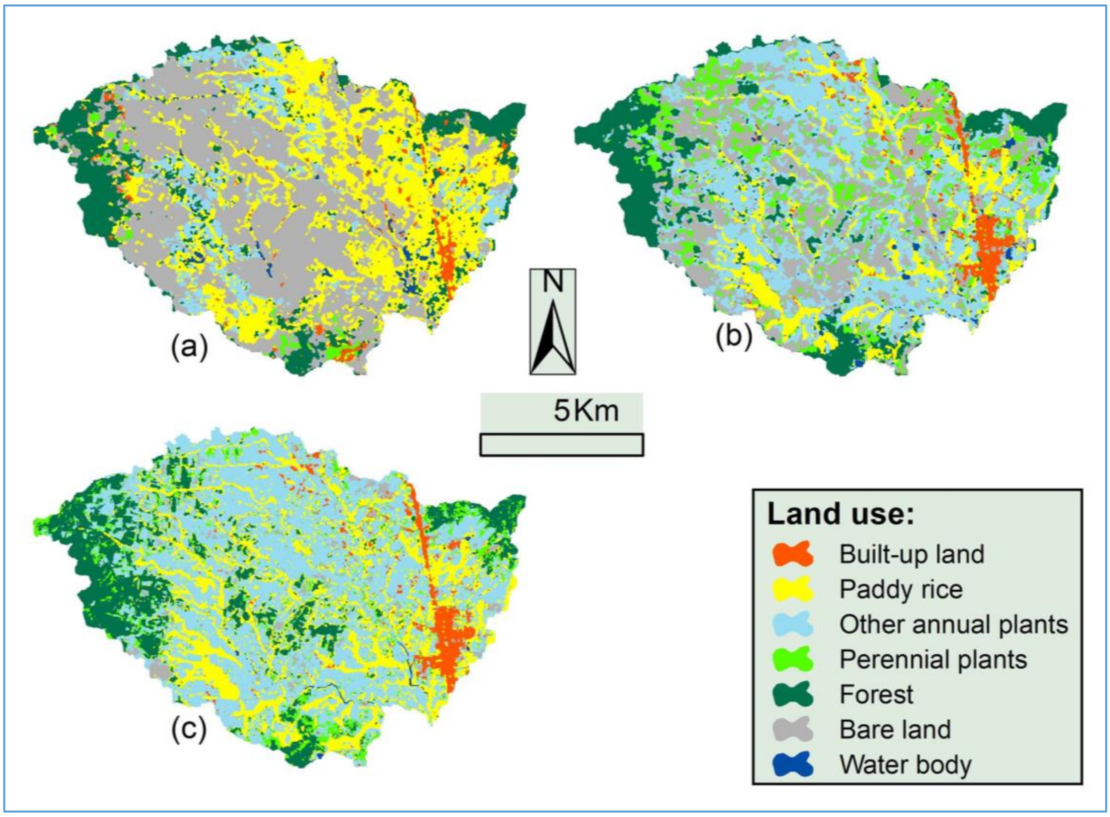

Figure 4.3. Land cover data for the years 2005 (a), 2010 (b) and 2016 (c), based on Tran et al. (2018).

Table 4.3. The probability matrix of land cover changes for 2005 to 2010

	Land cover classes	Land cover 2005															
		Bare land		Built up		Forest		Other annual plants		Paddy rice		Perennial plants		Water body		**Total**	
		(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	**ha**	**(%)**
Land cover 2010	Bare land	1,911	19.3	21	0.2	76.5	0.8	111.3	1.1	370.4	3.7	10.4	0.1	7.6	0.1	**2,508**	**25.3**
	Built up	14	0.1	88	0.9	6.9	0.1	2.3	0.0	204.7	2.1	0.0	0.0	2.3	0.0	**319**	**3.2**
	Forest	299	3.0	29	0.3	872.2	8.8	5.3	0.1	122.2	1.2	36.5	0.4	3.9	0.0	**1,368**	**13.8**
	Other annual plants	1,045	10.5	16	0.2	246.0	2.5	696.3	7.0	1,228.1	12.4	14.0	0.1	27.6	0.3	**3,273**	**33.0**
	Paddy rice	271	2.7	44	0.4	46.1	0.5	57.9	0.6	771.2	7.8	39.3	0.4	54.9	0.6	**1,284**	**12.9**
	Perennial plants	567	5.7	24	0.2	78.3	0.8	21.4	0.2	368.8	3.7	9.5	0.1	0.5	0.0	**1,070**	**10.8**
	Water body	37	0.4	4	0.0	2.9	0.0	1.9	0.0	40.7	0.4	1.3	0.0	10.7	0.1	**98**	**1.0**
	Total	**4,144**	**42**	**226**	**2**	**1,329**	**13**	**897**	**9**	**3,106**	**31**	**111**	**1**	**107**	**1**	**9,920**	**100**

Table 4.4. The probability matrix of land cover changes for 2010 to 2016

	Land cover classes	Land cover 2010															
		Bare land		Built up		Forest		Other annual plants		Paddy rice		Perennial plants		Water body		**Total**	
		(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	**ha**	**(%)**
Land cover 2016	Bare land	227	2.3	0	0.0	11.2	0.1	38.4	0.4	13.8	0.1	38.4	0.4	4.3	0.0	**334**	**3.4**
	Built up	21	0.2	319	3.2	1.9	0.0	10.0	0.1	7.9	0.1	6.9	0.1	1.8	0.0	**368**	**3.7**
	Forest	305	3.1	0	0.0	785.0	7.9	218.0	2.2	17.6	0.2	187.7	1.9	3.3	0.0	**1,517**	**15.3**
	Other annual plants	1,408	14.2	0	0.0	234.9	2.4	2,195.6	22.1	306.6	3.1	518.7	5.2	30.8	0.3	**4,695**	**47.3**
	Paddy rice	345	3.5	0	0.0	155.7	1.6	635.0	6.4	909.4	9.2	180.4	1.8	43.4	0.4	**2,269**	**22.9**
	Perennial plants	195	2.0	0	0.0	179.2	1.8	170.6	1.7	26.6	0.3	137.6	1.4	5.3	0.1	**714**	**7.2**
	Water body	7	0.1	0	0.0	0.5	0.0	5.3	0.1	1.8	0.0	0.1	0.0	9.1	0.1	**24**	**0.2**
	Total	**2,508**	**25**	**319**	**3**	**1,368**	**14**	**3,273**	**33**	**1,284**	**13**	**1,070**	**11**	**98**	**1**	**9,920**	**100**

4.3.3 Land cover change scenarios

The actual land cover data for the year 2016 was considered the base scenario (S0). In total, 12 land cover scenarios were developed from this base scenario (see SI.1 in chapter 3 for details). In the base scenario (S0), there were 15 land use classes (see Table 4.2). The land use pattern was quite complicated, as there was a strong mixture of cropped land and residential areas. In general, the area was dominated by agricultural lands, which accounted for 64.7% of the total catchment area, and were mostly located in the lowland area in the centre of the catchment. The small town of Ngo May in the southeast corner of the catchment is dominated by built-up land (see Figure 4.3). The forest cover occurs mostly in the mountainous area at the edges of the catchment.

The first eight developed land use scenarios involve the development of water-saving irrigation techniques and the consequent replacement of water-efficient crops with water-intensive ones. In the first two scenarios, S1 and S2, the cropping patterns were not changed compared to the base scenario (S0), but the amount of water consumed for irrigating peanut and cassava was reduced by 25% and 50% respectively. In addition to the changes made to S1 and S2, in the scenarios of S1b and S2b, cassava was replaced by peanut as a consequence of saving water on irrigation. An increase of 500 ha of perennial plants (mango and coconut) at the expense of forest cover at the centre of the catchment was part of the S1c and S2c scenarios, compared to S1b and S2b. Finally, the conversion of barren land (334 ha) to peanut was implemented as a further change in the S1d and S2d scenarios, compared to the scenarios of S1c and S2c.

The next three scenarios looked at the conversion of water-intensive crops of paddy rice and peanut to the water-efficient crops of maize and cassava, respectively, as well as the filling in of barren land by non-irrigated cassava. In S3, paddy rice (in the base scenario S0) was replaced by maize in the second half of the dry season (May to August), resulting in the conversion of 364 ha of paddy rice (double) and 143 ha paddy rice (triple) land to become a newly added class of paddy rice and maize (planted in a rotation). In scenario S4, cassava replaced peanut, resulting in a change of 3,053 ha of peanut lands to become cassava lands, compared to the base scenario (S0). In addition to the changes in S4, in the scenario S4b, 334 ha of barren land became cassava.

The final scenario, S5, is based on the prediction of a need for more vegetables. As such, 714 ha of perennial plants of mango and coconut was converted to vegetables, classified as ‘other annual plant’, resulting in an increase of this land cover from 1,169 ha to 1,883 ha, compared to the base scenario (S0).

4.3.4 Variation in climatic precipitation

The data of precipitation at An Nhon station for a 30-year period (1978–2017) showed that annual rainfall varied from 1,099 mm to 2,674 mm. Three years of 1988, 2006 and 2012 were categorised as dry years, with annual precipitation of less than 1,239 mm; the years 1991, 1993 and 2016 were considered normal years, with annual precipitation ranging from 1,678 mm to 1,738 mm; and the years 1996, 2008 and 2012 were wet, with annual rainfall above 2,572 mm. Even though annual rainfall was clearly different with increasing order of magnitude from dry to average then wet years, these differences were not unique for every month, particularly for the dry period (see Figure 4.4). Also, potential evapotranspiration, another significant factor for the groundwater budget, did not have clear trends between the different conditions of dry, average and wet.

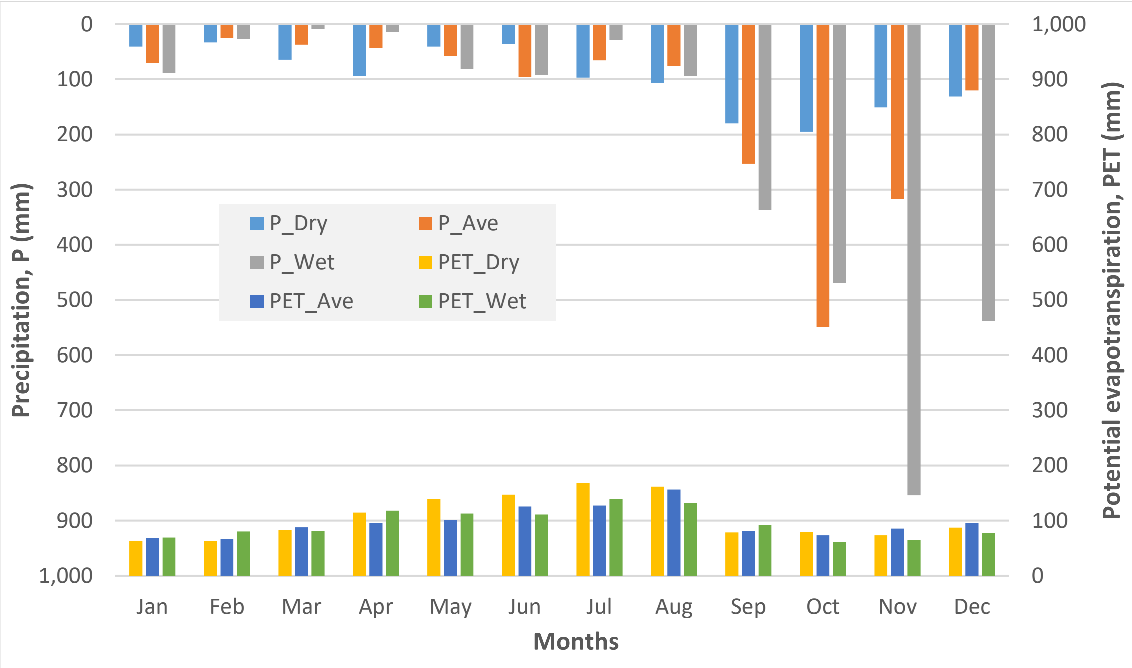

Figure 4.4. Temporal variation of precipitation (P) and potential evapotranspiration (PET) of dry, average (Ave) and wet climatic conditions.

4.3.5 Alteration of groundwater demands

The variation of cropping patterns and irrigation requirements between different land use scenarios resulted in changes in groundwater demands for irrigation for different scenarios and times (see Figure 4.5). Total annual catchment groundwater consumption for irrigation between scenarios ranged from 17.45 x 10^6 m^3 (S4 and S4b) to

57.14 x 10^6 m^3 (S1d), with the total annual catchment consumption of the base scenario (S0) estimated to be 40.53 x 10^6 m^3. Regarding the temporal changes, intensive consumption is observed for the first half of the dry season (from January to April), or the entire dry season (until August) for some scenarios, as this was the intensive cropping (and irrigating) season. Total groundwater consumption for the dry period (January to August) accounted for 80–92% of the total annual consumption for irrigation in every land use scenario. Irrigation was dominant in groundwater consumption and contributed 97.5% of the total groundwater abstraction (for all purposes), while the amount of groundwater abstraction for domestic use and livestock was the same between scenarios. Therefore, the spatio-temporal variation of total groundwater abstraction was mostly the same as this for irrigation purposes. The groundwater abstraction ratio (proportion of annual groundwater abstraction to annual recharge) of all scenarios ranged from 0.20-1.58 with a mean value of 0.72. Averaging all land use scenarios for each climatic condition resulted in abstraction ratios of 1.07, 0.68 and 0.42 for dry, average and wet conditions, respectively.

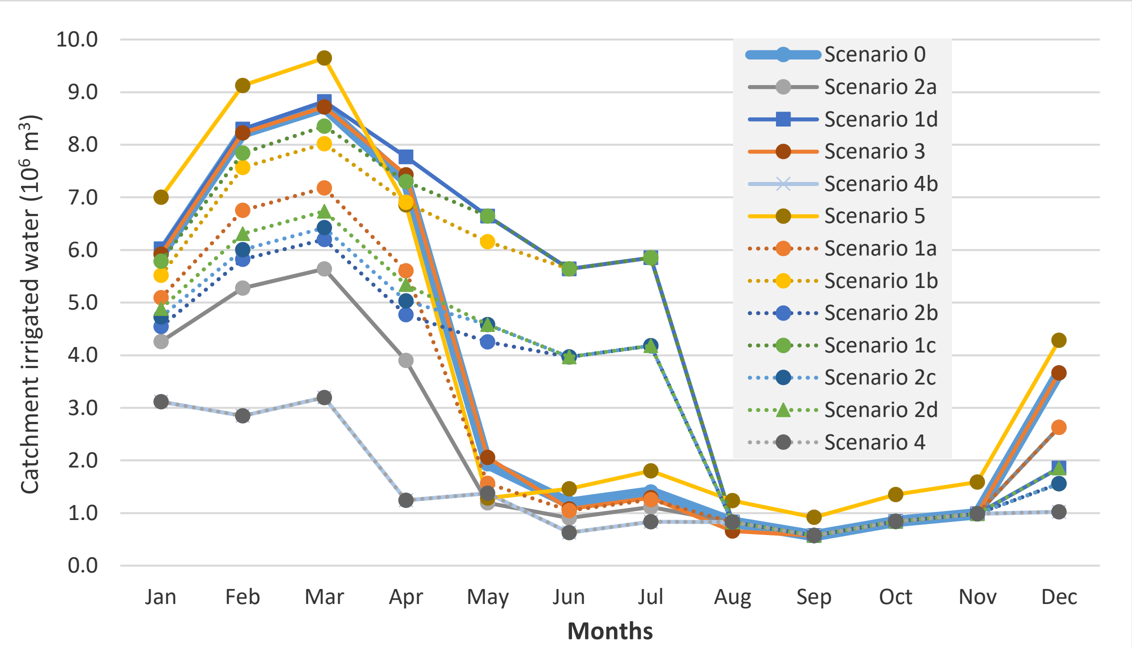

Figure 4.5. Temporal and cross-scenario variation of the calculated catchment groundwater abstraction for irrigation. Scenarios presented in the solid lines are used in the groundwater modelling for evaluating their impact on the groundwater resources.

4.3.6 Variation in actual evapotranspiration (ET)

Actual evapotranspiration varied significantly between land use scenarios (see Figure 4.6, line charts) during the dry period (from January to August). The S1d scenario showed the highest evapotranspiration of all scenarios. Its evapotranspiration in June was 21 mm (or 44%), and for the eight-month dry season 70 mm (15%), higher than that of the base scenario (S0). Conversely, the S4b scenario exhibited the lowest evapotranspiration, at 12 mm (or 19%) and 28 mm (6%) lower compared to the S0 scenario for April and the whole dry period, respectively. In the rainy season, variation in evapotranspiration between land use scenarios was negligible. This variability aligned well with the amount of irrigation, with S1d and S4b being the highest and lowest groundwater-irrigated scenarios, respectively. Differences in evapotranspiration between climatic conditions (see Figure 4.6, bar charts) are not clear, and differ from month to month.

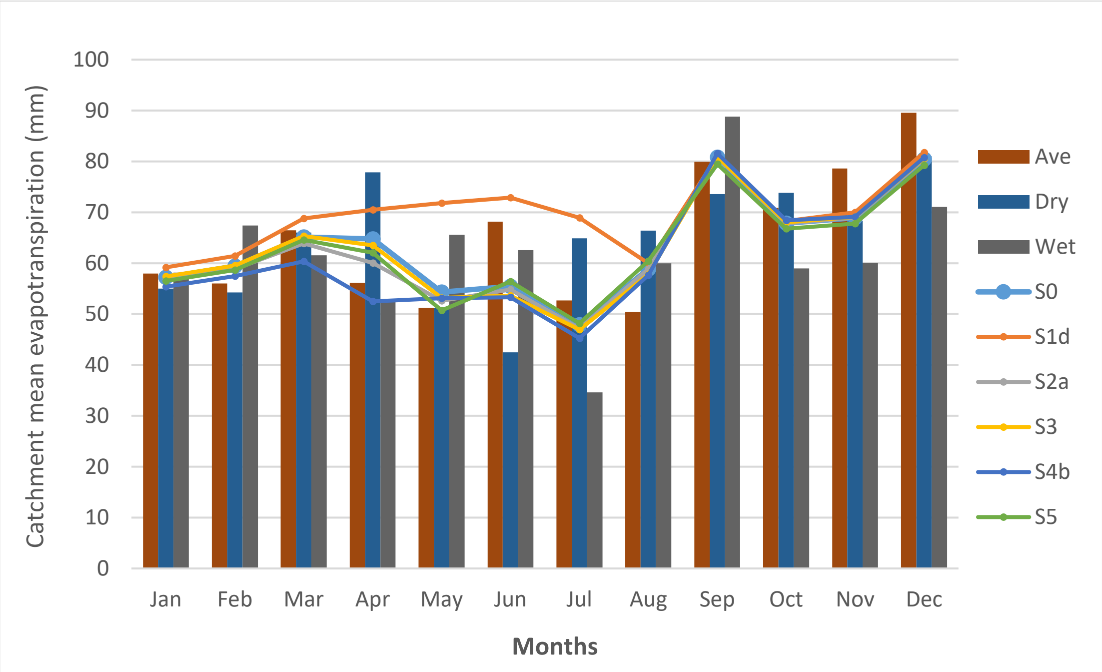

Figure 4.6. Temporal variation of the monthly simulated evapotranspiration for different land use scenarios, averaging over dry, average and wet climatic conditions (line chart) and for dry, average and wet climatic conditions averaging over all land use scenarios (bar chart).

4.3.7 Variations in net recharge

Net recharge was mostly influenced by climate, and seasonal variation was obvious (see Figure 4.7). In all combinations of land use and climatic conditions, simulated net recharge was low in the dry season from January to August, and it reached the lowest values in March and April when precipitation was extremely low, with no or even negative net recharge observed. High net recharge was simulated for the rainy season, from September to December, with an average net recharge for the whole catchment of about 100–160 mm monthly. Total net recharge for the four months of the wet period was 497 mm, accounting for 81% of the annual recharge in the base scenario (S0).

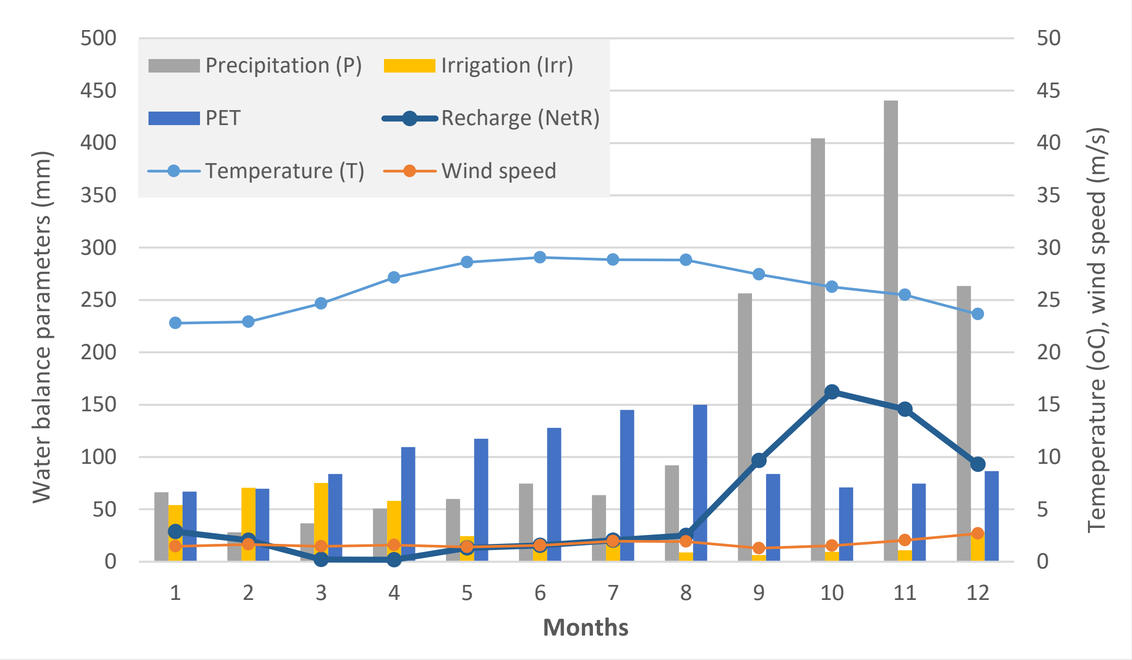

Figure 4.7. Temporal variation of the monthly simulated net recharge by WetSpass-M and other climatic and water balance component data as inputs, averaging for all combinations of land use scenarios and climatic conditions.

In the first half of the dry period (January to April), when precipitation was low and return flow from irrigation was a main source for recharge to groundwater, the simulated recharge for the different scenarios varied slightly (see Figure 4.8). The lowest recharge was obtained for the S4b scenario, followed by S2a. S5 exhibited the highest recharge, slightly above that for the S0 scenario. For the rest of the year, when precipitation started increasing and irrigation reduced, the differences in the simulated recharge between scenarios were negligible (see Figure 4.8). Comparing to the base (current) land use scenario, all other scenarios had a lower annual net recharge, with a 0.2–7.0% reduction from the 633 mm of net recharge for the base scenario (equal to 1.2–41.6 mm). Comparing between the climatic conditions, the average condition had an estimated net recharge of 568 mm/year, while the values for the dry and wet conditions were 345 mm/year and 933 mm/year, respectively, equating to 61% and 164% of the net recharge for the average condition. In the rainy season (September to December), the discrepancies between the recharge in the different climatic scenarios were obvious and their magnitude corresponded to that of rainfall. However, for the dry months (January to August), these differences were not consistent.

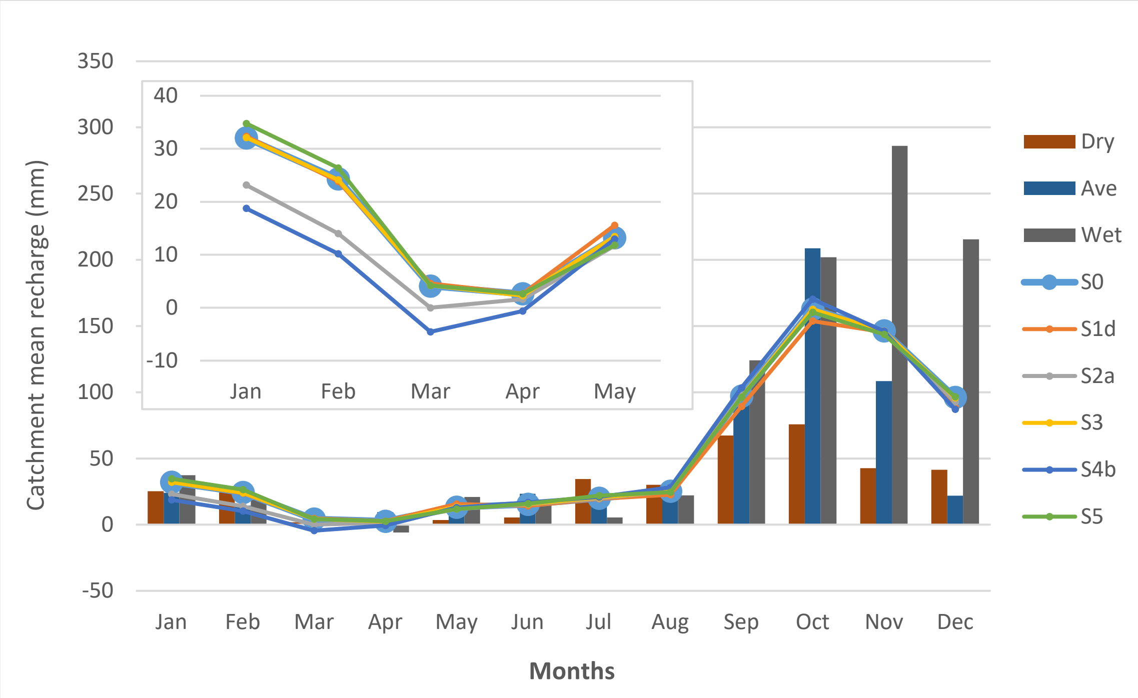

Figure 4.8. Temporal variation of the monthly simulated net recharge for different land use scenarios, averaging over dry, average and wet climatic conditions (line chart) and for dry, average and wet climatic conditions, averaging over all land use scenarios (bar chart). The inset shows the temporal variation of the net recharge for the dry period for different land use scenarios.

4.3.8 Variation on other flow components and groundwater storage

Negative change in groundwater storage (withdrawal) was observed in the dry period (January to August) and positive change (recharge) was observed in the rainy season (September to December). Changes in groundwater storage reflected the variation in groundwater demand for irrigation over the range of land use scenarios (i.e., an increase in groundwater demand caused a decrease in groundwater storage), particularly during the dry period. Compared to the base scenario, scenarios S1d and S5 showed an increase in groundwater storage of 44% and 3% (for the dry period) and 26% and 2% (for the wet period), respectively. Conversely, S4b and S2a showed a decrease in groundwater storage by 39% and 24% (for the dry period) and 33% and 19% (for the wet period), respectively. The groundwater storage of S3 was similar to that of the base scenario S0. When averaging for all land use scenarios, changes in groundwater storage between climatic conditions were smaller in the dry season than in the rainy season, as the magnitude of precipitation, and hence recharge, in the dry season is much smaller than in the rainy season.

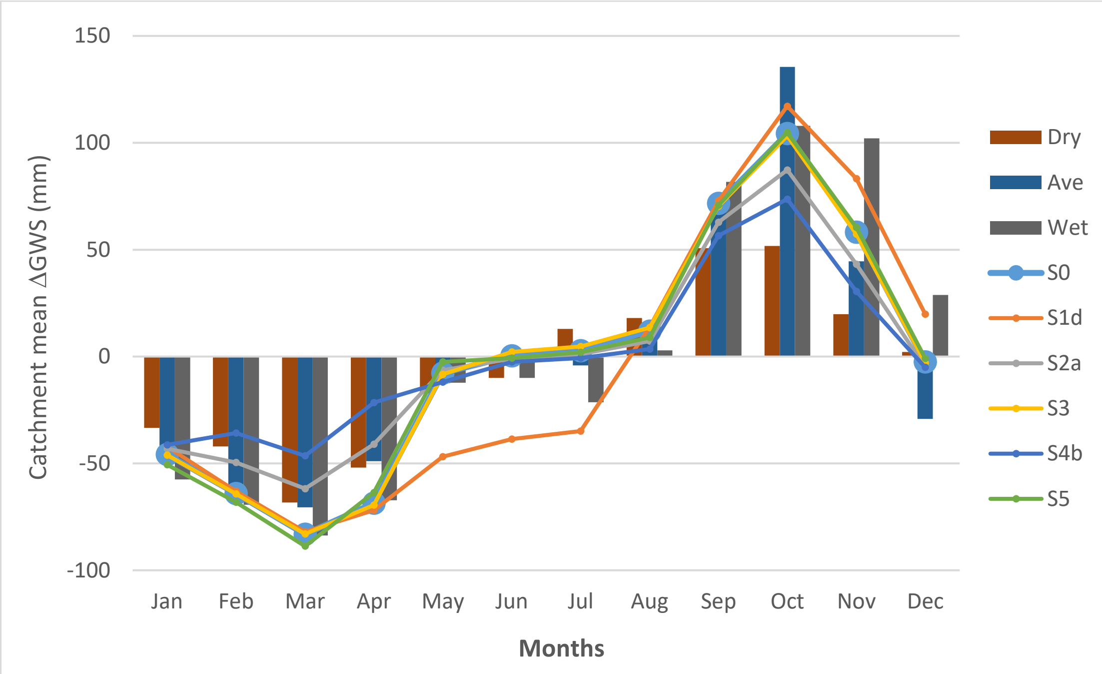

Figure 4.9. Temporal variation of the monthly simulated change in groundwater storage for different land use scenarios, averaging over dry, average and wet climatic conditions (line chart) and for dry, average and wet climatic conditions, averaging over all land use scenarios (bar chart)

Base-flow was relatively small, varying between 10% and 40% of groundwater abstraction or change in groundwater storage, during the dry period, particularly for the first four months (January to April). However, during the rainy season, base-flow was the most significant sink of the aquifer, with the total base-flow for the four-month rainy season being four times higher than that of the abstraction, and five times higher than that of the change in groundwater storage. The different scenarios all show that the base-flow was small during the dry period (January to August), about 30% of the total yearly base-flow. However, in the wet season (September to December), total base-flow was much higher, approximately 70% of the total yearly base-flow. The beginning of the year (which is also the beginning of the dry season) until April showed a decreasing base-flow, while then starts rising from May until the end of the year. Base-flow varied between each land use; respectively, S4b and S2a had a base-flow that was 70% and 30% (annually) and 124% and 47% (for the dry period) higher than in the base scenario (S0). S1d and S5 had lower base-flow compared to the base scenario, by 33% and 15% (annually) and 30% and 15% (for the dry period), respectively. S3 had the same base-flow as S0. Considering that recovery of groundwater levels in response to pumping in different scenarios is a slow process, the differences in the wet season base-flow across the different land use scenarios were still significant, varying from -34% to 56% compared to the base scenario.

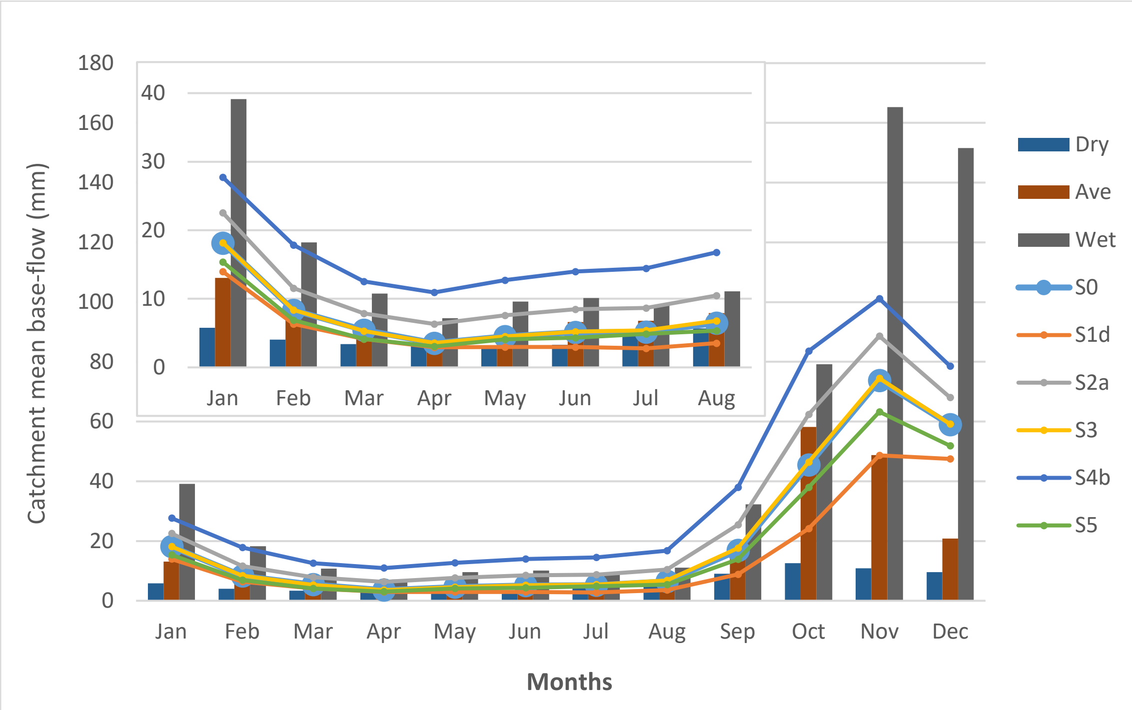

Figure 4.10. Temporal variation of simulated base-flow to streams for different land use scenarios, averaging over dry, average and wet climatic conditions (line chart) and for dry, average and wet climatic conditions, averaging over different land use scenarios (bar chart). The inset shows data for the dry period (January to August).

4.4 Discussion

Changes in land use have been increasingly occurring over the recent decades. The main trend in land use change has been the expansion of human settlements, agriculture and urban land, at the detriment of natural ecosystems, forests and wetlands, for satisfying the needs of the increasing world population (DeFries & Eshleman, 2004). Developing regions have been prone to land use changes. Variability in climatic conditions, particularly strongly seasonal fluctuations in precipitation, are typical of humid tropical climates (Nolte *et al.*, 1997). Both land use change and climate variability cause alterations in the flow components of surface and subsurface water systems (Nolte *et al.*, 1997; DeFries & Eshleman, 2004; Costigan *et al.*, 2016; Vu *et al.*, 2018). The combined influences of these modifications are expected to be strong in developing areas under humid tropical conditions, such as Vietnam.

The combined impact of land use change and climate variability on groundwater budgets occurs through a complex set of processes involving both direct and indirect interactions. Changes in climatic conditions influence the availability of water for infiltration with implications for the magnitude of groundwater recharge, while land use changes modify surface runoff and transpiration processes (by differences in cropping patterns). As the results of this study show, given certain factors of soils and hydrogeology (depth to groundwater levels), net recharge is strongly determined by climate, particularly rainfall, and to a lesser extent by land use changes. An indirect consequence of changes in land use affecting groundwater budgets is modified anthropogenic groundwater abstraction for irrigation. Differences in groundwater abstraction (for irrigation) cause changes in the groundwater balance by modified recharge, discharge and groundwater storage. Most directly, groundwater abstraction causes reduction of groundwater storage, which in turn causes reduced groundwater base-flow to streams. Irrigated water applied on the ground surface has the potential to increase recharge as return flow (Groundwater Resource Estimation Committee, 2009). However, water demand for irrigation is normally determined by the evapotranspiration of the irrigated crops; that is, irrigation practices normally aim to supply the amount of water required for optimal growth of crops (Allen *et al.*, 1998). Hence, irrigation water mainly supports the actual evapotranspiration of the particular land use, rather than increasing the recharge to groundwater. This complex relation between the change of one flow component to another reveals the fact that groundwater exists in a (dis-)equilibrium, such that changes in any of the flow components in turn cause variations in others (Bredehoeft *et al.*, 1982; Fetter, 2018).

As illustrated by the results of this study, changes in groundwater storage were strongly influenced by land use variations in dry the period (January to August) and climatic variability in the rainy season. In the dry season, variations in the amount of groundwater abstraction for irrigation were of the magnitude of the changes in groundwater storage. Abstractions caused up to a 51% decrease (in S1d) and a 54% increase (in S4b) in base-flow to streams for the dry period, compared to the base scenario of land use change (S0). In the wet season, variations in demands for irrigation between land use scenarios were negligible. Conversely, significant differences in precipitation among climatic conditions caused substantial changes in recharge, which determines variations of base-flow to streams. A linear relationship between irrigation and actual evapotranspiration between scenarios (see Figure 4.11) was observed, rather than modifying the amount of recharge. Modifications of change in groundwater storage by groundwater abstraction rather than increasing recharge or ceasing discharge to streams proves the theory developed by Bredehoeft *et al.* (1982) that it takes time for groundwater developments to 'capture' discharge or induce recharge.

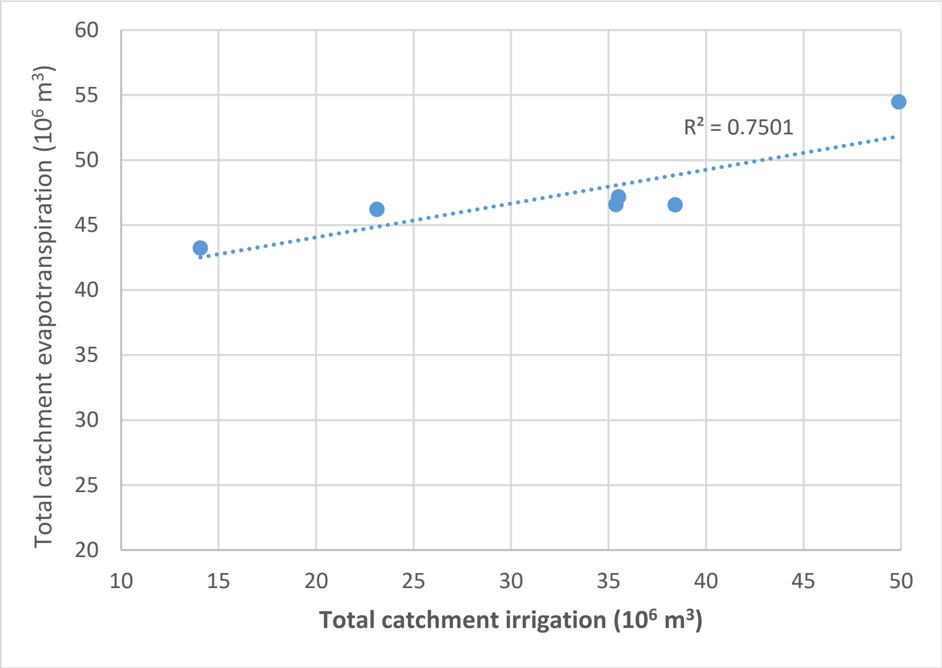

Figure 4.11. Linear relationship between actual evapotranspiration and amount of water used for irrigation by different land use scenarios.

Land use change has occurred and will continue in the future in many parts of the world, particularly in agriculturally dominant catchments in developing countries. Hence, there is a concern for the development of sustainable groundwater use as a function of the increasing demand for groundwater abstraction for irrigation. As seen in this study, more crops would result in higher demand on groundwater abstraction and increasing evapotranspiration, while there is no significant change in the amount of recharge to groundwater by return flow from irrigation. Consequently, more stress on groundwater abstraction may result in overexploitation of groundwater resources and would threaten groundwater-dependent ecosystems. For all the land use scenarios tested in this study, annual groundwater abstraction indicators (i.e., ratio between annual abstraction over recharge) range from 0.20–1.58. Only 17% (3/18 scenarios) of these have a ratio smaller than the sustainable development indicator of 0.35 as suggested by Henriksen *et al.* (2008). None of the scenarios is sustainable under the dry climatic conditions when the recharge is small due to low precipitation. This situation suggests that more attention should be paid to reducing the amount of groundwater abstraction when planning land use. Specifically, water-intensive crops could be replaced by water-efficient ones, as seen in land use scenario S3, or water could be saved by applying modern irrigation techniques as demonstrated in scenario S2a. This would reduce groundwater consumption, thereby reducing the stress on groundwater resources.

As has been shown in several studies (e.g. Bormann *et al.*, 2007; Li *et al.*, 2009; Wijesekara *et al.*, 2012; Kalantari *et al.*, 2014), using a multi-model approach is useful for taking into account the advantage of each model to deal with the complex interactions happening in complex groundwater resource systems. In this study, different models were used to simulate each particular process. First, WetSpass-M was used for simulating recharge. This model takes into account the climatic inputs of rainfall, temperature, PET, number of rainy days and wind speed; land use inputs (e.g., LAI, root depth); and topography (slope) and hydrogeological data (soils, depth to groundwater table) for estimating various surface processes of surface runoff, actual evapotranspiration, interception and surface runoff, before using the water balance for estimating actual recharge to groundwater as the residual term of the water balance equation (Abdollahi *et al.*, 2017). WetSpass-M also provides the possibility to estimate return flow from irrigation by considering irrigation water as an additional source of water to the surface, along with precipitation. To do that, return flow from irrigation is estimated by considering all other water balance components happening on the ground surface. This procedure is more realistic than a rough estimation of irrigation return as a fixed proportion of the amount of water used for irrigation. Output from the WetSpass-M model of net recharge was then fed into the MODFLOW model, which has been found to be an appropriate tool for simulating 3D groundwater flow (Harbaugh, 2005).

Despite the advantages of applying a multiple-model approach, there are still uncertainties associated with the results provided by this study. Land use data was drawn from satellite images, which were then used for estimating groundwater abstraction for input into the models. The process of producing land use data and converting them to groundwater extraction would include errors for the results of land use and estimated groundwater. Using these errors as inputs would propagate through the model and appear in the final results of the estimated flow components. Providing more observations for calibration as a means of crosschecking would be one possible solution to reduce possible uncertainties. For example, more ground truth data would be useful for checking the accuracy of the classified land use.

4.5 Conclusion

Land use change has been occurring in many parts of the world, particularly where there is a demand for land to satisfy the needs of growing populations, such as in developing regions. Climatic variation is typical for humid tropical climates. Land use change and climate variability are the main causes for alterations in groundwater budgets or groundwater flow components. These modifications are more obvious in developing countries in humid tropical climates, like Vietnam, as both influence groundwater resources. The impacts can be (1) direct modifications of flow components (e.g., recharge) and/or (2) variations in groundwater demands or anthropogenic abstraction for irrigation. Land use alteration makes changes in demand for groundwater abstraction more likely, while variation in climatic conditions affects both the availability of water sources for recharging groundwater and the processes of discharging groundwater (e.g., evapotranspiration). The overexploitation observed in the case of the agriculture-dominant catchment of La Vi necessitates that water managers direct more attention towards planning for sustainable water resources management.

Chapter 5. Conclusions and Recommendations

5.1 Main findings

Some main findings from this study are:

(1) As found in Chapter 2, seasonal variation in precipitation and groundwater abstraction are the two main causes of fluctuation in base-flow from groundwater to streams in humid tropical catchments. Local hydrology plays a less important role. Both groundwater and in-channel water levels are highly sensitive to local precipitation, which in turn causes variation in fluxes between groundwater and surface water (i.e., base-flow), and river flow regimes. Local hydrology (soil conductivity) and human abstraction are other causes of changes in base-flow, although to a lesser extent.

(2) A lack of information on groundwater abstraction in ungauged catchments is typical for many developing regions in the world. However, this problem of data paucity can be overcome by using estimation techniques based on 'soft data' from local knowledge. Groundwater level fluctuation and land use data, in combination with data about cropping practices, can be used to indirectly estimate groundwater abstraction. However, the uncertainties associated with these estimations are large and efforts are needed to reduce these. Applying multiple approaches to a single area is helpful for creating more confidence in the estimated results by means of crosschecking.

(3) Land use change and climate variability are the two main factors influencing groundwater budgets or the flow components of net recharge to groundwater, change in groundwater storage, base-flow to streams and anthropogenic abstraction, particularly for agriculture-dominated catchments in developing countries in the humid tropical regions. Land use change that results in a variation in groundwater abstraction significantly modifies the values of groundwater storage during the dry season, when abstraction is intensive and precipitation is low. Conversely, in the wet season, when precipitation is high and little irrigation is used, variability in climate becomes the main cause of change for groundwater and base-flow to streams. The results also revealed that groundwater was being overexploited due to high demand for irrigation in the catchment; a finding that may reflect conditions in many other agriculture-dominated catchments. This problem of groundwater overexploitation must not be overlooked by water

managers when planning for sustainable and appropriate water use in the catchment.

(4) Combining all the results from this study, several conclusions can be drawn:

   i. From a scientific perspective, the multiple-model approach, which uses several models in tandem, provides a useful tool for testing water-resource problems of concern. As each tool was developed for a particular purpose, using them together provides the benefits of every single tool. Current developments in IT make it quite feasible to couple more than one tool or model for a study. However, careful attention should be paid to the availability of required information and knowledge, as well as the purposes of every use of each simulation. One example for this can be seen in the difference between how the WetSpass-M simulations were used in Chapters 3 and 4. In Chapter 3, WetSpass-M simulation was used as one step in the process of estimating groundwater abstraction. Return flow from irrigation estimated from land use was not included in this simulation, to avoid dependency in the results of compared methods. Conversely, in Chapter 4, WetSpass-M simulation was used to test the whole groundwater system, with return flow from irrigation included to improve the accuracy.

   ii. In terms of management, this study recommends cooperation and the transfer of knowledge between professionals and managers, to avoid water resource–based problems associated with poor decision-making.

5.2 Recommendations for future research

This study focused on the availability and variation of groundwater resources in terms of quantity by examining volumetric flow components rather than groundwater quality. However, the problems associated with groundwater resources concern both quantity and quality. Therefore, future work is recommended on groundwater quality problems, particularly in agricultural tropical climate basins. Some possible areas of research are:

1. Studies on chemical reactions between surface water and groundwater due to the water-cycling process at their interface in response to precipitation events and groundwater-pumping regimes.
2. Studies on the biochemical processes influencing water quality in relation to agricultural practices (e.g., overuse of fertilizers and pesticides).

3. As found in this study, uncertainties associated with the estimations using 'soft-data' are usually large. Hence, detailed studies about the error's behaviours with applicable suggestions on how to control and reduce the associated uncertainties should be of interests for researchers using 'soft-data' to overcome the problems of data paucity in water management in particular and other fields in general. Research combining 'soft-data' and 'hard-data' (e.g. using groundwater models) would also be very useful.

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