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Groundwater and Surface Water Interactions in Sukhuma District, Champasak Province, Southern Laos: A Preliminary Assessment

Sinxay Vongphachanh[1], William Milne-Home[2], James E Ball[3]

[1]PhD Student, School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology, University of Technology Sydney, Australia
E-mail: sinxay.vongphachanh@student.uts.edu.au

[2]Co-supervisor, School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology, University of Technology Sydney, Australia
E-mail: William.Milne-Home@uts.edu.au

[3]Principal Supervisor, School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology, University of Technology Sydney, Australia
E-mail: James.Ball@uts.edu.au

Abstract

Southern Laos is undergoing economic and agricultural development, resulting in a large increase in groundwater and surface water use. However, these water resources are not known in detail. This study aims to investigate the groundwater and surface water interactions in the Sukhuma District of Champasak Province using a network of sixteen rain gauges and groundwater levels measurement points. Groundwater levels are measured weekly in eleven domestic wells, which are pumped irregularly, and also in five observation bores. Aquifer recharge occurs from direct infiltration of rainfall and also is derived using baseflow calculated from daily streamflow measurements at the re-established gauging station on the Khamouan River in Sukhuma District. The Khamouan River is connected to the groundwater in its lower reaches in both dry and wet seasons. Baseflow proportion to the total streamflow in the wet season 2015 has been estimated at 46%. The distribution of direct recharge has been mapped with ArcGIS and is spatially variable. Preliminary estimates of rainfall recharge have been calculated by the water table fluctuation method for 2015 but show a high degree of uncertainty related to the specific yield estimates. Time series analysis has confirmed the observed lag of some three to four weeks between the wet season start and rise in groundwater levels. These preliminary results indicate that there is close interaction between groundwater and surface water in the Sukhuma District. Further analysis will refine these results and extend them through remote sensing across southern Laos for application to integrated water resources management.

1. INTRODUCTION

Water is a vital natural resource for the environment and for socio-economic development. However, in many developing nations there is a lack of the data necessary to study the interaction between surface water and groundwater (GW-SW) for assessing sustainable water use. Laos is a developing country located in Southeast Asia. it is recognized as a water-rich country in the region, with fresh surface water resources estimated at 54,565 m^3 per annum per capita (FAO, 2011). About 80 percent of the country's area is mountainous, particularly in the north and east. In contrast, about 70 percent of the population live in lowland areas, which are at risk from floods and droughts. Groundwater is the main source for domestic water supply in the floodplain areas. In Southern Laos, for example, there are plans for developing groundwater for irrigation and water supply to alleviate dry season water shortages.

However, an integrated assessment of the available surface and ground water resources in this region has been hampered by limitations in the available data. Groundwater data in the region is very limited although some rainfall and stream flow data are available from Lao government agencies, such as Department of Meteorology and Hydrology (DMH) and the Mekong River Commission (MRC). Fortunately, with the increasing number of remote sensing satellites, it is possible to improve estimation of groundwater and other components of hydrological cycle. For this study, the water balance equation will be used for assessing the interaction between groundwater and surface water in the area with limited field observation data, such as groundwater level, stream-flow, geology, and climate data.

2. METHODOLOGY

The water balance technique is crucial for assessing water resources sustainability (Mays, 2012). Water balances are used to identify the water movement through the hydrologic cycle and to investigate the interactions between surface water and groundwater (Todd & Mays, 2005). The water balance method has been used by many researchers on a variety of space and time scales, ranging from local scales to global scales (Mays, 2012, Scanlon *et al*, 2002, Todd & Mays, 2005).

According to Fitts (2002) and Mays (2012), the components of the water balance equation for a catchment commonly include the groundwater recharge (R) from rainfall and stream water on the catchment, the groundwater inflow (G_i), the groundwater outflow (G_o), the groundwater discharge to streams or baseflow (G_S), the evapotranspiration (ET), the groundwater abstraction (Q_w), the stream outflow (Q) from the catchment, all in terms of volume over a time interval. The fluctuation of total water storage (TWS) in the catchment (ΔS) can be estimated from the equation below:

$$\Delta S = R + G_i - G_o - G_s - ET - Q_w - Q \quad (1)$$

2.1. Study Area

In Laos very few studies have been done on groundwater in terms of quantity, and not any scientific research on the seasonal fluctuations of groundwater and surface water interactions. A site, Sukhuma District, Champasak Province in southern Laos was selected for this study, where groundwater is the main source for domestic water use but there are very few studies of its occurrence. Sukhuma has more basic geological and hydrogeological data than other districts in Champasak Province, as well as elsewhere in southern Laos. Sukhuma is located in the Lower Mekong Basin on the flat land of Champasak Plain. Extensive irrigation development and rapid economic growth are anticipated in the region. Nearly 100 percent of households in the district use groundwater (Vote *et al*, 2015). Therefore, it was selected for this study.

The Khamouan River divides Sukhuma into two parts. The eastern part is the floodplain area, which is mainly used for agricultural activities, particularly rice paddy fields in the wet season, while the western side area of the Khamouan River is mostly forested. In addition, the Mekong River, the biggest river in Laos, lies to the east of Sukhuma. Figure 1 shows the location and physical features of Sukhuma.

2.2. Data Availability and Collection

Currently, the availability of input data for this study includes rainfall, stream stages, stream discharge, groundwater levels, and remote sensing data. Sources and available periods for these data are described in Sections 2.2.1 to 2.2.4

2.2.1. Precipitation Data

Historical daily rainfall data in Sukhuma are available from January 2012 to July 2013 at 16 rain gauges. These rainfall data were collected by the previous project of the Australian Centre For International Agricultural Research (ACIAR) (ACIAR, 2015, Vote *et al*, 2014, Vote *et al*, 2015). A long record of rainfall data from 1993 to 2015 is also available from Sukhuma District Agriculture and Forestry Office (DAFO) and is used in this study. Also, this study continued the collection of rainfall data from the same 16 rain gauges from June 2015 to May 2016. Additionally, historical daily rainfall data at Pakse Meteorological station is also available from 1990 to 2015 and will be used for this study. More climatic data (wind speed, solar radiation, air temperature and relative humidity) and rainfall data in southern Laos will be collected from the Department of Meteorology and Hydrology (DMH), Ministry of Natural Resources and Environment (MONRE) in Vientiane Capital, if supporting funds become available.

2.2.2. Stream-flow Data

Historical stream stage data of in the Khamouan River are available from 1997 to 2006. In order to continue collecting the stage data for the Khamouan River, particularly for this study, a new stream gauge was established on 27 May 2015. The discharge observations in Khamouan River from June 2015 to May 2016 are also available. Location of the gauge is presented on Figure 1.

2.2.3. Groundwater Data

Historical data on groundwater levels, electrical conductivity and temperature in Sukhuma district at weekly intervals are available from October 2011 to June 2013. The groundwater levels were monitored for eleven domestic wells and five paired deep and shallow observation wells by the previous ACIAR project and used by Vote *et al* (2014). From June 2015 to May 2016, groundwater table data have been collected again for the same wells. Figure 1 shows the bore locations which are monitored for this study. A comparison of groundwater table elevations for the wet season 2015 along the profile of the Khamouan River is shown in Figure 2. It can be seen that the lower part of the river is connected to the water table throughout the wet and dry seasons, whereas the upper portion is disconnected.

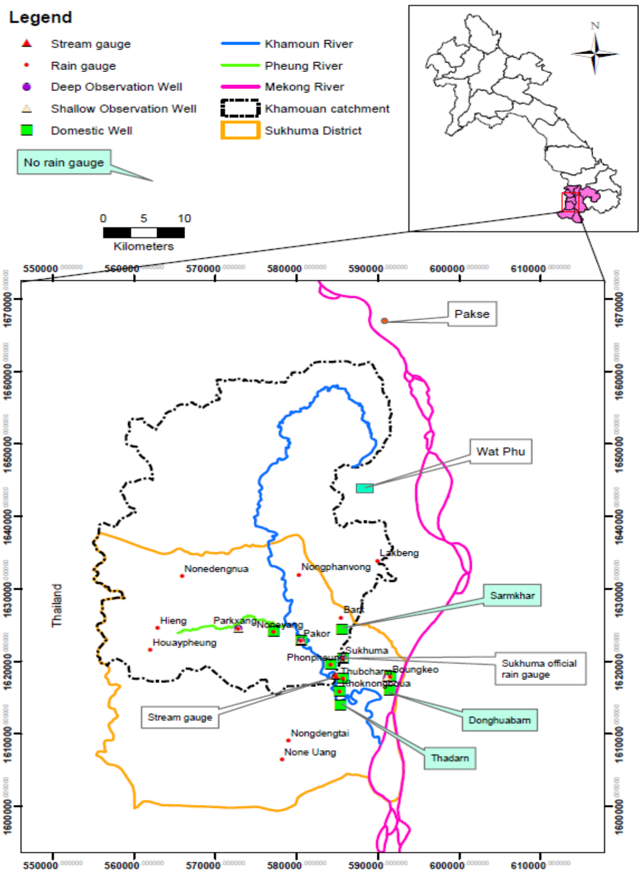

Figure 1 Location Map of Sukhuma, showing Wells, Rain Gauges and Stream Gauge.

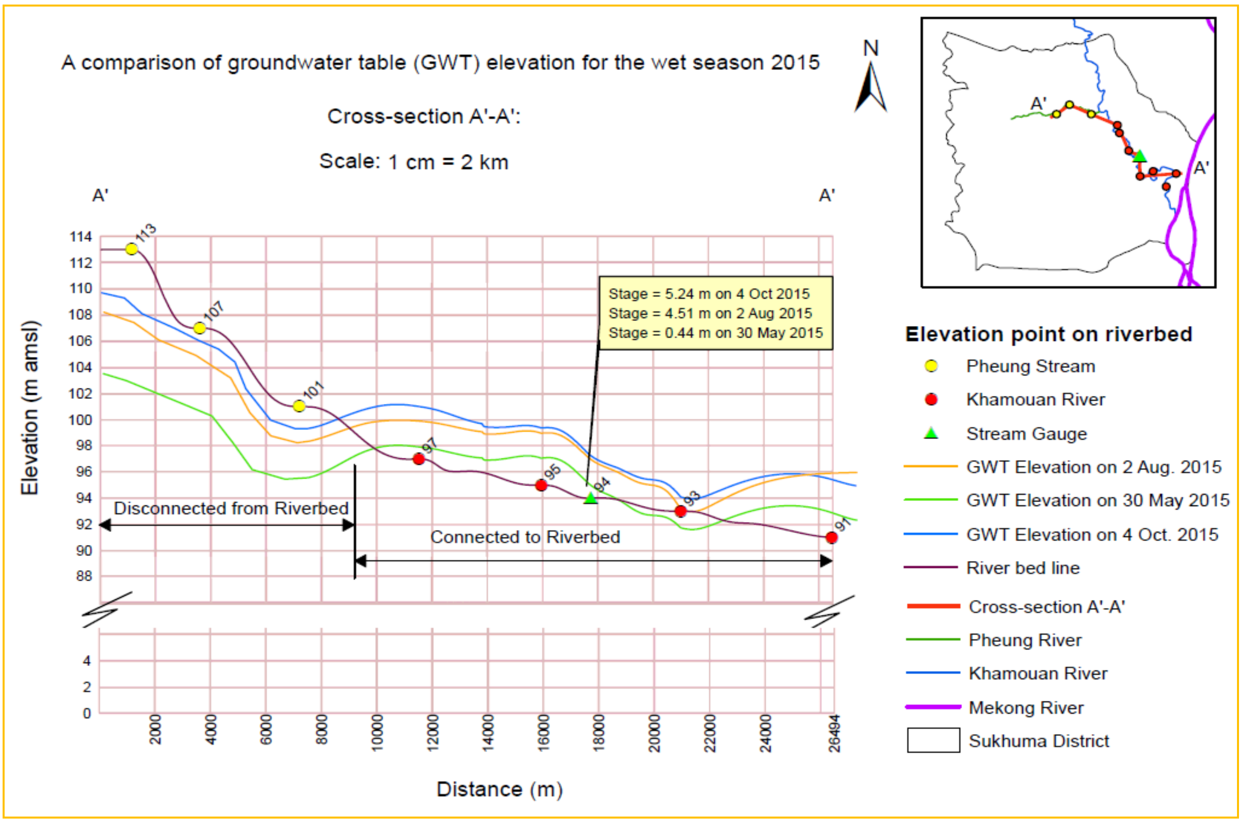

Figure 2 Comparison of Groundwater Table Elevation with Khamouan River Bed Elevation for the Wet Season 2015.

2.2.4. Remote Sensing Data

The Gravity Recovery and Climate Experiment (GRACE) gravity satellite program was jointly developed by the National Aeronautics and Space Administration (NASA) of the United States and the German Aerospace Centre (DLR) and launched in March 2002 to measure changes in the earth's gravity field (Tapley *et al*, 2004). These changes are caused by movement of mass in surface water, soil water and ground water. GRACE measurements are processed mathematically to extract estimates of total water storage (TWS) expressed as equivalent water height (EWH). GRACE date have a spatial resolution of about 200,000 km^2, or ~400 km.

The GRACE-derived TWS consists of a combined total storage of groundwater, soil moisture and surface water (including lakes, reservoirs, and in river water) (Leblanc *et al*, 2009). GRACE satellite data has been widely utilised to determine the variations of groundwater storage in many countries, including the areas with limited field observation data (Shamsudduha *et al*, 2012). For about 13 years, many studies have used data derived from GRACE to estimate the variations of hydrological processes. These include changes in groundwater storage (Rodell *et al*, 2007, Shamsudduha *et al*, 2012) and correlations with peak observed water level during flood season (Steckler *et al*, 2010). We have observed good correspondence between Mekong River flood levels in September 2011 at Pakse and EWH from GRACE.

Since field observations of soil moisture are not available in Sukhuma district and in the districts nearby, reliance is placed on the remote sensing data from NASA's Earth Science Data System website [https://earthdata.nasa.gov/] or data derived directly from the Global Land Data Assimilation System (GLDAS) web link [http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=GLDAS 025_3H] with a spatial resolution of 0.25 degree (28 km) (Hualan & Hiroko, 2015). The GLDAS version 1 (GLDAS-1) product is being investigated from this web link and is being considered for this study. These data are simulation products from the National Centers for Environmental Prediction/Oregon State University/Air Force/Hydrologic Research Laboratory (NAOH). This website provides soil moisture data for four soil depth layers ranging from 0 to 10, 10 to 40, 40 to 100, and 100 to 200 cm. The unit of soil moisture data is kg/m^2. Moreover, it also allows users to download rainfall, total evapotranspiration, total canopy water storage, and other climatic data. Therefore, these satellite data will be analysed and validated with field data.

Initial results from GRACE TWS data and GLDAS soil moisture data show good correspondence with field observations in both the Sukhuma area and Southern Laos. However, this investigation utilised only simple comparison techniques. Therefore, more sophisticated analysis is required for future work in order to increase the precision using satellite data from GRACE and GLDAS.

2.3. Groundwater Recharge Estimation

2.3.1. Estimate Groundwater Recharge from Groundwater Level Measurements

The in situ groundwater level observations in Sukhuma from October 2011 to June 2013 and from June 2015 to May 2016, provided useful information to estimate groundwater recharge by the water table fluctuation (WTF) method. The WTF method estimates groundwater recharge from groundwater level height increases in observation wells during/after a rainfall event times the specific yield (Healy & Cook, 2002). The method is very sensitive to the value of specific yield (S_y).

A reliable estimate of specific yield is commonly determined from the analysis of pumping tests with observation wells. However, these are non-existent in Sukhuma and in southern Laos. The Parkxang deep observation well was pumped and levels in a nearby domestic well were monitored. The value of S_y was estimated at 1.20 x 10^{-2}. For comparison, S_y in the study area was estimated from groundwater recession hydrograph at each well. The range of S_y by this method is from 10^{-3} to 10^{-2}. Vouillamoz *et al* (2016) estimated a similar range of values for a sandstone aquifer in the same geological formation in North-West Cambodia. Use of this range in Sy values give a range of estimated of recharge, as a percentage of rainfall, between 2.3% and 3.3%. Future work will attempt to refine these estimates.

2.3.2. Estimate Groundwater Recharge Using Cumulative Groundwater Fluctuation

Moon *et al* (2004) estimated groundwater recharge by comparing the water table fluctuations with cumulative rainfall and analysing how groundwater level changes related to corresponding rainfall. The assumption for this WTF method is that all increases in groundwater table are affected by rainfall and does not incorporate the G_i, G_o and G_s terms of the water balance equation. Groundwater recharge is quantified as the ratio of the rise in groundwater level to the cumulative rainfall during the rainy period.

In this research, following Moon *et al* (2004), a relationship between cumulative rainfalls and groundwater level changes for each domestic well in the wet season of 2015 was developed. A lag between groundwater fluctuations and rainfall was found and was studied by time series analysis.

The relationships between rainfall and groundwater levels for the domestic bores in Sukhuma district were analysed by using the Cross-correlation Function (CCF) in SPSS software. Figure 3 is an example from the Sukhuma domestic well and a nearby rain gauge. The peak at lag 3 between the two series can be interpreted as an average lag time of three weeks between the start of the rainy season and rise in water level in the Sukhuma domestic bore (Figure 3). The cross-correlation coefficient of the two time series is 0.398. This result will be used for estimating groundwater recharge by using cumulative groundwater fluctuation method in the next steps of this study.

2.4. Baseflow Separation

A baseflow separation method, using the Chapman filter (Chapman, 1999), is applied in this research to estimate the groundwater discharge to the stream, G_s. The input data for this method is the daily streamflow. In this study, daily flow data are calculated from daily stage observations at the stream gauge and from two field discharge measurements in the Khamoun River. Baseflow proportion to the total streamflow in the wet season 2015 has been estimated at 46%.

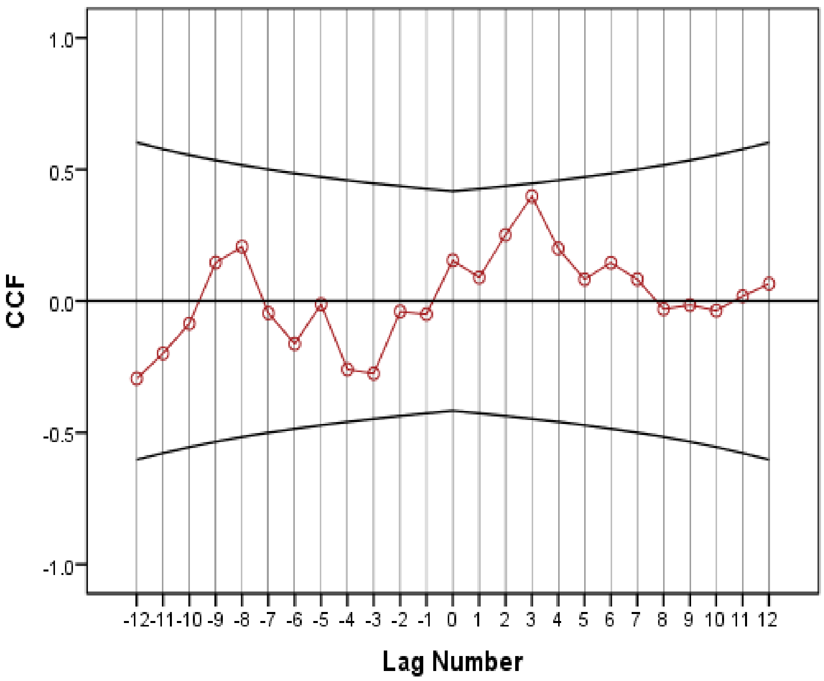

Figure 3 Cross-correlation between Weekly Rainfall and Weekly Groundwater Table Fluctuations at Sukhuma Domestic Well During 31 May to 1 Nov. 2015.

3. CONCLUSIONS

The scarcity of field data observation is a remaining challenge for studying the interaction between groundwater and surface water in any developing country. Groundwater data are very limited compared to stream-flow and rainfall data. More importantly, the aquifer systems are not yet clearly identified not only in the study area but also in the rest of the country. Therefore, this research is developing a methodology for assessing the connection between groundwater and surface water for the region with limited observation data by combining the availability of field data with remote sensing data from GRACE and GLDAS.

4. ACKNOWLEDGEMENTS

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