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Flux dynamics at the groundwater-surface water interface in a tropical catchment

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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.

Introduction

Intermittent streams constitute more than half of the world's river networks, and some of the most vibrant ecosystems (Datry et al., 2014; Larned et al., 2010). 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 and 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., 2015). 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., 2015).

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 (Costigan et al., 2015; Nolte et al., 1997). 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 and Sheaves, 2010).

Recently, research on interaction between groundwater and surface water has shifted from large-scale to smaller scale, and an increasing number of modeling 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 modeled to understand flow dynamics within the streambed.

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 (Fig. 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 20,000 people live within the river basin, primarily in three communes. Roughly 70% of the river basin is covered by agricultural land, of which 30% is irrigated and 40% percent is rainfed; the remaining land is broadleaved evergreen forest (10%) and shrubland (20%). 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 and 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 1300 and 2600 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 1200 and 1400 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.

Methods

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; Fig. 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 analyzed 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 and 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.

Modelling methods

A two-dimensional (2D), variably saturated model was built for each of the three cross-sections using VS2DH (Healy and Ronan, 1996; Lappala et al., 1987) 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 (Fig. 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 gaging 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 (Fig. 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 and Gribb, 2004). Soil thermal properties were obtained from the literature (Naranjo et al., 2012).

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 and 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 1.

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 modeling 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.

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 (Fig. 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 (Fig. 3).

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 (Fig. 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 ^{o}C. Nevertheless, the trend and amplitude were well captured by the model for this site (Fig. 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 ^{o}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.

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 (Fig. 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 (Fig. 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 (Fig. 3).

With pumping effects removed, modeled 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.

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 modeled GW-SW interaction at the river on February 25 in S1 (Fig. 6c; not seen in Fig. 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).

Discussion

Fluxes of water into the streambed and banks have been shown to have long-lasting consequences (McCallum and Shanafield, 2016) and can be important for biogeochemical cycling within the streambed, which in turn influences in-stream water quality (Bencala et al., 2011; Boulton et al., 2010). As summarized in Fig. 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 Fig. 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.

(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 modeling 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. Anibas et al., 2009; Conant, 2004; Schmidt et al., 2006) .

Human activities such as groundwater abstraction and dam operation have been shown to have effects on water exchange between rivers and nearby sediments (Francis et al., 2010; Nyholm et al., 2003). 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 Fig. 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.

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., 2015), 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 and 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., 2015). 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 modeled boundary conditions (Healy and 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 suggests 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 (McCallum and Shanafield, 2016; Rahimi et al., 2015). These processes might function differently for intermittent compared to perennial river systems (Costigan et al., 2015; Datry et al., 2014). 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.

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.

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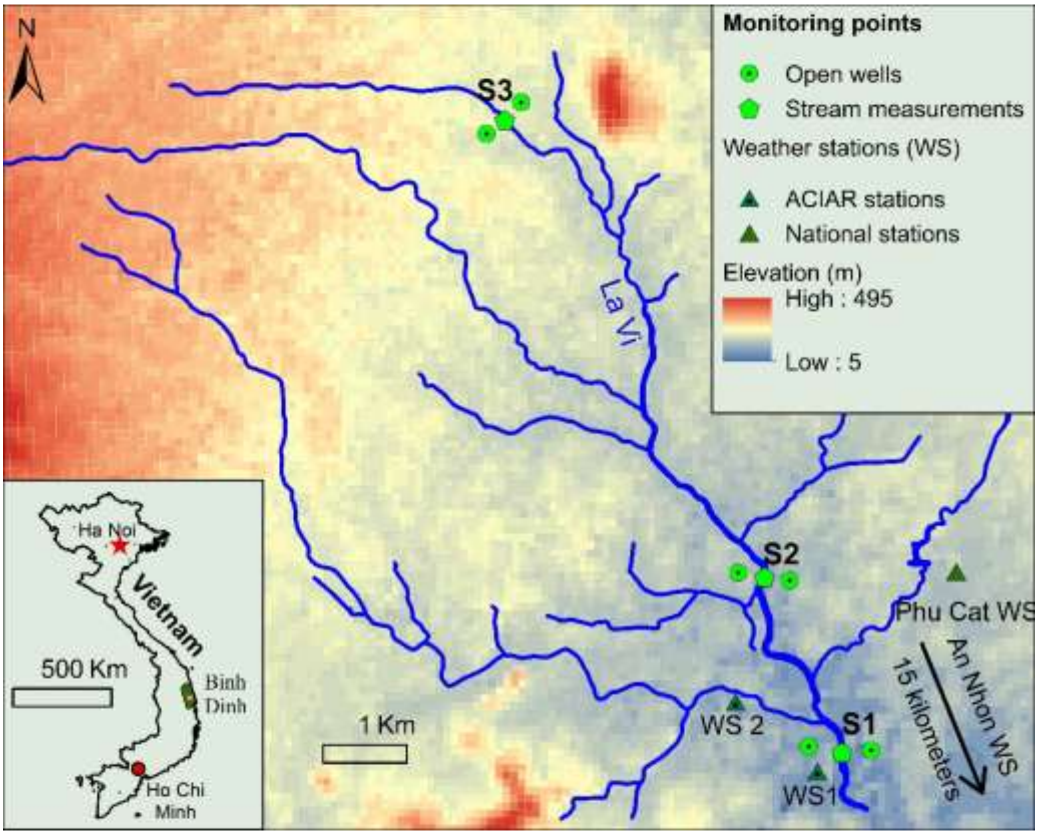

Fig. 1. Map of the La Vi River Basin in Binh Dinh Province, Vietnam. The inset shows a map of Vietnam with the Binh Dinh Province shaded and the location of the La Vi Basin marked with an orange dot (Source: Vietnam Publishing House of Natural Resources, Environment and Cartography). The three study sites (S1, S2, and S3) with well and stream water level locations as well as weather stations are indicated.

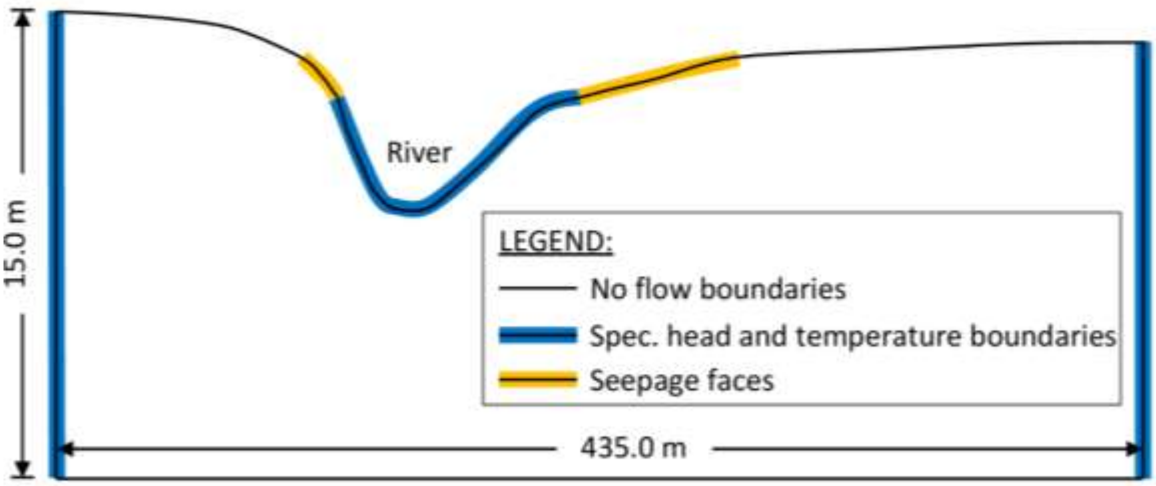

Fig. 2. Model setup for the downstream cross-section (S1): Boundary conditions for the other cross-sections were the same, but the shape of the cross-section was slightly different (based on the survey data).

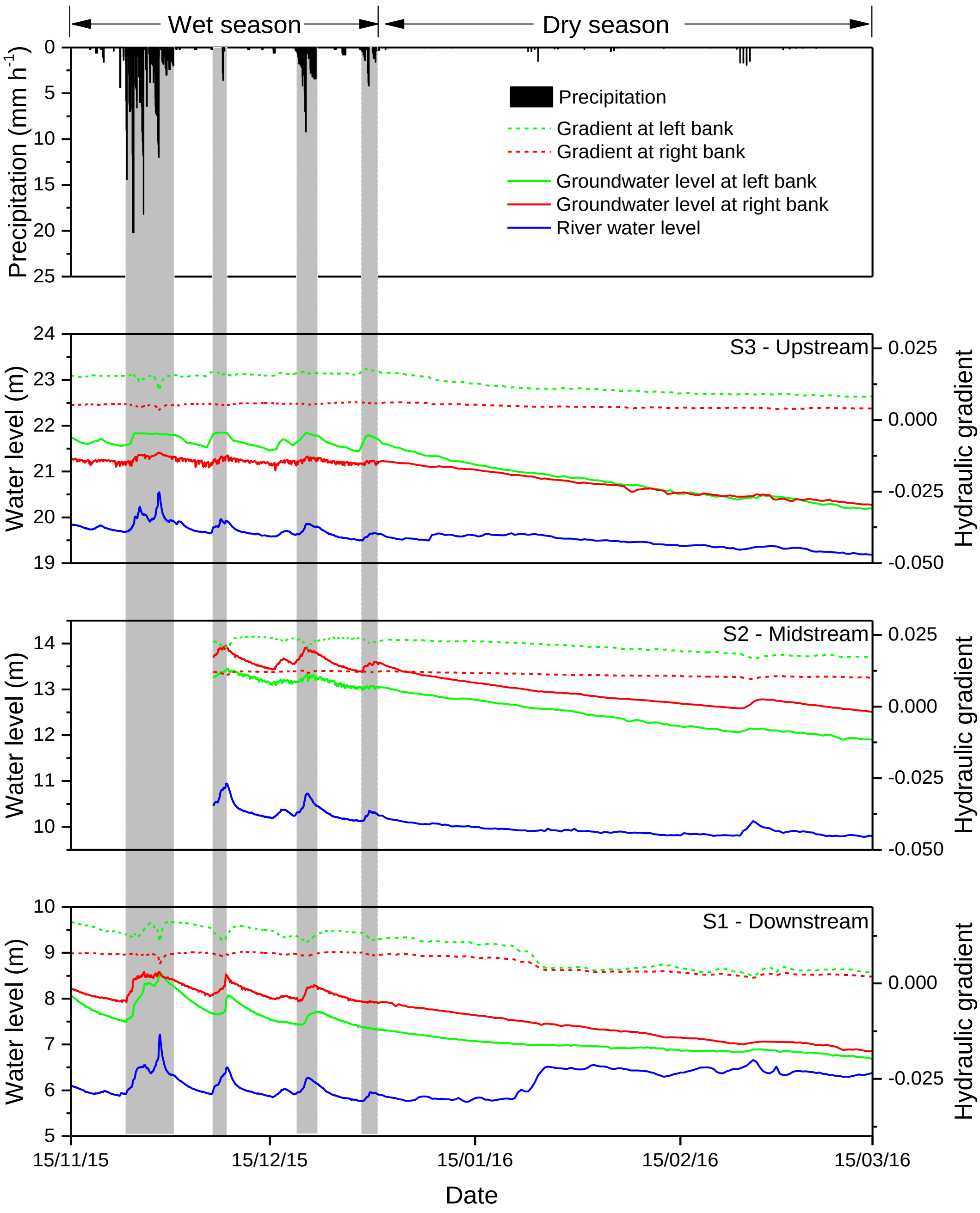

Fig. 3. Local precipitation (top) and measured water levels and gradients in the three cross-sections from 15 November, 2015 till 15 March 2016. Grey shaded periods show the days of storm events.

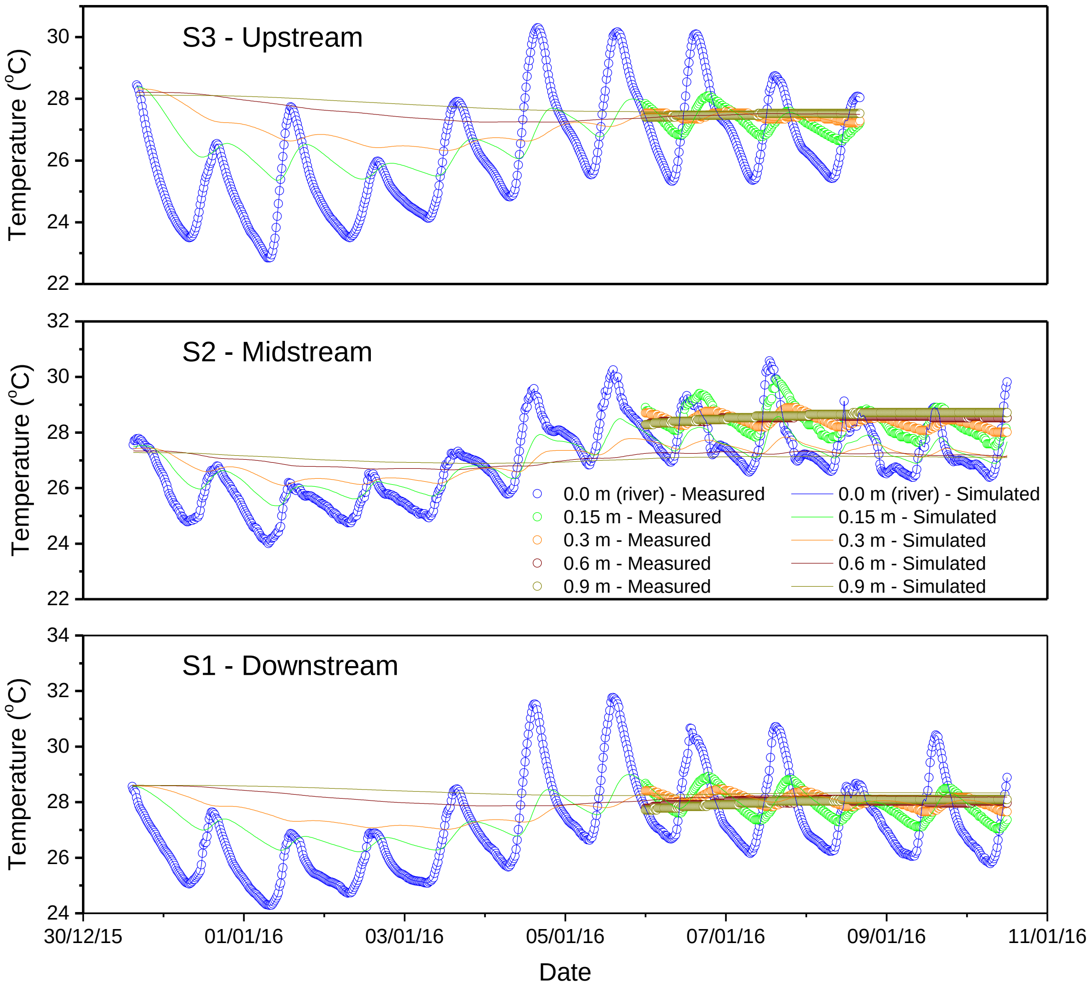

Fig. 4. Comparison of measured and simulated temperatures in the river at 0.15, 0.3, 0.6 and 0.9 m in the river bed for the three simulated sites over the calibration period. Temperature measurements in the river bed start 6/1/2016.

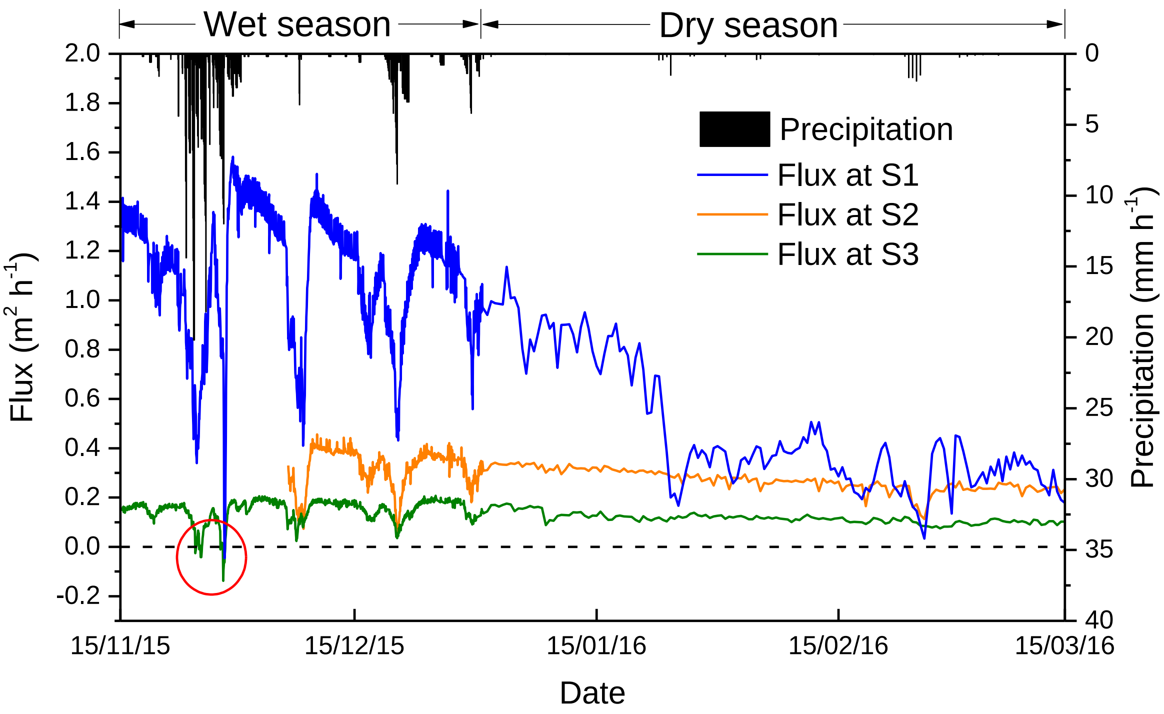

Fig. 5. Modeled flux of groundwater discharge to the river at the three sites using groundwater level long-term trends (pumping effects removed). Modeled flux reversed from discharge to the river to infiltration into the banks (marked in the red circle) at the upstream and downstream sites (S3 and S1) 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.

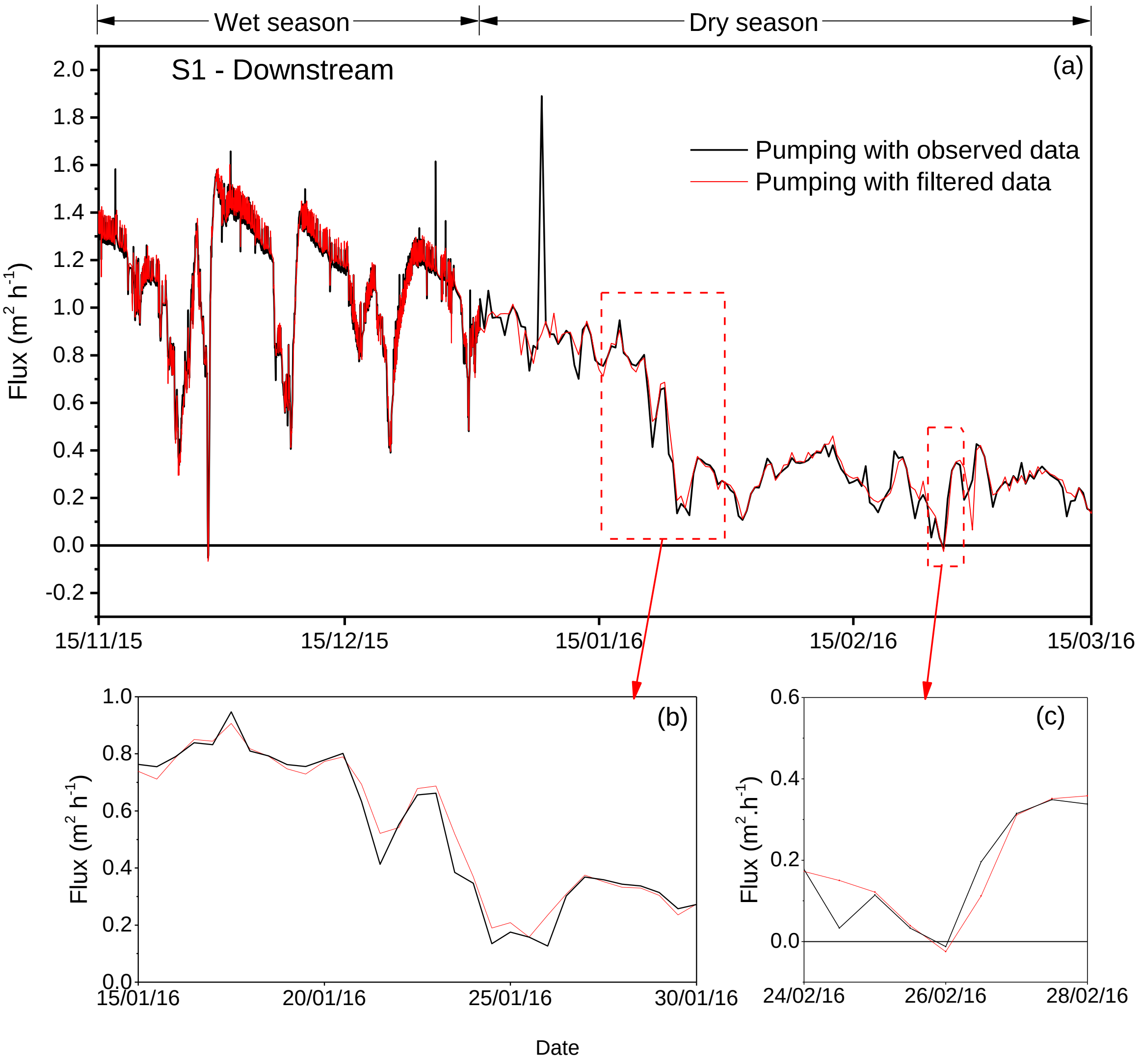

Fig. 6. Simulated fluxes from groundwater to the river with pumping included, using observed data and data filtered with 12-hour moving average for the whole period of simulation (a); focused in to show the period at the beginning of the dry season when pumping is intensive (b), and the flow reversal on 26 February (c).

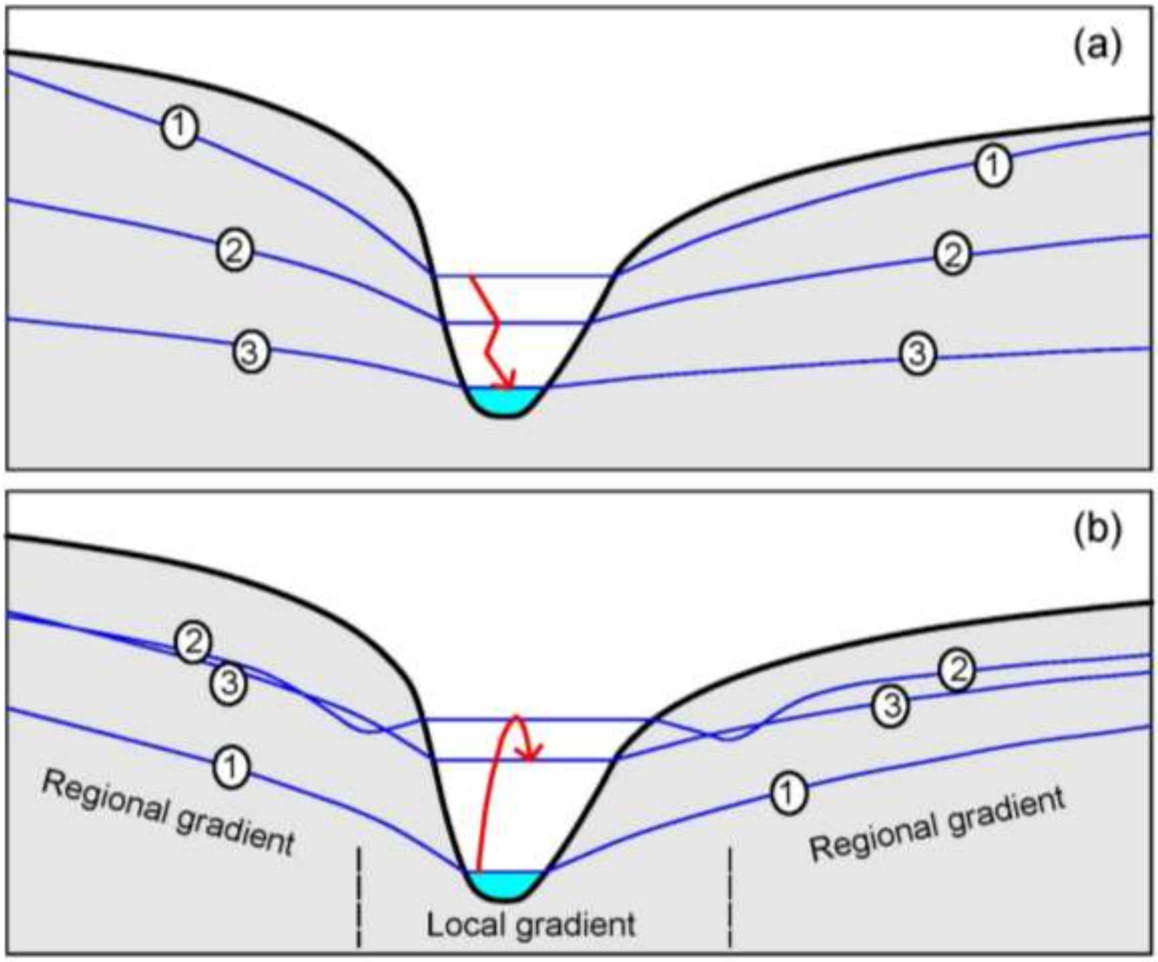

Fig. 7. Summary of seasonal and storm influences on the GW-SW interaction dynamics for the tropical study site.

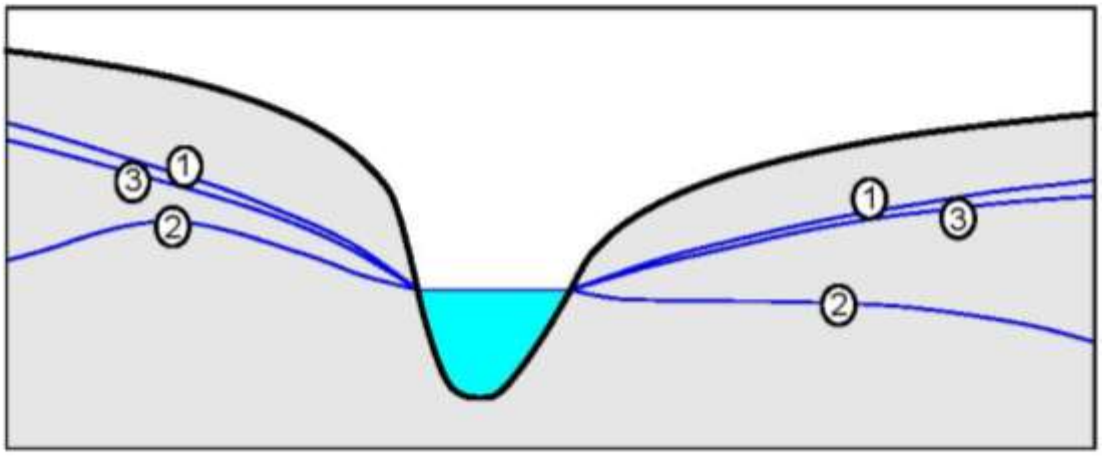

Fig. 8. The influence of groundwater abstraction on the GW-SW interaction dynamics: 1) before the abstraction, the flow is from groundwater to the river (i.e. gaining). 2) Onset of pumping causes a drop in groundwater level, which in turn causes a decreased the gradient to the river. Therefore, the groundwater 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.

Table 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}