Research papers

Groundwater recharge indicator as tool for decision makers to increase socio-hydrological resilience to seasonal drought

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Communities in regions with seasonal rainfall face annual dry seasons, during which water shortages and conflicts between different water use sectors may erupt. These difficulties increase following wet seasons with low rainfall, such as in relation to El Niño events in the wet-dry tropics of Central America. Hydrologic data are typically scarce in this region, making the development of drought adaptation strategies challenging. Many communities in the region depend on groundwater as their primary water source. For instance in the Province of Guanacaste in Costa Rica, groundwater supplied 78% of the total domestic water demand in 2015 and groundwater recharge from the wet season provides the primary water supply for the subsequent dry season. In this research we present a ‘groundwater recharge indicator’ that can support water managers in preparing for seasonal droughts. We developed this tool for an aquifer in northwestern Costa Rica where we conducted hydrological monitoring of streams and groundwater levels for 2.5 years, obtained further hydrological data (groundwater levels from 2005 to 2016), and worked with communities to assemble water use data. We combined these datasets in a hydrologic model (the Water Evaluation And Planning system, WEAP) and modelled groundwater recharge from 2005 to 2016, permitting a characterization of the relationship between rainfall and groundwater recharge. The groundwater recharge indicator is based on this relationship, and allows estimating total groundwater recharge for a wet season from cumulative rainfall measured to date. The indicator permits water managers to assess if the current year will likely fall into a low recharge category prior to the end of the wet season. This information can then be used to trigger short-term adaptation strategies with the goal to ‘bank’ groundwater while surface water sources are still available in the wet season. This indicator-based tool was refined through feedback provided in local stakeholder workshops. We also assessed the overall accuracy of predicting end-of-wet-season groundwater recharge with cumulative rainfall to date, and found that after the first 2–3 months of the wet season, prediction accuracies are high, leaving 5–6 months of wet season to respond adaptively to the prediction. The indicator can help water managers to plan ahead, and communicate the need for water conservation (demand management) and consideration of other water sources such as rain and surface water (supply management). This idea is transferable to other communities in regions with seasonal rainfall, and can support decision makers in increasing the socio-hydrological resilience of communities to seasonal droughts.

1. Introduction

Inter-annual variability of seasonal rainfall and groundwater recharge can pose water challenges for communities in regions with extended dry seasons that are reliant on shallow groundwater to meet their water demand. These challenges will likely increase in the future with projected increases in seasonal and inter-annual rainfall variability in Central America (Magrin et al., 2014) and increasing water demands (Wada and Bierkens, 2014). Seasonality of rainfall defines many climate systems around the world. The Pacific coast of Central America is one of the hotspots of rainfall seasonality, together with northeastern Brazil, western sub-Saharan and central Africa, northern Australia and parts of Southeast Asia (Feng et al., 2013). In these regions, a temporal mismatch between water availability and water needs can lead to natural and technical water shortages and conflicts between different sectors (i.e., agriculture and domestic water demand), and between human and natural system needs (Ballesteros et al., 2007; Kuzdas and Wiek, 2014; Kuzdas et al., 2015b).

In addition to the seasonal rainfall regime, high inter-annual rainfall variability characterizes the wet-dry tropics of Central America. One of
the main drivers for this is the El Niño Southern Oscillation (ENSO), with lower rainfall to this region during El Niño periods (Steyn et al., 2016; Waylen and Laporte, 1999; Waylen et al., 1996). This in turn can lead to increased water shortages, such as during the 2014–2016 El Niño event (Sánchez-Murillo et al., 2016; Vignola et al., 2018), when about 3.5 million people were considered food insecure due to failing crops within the drier Pacific coast region of Central America (FAO, 2016). With climate change, increases in rainfall variability and extremes have been observed over the last decades for Central America, and more frequent temperature and rainfall extremes are projected for the future. Due to the high inter-annual rainfall variability and the complex interplay of many local and global climatic forces, future climate projections have high uncertainty for the region, but will likely include more frequent dry conditions (Hidalgo et al., 2013; Magrin et al., 2014).

Drought (i.e., the temporary lack of water compared to normal conditions) is a combination of both climate-induced as well as human-induced drought (Van Loon et al., 2016). The propagation of meteorological droughts (rainfall deficits) to hydrological droughts (reduced water availabilities) is influenced by both catchment properties as well as human actions (Van Loon et al., 2016), and in the case of the wet-dry tropics of Costa Rica, growing water demands and lack of adaptive management have increased drought conditions in the past (Ballestero et al., 2007; Kuzdas et al., 2015a). Population growth in Costa Rica is projected to increase by 33% by the year 2050 relative to 2011 (INEC, 2014), which will likely put more pressure on water resources and increase vulnerabilities of communities to drought. As in many regions with seasonal rainfall regimes, communities in the wet-dry tropics of Costa Rica depend primarily on groundwater, which supplied 78% of the total domestic water demand in 2015 (Province of Guanacaste, CTI, 2017; Guzman, 2015). The Province of Guanacaste has a history of water conflicts between different sectors such as tourism, agriculture and communities (Kuzdas et al., 2014; Kuzdas and Wiek, 2014). Between 1997 and 2015, 95 water-related conflicts have been reported in Guanacaste (Esquivel-Hernández et al., 2017; Ramírez-Cover, 2008). Many of these conflicts evolved around groundwater extractions, groundwater allocations between domestic, tourism and agricultural sectors, and weak water governance structures (Kuzdas et al., 2015a, 2014).

For many communities, groundwater provides the primary water source during the dry season when streamflow is low (Ballestero et al., 2007; Kuzdas et al., 2015a). Therefore, seasonal groundwater recharge during the wet season is key for replenishing aquifers (Jasechko et al., 2014) and assuring water supply. Yet, groundwater recharge in the tropics is strongly dependent on the intensity of rainfall during the wet season (Jasechko and Taylor, 2015), and is more pronounced in years of extreme seasonal rainfall (Owor et al., 2009; Taylor et al., 2012). This in turn means that in years of low seasonal rainfall, groundwater recharge tends to be lower. For communities depending on renewable shallow groundwater for their livelihoods and agricultural irrigation, this can lead to significant water stress as happened during the dry season following the El Niño 2014–2016 event in the dry corridor of Costa Rica, when many community wells ran dry and drought emergencies were declared (Vignola et al., 2018).

Therefore, groundwater has to be managed carefully to ensure water supply lasts throughout the dry season, and baseflow and environmental flow needs are respected. Yet, groundwater management is a challenge in the region due to scarce hydrological data and aquifer studies, limited oversight of groundwater pumping by government agencies, and inefficient water governance (Ballestero et al., 2007; Kuzdas et al., 2014; Vignola et al., 2018).

The impacts of droughts on communities depend not only on the meteorological events themselves (i.e., the hazard), but also on exposure and vulnerability of communities to these extreme events (Magrin et al., 2014). Historically, Central America has been considered as a region with high vulnerabilities of communities to natural disasters, due to the levels of poverty and livelihood structures (Magrin et al., 2014). Agriculture is one of the most important livelihoods in Central America and in particular, smallholder and subsistence farmers can be severely impacted by droughts (Hannah et al., 2017). In the wet-dry tropics of Costa Rica, most farmers use groundwater-based irrigation agriculture in the dry season, and rainfed or irrigation (both surface water and groundwater-based) agriculture in the wet season (INEC, 2015). The rural and agricultural communities depend directly on their local water resources, and especially rural communities with weak water management structures often suffer the direct effects of droughts (Kuzdas et al., 2015a). In these agricultural watersheds, social and hydrological processes are tightly connected, and processes from one system component will affect the other (coupled human-water systems, socio-hydrology) (Sivapalan et al., 2012). This has to be considered when aiming to increase resilience to drought. Here, resilience refers to the capacity of the system to absorb and adapt to recurrent disturbances without major system shifts and to develop with a changing environment (Folke, 2006; Folke et al., 2016; Mao et al., 2017). Hydrological resilience (i.e., focusing on the response of the water subsystem to extreme events or anthropogenic impacts) should not be considered separately from the social system (i.e., social resilience to hydrological hazards), but rather the combined socio-hydrological resilience should be considered (i.e., the coupled human-water system) (Mao et al., 2017). To support the development of socio-hydrological resilience to droughts, it is crucial for scientists to integrate their research within communities and communicate scientific results to local decision makers in a way that they can directly apply and act upon.

Our main goal in this study was to develop a tool that can support water managers to increase the resilience of their communities to seasonal drought. Groundwater recharge in the wet season is the key process for determining water supplies in the dry season when communities and agriculture rely on groundwater as their primary water source. Thus, we first evaluated the relationship between seasonal rainfall and groundwater recharge for an aquifer in the wet-dry tropics of Costa Rica. Next, we analyzed water use (groundwater versus surface water) to determine potential sensitivities of the socio-hydrological system to external impacts (such as, reduced rainfall). We then combined these hydrological and social analyses to characterize the resilience properties of the system (i.e., adaptive and absorptive capacities), and determined how external drivers can lead to negative consequences for the system, as well as opportunities for increasing resilience (focusing on seasonal droughts following rainfall years with less than normal rainfall). We then used these findings to develop a groundwater recharge indicator as a decision-support tool for local water managers that could help to increase the socio-hydrological resilience to droughts in regions with highly seasonal rainfall and interannual rainfall variability.

2. Materials and methods

2.1. Site description

This study focuses on two adjacent watersheds (Potrero and Caimital) that share the same aquifer (Potrero-Caimital aquifer), and are located in the Province of Guanacaste on the Nicoya Peninsula in Northwestern Costa Rica (Fig. 1). The surface water divide between both watersheds crosses through the relatively flat alluvial valley that is underlain by the aquifer (Figs. 3 and 4). Considering that the Potrero-Caimital aquifer extends through both watersheds, and that groundwater extractions, surface water–groundwater interactions and other hydrological processes will affect and be affected by processes in the two watersheds, we included both watersheds in our analysis. The Potrero watershed comprises about 36 km² and drains to the northeast into the Grande River. The Caimital watershed (41 km²) drains to the southwest into the Quirimán River, a tributary to the Nosara River. The two river mainstems (the Potrero and Caimital rivers) are groundwater-
fed and perennial, but have low baseflows during the dry season. Ephemeral tributaries contribute to streamflow from the hillsides during the wet season and are dry during the dry season (Fig. 3).

The Province of Guanacaste has a wet-dry tropical climate. Mean annual rainfall in Nicoya (nearby the Potrero and Caimital watersheds) is 2130 mm (mean from 1980 to 2016 in Nicoya; ranging from 1310 mm to 3230 mm), and is characterized by a bimodal rainfall distribution, with a dry season from December to March and a wet season from April to November (Fig. 2). The wet season is interrupted by a period of lower rainfall in July and August (mid-summer drought). The region also experiences high inter-annual variability in rainfall due to a complex interplay of local and remote climate processes. One of the main drivers for this is ENSO with significantly lower rainfall during El Niño years (Steyn et al., 2016).

The geology of the hills surrounding the valley of the Potrero and Caimital rivers is dominated by the Nicoya Complex (basaltic sequence) and the topography is generally characterized by slopes > 10% in this zone (Denyer and Baumgartner, 2006). Loose and non-consolidated sandy colluvial sediment deposits dominate along the transition zone from hills to the relatively flat valley (Losilla and Agudelo, 2003). Within the valley plain (slope < 10%), Quaternary alluvial-colluvial sediments overlay a layer of fractured basaltic rocks and the low-permeability bedrock of the Nicoya Complex (Fig. 4). The alluvial-colluvial deposits consist of a top layer of 3 to 8 m of silty clay and loam above a layer of sand to gravel with clay lenses (Losilla and Agudelo 2003; Denyer et al., 2013a,b). The Potrero-Caimital aquifer extends through the alluvial-colluvial valley zone, and its lower boundary is formed by the low-permeability rocks of the Nicoya Complex (Fig. 4) (Agudelo, 2006). The aquifer is unconfined to semi-confined (Agudelo, 2006). Groundwater recharge to the Potrero-Caimital aquifer consists of both diffuse (direct) recharge from infiltration and percolation through...
the soil layer, and focused (indirect) recharge from downward movement from surface water to the aquifer (Agudelo, 2006).

Land use in the two watersheds includes forest (52%), pasture (38%), agricultural (8%), as well as residential (2%) (Fig. 3) (based on a 2010 land use classification by Garcia-Serrano, 2015). Most agricultural fields are double-cropped (rainfed rice during the wet season, and groundwater-irrigated melons during the dry season), whereas on some fields, rice is planted during the wet season and fields lie fallow in the dry season.

The Potrero and Caimital watersheds provide domestic water supply for many communities in the Nicoya region. Domestic water demand in the studied watersheds includes small rural villages located within the watersheds (total population of 3823 in 2014, data obtained from Ministerio de Salud in Nicoya). Furthermore, water is transferred via pipelines to the nearby towns of Nicoya (24,833 inhabitants, District of Nicoya; INEC, 2011), and Hojancha (4245 inhabitants, District of Hojancha; INEC, 2011) (Fig. 3). Groundwater use dominates, although the town of Nicoya has a water treatment plant for surface water intake from the Potrero River. Groundwater-based irrigation agriculture during the dry season is another important water demand.

2.2. Hydrological monitoring network

Limited hydrological data were available for the Potrero and Caimital watersheds, and in particular, no continuous streamflow data existed. Therefore, a first step in our project was to install a hydrological monitoring network within the Potrero and Caimital watersheds that included five stream and three groundwater level stations (Hund et al., 2016). We monitored water levels at 10-minute intervals for 2.5 years (from June 2014 to December 2016). Discharge measurements were made using the salt solution slug injection method (Moore, 2005) to develop stage-discharge rating curves. We also installed an eddy covariance (EC) equipped monitoring station at a melon-rice farm located at the watershed divide between the two studied watersheds within the alluvial valley (Fig. 3). This EC monitoring station includes a sonic anemometer and a LI-COR open path EC system to monitor actual evapotranspiration, a Vaisala WXT520 weather transmitter to monitor rainfall, air temperature, relative humidity, wind speed and direction, and air pressure, and additional soil and radiation sensors, with continuous data recorded in 30-minute intervals from July 2014. Within the same farm only 600 m away from our EC monitoring station is a Davies Weatherlink weather station operated by the farm owners and Davies Instruments recording hourly values of rainfall, air temperature, relative humidity, air pressure (available since 2007), and short-wave solar radiation (available since 2014). Rainfall data from the Weatherlink station were used to gap-fill the rainfall records from our EC monitoring station during occasional data outages between July 2014 to December 2016 (11% of rainfall data were gapfilled this way).

2.3. Hydrological modelling

We developed a hydrological model of the two watersheds using the Water Evaluation And Planning system (WEAP) (Yates et al., 2005). WEAP is a physically-based, semi-distributed model based on the water
balance approach, and includes a rainfall-runoff routine, surface water and groundwater storage. Furthermore, it allows hydrological system components to be combined with aspects of the social system, such as water use from surface and groundwater sources, and representation of irrigation practices. The modelled river reaches were the main stems of the Potrero and the Caimital rivers and their main tributaries. These reaches traverse the alluvial valley underlain by the Potrero-Caimital aquifer (i.e. surface water–groundwater interaction can occur). Both focused recharge through infiltration from the river bed, and diffuse recharge through percolation through the soil were modelled. Evapotranspiration from river reaches was assumed at 2.5% of daily streamflow, based on a study on riparian evapotranspiration for tropical headwatersheds in Costa Rica (Cadol et al., 2012).

2.3.1. Sub-catchment delineation

Watershed processes such as rainfall-runoff, evapotranspiration and diffuse groundwater recharge are modelled through the catchment routines in the WEAP model. A watershed is divided into sub-catchments (SCs), and for every time step in the model, a water balance without flows from and storage changes within the SC is calculated. Outflows from a SC can be routed to rivers or aquifers. Each SC is fractionally divided into several classes, or Hydrological Response Units (HRUs). HRUs represent an area of similar characteristics (such as land use, soil type, or slope) for which it can be assumed that the hydrologic response to rainfall in regards to runoff generation, groundwater recharge, or evapotranspiration would be similar.

We used the following criteria to guide the delimitation of SCs

Fig. 4. (a) Geological units in the Potrero and Caimital watersheds; and (b) Geological cross section sketch. Geology units obtained from SENARA; geological sketch developed based on (Agudelo, 2006; Garcia-Serrano, 2015; Losilla and Agudelo, 2003). Topographical cross section based on HydroSHEDS DEM (Lehner et al., 2008), and processed with QGIS qProf. MT-344, MT-343, MT-238 and MT-351 are wells with lithology profile (obtained from SENARA).
within the model: 1) the upslope areas of the monitoring sites; 2) the sub-catchments of the tributaries to allow routing of tributary runoff into the main stems of the Potrero and Caimital; and 3) the connection of SCs to the aquifer to allow modelling diffuse groundwater recharge (Fig. 5). Criteria one and two were based on a digital elevation model (DEM). We used the HydroSHEDS (3 s) DEM that for the region has an approximately 90 m spatial resolution (Lehner et al., 2008). We hydrologically-conditioned the DEM with a detailed local stream layer (obtained from the Area Conservación Tempisque), and delimited the SCs using the open-source programs Whitebox GAT (Lindsay, 2016), SAGA-GIS and the SAGA plug-in in QGIS (Conrad et al., 2015; Olaya, 2004; QGIS Development Team, 2017).

Next, each sub-catchment was divided into HRUs or fractional areas that were assumed to respond hydrologically similar to a rainfall event. The first criterion for the HRU definition was land cover, which was based on a land use map delineated from satellite imagery from Digital Globe ESRI (Date: December 28, 2010) with a 5 m resolution, and was developed in support with field visits by Garcia-Serrano (2015). We simplified the land use classifications into the main categories of forest, pasture, residential, agriculture (rice only), and agriculture (rice and melons, which is a double cropping system of the two crops grown sequentially during a single 12-month period). The separation into the rice and melon categories in the agriculture classification accounts for the fact that rainfed rice is grown on a larger area than groundwater-irrigated melons, and that part of the rice fields (wet season) lie fallow during the melon season (dry season), with consequences for evapotranspiration and irrigation.

To assess potential changes in land use between the start of the modelling period (2005) and the end of the modelling period (2016), we conducted a land use change analysis using QGIS and Google Earth. Specifically, we digitized land use from Google Earth imagery from March 2005 and February 2016, and compared it to the 2010 land use map for the extent of the watersheds. From 2005 to 2010, we found that forest cover increased by approximately 1%, pasture cover decreased by 3%, agriculture cover did not change, and residential coverage increased by 15% (which represented less than 0.4% of the total watershed area). From 2010 to 2016, forest coverage increased by 6%, pasture decreased by 6%, and agriculture and residential increased by 5% and 1%, respectively. Overall, all land use changes between 2005 and 2016 affected less than 4% of the total watershed area. Considering this low percentages of land use change found, and the limitations of this analysis due to the lack of high-resolution imagery, we assumed for hydrological modelling purposes that the land use of the studied watersheds was adequately described by the mid-point 2010 land use map and was treated as constant throughout the modelling period from 2005 to 2016.

The second criterion for HRU definition was soil and geology, which was based on the three geological categories: basalt, colluvial and alluvial material. This simplification into three categories was based on available soil and geology data for which no more detailed spatial data existed. Land cover within the basalt zone was dominated by pasture and forest, and no residential or agricultural classes were present.

Slope was the third HRU criterion. It was determined based on the HydroSHEDS DEM, aggregated into four slope classes. The alluvial-colluvial valley zone was mostly flat (0 to 10% slope). The basalt zone was generally steeper than the alluvial-colluvial valley zone and all four slope classes (0–10%; 10–20%; 20–30%; 30–80%) were represented within the HRUs of this zone. Within a SC of the basalt zone there could therefore be eight different fractional areas (HRU), and within a SC of the alluvial-colluvial zone (connected to aquifer) there could be ten different fractional areas. Considering limited data availability and modelling capacities, we assumed that an HRU with the same...
characteristics in one SC was characterized by the same soil parameters as the same HRU in another SC.

2.3.2. Rainfall-runoff modelling

The rainfall-runoff response in a SC can be modelled by different routines within the WEAP model. We used the soil-moisture module that allows modelling surface-runoff processes by representing each sub-catchment with two soil layers (Sieber and Purkey, 2015; Yates et al., 2005). If the SC is connected to an aquifer (as the studied one is), the second soil layer is replaced by the aquifer layer. For each fractional area (HRU) in a SC, a water balance is computed at each time step. Change in soil moisture in the upper soil layer is determined by antecedent soil moisture, input through rainfall, and loss through evapotranspiration, surface runoff, interflow and percolation to the lower soil layer (or aquifer). Surface runoff and interflow contribute to streamflow, while percolation through the upper soil layer provides diffuse recharge to the underlying aquifer. If a stream is hydrologically connected to an aquifer, the aquifer provides baseflow to the stream, and on the other hand, the stream can contribute focused recharge to the aquifer depending on conditions (more details on groundwater-surface water interaction are described in the groundwater section).

For the model soil parameter available water holding capacity, we used reported values from in-situ measurements conducted in the watersheds (Garcia-Serrano 2015). Soil hydraulic conductivities were used as a calibration parameters, as only infiltration capacities at the root zone existed as field measurements, and these did not reflect the modelled soil zone which extended between 2 and 10 m in depth. Soil depth within the alluvial zone was based on lithology profiles of 29 wells available from the National Groundwater, Irrigation and Drainage Agency of Costa Rica (Servicio Nacional de Aguas Subterráneas, Riego y Avenamiento, SENARA). No soil depth data existed for the basalt and colluvial zone, and these were used as calibration parameters.

The runoff resistance factor (RRF) is related to aspects such as slope and leaf area index (LAI), or land use/land cover. Higher values of the RRF lead to less surface runoff (higher resistance), whereas lower values lead to higher surface runoff, and it is usually used as a calibration parameter (Sieber and Purkey, 2015). However, LAI and surface resistance will change over the course of a year, in particular in a region like the wet-dry tropics where greening-up of vegetation and senescence are so pronounced. Therefore, we used LAI data to estimate the intra-annual variability of the RRF. We used the MODIS LAI product (MODIS 15A2 Leaf Area Index and Fraction of Photosynthetically Active Radiation (FPAR) 8 Day composite MODIS Collection 5 Land Product) for the period 2000-02-18 to 2017-01-01 (ORN DAAC, 2008a). In order to capture the long-term annual seasonality of LAI for each land use type (forest, pasture or agriculture) we first assigned a MODIS LAI value to each land use type, and then estimated a mean value of MODIS LAI for each day of the year for the period 2000–2016. To relate LAI to different land covers, MODIS cells with a high fraction cover (fraction cover > 89% for forest and pasture; > 50% for agriculture) of one single land use (forest, pasture or agriculture) were selected and mean LAI was calculated from all pixels of the same dominant land use. Next, we estimated the 2000–2016 mean value of each 8-day period of the year reported by MODIS for each land use type. Then, 8-day mean values were linearly interpolated to obtain a daily time series of LAI per land use type for the period 2000–2016. Annual means of LAI per land use type were also calculated for each land use type. Daily RRF values were expressed in the WEAP model as the annual mean LAI per land use plus or minus the daily variation of LAI from the annual mean. This allowed us to use the annual mean for the three land use types as a calibration parameter and change this value according to calibration, while maintaining seasonal variability. The RRF was assumed constant over time for the residential land cover type. RRF values were also differentiated between the four slope classes from the HydroSHEDS DEM, with initial values adjusted during calibration. The preferred flow direction (PFD) parameter, also required for the WEAP model, is a partitioning coefficient related to soil, land cover, and topography that fractionally partitions between vertical and horizontal flows, and was also adjusted during model calibration.

We ran the model at a daily time-step from 2005 to 2016, the time period for which water use records, groundwater levels as well as meteorological data were available. Monthly values of water table depth were obtained from monthly manual measurements recorded by the National Groundwater, Irrigation and Drainage Agency of Costa Rica (Servicio Nacional de Aguas Subterráneas, Riego y Avenamiento, SENARA) for 26 wells from June 2015 to September 2015 (for 6 wells starting in June 2005, for 2 wells starting in October 2005, for 13 wells starting in June 2012, and another 5 wells starting in July 2012).

Climate was assumed to be uniform over the two adjacent and relatively small watersheds. Historical daily precipitation data were obtained from the National Meteorological Institute of Costa Rica (Instituto Meteorológico Nacional, IMN) for Nicoya from January 2005 until June 2014 to run the model. Daily precipitation data measured at our EC monitoring station were used for the modelling period from July 2014 to December 2016.

2.3.3. Evapotranspiration modelling

Evapotranspiration (ET) is estimated by WEAP applying the crop coefficient method (Doorenbos and Pruitt, 1977). This way evapotranspiration from each HRU within a sub-catchment is estimated as the product of a “crop” coefficient (Kc), that incorporates land cover characteristics and water requirements, and a reference evapotranspiration (ETref) that represents atmospheric water demand based on meteorological conditions. The daily ETref is calculated by WEAP using the Penman-Monteith equation modified for a standardized crop of grass (Shuttleworth, 1993; equation 4.2.31), with the input variables including air temperature, relative humidity, wind speed and cloudiness fraction. To estimate ETref for the modelling period from 2005 to 2016, a combination of different meteorological datasets had to be used. Best quality measurements of air temperature, relative humidity and wind speed data were available from the EC monitoring station for the duration of the calibration period from 2014-07-04 to 2016-12-31. For the early period from 2005 to 2007, no meteorological data were available from meteorological stations in the region. Therefore, we used Climate Forecast System Reanalysis (CFSR) air temperature, relative humidity and wind speed data (Saha et al., 2010; Dee et al., 2014) for this period. From February 2007 to September 2012, Weatherlink station data (for location see Fig. 3) were available for air temperature and relative humidity, and the CFSR wind speed data were used. CFSR data were also used from September 2012 to the start of our own monitoring in July 2014. Cloudiness fraction was another necessary input to estimate ETref. In the WEAP model, this variable describes the number of bright sunshine hours per day over the total hours of daylight, and we estimated it based on total incoming short-wave solar radiation (available from the Weatherlink station from 07-2014 to 12-2016, and from the CFSR dataset for the earlier time period), modelled extra-terrestrial solar radiation and the angstrom coefficients (Shuttleworth, 1993; equation 4.2.14). We estimated the angstrom coefficients based on the maximum and minimum of the ratio of the measured incoming short-wave radiation and the extra-terrestrial radiation during that period \(a = 0.05; b = 0.7\).

The crop coefficient Kc represents the ratio between actual ET and \(ET_{ref}\) of each land class type. Five main land use types exist within the Potrero and Caimil watershed (forest, pasture, melon crops, rice crops, and residential). Mean Kc values for each day of year were estimated for melon and rice crops from ET values measured in the EC monitoring station at the melon-rice farm and estimated \(ET_{ref}\) (as calculated by WEAP using the Penman-Monteith equation), but no ET measurements were available for the other land use types. The Food and Agricultural Organization (FAO) of the United Nations provides Kc estimates for pasture (Allen et al., 1998), but these values were developed for the Northern hemisphere and do not reflect the strong seasonal
behavior of the wet-dry tropics, and further, no Kc estimates were available for seasonally-dry forest in the literature. Therefore, we estimated Kc for the non-crop land use types using the MODIS evapotranspiration product MOD16 (MODIS 16A2/Terra Evapotranspiration 8-Day (1000 m spatial resolution) (ORNL DAAC, 2008b). To relate MODIS ET to different land use types within the Potrero-Caimital watersheds, similarly to the LAI analysis, we selected MODIS pixels that were dominated by one land use type (fraction cover > 89% for pasture and forest), according to the Senara land use classification from 2010 and under the assumption that land use change throughout the study period was minimal. ET values were extracted for each selected homogeneous land use MODIS pixel, and mean values of all homogeneous pixels for each land use type were calculated for each 8-day period from 2005 to 2014 (MOD16 was not available for 2015 and 2016 at the time of the WEAP model calibration). Daily ET values were extrapolated from the 8-day period MODIS ET obtained for each land use. Daily Kc values for the period 2005 to 2014 were then calculated as the ratio between the daily extrapolated MODIS ET for each land use type and estimated daily ETref (as calculated by WEAP using the Penman-Monteith equation; Shuttleworth, 1993, equation 4.2.31). To generate a daily Kc value to be used for every year of the modelling period (considering that not all years had available MODIS ET data), we calculated a long-term mean value of daily Kc for each land use type for each day of year based on the daily Kc series from the period 2005 to 2014. For fields where only rice was planted in the wet season and fields lay fallow during the dry season, Kc values derived from measured ET were used during the rice growing season (wet season), and Kc values obtained from MODIS ET for pasture land use type were used for the dry season. We used these Kc values as starting point for our analysis, but we found that the WEAP model underestimated daily ET for the three main cover types (agriculture, forest and pasture) relatively to measured values (from the EC monitoring station and MODIS ET). We found this underestimation of ET was due to an oversimplification of the soil water content dynamics by the model, which in turn determines soil water available for evapotranspiration based on the atmospheric water demand (ETref) and the land cover characteristic (Kc). WEAP uses only one soil layer if the sub-catchment is connected to an aquifer. This layer has to represent the entire vadose zone, which in the Potrero and Caimital watersheds ranged between 2 and 10 m in depth. This over-simplification of the soil layer resulted in a systematic underestimation of the soil water content of the root zone and reduction of ET values. To account for this, we rescaled the initial Kc values using a constant scaling factor. The scaling factor was estimated for each land use type by optimization, so that the error of the annual modelled evapotranspiration was minimized in comparison to the empirical evapotranspiration measurements (from the EC monitoring station for agriculture, and from MODIS for forest and pasture).

2.3.4. Groundwater modelling

The Potrero-Caimital aquifer extends through the alluvial-colluvial zone (Fig. 4), and therefore, sub-catchments (SC) in this zone were connected to an aquifer module in the WEAP model. The lower soil layer of the hill zone (Nicoya complex) contributes to baseflows of the streams and tributaries. The Potrero-Caimital aquifer was presented as one aquifer storage unit within the WEAP model. The model allows moulding of both diffuse and focused groundwater recharge. Diffuse recharge is modelled through the catchment routine (soil-moisture module) where downwet percolation through the upper soil layer of each HRU enters the aquifer (if the SC is connected to an aquifer such as in the alluvial-colluvial zone).

Focused recharge is modelled through the surface water – groundwater interaction routine. In the WEAP model, it is possible to dynamically link river reaches to an alluvial aquifer, which was done for all modelled stream reaches within the alluvial-colluvial zone that are underlain by the Potrero-Caimital aquifer. Stream reaches can gain water from the aquifer (gaining stream) or contribute focused recharge to the aquifer (losing stream), depending on the level of groundwater in the aquifer (Sieber and Purkey, 2015). Surface water – groundwater interactions are modelled through a stylized groundwater wedge that is connected along to the length of the river reach (Sieber and Purkey, 2015). If aquifer levels rise higher than level of equilibrium with the stream, seepage occurs from the aquifer to the stream, and vice versa, if stream water levels rise, seepage occurs from stream to aquifer.

Aquifer characteristics such as specific yield and saturated hydraulic conductivity were based on values reported by the Costa Rican groundwater agency Senara (Garcia-Serrano, 2015; Losilla and Agudelo, 2003), while parameters related to modelling surface water – groundwater interaction were used as calibration parameters. These parameters included wetted depth in river, groundwater storage at equilibrium with the river, and horizontal distance from farthest edge of aquifer to river. Previous authors conducted five pumping tests to estimate the specific yield of the studied aquifer, and found that it varied between 0.0007 and 0.008, with a mean of 0.002 (Losilla and Agudelo 2003). They estimated the total storage volume of the aquifer as 40 Mm³, assuming an area of 20 km², a mean aquifer thickness of 20 m, and a mean specific yield of 0.002. Transmissivity measurements based on pumping tests existed for 49 locations within the study area, and varied between 37-2824 m²/day within the alluvial-colluvial layer, and between 5.6–28.6 m²/day within the fractured basalt layer (Garcia-Serrano, 2015; Losilla and Agudelo, 2003). Reported values of saturated hydraulic conductivities (determined based on the transmissivity measurements and aquifer thickness) varied between 4.5 and 95 m/day, with a mean of approximately 26 m/day (Garcia-Serrano, 2015; Losilla and Agudelo, 2003). Considering uncertainties and limited details available regarding the hydraulic conductivities and the specific yield, we explored a range of values during the calibration process, but found that ultimately the reported values represented the aquifer conditions best, and adopted these for our modelling.

2.3.5. Water demand modelling

The Potrero and Caimital watersheds are the key water supply sources for the domestic water demand of many communities in the region. Water demand is modelled explicitly in WEAP, allowing integration of social aspects of the socio-hydrologic system into hydrologic modelling. Total water demand is disaggregated into demand sites that differ in their end-use, in their distribution system, water supply type or water allocation preference. Domestic water demand in the Potrero and Caimital watersheds includes both rural villages located within the watersheds, as well as water transfers via pipelines to the towns of Nicoya and Hojancha located outside the watersheds. Rural water boards (Las Asociaciones administradoras de los Sistemas de Acueductos y Alcantarillados, ASDAs) manage the water distribution from a well in each of the rural villages. The national water agency AyA (Instituto Costarricense de Acueductos y Alcantarillados) in Nicoya and Hojancha manages the water transfer from wells in the Potrero-Caimital aquifer to both towns, as well as from a withdrawal site for a surface water treatment plant at the Potrero River to Nicoya. Most rural households also have their own artisanal well or surface water pump that supplements the water received from the ASDA distribution system, with this supplemental water typically used for laundry and outdoor water uses. Based on this context, to model surface water and groundwater demand from the studied watersheds, we accounted for: artisanal pumping per household, domestic water use per household from rural villages (supplied by ASDA’s), water extractions (managed by AyA) for water supply to Nicoya and Hojancha, groundwater extractions for irrigation of melon crops, and water use for cattle ranching as detailed below.

Population was estimated annually for years 2001, 2004 and 2011 based on census data (INEC, 2011, 2001), Morataya Montenegro (2004), and more recent (2014) data that we had obtained from the Ministerio de Salud in Nicoya. To interpolate population data between years and extrapolate to 2016, we calculated the annual geometric
growth rate for each town (ranging from 1% to 7%, mean 4%). Overall, the population within the studied watersheds (including Nicoya and Hojancha) increased from 29,136 in 2005 to 35,435 in 2016.

We estimated the water demand from household pumping based on pumping records at one of our monitoring stations that is located in an artisanal well. To our knowledge, no other data are available for this type of water use. For the rural villages, water use data from rural water boards (ASADAs) on a household level were only available for the village of Caimital from 2012 to 2015, which we had digitized from water bills, so we had to assume that the other rural towns had the same per person annual water use than Caimital. Considering that we had both population data and total water use data for Caimital from 2014, we assumed the annual water use rate per person from 2014 for all years where no other water use data were available. For Nicoya and Hojancha, we obtained water extraction data from the AyA in Nicoya, including information on water sources (i.e., surface water, groundwater). Based on our analysis of the AyA extraction data, we found that between 2005 and 2016, Nicoya used annually between 49-73% groundwater, and 27–51% surface water, while Hojancha used only groundwater to meet their water demands. Agricultural groundwater-based irrigation per hectare was available from one of the main melon farms in the watersheds and we assumed the same water use per hectare for other melon farms. Cattle pastures are another important land use in the watersheds, and we estimated water use for cattle based on the mean number of cattle per hectare in the region (INEC, 2015) and estimated drinking water use per cattle (35.5 L/day; Ayantunde et al., 2002). All water operators with a water extraction site (well or surface water extraction) have to apply for a license at the Dirección de Agua from the Ministerio de Ambiente y Energía (MINAE). These licenses contain information on location, operator name, water source, allowed pumping rates, and type of use. Most of the water operators with a water license are the ASADAs, the AyA and the big melon-rice farms, and were therefore already included in our model. For all the other operators, we added the water demand indicated in the license to the model. While the water licenses provide some indication on water extractions, only pumping rates are reported in the license. Thus, it is unclear how many hours an operator might be pumping and what total water volume was extracted. Further, unregistered/unlicensed wells also exist in the area. Therefore, real water extractions are likely higher than is reported through the water licenses. The water use estimates for this study were however mostly based on monthly extracted volumes and where in many cases no detailed data were available for the region.

2.4. Groundwater recharge indicator development

Total groundwater recharge to the Potrero-Caimital aquifer was calculated as the sum of modelled recharge from sub-catchments (diffuse recharge) and from surface water (focused recharge) for each year of the modelling period from 2005 to 2016. To explore the relation between rainfall and groundwater recharge, we fit a linear regression model to total annual rainfall and total annual groundwater recharge. For comparison to modelled recharge, we also attempted to estimate groundwater recharge empirically using the groundwater level fluctuation method as well as by residual of the water budget. However, due to too many missing components and uncertainties of the empirical data (for instance, groundwater levels influenced by pumping, uncertainties of baseflow), neither method could be applied successfully.

Next, we calculated the cumulative rainfall and cumulative modelled groundwater recharge throughout each year based on daily data, and used this relationship to develop a groundwater recharge indicator. Here, we calculated the 0, 25, 45, 55, 75 and 100 percentiles for each day of year based on the daily distribution of the 12-years of the modelling period for both cumulative rainfall and cumulative groundwater recharge. Based on the percentiles, we determined five categories: 0 to < 25, 25 to < 45, 45 to < 55, 55 to < 75, and 75–100. To quantify how well groundwater recharge can be predicted based on cumulative rainfall throughout the wet season, we calculated confusion matrices (Kuhn, 2008) for each day of year for each of the five percentile categories. Confusion matrices 1) count the number of times that a predicted value matches the ‘true’ value, and 2) report the number of true positives, false positives (type I error), false negatives (type II error) and true negatives. For each day of year, we determined the percentile category into which the cumulative rainfall fell. From this, we predicted the percentile category into which the cumulative groundwater recharge would be expected to fall at the end of the year (predicted category). The percentile category of the cumulative groundwater recharge at the end of the year represented the ‘true’ category. We calculated a confusion matrix for each day of the year for each of the 12 years of our modelling period, and extracted the overall accuracy. We then used locally weighted smoothing (Wickham, 2009) to show the pattern of the overall accuracy throughout the wet season, and fit the curve through the origin after the first month of the wet season.

3. Results and discussion

3.1. Water use

Water extractions from the Potrero and Caimital watersheds increased by 26% between 2005 and 2016 (Table 2). This was primarily driven by a fast-growing population with annual population growth rates between 1 and 7% (mean 4%), while land use stayed relatively constant. Population is expected to continue to grow, with a total growth of 23% by 2025 relative to the last census from 2011 for the Province of Guanacaste, and specifically, with a 13% increase for the District of Nicoya and a 9% increase for the District of Hojancha (INEC, 2014a). By 2050, a total increase in population by 33% is expected for all of Costa Rica, relative to the 2011 census (INEC, 2014b). This indicates increasing pressures on water resources from anthropogenic extractions, if water management practices are not adapted. According to our study, dominant water extractions from the Potrero and Caimital watersheds are for domestic purposes (94.4% of total extractions in 2016), whereas water extractions for agricultural irrigation (3.9%) and cattle ranching (1.7%) are lower, due to both high land use coverage of forest (52% of total land) and seasonal irrigation (only during dry season). Further, 69% of total domestic extractions in 2016 were for
fluctuations may be a typical feature of alluvial aquifers in this region.

3.3. Simulated groundwater recharge

Over the modelled time period from 2005 to 2016, high seasonal rainfall resulted in high seasonal groundwater recharge with a range between 98 mm/year and 252 mm/year (Fig. 7a). Total annual rainfall (measured) and total groundwater recharge (simulated) had a significant linear relationship ($R^2 = 0.97$, $p < 0.001$; Fig. 7b). The percentage of total annual groundwater recharge to total annual rainfall stayed relatively constant for both low and high total annual rainfalls at 7 to 8%. In contrast, the percentage of total annual streamflow to total annual rainfall increased from 34% to 50% from low to high annual rainfalls, suggesting the increased generation of overland flow during high intensity rainfall events. Overland flow runoff was also evident by high sediment loading in rivers after intensive rainfall events, as was observed in the field.

Similar to other tropical aquifers (Jasechko and Taylor, 2015; Mileham et al., 2009; Owor et al., 2009; Sánchez-Murillo and Birkel, 2016; Taylor et al., 2012), intensive seasonal rainfall is important for recharging the Potrero-Caimital aquifer. Sánchez-Murillo and Birkel (2016) showed the importance of the intensive rainfalls of the second wet season peak in September and October for groundwater recharge for aquifers in the wet-dry tropics of Costa Rica (Pacific lowlands). This is reflected in the increased groundwater recharge that we found for the Potrero-Caimital aquifer in years of high annual rainfall, in which monthly rainfall is typically highest during the fall months (second peak of the wet season) (Steyn et al., 2016). Similarly, Jasechko and Taylor (2015) showed that intensive monthly rainfalls contributed disproportionately to groundwater recharge for 14 tropical aquifers across different continents. While Owor et al. (2009) showed that the sum of

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**Table 1**

Goodness-of-fit measures between modelled and observed daily streamflow data near the outflow of the Potrero watershed (SW1), upstream at the Potrero River (SW3), upstream at the Caimital river (SW4), and near the outflow of the Caimital watershed (SW5).

<table>
<thead>
<tr>
<th>Objective Function</th>
<th>Potrero River Outflow (SW1)</th>
<th>Potrero River Upstream (SW3)</th>
<th>Caimital River Upstream (SW4)</th>
<th>Caimital River Outflow (SW5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nash-Sutcliffe Efficiency (NSE)</td>
<td>0.61</td>
<td>0.25</td>
<td>0.53</td>
<td>0.38</td>
</tr>
<tr>
<td>Pearson correlation coefficient ($r$)</td>
<td>0.78</td>
<td>0.52</td>
<td>0.76</td>
<td>0.63</td>
</tr>
<tr>
<td>Coefficient of Determination ($R^2$)</td>
<td>0.61</td>
<td>0.27</td>
<td>0.57</td>
<td>0.39</td>
</tr>
<tr>
<td>RSR (Root Mean Square Error/Standard Deviation)</td>
<td>0.63</td>
<td>0.87</td>
<td>0.69</td>
<td>0.79</td>
</tr>
</tbody>
</table>

**Table 2**

Surface water and groundwater extractions (in million cubic meters) from 2005 and 2016 for the Potrero and Caimital watersheds, Guanacaste.

<table>
<thead>
<tr>
<th>Year</th>
<th>Surface water extraction Mm$^3$/year</th>
<th>Groundwater extraction Mm$^3$/year</th>
<th>Total extraction Mm$^3$/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>0.78</td>
<td>1.59</td>
<td>2.37</td>
</tr>
<tr>
<td>2005</td>
<td>0.00</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>2016</td>
<td>0.54</td>
<td>2.44</td>
<td>2.98</td>
</tr>
<tr>
<td>2016</td>
<td>0.00</td>
<td>0.82</td>
<td>0.82</td>
</tr>
</tbody>
</table>

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**Fig. 6.** Observed water table depths for two wells in the Potrero-Caimital aquifer and monthly total rainfall (composite dataset IMN Nicoya, EC monitoring station): (a) Monthly water table depths for well X29 in Honduras (see Fig. 3 for location, ~50 m from nearby creek), from 06-2005 to 09-2015. Data obtained from Servicio Nacional de Aguas Subterráneas, Riego y Avenamiento (SE-NARA); (b) Mean daily water table depths, calculated from observed 30-minute water level data from our monitoring station at GW2 in Dulce Nombre, see Fig. 3 for location (~190 m from nearby creek). In Spring 2016, water levels were below sensor depth (depth > 9.4 m) and the well ran dry.
daily rainfall events and groundwater recharge were linearly related for an aquifer in Uganda, with better coefficients of determination when only considering daily rainfall events larger than 10 mm, a good linear correlation between rainfall and groundwater recharge is not always found. Studies from large aquifers in East Africa (Mileham et al., 2009; Taylor et al., 2012) found a non-linear relation between rainfall and groundwater recharge, where episodic recharge events resulting from abnormally high seasonal rainfall interrupted multiannual groundwater level declines (Taylor et al., 2012). In contrast to the majority of the aquifers mentioned above, the Potrero-Caimital is a fairly small aquifer with a dominance of clayey-loamy soils, where flashy surface runoff is the dominant response to intensive rainfall events, which helps to explain the good agreement found between annual rainfall and groundwater recharge.

It is important to remember that the groundwater recharge estimates carry some uncertainty due to modelling assumptions and available input data. For instance, the definition of the HRUs and related simplifications regarding land use and soil may impact modelled diffuse recharge. For example, Tooley et al. (2018) showed that soil hydraulic conductivity and percolation was higher at a forest site than at a pasture site for a watershed in the wet tropics in Costa Rica. Also, the simplified representation of surface water – groundwater interactions in the model may have introduced some uncertainties. Genereux and Jordan (2006) showed the importance of groundwater contributions to streams for lowland tropical rainforest watersheds in the wet tropics in Costa Rica; in this case however driven by high interbasin groundwater flow.

3.4. Socio-hydrological resilience

Increasing water use and seasonal fluctuations of groundwater levels have led to water shortages in the dominantly groundwater-dependent communities of the studied region. Thus, droughts and water conflicts often manifest themselves in dry seasons following wet seasons with lower than normal rainfall, as occurs in relation to El Niño events in western Central America. The current socio-hydrological system is not resilient to these external impacts from reduced rainfall (Fig. 8, left), and communities and ecosystems experience socio-hydrological drought as a consequence. To move towards a more drought-resilient system, we must first define what ‘socio-hydrological resilience’ means in the context of seasonal droughts in this system (conceptualized in Fig. 8). Resilience, or the capacity of a system to absorb disturbances without significant challenges to its functioning or structures, is composed of absorptive, adaptive and transformative capacities (Mao et al., 2017; Miller et al., 2010). Here, absorptive capacities refer to system components that can help to lessen impacts of an external event, such as reduced rainfall, and reduce consequences for both social and hydrological sub-systems. Adaptive capacities are the ability of system components to respond to a disturbance, again with the goal of reduced impacts. We recognize that what we are defining here as external impacts for this analysis (i.e., rainfall variability) is in fact not external to the socio-hydrological system, as human-caused climate change (Magrin et al., 2014) and land use change (with related changes in evapotranspiration and precipitation recycling; Ellison et al., 2012) influence the temporal and spatial variability of rainfall.

In the studied, non-resilient system, reduced rainfall (i.e., a meteorological drought) leads to reduced groundwater recharge, such that many wells become dry and groundwater extraction becomes insufficient to meet the needs of the rural communities. The adaptive capacity of the social sub-system is low, as there is no direct response in the form of differential water management activities or restrictions due to reduced recharge. Groundwater pumping continues at high rates until groundwater levels drop below the depth of many wells, and water shortages begin to impact rural communities as well as ecosystems. Absorptive capacities are also low, as communities rely mostly on the single resource of groundwater, and are not using other water supplies, which could help to dampen the shock of reduced groundwater levels. While annual renewal rates of the aquifer are relatively high (mean of 13%, for an estimated total aquifer storage of about 40 Mm$^3$), current borehole depths often do not reach lower groundwater levels, leading to technical water shortages.

In contrast, in a more resilient system (Fig. 8, right), communities would respond adaptively to reduced groundwater recharge during a wet season with reduced rainfall and decrease their groundwater pumping as one measure to lessen impacts on groundwater storage for the subsequent dry season (the hydrological sub-system). One of the barriers to this is information, i.e., that communities become aware of pending challenges early enough to adapt their behavior. For wet-dry tropical systems, the main impacts from reduced rainfall in the wet season (i.e., meteorological droughts) often occur later in the following dry season. This delay provides an opportunity to make the system more resilient to oncoming impacts. An adaptive response and increased absorptive capacity of the system can help to make the socio-hydrological system more resilient towards reduced rainfall and seasonal droughts. For example, once it becomes apparent that total recharge is likely to be lower than normal for a given wet season, there is the potential to shift to other water sources such as rainwater harvesting or increased surface water use during the remaining wet season. This also increases the absorptive capacity of communities by reducing reliance on groundwater. Further adaptive responses could include
reducing water permits for irrigation of dry season crops after wet seasons with low recharge, and improving agricultural soil and water management. Considering the relatively high total storage volume of the Potrero-Caimital aquifer and groundwater reserves, there may also be some buffer capacity for droughts. Deepening well screen depths of boreholes could reduce technical water shortages and increase resilience to drought. However, it is a more expensive approach that could lead to equity issues, as drilling of deeper boreholes may be restricted to communities or individuals with more financial capacities. Additionally, extracting deeper groundwater may lead to extractions above the sustainable yield of the aquifer (i.e., above the withdrawal rate at which no adverse impacts on ecosystems, land subsidence or other aspects of the hydrologic system occur (Healy, 2010)), and it could lead to a long-term decrease in groundwater levels.

3.5. Groundwater recharge indicator

The key for making the socio-hydrological system more resilient to droughts is to increase both absorptive and adaptive capacities. Absorptive capacities can include more long-term strategies, such as diversifying water sources from pre-dominantly groundwater use. Adaptive responses need to be made in time for them to be effective in the wet-dry tropical climate where drought impacts often occur as a delayed response to the highly variable external driver of reduced rainfall. For this, adequate information is needed for local decision makers to both assess the situation in time, and also, to communicate to the general public the need for adaptive response (such as, water restrictions). To address this need, we developed an indicator-based tool that allows local decision makers to assess the likely status of the aquifer in order to provide a framework to react adaptively before major impacts of drought hit. One of the main challenges of groundwater is that it is often poorly monitored and inadequately managed as it is less visible than surface water (Famiglietti, 2014). On the other hand, rainfall is monitored, at least sparingly, in most countries of the wet-dry tropics and most decision makers have access to rainfall data through their national meteorological institutes. We used the strong relation between rainfall and groundwater recharge (Fig. 7) to develop a groundwater recharge indicator (Fig. 9) that represents a) cumulative rainfall and b) cumulative groundwater recharge over the wet season. The 12 years of the modelling period represented a wide range of wet and dry conditions, from 1310 mm to 3235 mm for total rainfall and from 98 mm to 252 mm for total groundwater recharge. For each day of year, we determined the daily distribution of cumulative rainfall and groundwater recharge which were then placed into five percentile categories of rainfall and groundwater recharge, respectively: very high (dark blue), high (light blue), medium (yellow), low (orange), very low (red). The trajectories of cumulative rainfall and groundwater recharge for each year showed that, after some variability at the beginning of the wet season, they tended to stay within one category for the remainder of the wet season.

To use this indicator tool, one determines the cumulative rainfall to date (e.g. August 1 in Fig. 9a) and the corresponding percentile category. This percentile category is then directly related to the projected groundwater recharge category for the same date to determine the projected cumulative recharge (Fig. 9b). To explore the validity of this indicator, we assessed the overall accuracy of the projected end-of-year-groundwater-recharge-category estimated from the day-of-year-rainfall-category using confusion matrices (Fig. 10). By the end of May to the end of June, the accuracy of the projection is high (> 75% accuracy) in most cases, in particular for drought projections. For high (light blue) and very high (dark blue) categories, overall accuracy lessens somewhat in July and August, which coincides with the timing of the mid-summer drought.

It is important to remember that any model is an abstract and simplified representation of reality (Beven, 2012), and as such, there are uncertainties associated with its predictions. Uncertainties within the modelling can be caused by uncertainties in field measurements (such as streamflow and soil measurements), in model assumptions, and model procedures. This should be kept in mind when using the groundwater recharge indicator. We tried to limit uncertainties by using the five broad categories of the percentile classes, instead of trying to project exact groundwater recharge numbers.
When using the groundwater recharge indicator, it is important to assess cumulative groundwater recharge early on during the wet season, i.e., while it is still raining and there is still water available, and not to wait until the end of the wet season, when adaptive responses are limited and negative impacts to groundwater storage may already have occurred. Should the groundwater recharge indicator point to low or very low groundwater recharge, immediate actions should be initiated with the overall goal to “bank” groundwater for the next dry season when it is the only water supply available. To this end, overall water use can be reduced, rainwater can be harvested during the wet season, and since high percentages of rainfall leave the watersheds as streamflow during the wet season, increased use of surface water during the wet season could reduce the overall impact on groundwater. Surface water cannot be used much during the dry season as baseflows are low and it would have negative impacts on ecosystems. Furthermore, water managers need to be aware that net recharge at the end of the wet season is likely much lower than total recharge, as groundwater pumping and groundwater contributions to baseflow continue throughout the wet season. For instance for the modelling period from 2005 to 2016, total annual baseflow (from the Potrero-Caimital aquifer to the Potrero and Caimital rivers and tributaries) ranged from 54 to 190 mm (between 55 and 85% of annual recharge).

The groundwater recharge indicator can allow water managers to plan ahead and make informed decisions, and importantly, to communicate the need for adaptive responses to the public. It should be used as a tool for a short-term (within a wet season) adaptive response to rainfall, and be integrated within a set of more long-term water management strategies that account for increasing water extractions,
land use change and climate change. Long-term strategies can also help to increase the absorptive capacities of the system and ease the adaptive response to low groundwater recharge predictions.

While rainfall and climate forecasts are available in the region, so far, limited translation to consequences on water supplies has been made, even though many water managers, farmers and general public members identified this as an important need (Babcock et al., 2016).

We presented the groundwater recharge indicator during stakeholder workshops in November 2017 in Nicoya, Guanacaste, Costa Rica, where it was well received, and we refined the tool through the feedback provided in these workshops. The concept of the groundwater recharge indicator is potentially adaptable to many regions around the world, though it is particularly relevant to regions that experience high rainfall seasonality, where a temporal lag between water availability and water needs necessitates an early adaptive response during the wet season to prepare for the following dry season. To adapt the groundwater recharge indicator concept to another aquifer, groundwater recharge would need to be measured or modelled, and the local relationship with cumulative rainfall determined. Importantly, the length of the time series available will impact the robustness of the indicator.

4. Conclusions

Communities in regions with seasonal rainfall face a temporal lag between water availabilities and needs. This often leads to water shortages and water scarcity during long dry seasons. Most seasonally-dry regions depend on groundwater as their primary water source during the dry season. However, if not carefully managed, groundwater recharge during the wet season may be insufficient to meet water demand during the subsequent dry season.

In this study, we developed a ‘groundwater recharge indicator’ for an aquifer in the wet-dry tropics of Costa Rica in order to provide a tool that can help communities prepare in a timely manner for dry seasons following wet seasons with low rainfall. The tool allows early prediction of the likely groundwater recharge at the end of the wet season based on accumulated seasonal rainfall to date. This tool will allow water managers to assess the likely state of groundwater during the wet season when water is still available, and implement adaptive responses to low groundwater recharge, such as using rain and surface water (supply management) or water conservation (demand management) to ‘bank’ groundwater for the dry season when it is the only water supply. This idea can be applicable to other groundwater-dependent communities in regions with seasonal rainfall regimes. The tool provides a way to communicate scientific results to decision makers to support them in increasing the socio-hydrological resilience of their communities to seasonal droughts.

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