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Quantifying human impacts on hydrological drought using a combined modelling approach in a tropical river basin in central Vietnam

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Abstract. Hydrological droughts are one of the most damaging disasters in terms of economic loss in central Vietnam and other regions of South-east Asia, severely affecting agricultural production and drinking water supply. Their increasing frequency and severity can be attributed to extended dry spells and increasing water abstractions for e.g. irrigation and hydropower development to meet the demand of dynamic socioeconomic development. Based on hydro-climatic data for the period from 1980 to 2013 and reservoir operation data, the impacts of recent hydropower development and other alterations of the hydrological network on downstream streamflow and drought risk were assessed for a mesoscale basin of steep topography in central Vietnam, the Vu Gia Thu Bon (VGTB) River basin. The Just Another Modelling System (JAMS)/J2000 was calibrated for the VGTB River basin to simulate reservoir inflow and the naturalized discharge time series for the downstream gauging stations. The HEC-ResSim reservoir operation model simulated reservoir outflow from eight major hydropower stations as well as the reconstructed streamflow for the main river branches Vu Gia and Thu Bon. Drought duration, severity, and frequency were analysed for different timescales for the naturalized and reconstructed streamflow by applying the daily varying threshold method.

Efficiency statistics for both models show good results. A strong impact of reservoir operation on downstream discharge at the daily, monthly, seasonal, and annual scales was detected for four discharge stations relevant for downstream water allocation. We found a stronger hydrological drought risk for the Vu Gia river supplying water to the city of Da Nang and large irrigation systems especially in the dry season. We conclude that the calibrated model set-up provides a valuable tool to quantify the different origins of drought to support cross-sectorial water management and planning in a suitable way to be transferred to similar river basins.

1 Introduction

River basins and their hydrological systems play a key role in providing freshwater to downstream deltaic systems, for irrigation and domestic water supply and to regulate salt water intrusion (Ribbe et al., 2017). The patterns of timing and magnitude of streamflow essentially depend on climatic variables such as precipitation (Zhang et al., 2007; Min et al., 2011; Souvignet et al., 2013; Ahn and Merwade, 2014), temperature, and the resulting altered evapotranspiration rates (Vörösmarty et al., 2000; Santer et al., 2011; Trenberth, 2011; Ahn and Merwade, 2014), as well as on the modification of the hydrological systems by humans introducing water infrastructure such as reservoirs and damming, interbasin water transfers, and construction of weirs.

Hydrological droughts are becoming more frequent disasters worldwide, which can also be attributed to both hydroclimatic and anthropogenic changes (AghaKouchak et al., 2015; van Loon et al., 2016; van Lanen et al., 2016). Regional studies show that larger changes in streamflow have been observed in anthropogenically modified river basins, in particular those altered by hydropower development and operation, than in hydrological systems which are only affected by climate variability and change (Arrigoni et al., 2010; Ahn and Merwade, 2014; Tang et al., 2014). Such alterations of the hydrological system often negatively affect downstream discharge patterns and communities dependent on the provision of freshwater for irrigation and domestic water supply (Rossi et al., 2009; Zhou et al., 2012; Song et al., 2015). Therefore, seasonal impacts of reservoir operation on low-flow patterns and trends need to be quantified in order to separate them from natural drought propagation and to inform downstream water users to properly manage water supply for irrigation, industry, and domestic water supply.

The effects of reservoir operation on streamflow have been assessed for instance in the Lena, Yenisei, and Ob' river basins of the Arctic Eurasian river system, on a seasonal and annual basis revealing that reservoir operation accounts for most of the seasonal changes in the three river basins, ranging from 60 to 100 %, particularly in winter and early spring. Reservoir operation was found to have little effect on annual trends (Ye et al., 2003; Adam et al., 2007; Adam and Lettenmaier, 2008). Räsänen et al. (2012) quantified hydrological changes in the upper Mekong basin due to hydropower operation in China, which showed that discharge increased by 34–155 % from December to May and decreased by 29–36 % from July to September. The impacts on streamflow of the Three Gorges Reservoir were quantified by Zhang et al. (2015), who assessed streamflow at three outlets on the southern bank of the Jingjiang River (a Yangtze tributary), providing evidence that the reservoir impacts were largely responsible for major droughts downstream.

Positive impacts of reservoir operation on downstream hydrological regimes have been reported for Chinese catchments (Song et al., 2015), suggesting a decreasing frequency of flood events in the Sanchahe River basin and by Tang et al. (2014), who showed an increasing surface runoff during the dry season at the upper Mekong/Lancang River in China.

Various approaches have been used to quantify and separate anthropogenic and climate change impacts on streamflow. The most commonly used approaches are streamflow time series analyses looking at seasonal and frequency patterns to assess impacts of human alterations on discharge. Wang and Hejazi (2011) used Budyko curves (Budyko, 1974) to detect human-induced changes in streamflow, investigating their deviation from the initial relationships between mean annual precipitation, evaporation, and potential evaporation as defined by the Budyko curves. Double mass curves (DMCs) are applied to compare the cumulative distribution of precipitation and discharge time series before and after human alterations (Wang et al., 2015) as well as linear regression to establish the relationship between discharge and different climatic variables (Johnson et al., 1991; Wang et al., 2012; Hu et al., 2015). However, although such relatively simple statistical analyses of hydro-climatic time series might give a first insight into system behaviour, they might not capture the non-linear nature of hydrological systems.

Several studies have applied hydrological models to assess the different causes of streamflow changes (Zhang et al., 2012; Bao et al., 2012; Tesfa et al., 2014; Chang et al., 2015), providing simulations of naturalized and reconstructed discharge time series to quantify and separate the different impacts. Alternatively, the paired basin approach has been used to model the impact of human-induced land cover changes on streamflow by comparing simulations in catchments of very similar characteristics (Bonell and Bruijnzeel, 2005; Seibert and McDonnell, 2010).

The coupled modelling approach, which incorporates hydrological modelling information into reservoir simulation models, appears to be a promising approach which has been recently used to investigate effects of reservoir operations on hydrological systems. For example, López-Moreno et al. (2014) applied a regional hydrological model (RHESSys model) combined with a reservoir simulation model to predict the changes in flow due to reservoir operation as well as climate and land use changes in the Aragón River, Spanish Pyrenees. Reservoir operation effects on downstream flow in the Lena, Yenisei, and Ob' river basins were evaluated using a reservoir routing model coupled offline to the Variable Infiltration Capacity (VIC) land surface hydrology model (Adam et al., 2007). Estimated changes in streamflow due to reservoir operation in the Greater Alpine Region were computed using a parsimonious rainfall–runoff model combined with a hydropower simulation model (Wagner et al., 2017). The coupled approach was also used at a global scale to identify the impact of human water consumption on the intensity and frequency of hydrological drought worldwide (Wada et al., 2013).

The studies described above focussed on the evaluation of either human impacts on general streamflow behaviour or on flood risk. The implication of reservoir operation and other human alterations of the hydrological system for drought severity, duration, and frequency length have not been addressed in such studies. Also, hydrological drought risk is usually looked at on a monthly, seasonal, annual, or long-term scale. Hydro-climatic dynamics in the tropics, however, are fast and water-management-related decisions need to be made based on daily information (e.g. to avoid salt water intrusion into the irrigation and drinking water supply systems) (Nauditt et al., 2017).

The overall aim of this study was therefore to quantify and separate the impact of hydropower reservoir operation on hydrological drought in the VGTB River basin. Its specific objectives were to (1) simulate discharge to obtain naturalized streamflow time series by applying a distributed hydrological response unit (HRU) (Pfenning et al., 2009) based rainfall–runoff model – J2000 (Krause, 2002; Fink et al., 2013); (2) model reservoir storage and operation for eight major hydropower reservoirs in order to simulate daily release rates, hydropower production, and storage using the HEC-ResSim

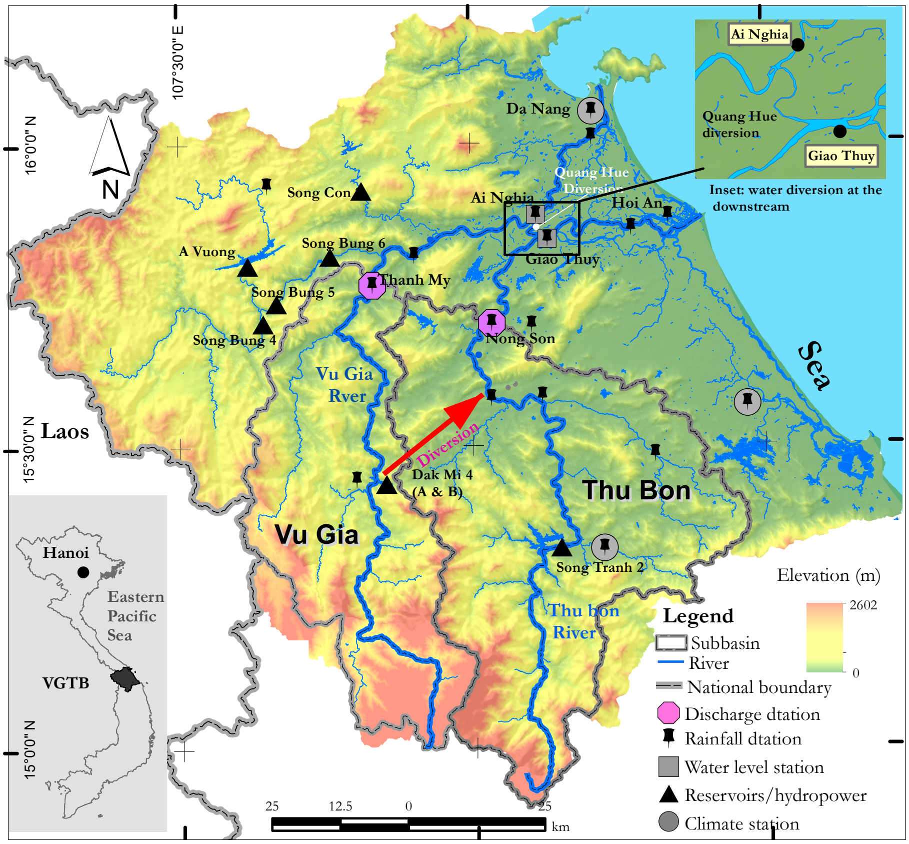

Figure 1. Topographical map of the VGTB River basin showing the hydrology, hydro-meteorological monitoring network, and eight major hydropower reservoirs as well as the diversion (in red colour) from VuGia to Thu Bon at Dak Mi 4 hydropower plant.

model (USACE, 2007); (3) simulate reservoir-impacted reconstructed streamflow for downstream stations at the two main river branches; and (4) quantify to which extent hydrological drought duration and severity can be attributed to hydropower reservoir operation or climate variability by applying the variable threshold method approach (Tallaksen et al., 2009; Sung and Chung, 2014) to reconstructed and naturalized streamflow time series.

The combined assessment approach developed in this study enables us to assess the interactions between climate, catchment, and reservoir operation on the one hand and water and energy demand on the other. Furthermore, it provides us with a tool to determine drought risk on a daily scale to support water management for irrigation and drinking water supply. The results of this research provide a detailed insight into the current and potential impacts of reservoir operation on the downstream water availability, which we provided to the water managers, the reservoir operating agencies, and other decision-makers.

2 Study area and data

2.1 Study area: Vu Gia Thu Bon River basin (VGTB)

The Vu Gia Thu Bon River basin (VGTB) is located in central Vietnam (6°55′–14°55′ N and 107°15′–108°24′ E) and covers a total area of approximately 12 577 km^2 (Fig. 1). The main provinces in the VGTB are Quang Nam and Da Nang. It is characterized by a steep topography and the altitude ranges from 0 m at the coast to 2598 m in elevation in the South Truong Son Mountains in the west, and by the Kon Tum mountain mass in the south (Viet et al., 2017). Almost half of the land area is covered by forest (47 %), followed by cropland (26 %) and grassland (20 %) (Avitabile et al., 2016). Paddy rice cultivation and livestock farming are the two main agricultural activities in the basin. Two crops of paddy rice are planted per year in the lowlands and areas along the major rivers, yielding 5.05 t ha^{-1} in 2013 (Quangnam Statistical Office, 2014). The VGTB is home to approximately 2.5 million inhabitants (2013), 80 % of whom live in the coastal lowlands, and 45 % of whom live in the urban areas (General Statistics Office, 2014). The VGTB river system is formed by two major rivers, the Vu Gia and the Thu Bon, which origi-

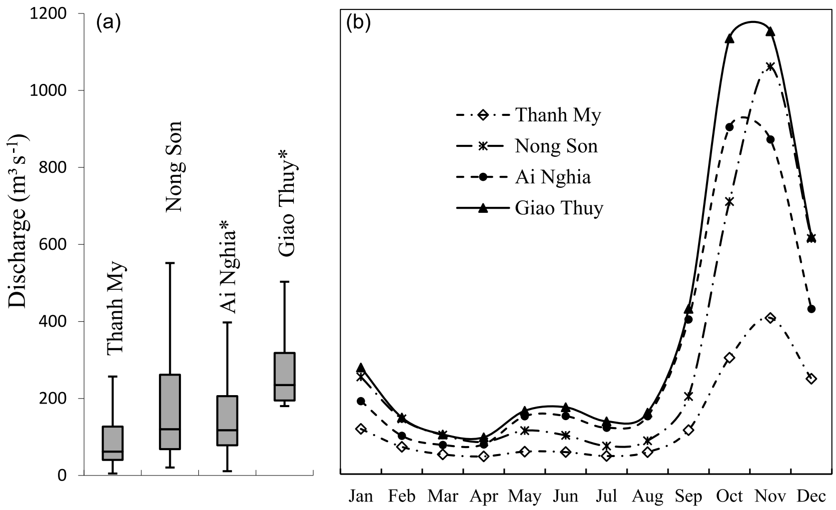

Figure 2. Mean monthly discharge at the four stations under study for the period 1979–2013 **(b)**. Naturalized flow data for Ai Nghia and Giao Thuy stations were simulated with J2000. Box plots **(a)** indicate the 25th, 50th (median), and 75th percentiles of the daily streamflow time series. Outliers have been removed from the plots. The whiskers are defined as the first quartile minus 1.5 × IQR and the third quartile plus 1.5 × IQR.

nate in the highlands and flow into the ocean near the cities of Da Nang and Hoi An.

The climate in the VGTB basin is characterized by a strong wet season with typhoons lasting from September to December and an extended dry season (Souvignet et al., 2013). Next to the two major seasons – which we here term the "dry" and "wet" seasons – there are four minor seasons observed in this region and referred to in this study as summer – June, July, August (JJA); autumn – September, October, November (SON); winter – December, January, February (DJF); and spring – March, April, May (MAM) (Souvignet et al., 2013). Rainfall during the wet season accounts for 65–80 % of the total annual rainfall, with 40–50 % of the annual rainfall occurring in October and November, and this high rainfall regularly causes severe floods (Souvignet et al., 2013). The long dry season lasts from January to August and is frequently accompanied by droughts (e.g. in 1982, 1983, 1988, 1990, 1998, 2005, 2012, and 2013) (Nauditt et al., 2017). February to April were considered the driest months – a period accounting for only 3–5 % of the total annual rainfall, resulting in severe water shortages and problems with saline intrusion at the coast (Souvignet et al., 2013).

The basin area of Vu Gia until reaching Ai Nghia station is approximately 5453 km^2, and the area of Thu Bon until Giao Thuy station is 3532 km^2. Around 3 km beyond Giao Thuy station, the river enters the tide-affected area and the hydrological regime of the river behaves under the interaction of tidal and upstream inflow. At two hydrological stations – Nong Son (Thu Bon River) and Thanh My (Vu Gia River) – discharge has been measured since 1976 (Fig. 1).

Water resources in the Vu Gia Thu Bon River basin (VGTB) have been intensively developed for a variety of uses, including hydropower generation, large rice irrigation systems in the delta, and domestic and industrial water supply. Inter-basin water transfer from the Vu Gia to Thu Bon sub-basins to generate electricity from Dak Mi 4 hydropower plant is causing significant changes in the respective flow regimes. Paddy rice is the dominant crop, as it accounts for approximately 70 % of irrigated agricultural area (Pedroso et al., 2016). Water stress during drought periods is a major constraint on agricultural production in the region. Figure 2 shows mean monthly inter-annual discharge for the four gauging stations addressed in this study (two discharges and two water-level stations).

2.2 Hydro-meteorological data

Hydro-climatic records were purchased at the Regional Centre for Hydro-meteorology (RCHM) within the scope of German Ministry of Education and Research (BMBF) funded research project "Land Use and Climate Change Interaction in Central Vietnam (LUCCi)" (www.lucci-vietnam.info). A detailed description of the spatial (e.g. soil, vegetation, digital elevation model, land use, geology) and hydro-climatic data used for the hydrological model J2000 was described in Fink et al. (2013, p. 1828) and Souvignet et al. (2013). At two hydrological stations, Nong Son (Thu Bon River) and Thanh My (Vu Gia River), discharge has been measured since 1976. Rainfall data at the 17 stations and climate data at the 3 stations are completely available from 1980 onwards. Based on the data availability, this study considers the time frame 1980–2013, which covers a suitable time frame (> 30 years) for most of the available stations. Two water-level stations further downstream, Ai Nghia (Vu Gia River) and Giao Thuy

Table 1. Reservoirs in the VGTB River basin (MOIT, 2015a, b; ICEM, 2008).

Item	Unit	A Vuong	Song Tranh 2	Dak Mi 4 A	Dak Mi 4 B	Song Bung 4	Song Bung 5	Song Bung 6	Song Con 2
First year of operation		2008	2011	2011	2011	2015	2014	2014	2009
River system		VuGia	ThuBon	Vu Gia	Vu Gia	VuGia	VuGia	VuGia	VuGia
Catchment area	km^2	682	1100	1125	29	1448	2369	2386	250.1
Mean annual flow	$m^3 s^{-1}$	39.8	106	67.80	1.1	73.7	118	119	13.2
Full supply level (FSL)	m a.s.l	380	175	258	106	222.5	60	31.8	275
Minimum operation level (MOL)	m a.s.l	340	138	240	105	195	58.5	30.0	274
Reservoir area at FSL	km^2	9.1	21.5	10.4	0.45	15.65	1.68	0.398	0.13
Reservoir area at MOL	km^2	4.3	9.3	7	0.4	7.8	1.68	0.398	0.12
Reservoir total storage	$10^6 m^3$	343.6	733.4	310	2.6	510.8	20.27	3.29	1.2
Reservoir active storage	$10^6 m^3$	266.5	521.1	158	0.6	233.99	17.82	3.29	0.7
Spillway design flood	$m^3 s^{-1}$	5730	11 069	7864	642	15 427	16 780	17 011	3217
Maximum tail water level	m a.s.l	86.6	87.5	108	71.5	121.3	32.33	15.5	29.7
Normal tail water level	m a.s.l	58	71	106	67.5	101.6	30.7	12	18
Design head	m	300	88.3	135	37.5	112.4	27	13.4	246
Total turbine design discharge	$m^3 s^{-1}$	78.4	209.7	121	122	172.7	239.24	243.2	22.8
Installed capacity	MW	210	162	141	39	156	57	29	46
Annual average energy potential	GWh	825	620.7	582	161	618	220	151	168

(Thu Bon River), are also included to capture the downstream impact of hydropower. They are strongly influenced by tide (Giao Thuy) and tend to be flooded during the rainy season (Ai Nghia).

Data uncertainties

Aside from the uncertainties related to hydro-climatic data described in Fink et al. (2013) and Souvignet et al. (2013), there are no discharge time series for the downstream irrigation region. We therefore developed our methodology based on the following assumptions: before Ai Nghia station in the Vu Gia delta region, water is diverted from Vu Gia to Thu Bon via the Quang Hue channel throughout the year. Due to the strong seasonality and tidal influences, it is difficult to predict the actual amount diverted towards the Thu Bon River. There are no data on quantities of water released from the reservoirs, but we rely on the routing rules of water diverted from Vu Gia to Thu Bon through the Quang Hue channel (see Table S1 in the Supplement) (Ministry of the Environment, MONRE). To avoid complexity, we assumed in the study that Ai Nghia station is located upstream of the diversion of the Quang Hue channel. We found that the proxy station can accurately capture the influences of reservoir impact on the downstream without leading to potential errors, as it accounts for the overall water balance.

2.3 Hydropower and reservoir data

From 2008 until 2014, eight large hydropower reservoirs and plants were constructed, which have a cumulative storage capacity of more than 2 km^3 (Table 1). The Dak Mi 4 (A & B) dam was built on the Vu Gia sub-catchment, but the water is diverted at its outflow to the Thu Bon River basin, since the turbines are located in the Thu Bon River basin (Fig. 1). The reservoir information is summarized in Table 1. The classification of the reservoirs is based on the Vietnamese description of large, medium, and small reservoirs (MOIT,

Table 2. Performance of efficiency statistics for the J2000 hydrological model: E^2, Nash–Sutcliffe efficiency; $\log E^2$, Nash–Sutcliffe efficiency with logarithmic values; R^2, coefficient of determination; and P_{bias}, relative volume error in percent.

Station	Thu Bon (Nong Son)		Vu Gia (Thanh My)
Time frame	Calibration 1 Nov 1996–31 Oct 2000	Validation 1 Nov 2000–31 Oct 2005	Validation 1 Nov 1996–31 Oct 2005
E^2	0.856	0.869	0.610
$\log E^2$	0.863	0.856	0.776
R^2	0.869	0.870	0.774
P_{bias}	−10.6	−5.37	8.59

2015a). Reservoirs which have an installed capacity of more than 29 megawatts (MW) of energy are considered large hydropower plants, while the medium and smaller plants are in the range of 10 to 29 MW. The remaining plants produce less than 10 MW (PPC, 2006). For this study we have considered all eight hydropower plants, but to evaluate the model results, we have used the hydropower release data from four of the eight reservoirs: A Vuong (February 2009 to August 2012), Dak Mi 4 A (January 2012 to December 2013), Song Con 2 (September 2010 to June 2012), and Song Tranh 2 (February 2011 to December 2013), for which the outlet data at the turbine discharge are available. Please note that A Vuong started its operation in September 2008 and that Dak Mi4 reservoir started its operation in September 2011 (Table 1). Three of the remaining four reservoirs have only been operational since 2013 (Song Bung 4, 5, and 6), and the data were not available. The last reservoir, Dak Mi 4 B, is considered a runoff reservoir, and therefore it was not necessary to account for its outflow in this study. Operational rules and rule curves were collected from the technical documents of each reservoir from the Department of Investment and Trade (DOIT) belonging to the national Ministry of Investment and Trade (MOIT) of Quang Nam Province, Vietnam (see details in Table S2).

3 Methods

3.1 JAMS/J2000 HRU-based rainfall–runoff model

The J2000 is a physically based distributed and process-oriented model, which is suitable for simulating the hydrological processes of meso- and macro-scale catchments (Kralisch and Krause, 2006; Fink et al., 2007). The model describes the hydrological processes as encapsulated or independent process modules. The model utilizes the HRU approach for the discretization of the basin, consisting of an overlay of land use, soil, geology, and the relief parameters topographic wetness index (Böhner et al., 2002), mass balance index, and solar radiation index (McCune and Dylan, 2002; Pfennig et al., 2009). Modules are described in more detail by Nepal et al. (2014) and in the online documentation (http://ilms.uni-jena.de/ilmswiki/index.php/Hydrological_Model_J2000). The J2000 model was calibrated and validated for the Nong Son gauging station for the period of 1996–2005 (calibration and validation), an undisturbed period before the reservoirs were constructed in 2009.

The calibration was conducted manually and automatically using the multi-objective NSGA2 algorithm (Deb et al., 2002). The model efficiency was tested by using different efficiency criteria, which include (1) the coefficient of determination (R^2) to show the goodness of fit for the general model dynamics, (2) the Nash–Sutcliffe (E^2) efficiency to judge the goodness of fit with a focus on peak flow and simulated volumes, and (3) the Nash–Sutcliffe efficiency ($\log E^2$) with logarithmic values to achieve a stronger focus on the low-flow periods (Krause et al., 2005). As an indicator of the overall simulated volumes, we used the percent bias (P_{bias}) (Table 2). Further information about the utilized objective functions is given in Krause et al. (2005).

3.2 HEC-ResSim reservoir operation model

We applied the HEC-ResSim reservoir system simulation model (USACE, 2007) to simulate reservoir release, hydropower production, and storage in the individual reservoirs of the VGTB at a daily time step. HEC-ResSim allows the development of simulations of single or multiple reservoirs in a hydrological network, based on the available hydrological (inflow) data, the physical reservoir characteristics, and the operating rules. The model is comprehensively documented in Klipsch and Hurst (2013). J2000-simulated inflow time series (compare locations in Fig. 3a) were introduced and routed, with reservoirs altering the routed flow based on physical constraints and operating rules (Fig. 3b). Based on the technical document provided by the MOIT (more details are provided in the Supplement for the operational rules of individual reservoirs; see Fig. S1), the reservoirs were first modelled individually, calibrated, and evaluated based on the available observed outflow at their outlets. For this study, we have used the hydropower release data from four of the eight reservoirs, A Vuong, Dak Mi 4, Song Con 2, and Song Tranh 2, for which the outlet data for the turbine discharges are

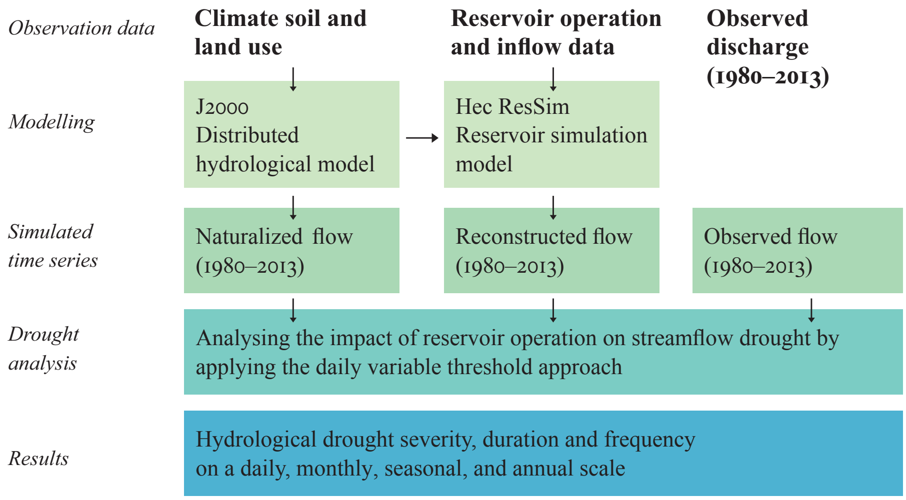

Figure 3. Drought assessment framework: (1) the Distributed Hydrological Model (J2000) (Krause, 2002) provides the simulated inflow data at various nodes and naturalized streamflow, (2) HEC-ResSim simulates reconstructed streamflow for the entire observation period, and (3) streamflow deficiency analysis through threshold-level methods provides information about the drought duration and extent. The reservoir impacts on the downstream flow have been assessed based on the reconstructed and naturalized streamflow differences.

available. Three of the remaining four reservoirs have only been operational since 2013 (Song Bung 4, 5, and 6), and the data were not available. The final reservoir, Song Con 1, is considered a runoff reservoir, and therefore it was not necessary to account for its outflow in this study.

At VGTB, the reservoirs were operated based on a defined management season, namely "*Flood season*" (from 16 September to 31 December), and "*Dry Season*" (from 1 January to 15 September) (MOIT, 2011). During the flood season, the first considerations are dam safety and spill discharge. If the inflow is greater than the maximum hydropower discharge capacity and the water level is above the flood control zone, then water is first diverted to its full capacity to produce hydropower and the excess water within that day will be released through spill discharge to ensure flood control. During the dry season, the guide curve will determine how the release of water from the reservoir will be managed. However, for each reservoir there is a monthly power production target, also controlled by the upper and lower limits of the reservoir level. Generally, if the water level is close to the upper limit of the guide curve, then energy production will be maximized, and if it is close to the lower limit, a limited amount of water will be released for hydropower production, and release rates are made considering the environmental flow.

3.3 The combined modelling–drought assessment framework

To analyse and quantify the impacts of reservoir operation on downstream low flows and to separate them from other impacts, longer time series for both the "pristine" and "impacted" periods are needed. We termed them "naturalized" and "reconstructed" discharge, respectively. The J2000 hydrological model was utilized to simulate daily discharge for upstream HRU outlets of the VGTB River basin system as input streamflow time series to the reservoirs and to provide time series for the "naturalized" flow for the four downstream stations addressed in this study (Fig. 1). Impacts of hydropower operation on downstream low flows were assessed by using the HEC-ResSim reservoir routing model coupled offline to the J2000 for the VGTB River basin (Fig. 3). The output of this integrated model is referred to here as "reconstructed streamflow". This provides the estimated streamflow at the two existing gauging stations (Nong Son and Thanh My) and at the two additional locations further downstream of the mouth of the two reaches (Ai Nghia and Giao Thuy), to capture the influences of reservoirs located further downstream (Fig. 1). In our analysis the observed discharge data were only used for evaluating the simulated results. In the modelling process, we assumed that all eight reservoirs came into operation in 1980, and then used the reservoir model to produce the synthetic streamflow termed here as reconstructed flow. This gave us the opportunity to evaluate the long-term influences of the reservoirs on streamflow. A drought analysis was then performed for the reconstructed (reservoir-impacted) and naturalized (pristine) streamflow simulations. Figure 4 provides an overview of the applied methods.

3.4 Hydrological drought assessment

The threshold approach (Zelenhasić and Salvai, 1987) is widely used to determine hydrological drought in temperate regions, where the discharge is usually greater than zero (Tallaksen et al., 2009; van Huijgevoort et al., 2012; van Loon

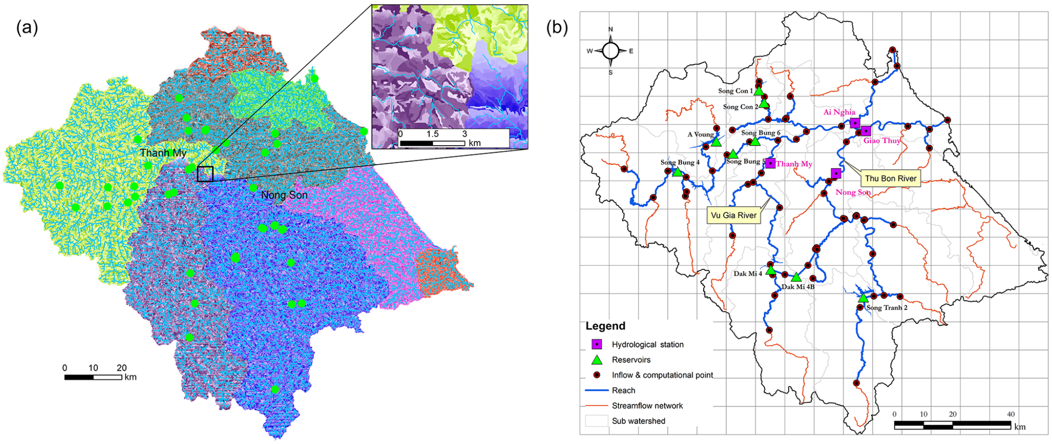

Figure 4. Coupling of the J2000 model with the HEC-ResSim model. **(a)** HRU of the J2000 model along the major sub-basin, virtual discharge stations (green points) for which J2000 simulated time series for the reservoir inflow, and relevant abstraction points in the downstream area. **(b)** The HEC-ResSim model node network, J2000 inflow discharge points (brown dots), and the locations of the reservoirs that have been incorporated within the reservoir model.

and van Lanen, 2012; Sung and Chung, 2014). It defines drought events based on a threshold value and provides information about its onset, duration, and severity (Stahl, 2011; Hisdal et al., 2004).

The daily variable threshold approach (Hisdal et al., 2004) based on flow duration curves (FDCs) has been applied to determine hydrological drought periods. We used the 90th percentile (Q_{90}) of the FDC as the daily variable threshold, which is obtained from the antecedent 365 daily streamflow values. This threshold has been selected to study the drought which has a severe impact on the livelihood of the downstream population, particularly the irrigation sectors within the VGTB River basin, and also has been used in various drought-related studies (e.g. Fleig et al., 2006; Wanders et al., 2015). Q_{90} is defined as follows: for a given day of the hydrological year d (in this study, 1 September is considered the start of the hydrological year), the daily varying Q_{90} (d) is calculated based on a moving average of 30 days centred on day d (i.e. 15 days either side), starting from the first day of the hydrological year (Prudhomme et al., 2011; Van Loon et al., 2015). Due to strong seasonality within the study region, we further introduce the break-days concept to calculate the threshold level for both dry and wet season separately. Here the break days are 1 September and 1 January, which are the starting dates of the wet and dry seasons, respectively. Furthermore, lower than average flow in wet seasons contributed to the development of drought in the following season (Sung and Chung, 2014). A binary approach has been considered to identify whether it is a dry day or normal day based on the daily low-flow varying threshold. Finally, the streamflow deficits of the naturalized and reconstructed streamflow are compared to quantify the impact of reservoirs on streamflow drought.

4 Results

4.1 J2000 hydrological model calibration to simulate naturalized discharge

The J2000 model was manually calibrated and validated for the Nong Son discharge station for the period of 1996–2005. We also performed an automatic calibration using the multi-objective NSGA2 algorithm (Deb et al., 2002), which yielded similar results using the same objective functions as for the manual calibration (Table 2). The second available gauging station (Thanh My) was not separately calibrated, but tested using the same parameter set calibrated for Nong Son (see details in Table S3 for the estimation of parameters). This was done to check the ability of the model to simulate discharge for those parts of the basin where no calibration was possible due to the lack of discharge data.

Table 2 shows the efficiencies for each objective function used for the calibration and validation period (1996–2005). It is worth noting that if the model is calibrated using the first half of the time series (1996–2000; E^2, Nash–Sutcliffe efficiency, of 0.856), the runoff for the second half (2000–2005) is reasonably well simulated (E^2 of 0.869), including the low flows during the drought period in 2005 (see details in Sect. S4 for the observed and simulated discharge plots). The average of the three efficiency criteria for Nong Son station resulted in 0.865 and 0.72 for Nong Son and Thanh My, respectively, when validated for the time period from 2000 to 2005 (Table 2). Following the classification of Nash–Sutcliffe efficiency criteria proposed by Moriasi et al. (2007), most of the calibrated models are rated as “good” (> 65 %) or “very good” (> 75 %). The objective functions log E^2 and R^2 show that the low-flow periods and the overall dynamics are well represented. For the calculation methods and fur-

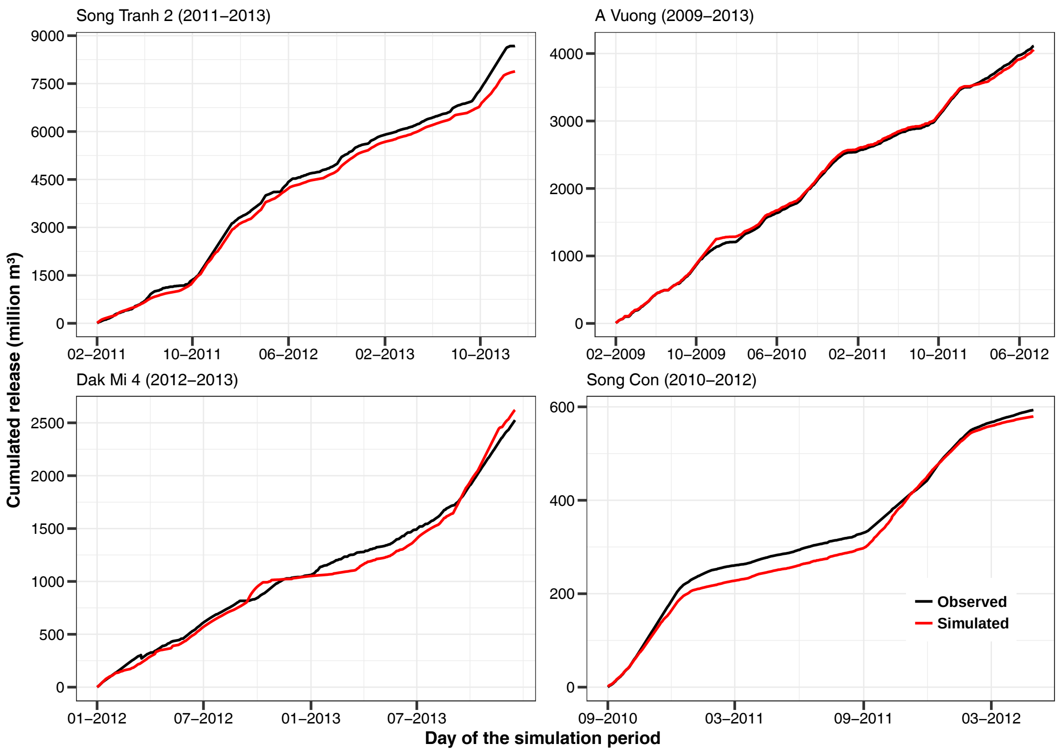

Figure 5. Simulated and observed cumulated daily release of the individual reservoirs.

ther information about the utilized objective functions, refer to Krause et al. (2005). Owing to the HRU concept of J2000 as well as the JAMS modelling framework, it is possible to generate hydrological state variables for each point in time and space. This facilitates the transfer of flow data at a daily time step at selected points along the river segments to the reservoir model (Fink et al., 2013), for example the points representing the reservoir inflow discharges.

4.2 Simulation of hydropower reservoir release discharge

We applied the Hec ResSim model to simulate reservoir release discharge for each individual reservoir in the VGTB at a daily time step. Inflow time series from J2000 hydrological models were introduced and routed at inflow locations (Fig. 4). The individual reservoir simulation results are presented in Fig. 5.

The simulation period varied for each of the reservoirs, depending on their year of construction and availability of the discharge data from the turbine. In the case of A Vuong, we compared the observed release data from February 2009 to August 2012 with the simulated cumulated daily discharge release values (Fig. 5), and there was very good agreement between the time series. There was also strong agreement at Dak Mi 4 with data from January 2012 to end of December 2012. However, for the summer period in 2013, the simulated discharge was consistently lower than the observed discharge (Fig. 5). Simulations for Song Con 2 for the period from September 2010 until the beginning of 2011 also showed good results, while the dry season cumulative discharge for the year 2011 was underestimated but improved during the wet season. The simulation result for Song Tranh 2 was unsatisfactory for the period after January 2012 (Fig. 5).

4.3 Reconstructed streamflow simulation

Reconstructed synthetic streamflow was simulated based on the individually simulated reservoir releases (Fig. 5). We simulated the reconstructed streamflow for the period 1980–2013, incorporating varying reservoir operation options such as cascade reservoir operation and flood and dry season control. This was performed for the gauging stations Nong Son (wetter Thu Bon catchment) and Thanh My (drier Vu Gia catchment) and two downstream stations: Giao Thuy (Thu Bon) and Ai Nghia (Thanh My). These latter stations are located in the delta region where water is abstracted for rice irrigation and for the drinking water treatment plant which supplies the city of Da Nang. These simulations were needed to capture the impacts of all reservoirs on water availability in the delta area. As there are only water level but no gauging stations at Giao Thuy and Ai Nghia for calibration, we used the naturalized streamflow simulated using J2000. To evaluate the efficiency of the calibration, we applied the performance statistics for the period of 2011 to the end of 2013 (Table 3). This time frame was chosen because the Dak Mi

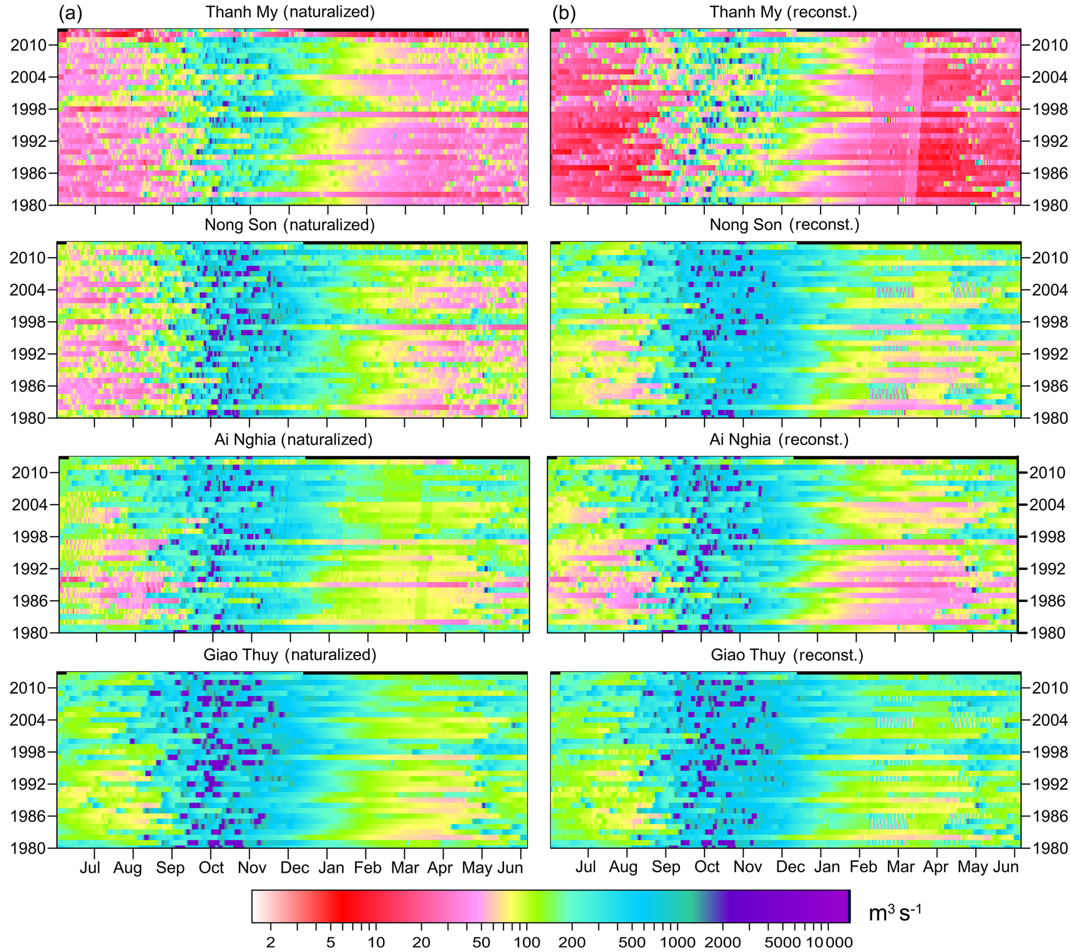

Figure 6. Daily values of discharge ($m^3\,s^{-1}$) at the four discharge stations. Each pixel in the plot represents 1 day and its colour denotes discharge. The x axis represents the hydrological year, starting in July and ending in June. **(a)** shows the naturalized condition based on the J2000 model simulation. **(b)** shows the reconstructed streamflow product based on the reservoir simulation model.

4 and Song Tranh 2 hydropower plants started operation after 2011 and measured data for calibration were available for this period. The efficiency statistics show reasonable results: e.g. E^2, Nash–Sutcliffe efficiencies of 0.907 and 0.716 for Nong Son and Thanh My stations, respectively (see details in Sect. S5 for the observed and reconstructed streamflow plots for the period from 2011 to 2013). This indicates that the reconstructed streamflow is able to capture the influences of reservoir operation on streamflow. The reconstructed streamflow also shows a very good result considering the overall water balance described by the P_{bias} (relative volume error in percent). The P_{bias} values for Nong Son and Thanh My are 0.0052 and −0.077, respectively.

Table 3. Performance statistics: Nash–Sutcliffe efficiency (E^2), $\log E^2$, R^2, and P_{bias} of the reservoir model (reconstructed streamflow) for the two gauging stations.

Stations	Nong Son	Thanh My
	1 Jan 2011–31 Dec 2013	1 Jan 2011–31 Dec 2013
E	0.907	0.716
$\log E^2$	0.79	0.74
R^2	0.954	0.809
P_{bias}	0.0052	−0.077

4.4 Daily, monthly, and seasonal effects of hydropower reservoir operation on streamflow in the subcatchments Vu Gia and Thu Bon

We compared the daily naturalized and reconstructed streamflow simulations in Fig. 6. For Thanh My station and Ai Nghia station in the drier Vu Gia catchment, low flows (pink to yellow colours) during the summertime are more prominent in the reconstructed streamflow than in the naturalized streamflow. For Nong Son and Giao Thuy stations, however,

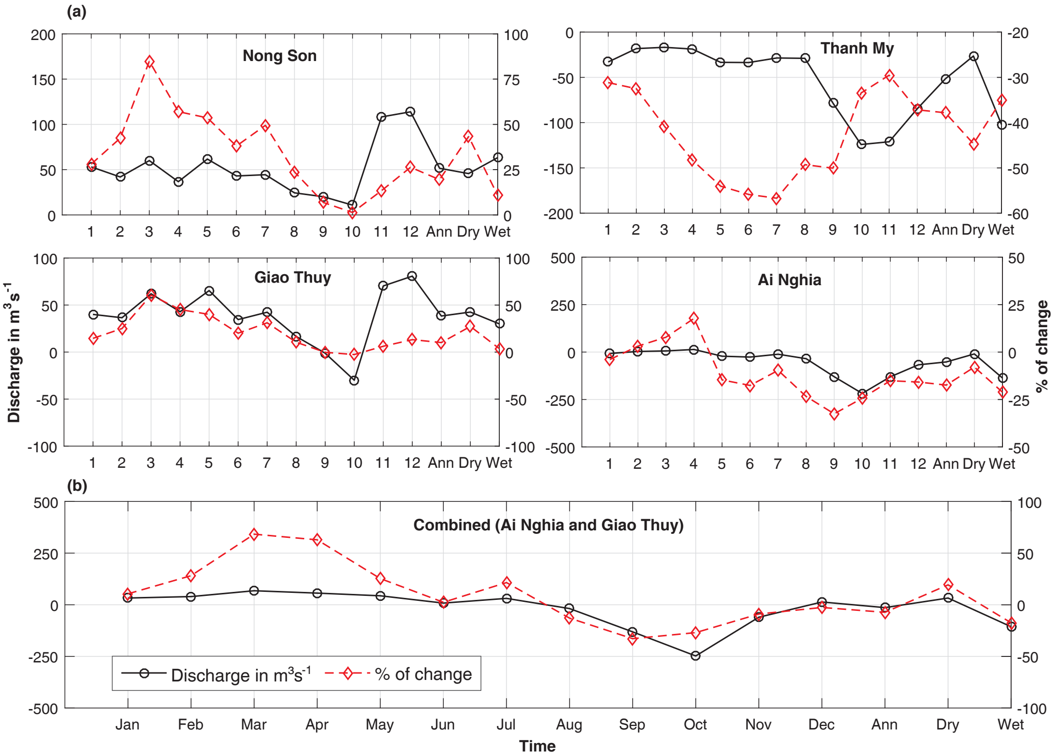

Figure 7. Reservoir impact on streamflow changes. **(a)** Mean differences of reconstructed streamflow pattern (discharge in $m^3\,s^{-1}$) and the percentage (%) of changes in streamflow from the naturalized mean flow for the period of 1980–2013. A negative value indicates a decreasing flow compared with the naturalized one. The number indicates the month starting with January referred to as 1. **(b)** Combined effect of reservoir impact for Ai Nghia and Giao Thuy, representing the overall impact on the streamflow on the VGTB basin due to reservoir construction.

fewer low flows were simulated in the reconstructed time series than in the naturalized one.

To quantify the mean monthly reservoir effects for the period from 1980 to 2013 (Fig. 7), we plotted the mean monthly values of the reconstructed streamflow against the naturalized discharges for the four stations. For Thanh My station located at the upstream of the Vu Gia River, monthly streamflow was reduced on average by approximately $51\,m^3\,s^{-1}$ (38 % of the observed flow). The impact of reservoir operation is most pronounced for the dry season (January to August), when flows decrease from 30 to 60 % compared to the naturalized mean monthly discharge. During the wet season (September to December), discharge decreased by 30 %. At Nong Son station, mean monthly streamflow increased by 24 to $62\,m^3\,s^{-1}$ (from 23 to 85 % of the observed discharge) for the period January to August. Although the mean discharge for September to December increased by 50 to $114\,m^3\,s^{-1}$, the percentage increase was rather low, varying from 1.3 % in October to 26.3 % in December (Fig. 7a). The Giao Thuy and Ai Nghia stations are located approximately 25 and 32 km downstream of the Nong Son and Thanh My stations, respectively, and exhibit a similar pattern of flow changes due to reservoir construction. Analysing the combined seasonal impact of reservoirs on water availability in both catchments, we found that overall discharge during the wet season decreased by 2 to 38 % and increased during the dry season from January to August in which a significant increase in flow augmentation was found during March to April (62–68 %) (Fig. 7b). Figure 8 shows the annual and seasonal mean monthly hydrographs for the four stations, comparing the simulated discharge on a seasonal and an annual scale. These results show that there are strong seasonal changes in streamflow for both sub-catchments, with a significant reduction of streamflow for the Vu Gia River especially in the dry season, and an increase in water availability in the Thu Bon River.

4.5 Impacts of reservoir operation on hydrological drought

Hydrological drought occurrence, length, and severity were determined by using the daily varying threshold-level method (Q_{90}) separately applied to the dry and wet seasons (break days were 1 September and 1 January). Figure 9 shows the drought onset and duration of the naturalized and reconstructed streamflow time series to evaluate the reservoir operation impact on hydrological drought. Thanh My station (Vu Gia catchment) shows more days under drought for the

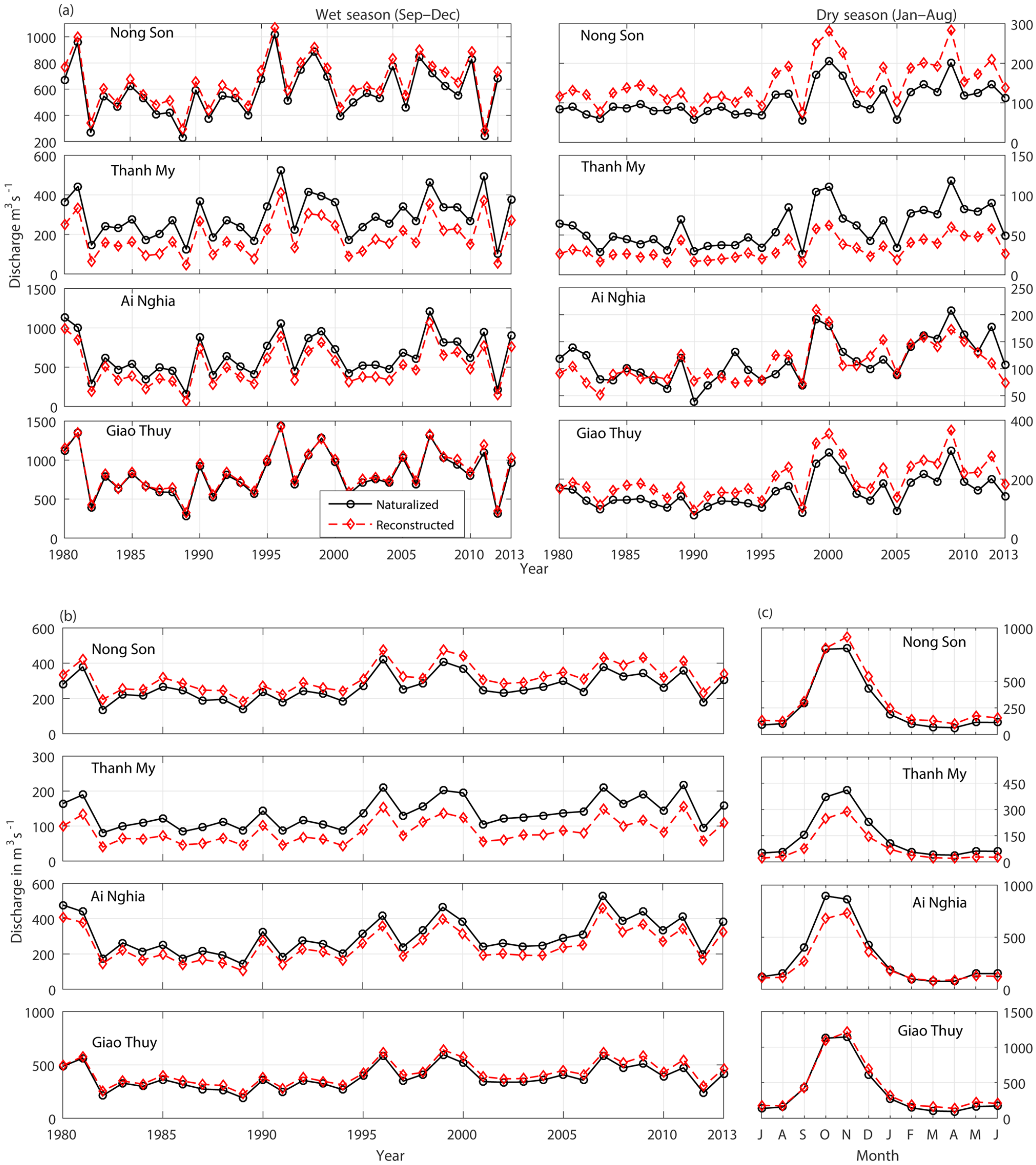

Figure 8. Comparison of mean streamflow pattern (naturalized and reconstructed streamflow): **(a)** comparison of mean seasonal flows for the dry (January to August) and wet (September to December) seasons; **(b)** comparison of mean annual streamflow; and **(c)** comparison of mean monthly streamflow ($m^3\ s^{-1}$).

reconstructed period (1061 days) compared to the naturalized period (774 days). Similarly, an increasing number of drought days and frequency was found for the reconstructed period at Ai Nghia (1286 to 1011 days).

At Nong Son station (Thu Bon River), the analysis shows a general shift of the occurrence of drought from spring (MAM) to summer (JJA) (Fig. 9). Nong Son (upper Thu Bon River) and Giao Thuy (lower Thu Bon River) stations exhibit a decreasing number of drought days, respectively, from 821 to 680 days and from 1025 to 713 days. These reductions are due to the diversion of the Dak Mi 4 reservoir from Vu Gia to Thu Bon. The number of drought days corresponding to the year at each of the stations are presented in the Supplement (Fig. S6).

5 Discussion

5.1 Simulating naturalized discharge with J2000 in a data-scarce environment

In the VGTB, only two discharge stations and related time series are available for calibration. Therefore, to assess changes in water availability in the delta region where water is needed for irrigation and other purposes (e.g. domestic and industrial

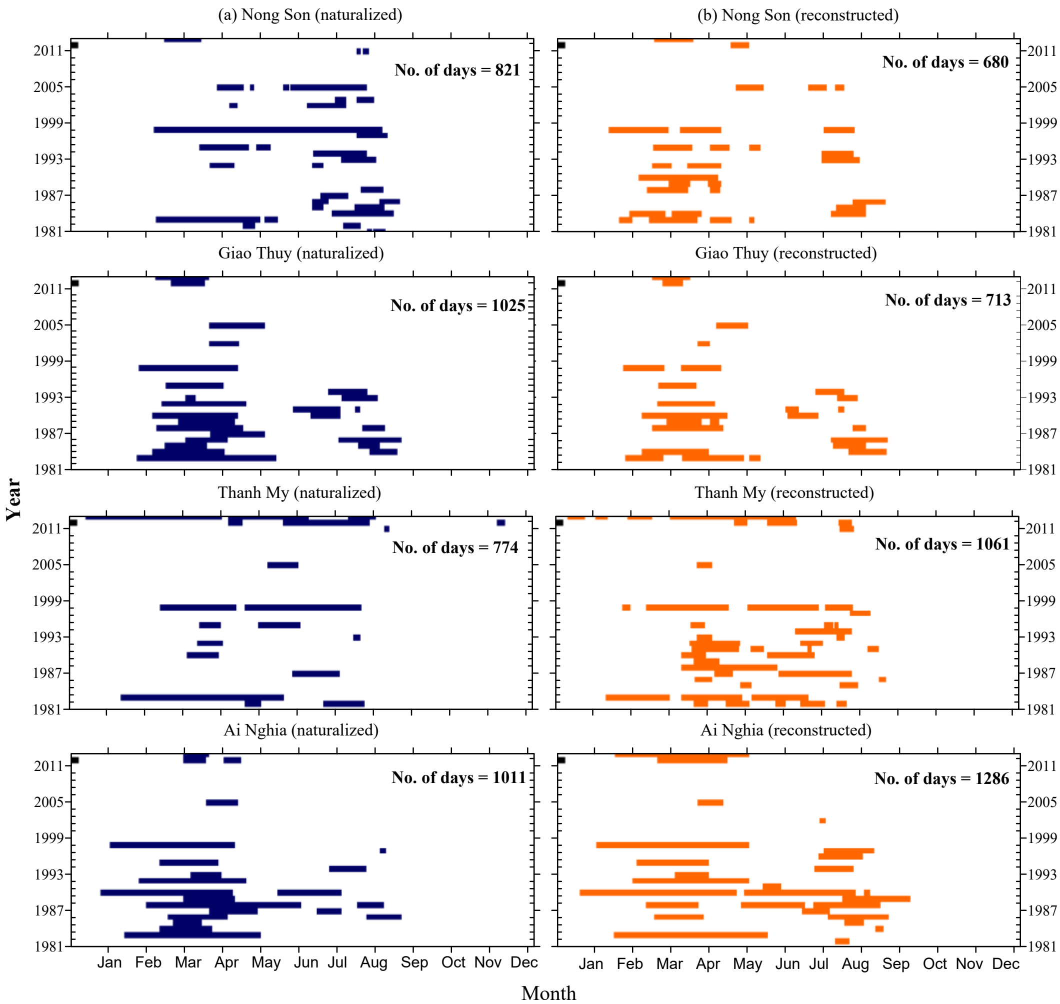

Figure 9. Number of days below the Q_{90} variable drought threshold for the VGTB at the four discharge stations (1981–2013). One day of streamflow drought is a day in which the 30-day running mean discharge is below the 10th percentile of 30-day mean discharge. The blue colour bars **(a)** show the drought onset and duration for the naturalized streamflow, whereas the orange colour bars **(b)** represent the reconstructed reservoir impacted discharge. "No." indicates the total number of drought days.

uses), we simulated discharges for locations where no validation data were available. The J2000 model was successfully calibrated and validated for the Nong Son gauging station for the period 1996–2005, an undisturbed period before the reservoirs were constructed in 2009. Results for the three applied efficiency criteria ranged from 0.72 to 0.87, which are considered very good simulation performances (Moriasi et al., 2007). The application of the Nong Son validated parameter set to Thanh My station also yielded reasonably good efficiencies (Table 2).

These results allowed us to use J2000 to simulate naturalized discharges for HRU outlets needed as reservoir inflow discharges and for the downstream delta locations Ai Nghia (Vu Gia sub-catchment) and Giao Thuy (Thu Bon subcatchment). They can be considered valuable discharge estimations for this study. A simulation uncertainty range is presented in the Supplement (Fig. S7).

5.2 Modelling discharge release from operating hydropower reservoirs

Overall individual reservoir modelling showed good results in simulating released discharges from the turbine (Fig. 5). Available release discharge time series from operating hydropower plants for reservoir model calibration were short, and the simulation period varied for each of the reservoirs depending on their year of construction and availability of discharge data for the turbine.

The simulation results for the Song Tranh 2 reservoir were unsatisfactory for the period after January 2012 (Fig. 5) due to reservoir leakages which led to the prohibition of any storage of water in 2012–2013 to ensure dam safety. Any water entering the reservoir was sent immediately through the turbine, increasing discharge from the turbine. As a result, there was no storage functionality in the reservoir during this period. After 2013, the leakages were repaired, and the reservoir returned to its normal operating condition. Data have been available since January 2012 for Dak Mi 4, which diverts the water from Vu Gia to Thu Bon. Despite general agreement over the entire data period, the simulated discharge was lower than the observed discharge for the summer period in 2013 (Fig. 5). Furthermore, simulations for Song Con 2 underestimated dry season cumulative discharge in 2011, but improved again during the wet season. These underestimations of the simulation results can be predominantly attributed to the reservoir release constraints associated with the reservoir operation during the dry season.

5.3 Is the integrated modelling framework suitable for assessing the hydrological regime under reservoir operation?

For reservoir impact assessment, time series for either the pristine or human-impacted period are usually too short to be used for calibration. For the first time, an integrated modelling framework was applied to a data-scarce tropical mountainous mesoscale catchment to assess hydrological drought risk by using naturalized and human-impacted reconstructed streamflow and two observed discharge time series. Comparing observed, simulated, reconstructed, and naturalized discharge time series is a widely used method to assess and quantify anthropogenic impacts on streamflow (Zhang et al., 2012; Deitch et al., 2013; López-Moreno et al., 2014; Chang et al., 2015; Räsänen et al., 2017). Our softly linked model set-up shows good results in terms of statistical efficiency performances and provides reliable simulations for both reconstructed and naturalized streamflow. This applies also to the low-flow simulations and hydrological drought periods which usually pose the greatest challenges to hydrological modelling (Pilgrim et al., 1988; Nicolle et al., 2014). This method presents several advantages compared to statistics-based approaches such as Budyko curves or double mass curves. The key advantages of this approach are (1) the possibility of comparing long-term pristine and modified streamflow without relying on long-term hydropower release time series, (2) larger flexibility to account for reservoir influences at the local level, thus accurately allowing prediction of long-term influences of reservoir on streamflow, and (3) the ability to simulate and analyse scenarios dealing with changes (land use, climate, etc.) in the catchment.

Our integrated modelling approach combined with the hydrological drought analyses provided a unique and suitable set of tools to assess drought risk in a data-scarce and reservoir-impacted catchment, and can be transferred to any region where reservoirs impact downstream water availability. Existing methods are mostly able to compare the streamflow behaviour for the hydropower operations before and after their construction, especially those which were built several decades ago. Several studies used the merit of the availability of long time series data to compare before and after the construction of the hydropower reservoirs (e.g. Ye et al., 2003; Adam et al., 2007; Adam and Lettenmaier, 2008; Arrigoni et al., 2010; Ahn and Merwade, 2014; Tang et al., 2014; Zhang et al., 2015). However, without the required after-construction data, such comparative visualization and characterization of impacts become immensely challenging. Therefore, the proposed integrated model offers quantification of the impacts of newly built hydropower resources on the downstream water users and resources.

Hydropower development is growing, and as of March 2014, 3100 hydropower reservoirs with a capacity of more than 1 MW have been either planned (83 %) or are under construction (17 %) (Zarfl et al., 2015). Most of this hydropower development is concentrated in developing and emerging economies of South-east Asia, South America, and Africa, where data availability is a major issue. This method offers an opportunity to quantitatively analyse and measure the impacts of these hydropower operations at the basin scale. The understanding of our methods can be used for streamflow simulation for ensuring environmental flow of water to produce a sustainable level of food and energy production to support the growing population.

5.4 Quantification of reservoir impacts on hydrological drought

For the first time we tested the integrated hydrological modelling–drought assessment framework based on hydrological indicators, reservoir operation, and rainfall–runoff processes.

This study reveals that the intensity and frequency of hydrological drought in the entire VGTB basin are largely dependent on hydropower operation associated with the inter-basin water diversion from Dak Mi 4. Our modelling results show that drought events simulated for the human-modified catchment system are intensified by 27–37 % in the Vu Gia sub-catchment compared to those under pristine catchment conditions (Table 4). This intensification is mainly attributable to the diversion of the Vu Gia River to the Thu Bon due to Dak Mi 4 hydropower generation which controls the reservoir operation in the study region.

Part of the decreased streamflow in the Vu Gia River could be buffered by increasing reservoir release from the Dak Mi 4 reservoir. According to the technical document (MOIT, 2011), the Dak Mi 4 reservoir is required to release a minimum of 25 $m^3\ s^{-1}$, a quota which has not been met throughout most of the dry season periods. Because of the high demand for energy during the dry season, some of the water needed for the minimum release towards the Vu Gia River was used for energy production and discharge to the Thu Bon River. As a result, at Nong Son and Giao Thuy stations, the drought intensity decreased by 17 and 30 %, respectively.

We found that for the entire Thu Bon catchment, there is an increasing downstream flow during the low-flow period when we consider the reservoir effects on both river dis-

Table 4. Impact of human alterations on drought intensity and changes in flow in the VGTB for the period 1980–2013 on an annual and seasonal scale. **(a)** Drought duration is calculated based on percentage changes in the number of drought days from naturalized condition to reconstructed condition (Fig. 9). **(b)** Changes in flow (%) are calculated based on the percentage changes in the mean flow between the naturalized and reconstructed streamflows for the corresponding time frame. **(c)** The changes in flow are calculated based on mean differences of reconstructed streamflow from the naturalized mean flow. The positive value indicates increasing flow or drought intensity in relation to the naturalized condition.

		Thu Bon		Vu Gia		Combined
		Nong Son	Giao Thuy	Thanh My	Ai Nghia	
(a) Drought duration (%)		−17.17	−30.43	37.08	27.20	−1.81
(b) Changes in flow (%)	Ann	19.46	10.09	−37.82	−17.41	−13.82
	Dry	43.3	27.23	−44.67	−7.91	32.54
	Wet	10.84	3.61	−35.03	−21.10	−106.53
(c) Changes in flow (in $m^3 s^{-1}$)	Ann	51.52	38.32	−51.66	−52.14	−7.32
	Dry	45.65	42.51	−26.43	−9.97	19.31
	Wet	63.25	29.93	−102.12	−136.47	−17.48

charges (Fig. 7b and Table 4). This alleviates the general hydrological drought conditions downstream, and the seasonal amplitude of simulated streamflow tends to decrease, which also reduces downstream flood risk.

However, the impacts of reservoir operation are particularly pronounced for the more vulnerable Vu Gia River (Figs. 6–9). The Vu Gia River supplies water to the city of Da Nang and large rice irrigation systems. While Thanh My station streamflow is reduced by 51.7 $m^3 s^{-1}$, which is 37.8 % less compared to the naturalized condition, downstream at Ai Nghia station, the streamflow reduction is less severe (17.4 % less water than the naturalized condition), as it receives water from tributaries and rainfall downstream of Thanh My (Table 4). Especially during the dry season, the damping effect of reservoirs belonging to the lower sub-basins increases (i.e. Song Bung 4, 5, 6; A Vuong and Song Con) due to their energy production during the dry season (Figs. 6 and 7a).

A further relevant impact of the reservoir operation on hydrological drought is the shift of drought occurrence from summer to spring (Figs. 7 and 9). As shown in the figures illustrating the naturalized flow simulations, low flows generally occur in spring (MAM) and extend towards summer (JJA) at all stations. Figures 7 and 9 show reconstructed flow simulations and indicate more hydrological drought periods during summer. The applied threshold-level approach (Q_{90}) was able to capture the drought events (Fig. 9) in VGTB, consistent with the observed drought events for VGTB (1982, 1983, 1988, 1990, 1998, 2005, 2012, and 2013) (Nauditt et al., 2017).

Generally, reservoir operation leads to reduced runoff volumes in the rainy season and increased runoff in the dry season, and typically serves to mitigate droughts rather than contribute to their aggravation (Wada et al., 2013; Wanders and Wada, 2015; He et al., 2017; Di Baldassarre et al., 2017). We found that the overall reservoir operation at VGTB leads to an increased flow during the dry season of approximately 32.54 $m^3 s^{-1}$, which is 27.23 % more than the naturalized situation, and a decreased flow during the wet season of approximately 106.53 $m^3 s^{-1}$, which is 3.61 % less than the naturalized situation (Fig. 4). A similar pattern of streamflow changes due to hydropower operation was found in the Mekong River basin, where the dry season discharge increased by 60–90 % and the wet season discharge decreased by 17–22 % (Hoanh et al., 2010; Lauri et al., 2012; Räsänen et al., 2012).

However, due to the increased energy demand in summer, the last months of the dry season (August and September) exhibit lower streamflow values under reservoir operation than under the natural flow condition. Also, there is a lower drought risk at the beginning of the dry season, because of the additional storage in the system. At the end of the dry season, the storage is lower, which might lead to a higher likelihood of droughts. These findings on the overall impact of the reservoir operation can be transferred to other locations featuring similar climatic and topographic conditions, whereas the separate findings for the Vu Gia and Thu Bon rivers are very much influenced by the diversion at Dak Mi 4, and are therefore specific to this catchment.

5.5 Consequences of the hydrological changes

Droughts are usually assessed at a large scale and based on indices which are related to parameters such as precipitation, soil moisture, or vegetation. However, human alterations of the hydrological system and abstractions from the rivers are not incorporated into such drought analyses (Van Loon et al., 2015). A variety of anthropogenic alterations of the natural environment and river network can cause changes in downstream water availability, and these anthropogenic alterations include land cover changes, major water abstractions, and infrastructure for irrigation and drinking water supply. Nauditt et al. (2017) used varying spatial basin characteristics, such as land cover changes, to simulate low flows in the VGTB basin, and found that these only play a minor role in runoff generation processes, which are instead dominated by precipitation inputs. Therefore, it can be assumed that all the quantified changes in this study for the different temporal scales can be considered net values for reservoir operation impacts on low flow discharge.

We found that reservoirs can have multiple effects on the downstream users, particularly if they are not operated properly. In the VGTB, hydropower reservoir operation strongly alters the natural hydrological functions of the river basin. In particular, one hydropower reservoir (Dak Mi 4) generates electricity by transferring water from the drier Vu Gia sub-catchment to the wetter Thu Bon sub-catchment, due to its superior slope to produce energy (Nauditt et al., 2017). During the dry season, the combined effect of the reservoir operations at Ai Nghia and Giao Thuy (Table 4 and Fig. 7b) indicated that overall flow increases during the dry season and reduces the wet season flows. These changes resulted in dampening of VGTB's annual flood pulse. This decreased flow pattern during the flood season is expected to reduce the sediment and nutrient transport, and can affect the aquatic habitat (Pitlcik and Wilcok, 2001). The fluctuation of water supplies due to the reservoir operation degraded the river bed immediately after the turbine discharge. This degradation is typically accompanied by a coarsening of the river bed with associated loss of useable habitat for fish and benthic invertebrates (Pitlcik and Wilcok, 2001). The loss of these important habitats, combined with changes in water quality due to sediment imbalance and introduction of non-native fishes, has potentially caused long-lasting impacts on the native fish community at VGTB.

One of the major concerns is that the seasonal shift of drought occurrences, from spring (MAM) to summer (JJA), was observed at most of the stations in the VGTB. This may have impacted the VGTB's ecological productivity, which is the basis for livelihood, income, and food security for millions of people. This shift could have impacted the cropping pattern of the downstream, which relies heavily on the water during the summer season. However, the results indicated that the dry season discharge may vary considerably due to rainfall and hydropower operations. For example, in 2013, due to the low rainfall in 2012 (September–December), there was a severe shortage of water for hydropower operation during the dry season, which exacerbated the drought in the downstream for the Vu Gia catchment.

6 Conclusion

We assessed human impacts on hydrological droughts in the VGTB River basin and found that the intensity and frequency of hydrological droughts in the entire Vu Gia Thu Bon basin are largely dependent on hydropower operation associated with the Dak Mi 4 related inter-basin water diversion. Our modelling results show that drought events simulated for the human-modified catchment system were intensified by 27–37 % in the Vu Gia sub-catchment compared to the ones under pristine catchment conditions. However, when combining the overall impact of reservoir operation for the entire VGTB, we found an increase in dry season flows (ca. 27 %) and reduced flood season flows (ca. 3.5 %) compared to the naturalized condition, and a similar pattern of changes due to reservoir operation was also found in another basin in the Mekong region.

Furthermore, a seasonal shift of drought occurrence from spring (MAM) to summer (JJA) was observed, severely affecting rice cultivation as the cropping season particularly relies on the water during the spring and summer. We also identified hydropower reservoir operation impact patterns which show how energy production and demand can influence seasonality in streamflow in a tropical environment.

The multi-model framework combined with the application of a daily varying drought threshold turned out to be a suitable method to analyse human-impacted hydrological drought. To our knowledge, a distributed hydrological model such as J2000 had never been applied to such a data-scarce tropical environment. Linking the physically based model with a reservoir operation model is an effective approach to assess such a complex river system with a large number of recently built operating hydropower reservoirs and a basin transfer. In combination with the hydrological drought analysis it represents an innovative integrated framework for drought risk characterization which can be applied to any data-scarce catchment worldwide where hydropower is developed, also suitable for snowmelt-driven environments.

We conclude that the calibrated model set-up combined with the streamflow drought analysis provides a valuable tool to support cross-sectoral water management and planning in a tropical monsoon dominated region of strong seasonality.

Data availability. The model data can be accessed via the VGTB-RBIS, which is the data repository for the LUCCi research project (http://leutra.geogr.uni-jena.de/vgtbRBIS/metadata/start.php).

The Supplement related to this article is available online at https://doi.org/10.5194/hess-22-547-2018-supplement.

Competing interests. The authors declare that they have no conflict of interest.

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