Application of deterministic distributed hydrological model for large catchment: a case study at Vu Gia Thu Bon catchment, Vietnam

Ngoc Duong Vo and Philippe Gourbesville

ABSTRACT

In order to create a tool to help hydrologists and authorities to have good understanding about occurrences in stream flow regime together with its variation in the future under the impact of climate change in the Vu Gia Thu Bon catchment, a deterministic distributed hydrological model has been developed and constructed. This model covers the major processes in the hydrologic cycle including rainfall, evapotranspiration, overland flow, unsaturated flow, groundwater flow, channel flow, and their interactions. The model is calibrated and validated against the daily data recorded at seven stations during 1991–2000 and 2001–2010, respectively. The quality of results is demonstrated by Nash–Sutcliffe and correlation coefficients that reach 0.82 and 0.92, respectively, in discharge comparison. With water levels, the obtained coefficients are lower but the quality of results still remains high; Nash–Sutcliffe and correlation coefficients reach 0.77 and 0.89, respectively, in the upstream part of the catchment. This analysis demonstrates the performance of the deterministic distributed modeling approach in simulating hydrological processes one more time; it also confirms the usefulness of this model with ungauged catchments or large catchments. Additionally, this analysis proves the role of multi-calibration in increasing the accuracy of hydrological models for large catchments.

Key words | deterministic hydrological modeling, long-term simulations, multi-calibration, sensitivity analysis, Vietnam, Vu Gia Thu Bon catchment

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INTRODUCTION

Water is seen to be the premier constitutive factor of human beings. Thus, it always plays an important role in the development of human society (Gleick 1993; Watkins 2006). However, water distribution is not equal across time and space. These imbalances result in many negative impacts to human societies and activities. Annually, the natural disasters related to water issues, such as floods, droughts, and storms, produce significant severe damage, not only to property but also to human life (Johnson *et al.* 1997; Guha-sapir *et al.* 2013). Furthermore, in recent years, under the impact of climate change, the consequences of catastrophic flood and drought events have been more frequent and serious (Vázquez *et al.* 2002). Gaining a deep knowledge of the hydrological factors and processes in a catchment is an essential objective for the hydrologist community in order to be able to transform disadvantages to advantages or to mitigate catastrophic damage. Nowadays, with the development of mathematics and computer science, the simulation of the hydrological cycle for a catchment has become easier and more accurate (Blöschl & Sivapalan 1995). These improvements linked to modeling methods help hydrologists to gain more concrete and truthful insights about what happens in hydrological processes and support the decision-making process for reducing natural hazard impacts over the catchment.

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To date, many hydrological models have been developed with different theories to simulate catchments' hydrological phenomena. They may be classified according to the description of the physical process as conceptual or physically based, and according to the spatial description of catchment processes as lumped or distributed (Refsgaard 1996). Each of these models has advantages and inconveniences for simulating the hydrological process. Lumped models are simple hydrological models which assume that all characteristics are constant across the catchment (Chow 1972), such as HBV, MIKE11/NAM, TANK, TOPMODEL, XINANJIANG. Lumped parameter models are considered much simpler in their treatment of spatial variation. In this kind of model, each parameter is described by a value that is uniform over the whole catchment. The parameters of lumped models cannot be determined directly from the physical characteristics of the catchment and they are generally determined via calibration (Chow 1972; Madsen 2003). Consequently, this kind of model cannot represent all hydrological processes precisely. Alternatively, a distributed model is constructed with sub-units that represent the divided catchment. Each unit integrates and represents all physical characteristics of the real area. This kind of model maintains the physical details at a given grid size and considers the distributed nature of hydrological properties such as soil type, slope, and land use (Refsgaard 1997; Vansteenkiste *et al.* 2013). In principle, the parameters of a distributed model could be obtained from the catchment data (Refshaard *et al.* 1995). Due to this characteristic, a distributed model is supposed to be able to translate hydrological processes in a catchment more accurately and concretely. One additional advantage of a distributed model is that the outputs, such as water levels, discharges, and other hydrological variables, could be perfectly extracted at any location in the catchment (Graham & Butts 2005). These efficiencies of the distributed model help to overcome difficulties in the lack of observed data, especially in developing countries, and which have a great significance for simulating the hydrological processes in a large catchment. As a result, they can provide more accurate predictions. From these pre-eminences, many distributed models have been developed and applied in recent years, such as MIKE SHE, SWAT, SWIM, LISFLOOD, and WETSPA (Cunderlik 2003). Nevertheless, which model is the best to simulate hydrological processes according to the objectives of the water-related project, such as resource optimization or long-term perspective? Until now, this question has not been clearly answered. In fact, there exist certain arguments related to the quality of different models that the lumped models, in many cases, perform just as efficiently as distributed ones with regard to rainfall–runoff simulation when sufficient calibration data exist (Refsgaard & Knudsen 1996). Moreover, even if the distributed model has drawbacks on computation time, initial parameter definition, or lack of spatial data for setting up the model as well as validation (Beven 2011), most of the modelers greatly estimate the capacity of the distributed model over the lumped one (Beven 1996; Refsgaard & Knudsen 1996; Golmohammadi *et al.* 2014).

The Vu Gia Thu Bon is one of the largest catchments located in central Vietnam. It is annually confronted with severe damage due to natural disasters such as catastrophic flood and drought events. Furthermore, according to the prediction of the IPCC's scenario (Pachauri & Reisinger 2007), under the impact of global warming, sea level increase, changes in the hydrological cycle, abnormal phenomena, e.g., El Nino and La Nina in the Vu Gia Thu Bon basin, flood and drought disasters are forecast to happen more frequently and be more extreme. This situation will generate more severe consequences for people, livelihoods, and socio-economic development. Hence, in order to mitigate the impact of these catastrophes on the region, an efficient tool is required to help hydrologists and authorities to have a good understanding of what is happening in the stream flow regime and its potential variations in the future. For this purpose, and as outlined above, a fully deterministic distributed hydrological model – based on MIKE SHE modeling system from DHI – has been chosen to simulate the hydrological processes in the Vu Gia Thu Bon catchment. In other respects, the study also aims: (1) to confirm the performance of distributed model types to simulate the hydrological processes and the capacity to translate climate scenarios for large catchments with very limited data sets (almost an ungauged catchment); (2) to evaluate the sensitivity of model parameters; (3) to compare the calibrated efficiency of multi-site versus single-site models; and (4) to analyze the uncertainty of input data and the model structure.

VU GIA THU BON CATCHMENT

The Vu Gia Thu Bon (Figure 1), which originates on the eastern side of the Truong Son mountain range and drains to the ocean near Da Nang and Hoi An cities, is the biggest river system of the coastal province in the central region of Vietnam. This system has two main rivers, the Vu Gia and Thu Bon rivers, which flow through many complex topographies. The relatively narrow mountainous area with a maximum elevation of 2,600 m at Ngoc Linh mountain, which features a large number of steep tributaries and the flat coastal zone at the downstream, is prone to annual flooding and consists of a complex interconnected coastal river system. This system is located in a tropical monsoon climate region where weather phenomena, such as extreme rainfall events and storms, happen in a complex way. With the typical characteristics of the region, the climate pattern in the Vu Gia Thu Bon basin is influenced by Truong Son Mountain in the west, which has quite high rainfall; the average annual rainfall of this area is from 2,000 mm to 4,000 mm. Even so, it differs by season; 65–80% of the annual rainfall is during the period of September–December. The precipitation has shown increasing trends from north to south and from low to high elevation areas. Moreover, the region is annually attacked by two to four typhoons that bring huge rainfall and whirlwinds (To 2005; RETA 6470 2011). Typhoons generate inundation disasters that happen frequently and are more serious. In contrast, droughts occur frequently in the remaining months. Despite these complicated climate conditions, the hydrological monitoring network infrastructure in the basin is still underdeveloped. The density of measuring stations is sparse, especially for the rainfall and the flow gauging stations in tributaries. Although this area covers around 10,350 km^2, there are only 15 stations (Figure 1) that record rainfall data. The lack of data and data quality mean certain difficulties in forecasting natural phenomena at the present time, as well as in the future.

METHODOLOGY

Deterministic distributed hydrological model

In the many current hydrological models, a deterministic distributed model is likely to have more advantages. The

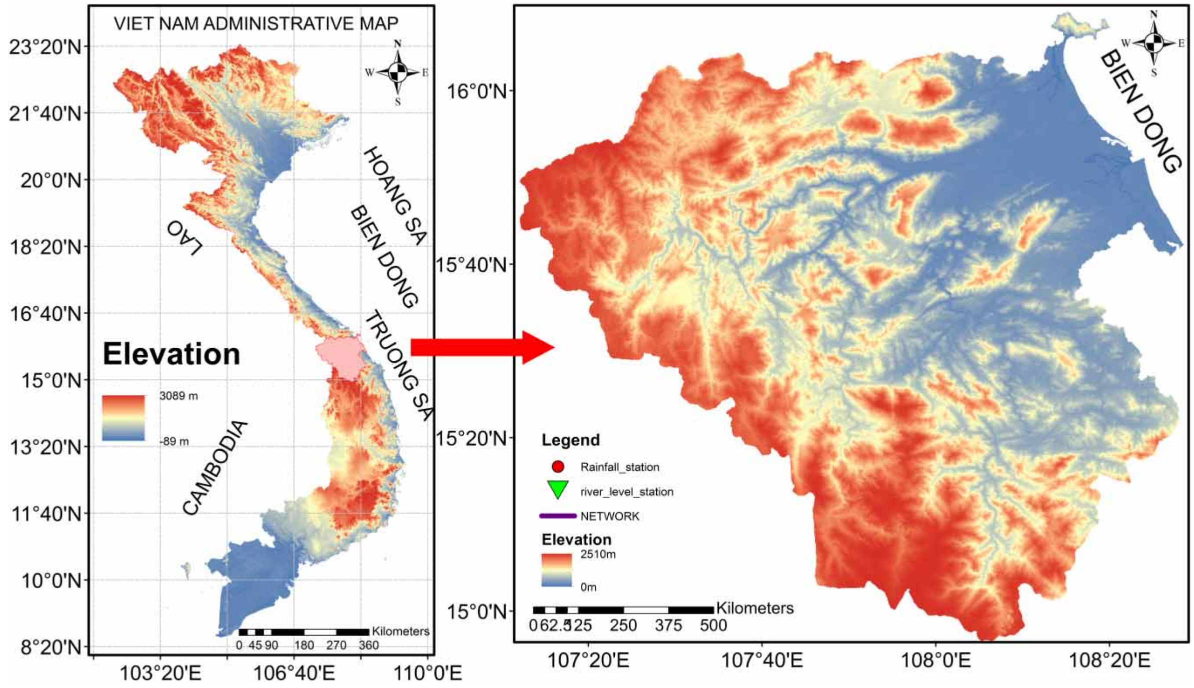

Figure 1 | Vu Gia Thu Bon catchment in central Vietnam, and hydro meteorological network.

main interest of a deterministic distributed hydrological model is to be able to provide hydrological data at any location within the catchment (Graham & Butts 2005). This possibility allows investigation, in depth, of the hydrological dynamic. Several tools are available today and could be used for such analysis. A typical model is the MIKE SHE modeling system developed and extended by DHI Water & Environment since the last decades of the 20th century (DHI 2012a). MIKE SHE covers the major processes in the hydrologic cycle and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, channel flow, and their interactions (Figure 2). Each of these processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modeling study, the availability of field data, and the modeler's choices (Butts *et al.* 2004). The representation of catchment characteristics and input data is provided through the discretization of the horizontal catchment into an orthogonal network of grid squares. In this way, spatial variability in parameters such as elevation, soil type (soil hydraulic parameters), land cover, precipitation, and potential evapotranspiration can be represented (Refshaard *et al.* 1995). Within each grid square, the vertical variations in soil and hydrogeological characteristics are described in a number of horizontal layers with variable depths. Lateral flow between grid squares occurs as either overland flow or subsurface saturated zone flow. The one-dimensional Richards' equation employed for the unsaturated zone (UZ) assumes that horizontal flow is negligible compared to vertical flow (Thompson *et al.* 2004).

Due to its performance, MIKE SHE has been used in a broad range of applications. It is being used operationally in many countries around the world by organizations ranging from universities and research centers to consulting engineering companies (Refshaard *et al.* 1995). MIKE SHE has been used for the analysis, planning, and management of a wide

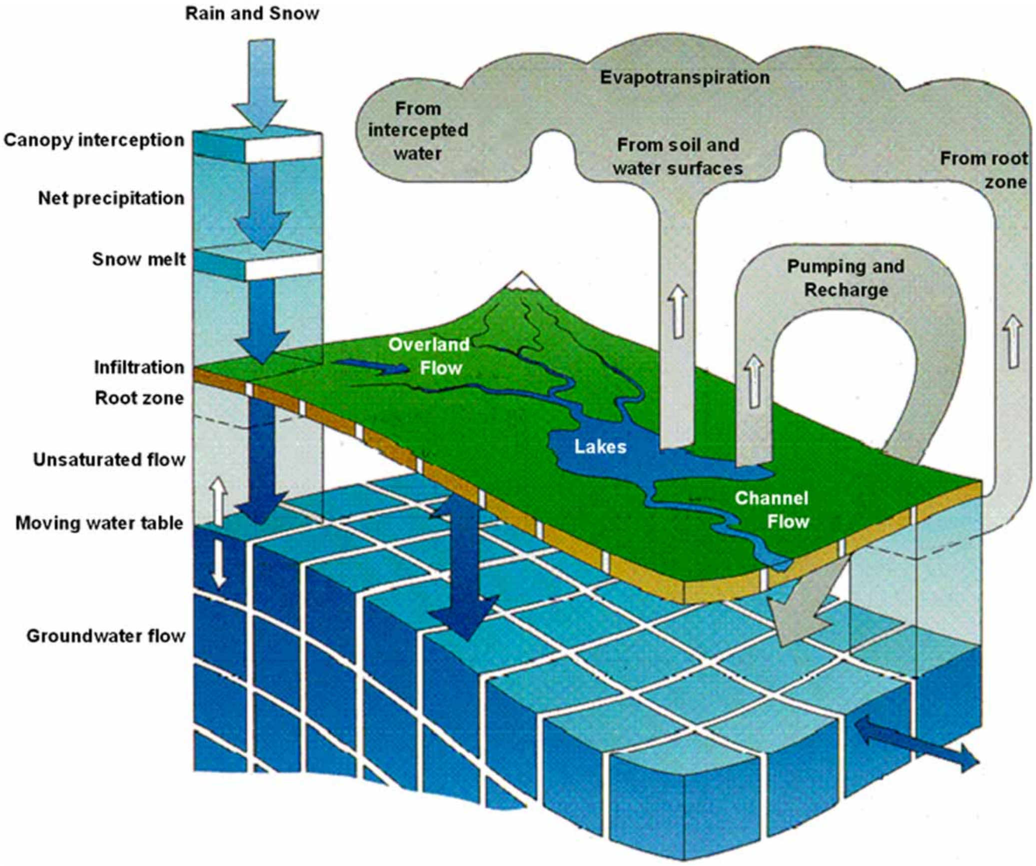

Figure 2 | Schematic of MIKE SHE model (DHI 2012a).

range of water resources and environmental and ecological problems related to surface water and groundwater, such as river basin management and planning, water supply design, management and optimization, irrigation and drainage, soil and water management, groundwater management, interaction between the water surface and ground water, ecological evaluation of flood plain studies, impact of land use and climate change. Graham & Butts (2005) applied the MIKE SHE model to simulate the hydrological process of the Senegal River Basin. This model was developed on an area of 375,000 km^2. The result was relatively representative of the catchment's characteristics with good statistical coefficients. Thompson *et al.* (2004) used this model to simulate the hydrological system in lowland wet grassland in south-east England. These authors used MIKE SHE coupled with MIKE 11 to present the hydrologic factors in Elmley Marshes catchment during 36 months. This research gave remarkable results in simulating surface flooding, groundwater, and flow in the channel. The application of the coupled MIKE SHE/MIKE 11 modeling system to the Elmley Marshes has demonstrated its potential to represent complex hydrological systems found within many wetland environments. By simulating the stream flow process at catchments ($<$100 km^2) in China and in Hawaii, USA, the works of Zhang *et al.* (2008) and Sahoo *et al.* (2006) have already proved the capacity of MIKE SHE to describe the flow in mountainous regions. Besides that, this model has a proven considerable competence in simulating the hydrological process in semi-arid areas. The study of McMichael *et al.* (2006) is an example demonstrating the above capacity of MIKE SHE. From the previous applications and regarding the specific issues in the Vu Gia Thu Bon catchment, MIKE SHE represents a reasonable alternative for hydrological modeling in a data scarcity situation. MIKE SHE is a deterministic modeling system based on physical laws. Most of the used parameters are physical variables that evolve in a range of values that can be defined according to physical processes. In such a context, realistic assumptions could be made on such variables and then allow the development of an efficient hydrological model over the large Vu Gia Thu Bon catchment. This approach has the objective of overcoming the lack of data that is a recurrent situation in many large catchments located in developing countries. The approach has already been implemented with success by Hundecha *et al.* (2002) and Ma *et al.* (2013). The developed deterministic model is supposed to provide a reasonably accurate estimation of the hydrological processes under the current climate conditions, and then to be used for assessing the impacts of the climate dynamic under various scenarios that define future conditions.

Input data and model setup

The MIKE SHE model is built with all of the available model components, e.g., overland flow, river and lake, unsaturated flow, evapotranspiration, and saturated flow (Figure 2). As a result, the model is expected to describe accurately hydrological processes in the Vu Gia Thu Bon catchment as well as to reduce the uncertainty when simulating future climate scenarios. The following data sets have been used.

Topography

The elevation data used in the model are taken from SRTM DEM (digital elevation model) with a horizontal resolution of 90 m from NASA (Figure 1) (http://www.cgiar-csi.org).

Precipitations

By analyzing the effect of spatial rainfall distribution on the stream flow, the study of Vo & Gourbesville (2014) showed that Kriging is the most suitable method to interpolate the rainfall distribution in this catchment. Hence, the simulations use rainfall data that are re-distributed spatially based on daily rainfall data from 15 rain gauge stations with the Kriging method. Unfortunately, no hourly data are available over the catchment. However, due to the size of the catchment – 10,350 km^2 – and of the different tributaries, the concentration times are always above 24 hours and up to 48 hours. The scale of the catchment contributes to reducing the underestimation of the high intensities that is the main difficulty with the daily data. At the same time, the planned application of the model is dedicated to addressing flooding processes and changes at the catchment scale. The quick hydrological processes are not the priority of the approach. The available data can match this objective knowing that the discharges and water level are recorded with more accurate time steps.

Evapotranspiration

Data are inherited from the study of Vu *et al.* (2008) .These authors calculated the potential evapotranspiration in the Nong Son basin by using the Penman–Monteith equation. A monthly mean potential evapotranspiration for each vegetation type and average over the catchment were constructed.

Land use and soil map

The land use and soil data are simplified from the data of the Land Use and Climate Change Interaction in Central Vietnam (LUCCI) project and the Impacts of Climate Change in Mid-Central Vietnam (P1-08 VIE) project. The input data are defined with five types of soil (Figure 3(a)) and nine types of land use (Figure 3(b)).

Vegetation

The harvest schedule is set up for main plant types such as forest, homestead, rice, sugarcane, and grass. Each kind of crop is specified by vegetation property. The vegetation property in this simulation is from DHI results (DHI 2012a).

River and lakes

In order to simulate the river flows better, the MIKE SHE model is coupled with a hydrodynamic MIKE 11 model (1D model). The model is developed over 44 major branches with a length varying from 20 to 202 km (Figure 3(c)). The geometry of each river branch is specified via cross sections. The cross sections applied in this model are from two sources: a few of them downstream are taken from the measurements, and the remaining ones are extracted from the DEM. The initial bed resistance is set up with a Stickler roughness coefficient (M) varying from 15 to 25 $m^{1/3}/s$ for upstream tributaries, and a value changing from 30 to 50 $m^{1/3}/s$ for downstream branches.

Overland flow

The overland flow appears after the net rainfall rate exceeds the infiltration capacity of the soil; water then ponds on the ground surface. The main parameter to calculate this flow is the Stickler roughness coefficient (M). For Vu Gia Thu Bon, this parameter is determined depending on the land use map and at 2–90 $m^{1/3}/s$ (Vieux 2001; Nguyen 2005a, 2005b; DHI 2012b).

Unsaturated zone

DHI suggested three methods for describing the flow in this zone: Richards' equation, gravity flow and two-layer UZ. However, the application demonstrates that the various approaches do not provide very different results. For the current application, the simple two-layer water balance method is chosen to reduce the computational time. The physical property of each soil type is presented via the water content

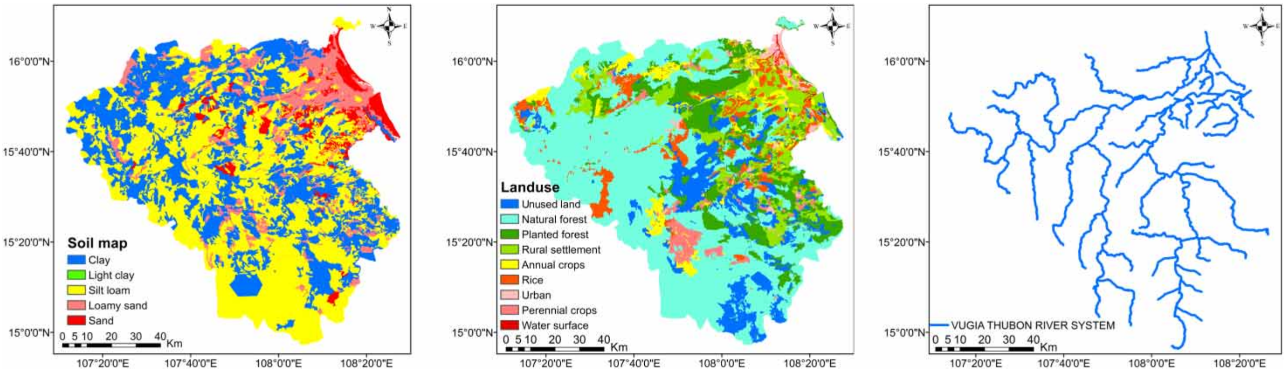

Figure 3 | (a) Soil map, (b) land use, and (c) river network at Vu Gia Thu Bon catchment (left to right, respectively).

at saturation, water content at field capacity, water content at wilting point, and saturated hydraulic conductivity.

Saturated zone

The groundwater is supplied by the Central Vietnam Division of Water Resources Planning and Investigation (http://www.ceviwrpi.gov.vn). The characteristic of the aquifer is mainly presented by horizontal hydraulic and vertical hydraulic conductivities.

Sensitivity analysis, calibration, and validation

In principle, the parameters of a distributed hydrological model should be assessable from catchment data (Refshaard *et al.* 1995), but this principle is partly invalid when the model is developed for a large catchment and due to potential scale effects. Owing to inaccurate input data as well as coarse simulated resolution, the distributed model could not represent precisely the physical property of the catchment at each point (Gurtz *et al.* 1999). These limitations lead to a reduction in the simulated performance of the model. In order to improve the weaknesses, a calibration process is required in order to find an optimal set of parameter values that simulates the behavior of the watershed as accurately as possible (Cunge 2003; Guinot & Gourbesville 2003). Calibrating a fully distributed model, which consists of many components and mutually dependent parameters, is a really complex task. It requires modelers to attach special importance to the various parameters even if these factors have an insignificant influence on the hydrographs. Nevertheless, in order to achieve consistent results, the calibration procedure with MIKE SHE has to be implemented according to an incremental approach based on a reduced set of parameters as developed by Refshaard *et al.* (1995). As mentioned by Guinot & Gourbesville (2003), variables do not have an equal contribution within the performance of the model, and calibration has to target first the most significant variables such as topography representation (DEM). These variables are decided in order to rely on the results of the sensitivity analysis process. As well, and in order to ensure a relevant choice, the elasticity analysis or sensitivity ratio (Equation (1)), which has been applied in many different models in science, engineering, and economics for sensitivity analysis, is performed to exhibit more clearly the level of influence of each parameter towards river flow (EPA 2001; Maidment & Hoogerwerf 2002):

$$\mathrm{SR} = \frac{((\mathrm{Y}_2 - \mathrm{Y}_1)/\mathrm{Y}_1) \times 100\%}{((\mathrm{X}_2 - \mathrm{X}_1)/\mathrm{X}_1) \times 100\%} \tag{1}$$

where Y_1: the baseline value of the output variable using baseline values of input variables; Y_2: the value of the output variable after changing the value of one input variable; X_1: the baseline point estimate for an input variable; X_2: the value of the input variable after changing X_1.

In addition, the sensitivity analysis quantifies the dependent rate of runoff on the change of these parameters. As a result, these rates make the calibration easier and allow acceptable values to be more quickly obtained. It is seen to be a prior step to the calibration process. For the model applied to the Vu Gia Thu Bon catchment, the sensitivity of each parameter is analyzed based on the response of discharge in the Nong Son and Thanh My stations. In such a complex system as hydrology, the implication of the change in magnitude of several model parameters due to other parameters is undeniable (Sivapalan *et al.* 1987; Muleta & Nicklow 2005; Wang *et al.* 2007). It is clear that the sensitivity analysis will be better when accounting for the interactions between model parameters (Mishra 2009). However, with a model containing many parameters such as the MIKE SHE model applied to a large catchment, the evaluation of the interaction between model parameters during the sensitivity analysis is complicated and requires many simulations. In this analysis, the sensitivity analysis was done manually by varying the values of the parameters individually, one by one. This method has been applied by many authors (Refsgaard 1997; Andersen *et al.* 2001; Wang *et al.* 2012). The model is set up for a long period, even so the sensitivity analysis process is only based on the runoff variation during the period of two typical years, 2003 for the 'dry year' and 2004 for the 'wet/flood year'. The parameter sensitivity is demonstrated via the variation tendency of the base flow and peak flow at the Vu Gia Thu Bon river system. Subsequently, the result of this process is expected to provide valuable information for the calibration process.

The available data over the Vu Gia Thu Bon cover the 1990–2010 period. The chosen strategy for calibration and validation has to be implemented within this period. The first period of 11 years from 1990 to 2000 is used for calibration. Over these 11 years, the recorded climate situations include two major flood events – 1996 and 1999 – with a return period of 100 years (ICEM 2008) and severe drought events in 1992–1993 and 1998 (Vu *et al.* 2014), as well as a moderate drought event in 1998 (Nguyen 2005a, 2005b). For the validation phase, the 11 year period from 2000 to 2010 also includes two major flood events – 2007, with a return period of 100 years; 2009, with a return period of 20 years (Chau *et al.* 2015); and a moderate drought event in 2002 (Nguyen 2005a, 2005b). The two periods allow analysis of the hydrological dynamic at the catchment scale and ensure representative results. Obviously, the availability of data – lack of measurements – is a serious constraint, but the proposed approach tries to overcome the difficulty by maximizing information production from the available data. In order to stabilize the model and establish proper initial conditions, the first year of each period is used for warming up the model. Hence, in this analysis, only 10 years of daily data are taken to calibrate and validate the model. The calibration is done manually. This process, of course, is based on the results of the sensitivity analysis. Only a few sensible model parameters are used for the calibration process.

The Vu Gia Thu Bon catchment has a complicated river system. Although the length of the two main rivers reaches 200 km, there is only one flow measuring station in the middle of each main river: Nong Son on the Thu Bon branch and Thanh My on the Vu Gia branch. This situation creates several difficulties for comparison of the results between simulations and observations. Especially, this is not only an inconvenience for predicting flood risk in the downstream region, but it is also a factor that produces uncertainty when assessing the impact of climate change on runoff. The lack of observation data for comparing with simulation results degrades the performance of the distributed model. Many hydrologists have suggested realizing calibration by multi-site, with not only the discharges but also the water levels (Wang *et al.* 2012). Accordingly, the water level at Ai Nghia station, Cam Le Station on the Vu Gia branch and Hiep Duc, Giao Thuy, Cau Lau stations on the Thu Bon branch are also compared with the MIKE SHE model outputs in order to increase the confidence and simultaneously to reduce the uncertainty in the projected climate scenario. The model assessment is performed with statistical measures of the root mean squared error (RMSE) (Equation (2)), the correlation coefficient (R) (Equation (3)), and Nash–Sutcliffe coefficient (E) (Equation (4)). The smaller the RMSE value is, the higher the model performance will reach. The perfect value of RMSE is 0 (Moriasi *et al.* 2007). The performance levels of R and E are classified in Table 1. The optimal values of these two factors are all 1 (Safari *et al.* 2012; Wang *et al.* 2012).

On the other hand, to evaluate the accuracy of simulation on the aspect of distributing extreme peak flow and low flow values, Willems has developed a tool to improve the performance of the model by using graphical goodness of fit plots: the WETSPRO method (Willems 2009). This comparison method is expected to increase the confidence in the simulation via scatterplot and extreme value distribution of peak flow and base flow. In the analysis, this method is used to assess the capacity of MIKE SHE to properly reproduce peak flow and low flow at the Nong Son and Thanh My stations:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{model,i}\right)^2}{n}} \tag{2}$$

$$R = \frac{\sum_{i=1}^{n}\left(X_{obs,i} - \bar{X}_{obs}\right)\cdot\left(X_{model,i} - \bar{X}_{model}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_{obs,i} - \bar{X}_{obs}\right)^2 \cdot \sum_{i=1}^{n}\left(X_{model,i} - \bar{X}_{model}\right)^2}} \tag{3}$$

$$E = 1 - \frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{model,i}\right)^2}{\sum_{i=1}^{n}\left(X_{obs,i} - \bar{X}_{obs}\right)^2} \tag{4}$$

where X_{obs} is observed value and X_{model} is modeled value at time/place i.

Table 1 | Performance criteria for model evaluation (Wang *et al.* 2012)

Performance indicator	Excellent	Good	Fair	Poor
E	>0.85	0.65–0.85	0.5–0.65	<0.5
R	>0.95	0.85–0.95	0.75–0.85	<0.75

RESULTS AND DISCUSSION

Sensitivity analysis

Most of the parameters in Vu Gia Thu Bon's MIKE SHE model are analyzed in order to estimate the runoff response. The results demonstrate the effects of the parameters on the simulated stream flows. These effects are not similar for all parameters. The results show that the difference is not only about the quantity but also about the timing of the peaks. The responses of river flow versus the variation of main parameters are shown in Table 2.

Parameters for the precipitation-dependent time step control are put forward to reduce the numerical instabilities (DHI 2012b). These parameters define the maximum rainfall value per time step and they are expected to have a great impact on river flows, at least on peak flows. In fact, the sensitivity analysis results in Table 2 demonstrate the role of these factors to peak flow. Accordingly, if the Max precipitation depth per time step ($P_{\mathrm{Max\ depth}}$) increases, the peak flow will reduce. For the Vu Gia Thu Bon catchment, the reduced quantity is around 70–120 $\mathrm{m^3/s}$ for an increase from 10 to 200 mm for $P_{\mathrm{Max\ depth}}$. This tendency happens similarly with Input precipitation rate requiring its own time step ($P_{\mathrm{Input\ rate}}$). However, the impact of $P_{\mathrm{Input\ rate}}$ on runoff is not as high as the $P_{\mathrm{Max\ depth}}$. The increase of this factor from 0.1 to 10 mm/h leads to a reduction of around 20–50 $\mathrm{m^3/s}$ of peak flow at the catchment. An important aspect for this factor is related to simulation time. The smaller $P_{\mathrm{Input\ rate}}$ is, the longer the model is running. Regarding the correlation between the Nong Son and Thanh My stations in connection with precipitation parameters, the results show that change at the Nong Son station is generally two times higher compared to the Thanh My station. This difference might be related to the characteristics of the catchment.

Overland flow simulates the movement of ponded surface water across the topography. It can be used for calculating flow on a flood plain or runoff to streams (DHI 2012b). In this case, the finite difference method is selected to solve the overland flow for the Vu Gia Thu Bon catchment. The Manning number (M), which is equivalent to the Stickler roughness coefficient, is estimated as the basic factor of the Overland flow module. Therefore, this part considers mostly the effects of the Manning number on runoff. In the Vu Gia Thu Bon catchment, there are many kinds of land use and soil. These lead to there being many corresponding Manning values. The effect of different Manning parameters corresponding to different land use types regarding river runoff is expected not to be equal. The disparity is due to the diversity in Manning values and distribution of land use. The difference is shown in Table 2. Nevertheless, there is one common point, that the change in Manning value greatly affects the peak flow, but mostly does not affect the base one.

The Manning number (M) is used to represent bed resistance in MIKE 11 as well. The river flow seems quite sensitive to the change in the bed resistance. It is expected to be the key factor in the calibration process. Nevertheless, in the Vu Gia Thu Bon catchment, it seems that the bed resistance only affects flood flow, specifically the peak flow is significantly impacted in the interval of Manning values from 5 to 10 $\mathrm{m^{1/3}/s}$. If the M value changes in this interval, the peak discharge could rise to 200 $\mathrm{m^3/s}$ at Thanh My and 400 $\mathrm{m^3/s}$ at Nong Son. The flow apparently does not change if the Manning value in MIKE 11 is higher than 10 $\mathrm{m^{1/3}/s}$.

The unsaturated zone is usually heterogeneous and characterized by cyclic fluctuations in the soil moisture as water is replenished by rainfall and removed by evapotranspiration and recharge to the groundwater table. Hence, this process plays a significant role in river runoff. Correspondingly, the variation of parameters in the unsaturated zone will deeply impact the runoff factor, on both base flow and peak flow. For simulating the unsaturated zone of the Vu Gia Thu Bon catchment, the two-layer UZ soil method is used. In this model, the physical characteristics of each soil are supplied, such as water content at saturation, at field capacity, at wilting point, and saturated hydraulic conductivity, yet only saturated hydraulic conductivity (K_{uz}) has a huge impact on the flow. The response of flow versus the K_{uz} variation is expressed in Table 2. According to this table, the peak flow goes down quite quickly when increasing the typical infiltration parameter. This change can reach more than 1,000 $\mathrm{m^3/s}$. Furthermore, the reduction of K_{uz} also makes the base flow decrease. The response of the base flow is small, around 10–20 $\mathrm{m^3/s}$, but it has a big

Table 2 | Response of stream flow versus the change in MIKE SHE model parameters at the Vu Gia Thu Bon catchment

					Thanh My		**Nong Son**	
Module	**Type**	**Parameter**		**Unit**	**Δbase flow**	**Δpeak flow**	**Δbase flow**	**Δpeak flow**
(a)								
Overland	Natural forest	M	1	$m^{(1/3)}/s$				
			5		1.83	190.16	0.98	26.4
			10		0.61	13.42	0.69	63.53
			20		0.88	32.73	0.88	−69.54
			50		0.42	11.88	0.29	−14.45
	Planted forest	M	1	$m^{(1/3)}/s$				
			5		0.22	−15.66	1.57	95.25
			10		0.14	5.58	0.5	21.18
			20		0.12	3.1	0.48	20.13
			50		0.12	2.94	0.46	13.58
	Unused land	M	1	$m^{(1/3)}/s$				
			5		0.04	3.85	0.67	49.74
			10		0.02	1.48	0.25	5.39
			20		−0.02	0.15	0.14	4.33
			50		0.01	−0.22	0.13	0.44
	Rural settlement	M	1	$m^{(1/3)}/s$				
			5		0.47	26.57	0.43	119.79
			10		0.15	−1.9	0.18	25.34
			20		0.13	−0.93	0.14	16.28
			50		0.18	4.1	0.21	12.6
River flow	Bed	M	5	$m^{(1/3)}/s$				
			10		−0.22	236.22	−11.49	389.39
			20		0	−0.01	0.01	−9.61
			30		0	0.01	−0.01	9.61
			40		0	0	0	0
Simulation parameters	Precipitation dependent time step control	$P_{\text{Max depth}}$	10	mm				
			20		−0.03	−4.36	−0.14	−10.33
			50		0.18	−5.78	−0.22	−14.46
			100		0.23	−35.58	−0.21	−72.3
			200		0.17	−10.81	0.14	−28.59
		$P_{\text{Input rate}}$	0.1	mm per hour				
			1		0.23	−6.96	0.22	−11.9
			2		0.2	−1.24	0.18	−6.52
			5		0.08	−12.15	−0.24	−13.51
			10		0.2	2.43	0.03	−20.19
(b)								
Unsaturated	Clay	K_{uz}	$1e^{-09}$	m/s				
			$1e^{-08}$		−2.18	−17.46	−3.45	−53.39
			$1e^{-07}$		−4.84	−66.43	−6.69	−166.38
			$1e^{-06}$		−3.87	−280.98	−5.7	−332.43
			$1e^{-05}$		−3.27	−476.99	−4.34	−592.19
	Light clay	K_{uz}	$1e^{-08}$	m/s				
			$1e^{-07}$		−0.42	−2.87	−0.47	−2.86
			$1e^{-06}$		−0.34	−18.35	−0.08	−6.81
			$1e^{-05}$		−0.18	−29.19	−0.26	−17.95
			$1e^{-04}$		−0.02	4.46	0.03	17.44

(*continued*)

Table 2 | continued

					Thanh My		**Nong Son**	
Module	**Type**	**Parameter**		**Unit**	**Δbase flow**	**Δpeak flow**	**Δbase flow**	**Δpeak flow**
	Silt loam	K_{uz}	$1e^{-07}$	m/s				
			$5e^{-07}$		−3.69	−249.9	−7.22	−428.98
			$1e^{-06}$		−5.34	−317.53	−7.1	−459.5
			$5e^{-06}$		−9.8	−1,321.32	−14.28	−1,648.9
			$1e^{-05}$		−0.65	−132.79	−1.9	−494.44
	Loamy sand	K_{uz}	$1e^{-08}$	m/s				
			$1e^{-07}$		−0.17	−7.1	−0.92	−9.21
			$1e^{-06}$		−2.16	−89.13	−1.83	−114.61
			$5e^{-06}$		−1.12	−194.24	−1.19	−213.99
			$1e^{-05}$		−0.17	−39.17	−0.31	−65.52
	Sand	K_{uz}	$1e^{-08}$	m/s				
			$1e^{-07}$		0	0	−0.07	−0.57
			$1e^{-06}$		0	0.02	−0.24	−5.13
			$1e^{-05}$		0	−0.01	−0.13	−3.74
			$1e^{-04}$		0	0	0	0
Saturated	Aquifer	K_h	$1e^{-05}$	m/s				
			$2e^{-05}$		7.5	−169.43	12.45	−55.98
			$4e^{-05}$		11.23	−104.78	18.68	−82.65
			$6e^{-05}$		7.15	−92.3	12.46	−168.03
			$8e^{-05}$		4.7	−98.18	8.69	−99.1

value in comparison with observed base flows. With variation in soil distribution, the change in the amount of runoff against soil property variation in Thanh My and Nong Son is very different, as presented in Table 2.

The groundwater plays a crucial role in the behavior of hydrological processes within the catchment. Thus, the variation of this component will significantly influence the river flow, especially the base flow when the discharge from groundwater is seen as its principal source. The groundwater is present in the saturated zone. The flow in the saturated zone is characterized by aquifer properties, of which horizontal saturated hydraulic conductivity (K_h) proves the most influential on saturated flow. For this reason, in the model only this factor is considered. For Vu Gia Thu Bon, the results in Table 2 demonstrate the primary impact of this factor on peak flow. The peak flow tends to reduce quickly when increasing K_h. The reduction is very clear, so when K_h rises from $1e^{-5}$ to $8e^{-5}$ m/s, the runoff goes down around 500 m^3/s at both the Thanh My and Nong Son stations. In contrast, K_h increases in the interval of $1e^{-5}$ to $8e^{-5}$ m/s, making the base flow rise by approximately 30 m^3/s at Thanh My and 50 m^3/s at Nong Son. In spite of the insignificant variation, it is quite important for adjusting the base flow.

Eventually, the different responses of flow factors due to the input parameters are compared to each other by the elasticity ranking in Figure 4. Following the above analysis, the saturated hydraulic conductivity of the saturated zone is the first factor that modelers need to notice when playing with base flow. As well, it is necessary to consider the role of the saturated hydraulic conductivity of clay, silt loam in the unsaturated zone towards the low flow component. The impact of these parameters on base flow discharge is not high but it is big enough to help get a better result. As there are not many parameters affecting base flow, the suggestion is 'try to calibrate base flow first before doing this process with peak flow'. Conversely, the peak discharge is affected by most of

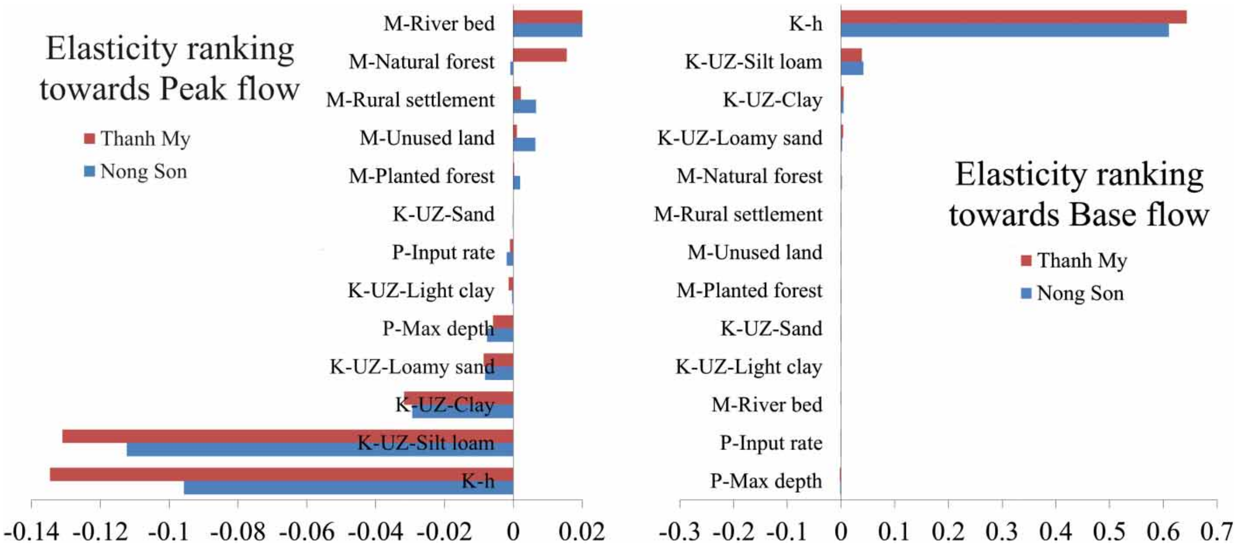

Figure 4 | Elasticity ranking of peak and base flow due to the input parameter changes.

the parameters. The change quantity of the peak is affected by the parameter and sub-catchment. Importantly, the interaction between these parameters with runoff might be considered for obtaining a better simulation.

Calibration and validation

MIKE SHE mode parameter values are varied based on the above sensitivity analysis. The optimal values reached from the calibrated process are shown in Table 3.

Hydrographs in Figure 5 demonstrate that the model simulates relatively accurately the runoff in the Vu Gia Thu Bon catchment. Simulated base flows at the two stations Nong Son and Thanh My are similar to the measurements. However, it seems that the peak of sub-main flood is not presented well. The quality of observation data may cause this limitation. In the dry season, the data in these two stations are only captured once or twice per day, so could not present precisely the time of the sub-main flood appearance. It is really difficult to overcome the problem of missing data, so the simulated base flow might be acceptable. Following the hydrographs, peak floods are almost the same as the observation data. Occasionally, some peaks are higher than in reality, but the difference is not very great and is reasonably acceptable. In theory, this problem could be completely controlled. This issue seems uncomplicated in the simulation for a

Table 3 | Calibrated parameter values of MIKE SHE model

Key parameter	**Unit**	**Optimal value**
River bed resistance – Strickler coefficient		
Tributary and upstream of Vu Gia	$m^{(1/3)}/s$	18
Tributary and upstream of Thu Bon	$m^{(1/3)}/s$	25
Linking branch	$m^{(1/3)}/s$	30
Downstream	$m^{(1/3)}/s$	40
Overland flow – Strickler coefficient		
Planted forest	$m^{(1/3)}/s$	5
Rural settlement	$m^{(1/3)}/s$	8
Rice	$m^{(1/3)}/s$	16
Annual crops	$m^{(1/3)}/s$	8
Perennial crops	$m^{(1/3)}/s$	8
Unused land	$m^{(1/3)}/s$	5
Natural forest	$m^{(1/3)}/s$	2
Urban	$m^{(1/3)}/s$	90
Water surface	$m^{(1/3)}/s$	33
Unsaturated flow – soil property		
K_{uz}-clay	m/s	$1.2\ 10^{-8}$
K_{uz}-silt loam	m/s	$2.45\ 10^{-6}$
K_{uz}-loamy sand	m/s	$8.5\ 10^{-6}$
K_{uz}-light clay	m/s	$2.085\ 10^{-4}$
K_{uz}-sand	m/s	$2.89\ 10^{-4}$
Saturated zone		
K_h – horizontal hydraulic conductivity	m/s	$6.7\ 10^{-5}$

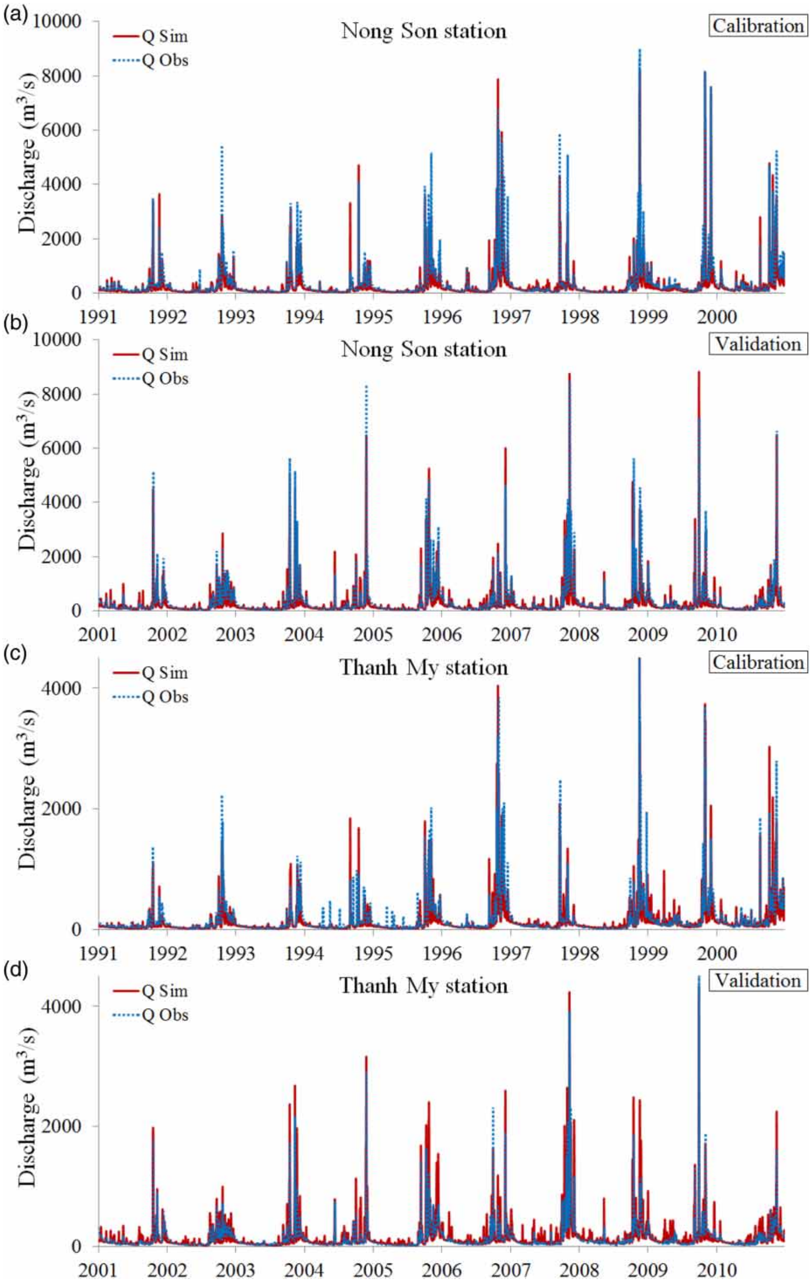

Figure 5 | Calibrated and validated hydrographs of discharge.

small area and a short time. However, for 10 year simulation in a large area, and a model containing many parameters as in this case, gaining a perfect result is really unrealizable. It is necessary to take more time to analyze and adjust parameters. One of the key questions is related to the definition of an acceptable result. Obviously the modeler has to define the expected quality of the results in order to stop the calibration process and the model refinement procedure. This procedure requires careful balance during the calibration process (Cunge 2003; Sahoo *et al.* 2006). Furthermore, the greater accuracy of the MIKE SHE model in describing the runoff in the dry season than the flood season might be understandable under the data aspect. The base flow is mainly composed of groundwater, so this component is not so dependent on data factors, such as rainfall. Therefore, this component of runoff is more stable over a long time and closer to the measurement if the model is set well. In contrast, peak flow is influenced by many factors of the hydrological process, such as overland flow, unsaturated flow, groundwater flow, channel flow, evaporation, and particularly the rainfall data. The time step of rainfall data input has a huge impact on concentration time, specifically to the time the peak discharge appears (Dendy 1987). For this reason, the rainfall data input using a large step might be the main cause of the differences in peak discharge in this MIKE SHE model, which uses daily rainfall input. The acceptability of this model can be explained by the safety aspect. Based on this aspect, the little overestimation of the model in the wet season might increase the safety when simulating extreme flood events. The quality of this simulation is affirmed through the validated period. The flow in 10 years is regenerated approximately with the observation (Figure 5).

The efficiency of the MIKE SHE model is also shown through the statistical coefficients in Table 4. Observed and simulated daily and monthly discharges are compared. These numbers demonstrate the accuracy of the model and its efficiency for describing the hydrological processes of the Vu Gia Thu Bon catchment. The R and E coefficients at Nong Son and Thanh My for the calibration period are 0.92, 0.89 and 0.82, 0.78, respectively. In the validation period, these factors slightly decrease. R and E coefficients at Nong Son station are 0.92 and 0.82 and at Thanh My, 0.90 and 0.69. The RMSE coefficients at Nong Son and Thanh My in both periods are relatively small. Over the 10 year period, the RMSE of simulation is only 132.3 m^3/s at Thanh My versus maximum observation 4,440 m^3/s–minimum observation 12.2 m^3/s. The value at Nong Son is 288.7 m^3/s versus maximum observation 8,920 m^3/s–minimum observation 21.7 m^3/s. The RMSE of validation at Thanh My is 123.2 m^3/s versus maximum observation 4,540 m^3/s–minimum observation 20.2 m^3/s and at Nong Son is 250.5 m^3/s versus maximum observation 8,410 m^3/s–minimum observation 21.9 m^3/s. Due to these big differences between maximum and minimum values of observed data, the values of the normalized root mean square error at these stations are quite small, with a value below 0.05. For the monthly analysis, the good performance of the model is obviously demonstrated by the figures in Table 4.

Figure 6(a) shows the comparison plot of maximum value at Nong Son in the calibrated period, which has relatively high scatter, yet simulated peak flows are almost concentrated in the interval of the mean±standard deviations and zero bias. These trends happen in a similar way to the Thanh My station; however, at Thanh My, the pilot (Figure 7(a)) shows a negative bias. The bisector line, situated higher than the others, expresses the peak discharge at Thanh My as being underestimated; even so this disparity is quite small. These comparisons demonstrate again the model performance in translating high values of runoff. Furthermore, it is easy to recognize the efficiency of the model via the frequency comparison. Figure 8 shows strongly the capacity of the model in simulating the peak discharge value. The simulated and observed discharge values corresponding to the return period of Thanh My and Nong Son

Table 4 | Statistical indices of the MIKE SHE model in the Vu Gia Thu Bon catchment

		Calibration (1991–2000)						**Validation (2001–2010)**					
		Daily			**Monthly**			**Daily**			**Monthly**		
	Station	**RMSE**	**R**	**E**	**RMSE**	**R**	**E**	**RMSE**	**R**	**E**	**RMSE**	**R**	**E**
Water level (m)	Thanh My	0.77	0.86	0.67	0.52	0.97	0.77	0.68	0.83	0.61	0.32	0.94	0.86
	Ai Nghia	0.70	0.81	0.63	0.41	0.96	0.81	0.66	0.78	0.56	0.35	0.94	0.83
	Cam le	0.26	0.83	0.12	0.18	0.94	0.32	0.28	0.8	−0.46	0.2	0.94	−0.13
	HiepDuc	0.77	0.89	0.77	0.44	0.97	0.88	0.91	0.83	0.59	0.63	0.92	0.67
	Nong Son	0.89	0.88	0.76	0.49	0.97	0,89	0.84	0.86	0.72	0.42	0.96	0.89
	Giao Thuy	0.85	0.85	0.61	0.6	0.97	0.73	0.73	0.82	0.6	0.4	0.95	0.82
	Cau Lau	0.44	0.84	0.56	0.16	0.96	0.9	0.47	0.83	0.16	0.2	0.97	0.25
Discharge (m^3/s)	Thanh My	132.3	0.89	0.78	58.06	0.96	0.89	123.2	0.9	0.69	47.03	0.96	0.87
	Nong Son	288.7	0.92	0.82	160.4	0.97	0.86	250.5	0.91	0.82	131.04	0.97	0.87

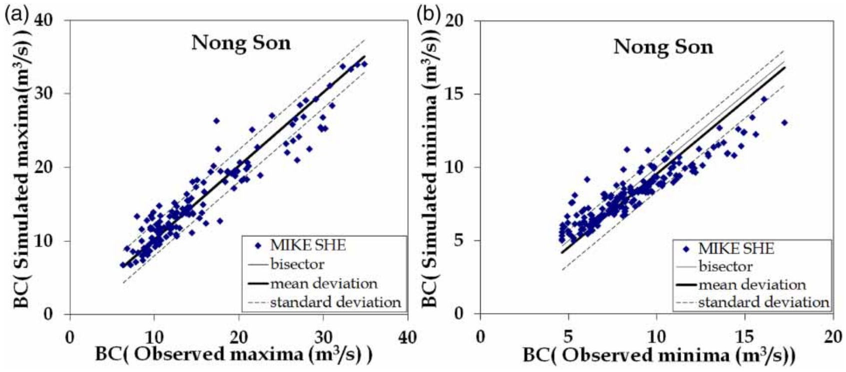

Figure 6 | MIKE SHE calibration versus observed nearly independent daily peak flow (a) and low flow (b) at the Nong Son station after Box–Cox transformation ($\lambda = 0.25$).

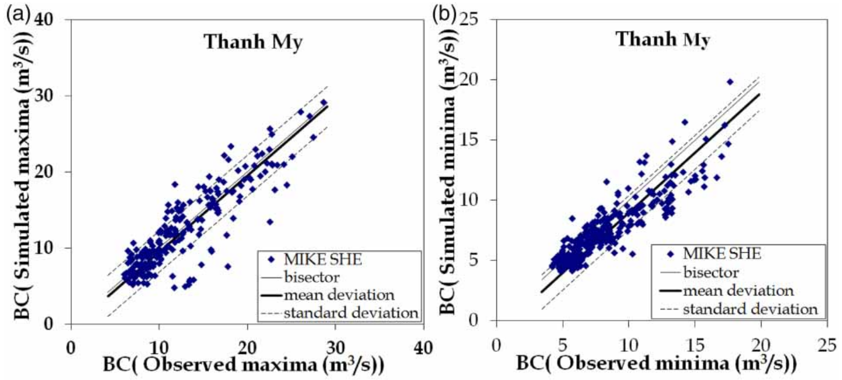

Figure 7 | MIKE SHE calibration versus observed nearly independent daily peak flow (a) and low flow (b) at the Thanh My station after Box–Cox transformation ($\lambda = 0.25$).

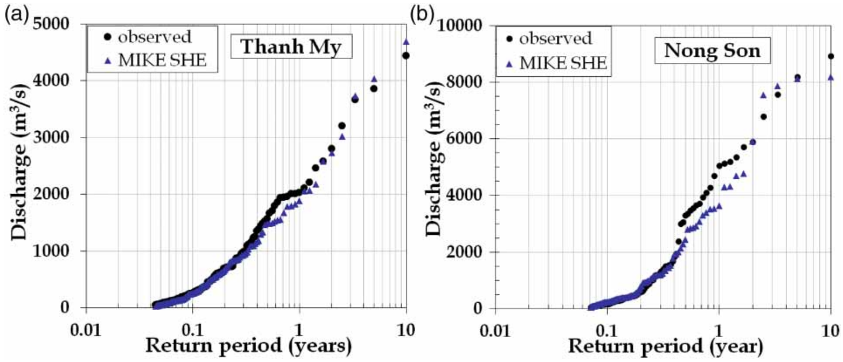

Figure 8 | The difference of peak flow empirical extreme value distributions between calibration and observation at Thanh My (a) and Nong Son (b).

are mostly similar. These analyses demonstrate the performance of the MIKE SHE model to simulate the peak discharge for this catchment.

Conversely, Figures 6(b) and 7(b) show the low flow values of simulation are distributed in a more dispersed manner than peak flow. Even though simulated low flows are mostly in the interval of the mean±standard deviations, they present a big negative bias. These negative values point to the underestimated trend of this MIKE SHE model with low flow. The trend occurred in a similar way at both stations, Thanh My and Nong Son. The low flow underestimation is also confirmed by the frequency comparison at the

Nong Son station (Figure 9(b)). In the case of the Thanh My station, the difference between observed and simulated frequencies is reduced (Figure 9(a)). Vansteenkiste *et al.* (2014) mentioned that the underestimation of most of the extreme low flows might be of high importance given that they point towards stronger underestimations for drier conditions.

Calibration and validation with water levels

In order to verify the efficiency of the MIKE SHE model for the Vu Gia Thu Bon catchment, the water levels recorded at several stations are compared with the results. However, the accuracy of simulated water levels is not as good as for discharges. Due to these differences, the statistical coefficients for water level comparison between simulation and measurements are not as high as the ones obtained for the discharges (Table 4). The relation coefficient in all stations is around 0.8–0.9, but Nash–Sutcliffe coefficients are low and vary from 0.6 to 0.7 at the upstream station and get smaller in stations under tidal effect. The source of this inaccuracy can be explained by the coarse resolution of topographic data, the lack of measured cross sections, and the large distance between two computed sections (dx) in MIKE 11 (Vázquez *et al.* 2002). Despite the fact that statistical coefficients for water levels are still low, calibrating the model relying on these factors probably adds a certain value to show the correlative level of model results with real data.

By mean of the analysis above, we can judge that the flow in the Vu Gia Thu Bon catchment is reproduced rather impressively by MIKE SHE. Therefore, this model is able to be applied to a flood event or the variability of stream flow under the impact of climate change. Moreover, these results also demonstrate the performance of deterministic distributed models in simulating the hydrological process, especially with a large catchment.

Uncertainty

Although trying to reflect most truthfully the hydrological dynamic in the catchment, the model has not yet gained the optimal results when inaccuracies still remain. The statistical coefficients, such as Nash–Sutcliffe and correlation coefficient (RMSE) are still weak. These coefficients could not get maximum values for many reasons. The model has many potential uncertainties for simulating hydrological processes. Uncertainty in hydrologic modeling may arise from several sources: model structure, parameters, initial conditions, and observed data used to drive and evaluate the model (Liu & Gupta 2007).

One of the most important factors regarding the model structure, and which may have a significant influence on the model accuracy as well as on the uncertainty of simulation, is the cell size issue (Egüen *et al.* 2012). The advantage of the distributed hydrological model is that it represents hydrological characteristics of the catchment cell by cell. However, the resolution used in the model is still coarse due to the limitation of topographic data and computation time. The 90 m topographic grid data used may not describe precisely enough the surface of the catchment. Thus, it derives some differences in surface flows between reality and the model. The land uses, the soil properties, or the roughness coefficients, which are simplified in order to optimize the calibration are the major causes of underestimation or overestimation for the model.

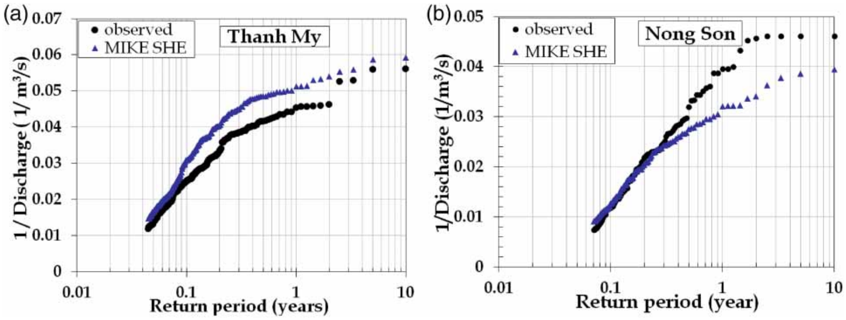

Figure 9 | The difference in low flow empirical extreme value distributions between calibration and observation at Thanh My (a) and Nong Son (b).

Another issue significantly influencing the model uncertainty is the rainfall, which is a key factor in the hydrological dynamic. Rainfall spatial variation heavily affects both runoff generation and the hydrologic process in a catchment (Moon *et al.* 2004). The spatial variability in rainfall may introduce a significant uncertainty in model parameters during the calibration process (Chaubey *et al.* 1999). The quality of spatial rainfall distribution usually depends on the characteristics of the study area and other factors, in particular, the rain gauge density. The network of rain gauge stations in Vu Gia Thu Bon is sparse, with, on average, one station for an area of 700 km^2. In the constructed model, the rainfall inputs are re-interpolated and could be considered as a great source of uncertainty. As well as the spatial distribution, the time factor is also a great potential source of uncertainty (Dendy 1987), especially within the Vu Gia Thu Bon catchment where the concentration time is short due to the steep topography. Using daily rainfall in this simulation probably affects the rising limb and the peak flow appearance. However, these data are the unique complete rainfall data set available for long-term simulations for the Vu Gia Thu Bon catchment. The analysis regarding the rainfall distribution in space and in time demonstrates again the impact of lack of data on simulation uncertainty.

The groundwater is an unignorable component when simulating hydrological processes (Winter 1999). In terms of input data, the insufficiency of ground water data is seen as a major source of uncertainty for simulating hydrological processes. The quality of the groundwater data of the Vu Gia Thu Bon catchment is not very good, and the collected data do not present the groundwater properties concretely. For the whole catchment, the model integrates a unique geological layer.

Regarding the modeling methods implemented in MIKE SHE, the selection of one or another method can potentially generate several sources of uncertainty. For example, there are three functions to select for unsaturated flow: Richards' equation, gravity flow, or the two-layer UZ. The Richards' equation is supposed to be the best method for simulating unsaturated flow. However, in the current application, the two-layer UZ was chosen due to the limited available data sets and the short processing time.

The coupling between MIKE SHE and MIKE 11 contains additional potential uncertainties. It could notably affect water exchanging between the floodplain and riverbed. The number of simulating branches and intervals in MIKE 11 is considered as a main source of uncertainty. In the model, the coupling between MIKE SHE and MIKE 11 is not set well due to the limited number of cross sections. Additionally, there is a difference between overland flow and river flow, but in the analysis, the river network presented in MIKE 11 is merely over 44 large branches. Understandably, the set-up manner of the coupling between MIKE SHE/MIKE 11 is estimated, producing a large uncertainty.

Based on Table 4, it is easy to recognize that statistical indices counting with monthly data are better than counting with daily data. Hence, an additional element affecting the quality of the hydrologic model concerns the time factors. The time step applied in this MIKE SHE model is fixed at 1 day. This time step is still high, so it may not present thoroughly what the hydrological cycle is in the catchment. As well, the timescale of the model is limited to 10 years. The simulation time is thought not sufficient to convey adequately extreme events from natural phenomena. Unavoidably, simulating the stream flow in the Vu Gia Thu Bon catchment will contain particular uncertainties.

CONCLUSIONS

The aim of the approach was to assess the capacity of a deterministic distributed hydrological model based on the MIKE SHE modeling system to simulate the hydrological process and to estimate climate change impacts on the runoff in the Vu Gia Thu Bon river system. The developed model integrates most of the hydrological processes – from surface flow to groundwater flow, and evapotranspiration – and is expected to reproduce the hydrological cycle within the catchment. The results demonstrate clearly the performance of the approach with reasonable physical hypotheses that contribute to simplifying the calibration procedure. At the same time, due to its physical foundation, the model is hoped to produce a good assessment, with an estimated accuracy, of the climate change impacts over the catchment. One of the advantages of fully deterministic distributed models is the possibility of overcoming the weakness and the lack of systematic data that is a frequent situation in many developing countries. The difference between actual and future runoff regimes could be compared anywhere over the catchment. Hence, an overview of changes in runoff regime across the whole catchment could be generated without difficulty. These points confirm the capacity and the efficiency of distributed models for assessing climate change impacts over hydrological processes.

The developed model was calibrated and validated against daily data and monthly data for the period 1991–2000 and 2001–2010, respectively. The performance of the model is demonstrated via the hydrograph shapes and statistical indices, comparing simulation results with data from seven gauging stations. The model efficiency is likewise confirmed by the capacity to predict the extreme peak flow and base flow. However, the model still contains uncertainties that originate from different sources, such as the model structure, the cell size, and the input data. Reducing these uncertainty sources is likely impossible. At the same time, it is not completely necessary, regarding the models whose assigned objectives are dedicated to operational purposes. Obviously, improvements may address priority cell size, data accuracy, and solving algorithms.

In the traditional vision of hydrological analysis, the availability of limited data resources, and the necessary computation performance to some extent, reduce de facto the use and the application of deterministic distributed models. However, they represent a relevant alternative and may provide useful results for operational management of catchments. Obviously, the calibration process is a key and compulsory task in the model development. The sensitivity analysis appears as an essential step in order to efficiently support the calibration procedure. The performed analysis suggests that the model comparisons should be carried out not only on the discharges, but also on the water levels in all locations where measured data are available in order to maximize the use of available information. The results of calibration confirm that it is necessary to compare the measurement and simulation at multi-sites. The multi-site calibration helps to increase the accuracy of translating what happens in the nature of the model and in minimizing the global uncertainty of the model as well. The analysis demonstrates likewise that the model validation versus extreme high and low values is also quite important. The validation on extreme runoff values is helpful for reducing the uncertainty in simulations.

The sensitivity analysis has to be focused on the factors and variables that are directly affecting the runoff process. The analysis has demonstrated that the runoff variation is strongly driven by parameter changes. In the Vu Gia Thu Bon catchment, the peak flow is significantly affected by most of the model parameters while the base flow, as expected, is merely influenced only by the horizontal saturated hydraulic conductivity of the saturated zone and the saturated hydraulic conductivity of the unsaturated zone. The analysis has demonstrated the interest of the sensitivity analysis in the calibration procedure, which requires a distributed deterministic hydrological model. At the same time, the sensitivity analysis approach helps to determine a useful range for each physical variable used for the stream flows and contributes to simplifying the calibration process.

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