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Hydrological stream flow modelling for calibration and uncertainty analysis using SWAT model in the Xedone river basin, Lao PDR

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Abstract

The hydrological stream flow modeling is applied by the Soil for Water Assessment Tool (SWAT) model in the Xedone River basin, covering an area of 7,224.61 km^2, in the southern part of Laos. The main objective of this research is to test the performance and feasibility of the SWAT model for predicting stream flow in the river basin. The model is calibrated and validated for two periods: 1993-2000 and 2001-2008, respectively, by using the SUFI-2 technique in this analysis. The SUFI-2 gives good results with the high value of R^2 and NSE larger than 0.70 respectively, for daily simulation. Monthly simulation results during calibration and validation are also good with $R^2 > 0.80$ and NSE > 0.80. The sensitivity analysis results of the model to each sub-basin delineation and hydrological response unit (HRU) in this basin are 230 HRUs in the whole basin. For uncertainty results, the 95% prediction uncertainty (95PPU) brackets very well with the observed discharge. All of sources uncertainty results are captured by bracketing value, higher than 65% of the observed river discharge. All of the results in this study are important to water discharge. The calibrated model can be used for further analysis of the effects of the climate and land use change, water quality analysis and sediment yield analysis; furthermore, the modelling can be applied for planning dam construction in the future and flood disaster risk management and thereby is useful for the sustainable development of the country.

Keywords: SWAT; Xedone River basin; hydrological modeling; uncertainty; stream flow; parameter; SUFI-2

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1. Introduction

Water is a key resource for sustainable economic and social development. Because of the human activities (e.g., increasing global population [1], land-use change [2], water pollution [3], [4], [5]) and climate change, water shortages have become the major crises of sustainable development of communities all over the world. Therefore, to improve water resources, managements are momentous for sustainable development of human society.

The Xedone River basin is a sub-basin of the Mekong River Basin (MRB). The existing land and water resources system of the area are adversely affected by the rapid growth of population, construction, development, deforestation, surface erosion and sediment transport. There is a need for hydrological research of the Xedone River basin that can support the improved catchment management programs and that can safeguard the alarming degradation of soil and water resources in Lao PDR highlands better. The analyses of the water resources and flood disaster in MRB have been carried out in many previous researches. A two-dimensional hydrodynamic model has been used for flood inundation simulation in the lower MRB [6]. It is found that this model could predict the magnitude and duration of the flood inundation with a reasonable level of accuracy. Mekong River Commission has played the important role in addressing the water resource problems by considering the population growth, environmental pollution, and urban development [7]. The future hydro-climatology of the MRB has been studied by using the high-resolution Japan Meteorological Agency (JMA) AGCM [8]. An increase in the number of wet days in the 'future' has been found in MRB. There is one report, which describes a brief introduction of the flood hazard map in the Xedone River basin [9]. However, we cannot find a detail study of the hydrological simulation in the Xedone River basin. The hydrological modelling is quite important to forecast the flood events in the future.

The Soil and Water Assessment Tool (SWAT) [10] is a physics-based, long-term, and distributed hydrological model and has been applied worldwide as an excellent assessment model for hydrological modelling and water resource management. This model is applied to runoff and soil loss prediction [11], [12], water quality modelling [13], [14], land use change effect assessment [15], [16] and climate change affects water quality modelling [17], [18], land use change effect assessment [19] and climate change impact assessment [20]. A comprehensive review of SWAT model applications is given by Gassman et al [21]. In the previous researches, we found several calibration and uncertainty analysis techniques [22], [23]. This SWAT model and the uncertainty analysis will be carried out in the Xedone River basin of Lao PDR.

In this study, we focus on calibration, evaluation and application of SWAT2009 model for simulation of the hydrology of the Xedone River basin. The main objective of this study is to test the performance and feasibility of the SWAT2009 model for prediction of stream flow in the Xedone River basin, which will contribute to the water resources management in the Xedone River basin and thereby is useful for the sustainable development of the country.

2. Study Area

The Xedone River basin is a sub-basin of the Mekong River basin which is located in the southern part of Lao People's Democratic Republic (PDR) as seen in Fig. 1. The area is located between 15°10'2.858" - 16°11'5.474" North Latitude and 105°35'31.379" - 106°44'51.956" East Longitude, and covers a total area of 7,224.61 km^2 equal to 0.89% out of 809,500 km^2 of the Mekong River basin area. The main river with a total length about 240.5 km has its origin in the northeastern side. The elevation of the basin ranges from 8 m to 1706 m above the mean sea level. The topography of the study area is a hilly area in upstream part, and flat land in middle and downstream. It has sources of water, its large middle part is suitable for agriculture, and last lower part is suitable for rice farming because of the availability of the irrigation. However, during the dry season, water resources availability is less to be seen in the region. The land covers are the vegetables and deciduous trees (46.16%), the agricultural land (14.19 %), the paddy field (17.08%), the shrub land / regrowth (21.21 %), the grassland (1.16 %), the water surface (0.02 %) and the urban area (0.18 %) in this basin that are shown in Fig. 2 (a). Major soil types in this river basin are predominantly Acrisols, Cambisols and Luvisols (sandy, loamy, clay and gravity). The soil type distribution is shown in Fig. 2 (b). The climate in the study area is characterized by two distinct seasons: a wet season (May to October) and a dry season (November to April). The mean annual temperature ranges from 18 to 34.8 °C. The basin receives about 2500 mm of the annual rainfall, during the wet season which contributes 60 - 70% of the annual rainfall due to monsoons, tropical cyclones, tropical storms, and depressions. The annual average discharge is 165.208 m^3/s, which covers 1.101 % of the Mekong River annual discharge.

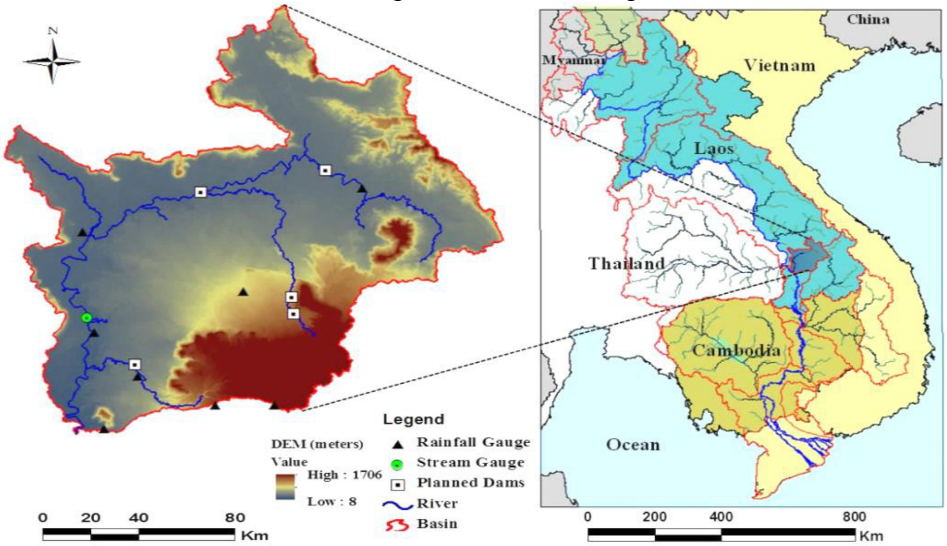


Fig. 1. Location of the Study Area, Rainfall Gauges, Stream Gauge and Location of Planned Dams

3. Methods and Data

3.1. SWAT Model

The SWAT model is a physically-based continuous time, spatially distributed model designed to simulate water, sediment, nutrient and pesticide transport at a catchment scale on a daily time step. It uses hydrological response units (HRUs) that consist of specific land use, soil and slope characteristics. The HRUs are used to describe the spatial heterogeneity in terms of land cover, soil type and slope class within a watershed. The model estimates relevant hydrological components such as evapotranspiration, surface runoff and peak rate of runoff, groundwater flow and sediment yield for each HRU. ArcSWAT ArcGIS extension is a graphical user interface for the SWAT model. The SWAT model is developed and refined by the U.S. Department of Agricultural Research Service (ARS) and scientists at universities and research agencies around the world. The water balance equation is the base of the hydrologic cycle simulation in SWAT:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} + Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (1)$$

in which SW_t is the final soil water content (mm), SW_0 is initial soil water content on day i (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm).

3.2. SWAT- CUP Model

The SWAT-CUP is a computer program for the calibration of SWAT models. SWAT-CUP is a public domain program, and as such may be used and copied freely. The program is linked to five different algorithms such as

Sequential Uncertainty Fitting SUFI-2 [24], [25], Particle Swarm Optimization, (POS), Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992) [26], Parameter Solution (ParaSol) [27], and Mark chain Monte Carlo (MCMC) [28] procedures to SWAT. It enables sensitivity analysis, calibration, validation, and uncertainty analysis of SWAT models. SUFI-2 is the algorithm for calibration of SWAT model. SUFI-2 can provide the widest marginal parameter uncertainty intervals of model parameters among the five approaches. Therefore, the SUFI-2 methods are applied in this study. The brief descriptions and procedures of SUFI-2 are given below.

SUFI-2

The parameter uncertainty is calculated from all the input and output source uncertainties such as the uncertainty in the input rainfall data, the land use and soil type, parameters, and observed data, in SUFI-2. The simulation uncertainty is quantified by the 95% prediction uncertainty (95PPU) which is referred to as the p-factor. The 95PPU is calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through Latin hypercube sampling [29]. Another measure quantifying the strength of a calibration or uncertainty analysis is the *r-factor* which is the average thickness of the 95PPU band divided by the standard deviation of the measured data.

The goodness of calibration and prediction uncertainty is judged based on the closeness of the *p-factor* to 100% (i.e., all observations bracketed by the prediction uncertainty) and the *r-factor* to 1 (i.e., achievement of a rather small uncertainty band [30], [31]. If the two factors are in satisfactory values, a uniform distribution in the parameter hypercube is explained as the following parameter distribution. The goodness of fit in SUFI-2 is quantified by the R^2 and Nash-Sutcliffe (NS) coefficient between the observed data and the best simulation. The average thickness of the 95PPU band ($\bar{r}$) and the r-factor are calculated by Equations (2) and (3) [32].

$$\bar{r} = \frac{1}{n}\sum_{t_i}^{n}\left(y^M_{t_i,97.5\%} - y^M_{t_i,2.5\%}\right) \tag{2}$$

$$r - factor = \frac{p - foctor}{\sigma_{obs}} \tag{3}$$

In which $y^M_{t_i,97.5\%}$ and $y^M_{t_i,2.5\%}$ represent the upper and lower boundaries of the 95PPU, and σ_{obs} is the standard deviation of the measured data.

3.3. Data Input

The spatially distributed data (GIS input) needed for the ArcSWAT interface include the Digital Elevation Model (DEM), soil data, land use and stream network layers. Data of the weather and river discharge are also used for prediction of stream flow and calibration purposes; observed daily rainfall data and discharge data are obtained from the Meteorology and Hydrology Department, and the Ministry of Natural Resource and Environment in Lao PDR. We use eight rainfall stations, such as Batieng, Khongxedone, Laongam, Nikhom34, Pakse, Paksong, Saravane and Selabam, and one station discharge at Souvannakhili for using calibration. The 30-m resolution DEM is taken from NASA, the 50-m land use map year 2002 and soil type maps 1998 shown in Fig. 2 (a) and (b) are obtained from the Forest Inventory and Planning Division (FIPD) and the Ministry of Agriculture and Forestry, Lao PDR, the stream network is obtained from the Mekong River Commission (MRC), and the observed daily discharge data period 1990-2009 used in this model is divided into two periods: model calibration (1993-2000) and validation (2001-2008). As the input data for the weather generator of SWAT, the daily temperature, humidity, wind speed and precipitation data are used. These hydrological and meteorological data are provided by the Ministry of Hydrology of Lao PDR. We combine and transfer the original polygon land use data to the land use raster map by using ArcGIS10.

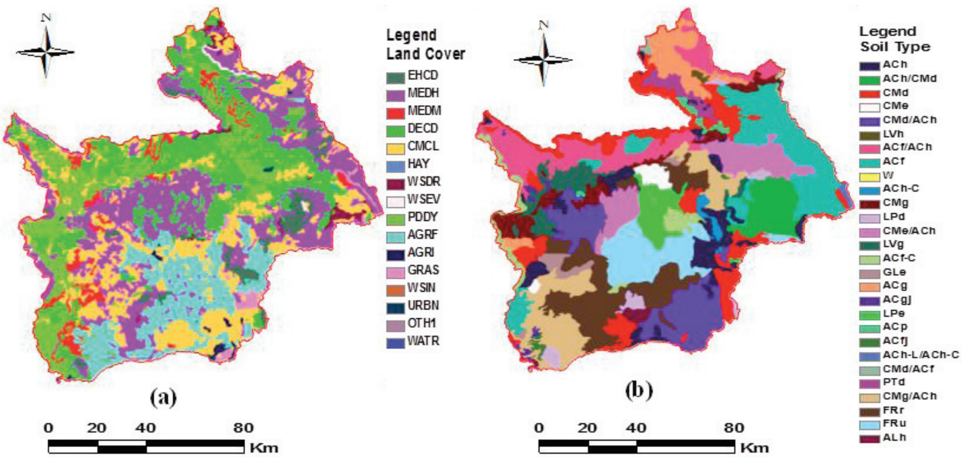


Fig. 2. Land Cover (a) and Soil Types (b) in the Xedone River Basin

3.4. Model Setup

Basin Delineation

Basin delineation depends on DEM to delineate the watershed and to analyze the drainage patterns of the land surface terrain. The ArcSWAT interface uses the mask area for stream delineation, and the stream networks are delineated from the DEM by using an automatic delineation to SWAT model. The model fills all of the non-draining zones to create a flow direction, and superimposes the digitized stream network into the DEM to define the location of stream networks.

The ArcSWAT proposes the minimum, maximum and suggested size of the sub-watershed area in hectare to define the minimum drainage area. Generally, the smaller the threshold area, the more detailed the drainage networks and the number of sub-basins and HRUs. In addition, more processing times and spaces are needed. In this study, the smaller area (5000 ha) is provided to get all sub-basin of the Xedone river basin and outlet is defined, in which it is later taken as a point of calibration of the simulated flows. As a result, there are 17 sub-basins of the Xedone basin.

HRU Definition

The analysis of HRU definition indicates that dominant type of HRU definition results in a single HRU for each sub-basin where the dominant land use, soil and slope within the basin are considered to be the land use, soil and slope of each sub-basin. This single HRU within each sub-basin is not able to properly represent the characteristics of the sub-basins. Accordingly, the simulated stream flow shows the unsatisfactory result as compared to the measured stream flows in the observed stations of the Xedone River basin. The multiple scenarios that account for 15% land use, 15% soil and 15% slope threshold combination give a better estimation of stream flow.

The Xedone River basin results in 230 HRUs in the whole basin. This scenario results in the detailed land use, slope and soil database, containing many HRUs, which in turn represent the heterogeneity of the study area. The comparison between the default model predictions and measured discharge produces the highest Nash-Sutcliffe efficiency (NSE). The distribution of land use, soil and slope characteristics within each HRU have the greatest impact on the predicted stream flow. As the percentage of land use, slope and soil threshold increases, the actual evapotranspiration decreases due to eliminated land use classes. Hence, the characteristics of HRUs are the key factors affecting the stream flow.

4. Results and Discussion

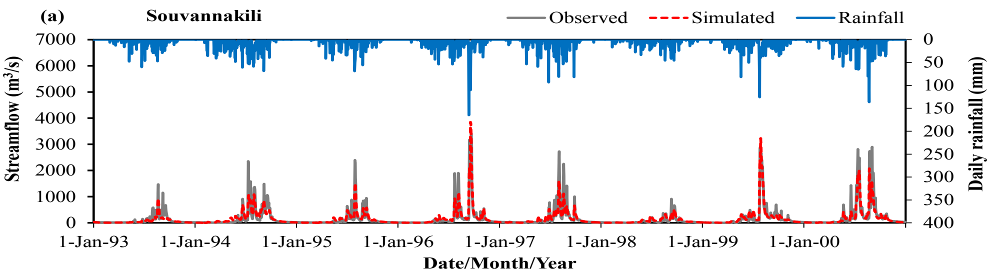
In this research, we have evaluated the relative sensitivity values found in the parameter estimation process. Thirteen parameters are found to be sensitive with the relative sensitivity values such as initial SCS runoff curve number to moisture condition II (CN2), base flow alpha factor (ALPHA_BF), groundwater delay time (GW_DELAY), threshold depth of water in the shallow aquifer for return flow to occur (GWQMN), groundwater "revap" coefficient (GW_REVAP), soil evaporation compensation factor (ESCO), Manning's "n" value for the main channel (CH_N2), effective hydraulic conductivity in main channel alluvium (CH_K2), base-flow alpha factor for bank storage (ALPHA_BNK), available water capacity of the soil layer (SOL_AWC), saturated hydraulic conductivity (SOL_K), moist bulk density (SOL_BD), and plants uptake compensation factor (SFTMP). These sensitive parameters are considered the model calibration in SWAT-CUP model. The models are calibration period 1993 - 2000 and validation period 2001- 2008.

4.1. Model Calibration and Validation

The calibration is the modification or adjustment of model parameters, within the recommended ranges, to optimize the model output so that it matches with the observed set of data. The calibration provides several different parameters for adjustment through user intervention. These parameters can be adjusted manually or automatically until the model output best matches with the observed data. This study is done by applying SWAT-CUP for calibrating outlet stream flow. The validation is the process of determining the degree in which a model or simulation is an accurate representation of the observed set of data from the perspective of the intended uses of the model. The discharge data were recorded during the years 1990-2008 at Souvannakhili station, and the daily discharges from 1993-2008 are used for calibration, but for the years 1990-1992 it was skipped for model warm-up.

4.2. Daily Calibration and Validation

The comparison between the simulated daily stream flow and the observed data is a good result for the calibration and validation periods respectively. The flow calibration and validation were performed for eight years from 1993 to 2000 for calibration and from 2001 to 2008 for validation. However, the flow had been simulated for sixteen years, including one year of the warm-up period. The simulated daily flow matches the observed values for the calibration and validation periods with R^2 = 0.821, 0.732 and NSE = 0.819, 0.707 respectively. The coefficients of the simulation are shown in Fig. 5 (a) and (b), in which there is a good agreement between simulated and gauged flows. The results show that SWAT is able to simulate the hydrological characteristics of the Xedone River basin very well. Hence, the model can be used for further hydrological studies in the basin.



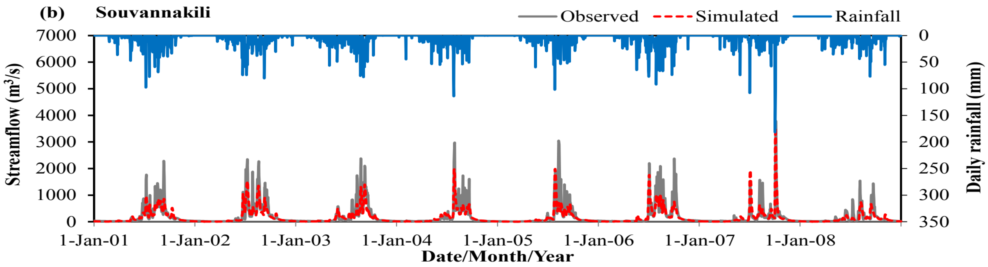


Fig. 3. Observed and Simulated Daily Stream Flow for: (a) Model Calibration and (b) Model Validation

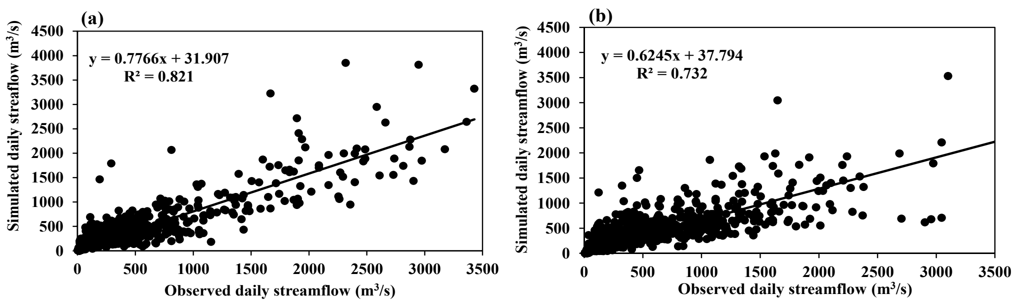
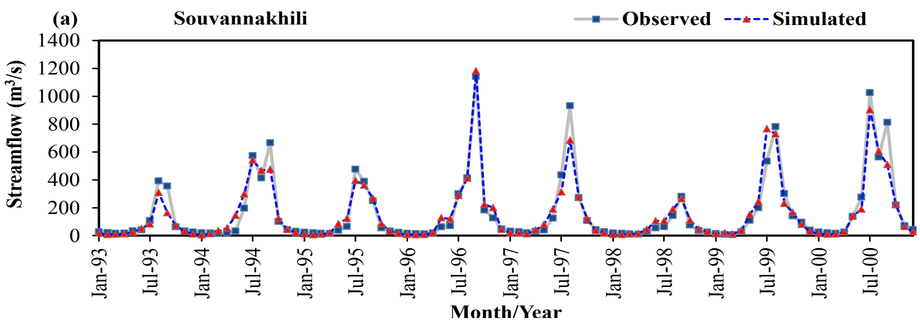


Fig. 4. Scatter Plot of Daily River Stream Flow for (a) Calibration Period (1993-2000) and (b) Validation Period (2001-2008)

4.3. Monthly Calibration and Validation

Comparing the monthly hydrograph and simulated flows at the Souvannakhili station during the validation period (2001-2008), we can see that the SWAT model under-predicts the high peak values as in Fig 6 (b). The poor prediction of the peak flows of the SWAT model has been reported by some researchers. The performance of the SWAT model for the study area is very good during the validation period also with R^2> 0.80 and *NSE*> 0.80 for the gauging sites. Therefore, the SWAT model can be adopted for the hydrological evaluation of the river basin in Lao PDR. The comparison of the observed and simulated discharges (daily and monthly) for the Souvanakhili station during the calibration period (1993-2000) is presented in Fig. 4 (a) and (b), and Fig. 6 (b). From the hydrograph of the daily observed and simulated flows shown in Fig. 4 (a), we can see that the simulated flows closely match the observed flows, except on 18/09/1996 when the peak of the simulation is high. High monsoon rainfall was reported during October, 1996. However, the same thing is not reflected in the observed runoff data in Fig. 4 (a). It is assumed that there may be some uncertainty in the data. Scatter plots of the simulated and observed discharges (daily and monthly) of the Souvanakhili station during the calibration period (1993-2001) are presented in Figs. 5 (a) and 7 (a)**.** Both plots show relatively good R^2values: 0.821 and 0.927, respectively.



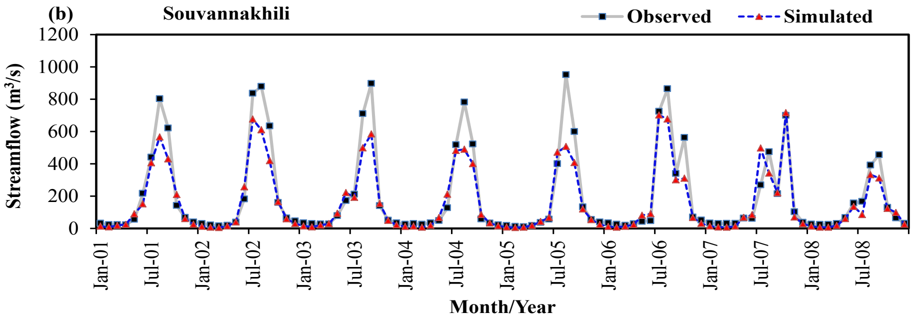


Fig. 5. Observed and Simulated Monthly Stream Flow for: (a) Model Calibration and (b) Model Validation

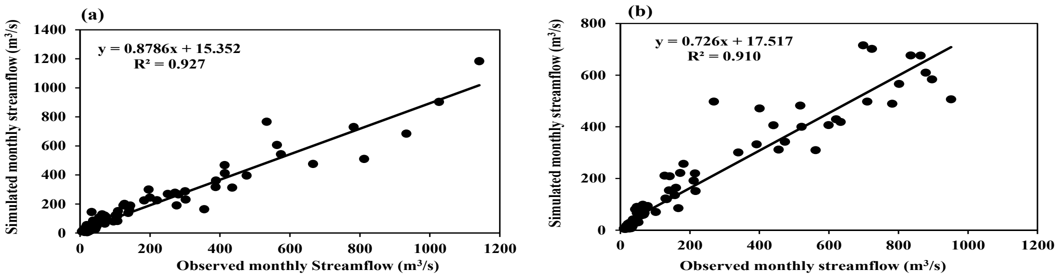


Fig. 6. Scatter Plot of Monthly River Stream Flow for (a) Calibration Period (1993-2000) and (b) Validation Period (2001-2008)

4.4. Uncertainty Analysis and Discussion

Mostly effecting parameters for the calibration of the stream flow are mainly parameters governing the surface runoff response, the parameters governing the subsurface response, and parameters governing the basin response used for the calibration shown in Table 1.

Sequential Uncertainty Fitting version 2, which appreciates SUFI2 embedded in SWAT-CUP, is selected to calibrate the Xedone model. SWAT-CUP is a computer program for calibration of SWAT models that links SUFI2, PSO, GLUE, ParaSol, and MCMC procedures to SWAT. SWAT-CUP enables sensitivity analysis, calibration, validation, and uncertainty analysis of SWAT model. SUFI-2 is given several iterations to get the acceptable result. Each of iterations provides the suggested values for the new parameters to be used in the next iteration. Finally, it provides the acceptable result with Values of the Nash-Sutcliffe, Coefficient of Determination and others embedded in SWAT-CUP. Moriasi et al. 2007 present general performance ratings of the SWAT model for monthly time step simulations. Based on these recommendations, the performance of SWAT model for the study area is very good during the calibration period with NSE > 0.70, and the less value of NSE assumes that there may be some uncertainty in the data. The uncertainty analysis indicates that the parameters of effective hydraulic conductivity in main channel alluvium (CH_K2) and base-flow alpha factor for bank storage (ALPHA_BNK) play important roles in the calibration and validation of SWAT model. Luo et al. [33] report that the parameters of CH_K2 and ALPHA_BNK have the significant impact on the model calibration, and the sampling size may also affect the model sensitivity. In this study, we do not check the uncertainty from the model structure and the input data. Based on this study, it is necessary to do the further study focusing on these topics of the uncertainty analysis.

Table 1. Sensitive Parameters and Fitted Values after Calibration Using SUFI-2

Parameter Names	Rank	Fitted Value	Min Value	Max Value
r__CN2.mgt	1	0.684	0.583	0.691
v__ALPHA_BF.gw	2	-0.047	-0.051	-0.037
v__GW_DELAY.gw	3	205.951	196.110	208.316
a__GWQMN.gw	4	2.546	2.499	2.619
v__GW_REVAP.gw	5	0.154	0.147	0.156
v__ESCO.hru	6	0.943	0.921	0.959
v__CH_N2.rte	7	0.634	0.598	0.672
v__CH_K2.rte	8	126.312	125.130	127.025
v__ALPHA_BNK.rte	9	0.684	0.676	0.727
r__SOL_AWC .sol	10	0.163	0.155	0.170
r__SOL_K .sol	11	0.726	0.676	0.747
r__SOL_BD .sol	12	0.166	-0.069	0.396

5. Conclusion

Hydrological stream flow modelling is successfully calibrated and validated in this study by using the SWAT model in the Xedone River basin. The good result is shown with the likelihood measure of the model calibration and validation for two periods: 1993-2000 and 2001-2008. The daily simulation values of R^2 and NSE are 0.821and 0.819 during the calibration period, and 0.732 and 0.707 during the validation period. Monthly results R^2 and NSE are 0.927 and 0.925 during the calibration period, and 0.910 and 0.856 during the validation period. The sensitivity analysis of the model to sub-basin delineation and HRU definition thresholds show that the flow is more sensitive to the HRU definition thresholds than sub-basin discretization effect. The results in this basin are 230 HRUs in the whole basin. The 95PPU brackets very well with the observed data in the calibration and validation periods. The p-factor and r- factor computed using SUFI -2 give good results by bracketing value higher than 65 % of the observed data. The SUFI-2 algorithm is an effective method, but it requires additional iterations as well as the need for adjustment of the parameter ranges. Despite data uncertainty, the SWAT model produces good simulation results of daily, monthly time steps, which are useful for the water resources management in this basin. The calibrated model can be used for further analysis of the effect of climate and land use change, water quality analysis and sediment yield analysis. Furthermore, the modelling can be applied for planning of dam construction in the future and flood disaster risk management, which will contribute to the water resources management in the Xedone River basin, and thereby is useful for the sustainable development of the country.

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