Generation of daily naturalized flow at ungaged control points

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ABSTRACT

The development of daily naturalized flow in the water rights analysis package (WRAP) model at ungaged stations has difficulties because of low daily flow measurement at gaged stations, low available monthly naturalized flow, and budget constraints. This study proposes a procedure for developing daily naturalized flow at ungaged stations. The soil and water assessment tool (SWAT) model was validated with little daily flows and used for predicting the daily flow at gage stations that are near ungaged stations. The predicted daily flow is transferred at ungaged stations using the drainage area ratio (DAR) method. The transferred daily flow is aggregated and compared with monthly regulated flow computed by the WRAP model with the mean, standard deviation, mean relative error, Nash–Sutcliffe model efficiencies, and correlation coefficient (R^2). The SWAT daily flow, which is referred to as the regulated flows, is converted using regression equations into naturalized flow and used as the daily pattern flow for monthly naturalized flow disaggregation. The system application of the SWAT and WRAP models with DAR and pattern methods provides alternative ways to generate daily naturalized flow at ungaged stations through disaggregating monthly naturalized flow at primary stations.

Key words | disaggregation, drainage area ratio, flow pattern method, regression equation, SWAT, WRAP

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INTRODUCTION

Factors such as site constraints, water rights, human activities, and budget limitations lead to intermittent or discontinuous stream flow measurement at many gage stations, but the United States Geological Survey has still measured stream flow continually at many locations. In particular, the land-use/land-cover modification derived from urbanization and water rights (e.g. municipal and industrial diversion and small dam release) has had impacts on the stream flow characteristics, requiring new gage stations and the removal of existing gage stations. However, the establishment of new gage stations in all of the required locations is impossible because of the aforementioned constraints, which leads to the selection of representative gage stations. Accordingly, stream flows at unselected locations are computed based on water distribution methods from gaged to ungaged stations. Among these water distribution methods, the drainage area ratio (DAR) method has been used widely to transfer the measured stream flow to other nearby ungaged stations because the method uses only the drainage area (Hirsch 1979; Ries & Friez 2000; Perry *et al.* 2002; Emerson *et al.* 2005; Wurbs 2005; Asquith *et al.* 2006).

Wurbs (2005) introduced the DAR method in the reference manual of the water rights analysis package (WRAP) model (Wurbs 2013a, b). The DAR method has been used in various circumstances for stream flow generation. DAR used in the WRAP is different from conventional DAR in that the DAR in WRAP considers the channel loss occurring between ungaged and gaged control point (Wurbs 2013a). Recently, a sub-monthly time-step model was developed (Kim & Wurbs 2011c; Wurbs & Hoffpauir 2013; Wurbs 2014). WRAP is a set of Fortran programs that includes Win-WRAP, SIM, SIMD (D for daily), HYD, DAY, SALT, and

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TABLES. WinWRAP is a user interface for executing the WRAP programs on microcomputers within Microsoft Windows®. Program SIM performs the simulation for modifying hydrologic period-of-analysis sequences of monthly naturalized flow for the effects of the water rights to obtain the resulting sequences of regulated flow and other flows. The stream flow terms used in this study are defined as follows. Naturalized (unregulated) flows are historical gaged stream flow data adjusted through removing the effects of water resources development, management, and use. Regulated flows are physical stream flows computed by the SIM program by adjusting naturalized flows for the effects of human activities modeled by the information contained in the SIM program input file (Kim & Wurbs 2011a). Accordingly, regulated flows are regarded as gaged flow because all information of water rights that include all land use, water use, and reservoir-related variables is considered in the SIM program simulation. SIMD is an expanded version of SIM with sub-monthly time-step, flow forecasting, routing, and flood control simulation features. The program HYD is a set of computational routines for converting sequences of monthly gaged stream flows to naturalized flows and compiling sets of monthly net reservoir evaporation less precipitation depths. DAY has routines for synthesizing daily or other sub-monthly time interval flows from monthly naturalized flows and calibrating routing parameters. The program SALT reads a SIM output file and salinity input file and tracks salt loads and concentrations through a river/reservoir system. The program TABLES organizes the SIM, SIMD, and SALT simulation results and develops frequency relationships, reliability indices, and summary statistics (Kim & Wurbs 2011c). There are no problems for the use of the DAR method in the conventional WRAP model, which is based on monthly time steps and uses monthly naturalized flow, net evaporation-precipitation, and water rights. However, the sub-monthly time-step model has one issue regarding the daily naturalized flow for the State of Texas, which has not been generated. Accordingly, monthly naturalized flow, which is flow without human activities, has been used for generating daily stream flow using several options, which include uniform distribution (option 1), linear (option 2), variability adjustment (option 3), and flow pattern (option 4). Options 1 and 2 disaggregate the monthly flow without the input of daily flow and require no additional data not already found in a monthly simulation data set, while options 3 and 4 disaggregate the monthly flow with the input of daily flow and reproduces the daily variability characteristics of available daily flow sequences (Wurbs & Hoffpauir 2013).

Daily flow generated at ungaged stations can mimic the daily flow characteristics by using options 3 and 4 and DAR methods. However, the measurement of daily flow at gage stations is limited and sometimes impossible. Accordingly, various watershed models have been used for generating daily stream flow at ungaged stations as computer technology has improved. Among these models, the soil and water assessment tool (SWAT), a physically based continuous-time mathematical model (Arnold *et al.* 1998), is widely used to predict the stream flow (Bosch *et al.* 2004; White *et al.* 2010; Obiero *et al.* 2011) using rainfall data (Sexton *et al.* 2010; Tuppad *et al.* 2010), land use, and soil type (Geza & McCray 2008; Heathman *et al.* 2009; Tong *et al.* 2009; Mukundan *et al.* 2010; Wang *et al.* 2010, 2011; Nejadhashemi *et al.* 2011) in rural and urban areas. The SWAT can also predict the impact of land management practices on water, sediment, and agricultural chemical yield in large complex watersheds with varying soil, land use, and management condition over long periods (continuous-time) of time and the effect of different management scenarios on water quality, sediment yields, and pollution loading in rural watersheds. The SWAT components are typically divided into land and routing phase of the hydrologic cycle. Routing phases can be further subdivided into two components routing in the main channel/reach and routing in the reservoir. The land phase of SWAT includes climate (weather), hydrology, land cover/plan growth, erosion, nutrients, pesticides, agricultural management. The routing component allows the users to route (1) flood flows, sediment, nutrient, and channel pesticide in the main channel/reach and (2) outflow, sediment, nutrient, and pesticides in the reservoir. Through stream network, loading at sub-basin outlets can be routed to the receiving reservoir or points of interest (Arnold *et al.* 1998; Neitsch *et al.* 2002). The SWAT model was simulated in this study for generating daily flows that are used as a daily flow pattern for disaggregating monthly naturalized flow. Also, these generated daily flows can be regarded as gaged flow because all SWAT input (e.g. land use, soil type, etc.) reflect the existing conditions of water use (i.e. water rights).

Development of the original hydrology data sets during implementation of the WAM system required considerable time and effort (HDR 2001a, b; Kim & Wurbs 2011b). Also, Kim & Wurbs (2011b) significantly reduced the effort that was performed by HDR (2001a, b) required to update the hydrology data sets (i.e. naturalized flow) by utilizing the information now available in the WAM system water right data sets that describe water resources development, allocation, management, and use compared with previous project. However, these previous projects focused on the monthly time-step variables (e.g. naturalized flow). To develop the sub-monthly (daily) time-step variables, similar steps (HDR 2001a, b; Kim & Wurbs 2011b) should be performed because there are few available variables though the DAY program disaggregate monthly variables based on several water distribution method (Wurbs & Hoffpauir 2013). The use of watershed model such as SWAT can reduce the previous complex procedures and save time and effort to develop the daily variables (i.e. naturalized flow). Accordingly, the objective was to develop the daily naturalized flow by disaggregating monthly naturalized flow with the flow pattern method (option 4) and DAR method. The monthly regulated flows, physical flows considering all water rights in the input data set (Kim & Wurbs 2011a), and daily flow are computed and predicted by the WRAP and SWAT models, respectively. The daily flows are adjusted into naturalized daily flow with monthly conversion factors and regression equations between monthly naturalized and regulated flows. The adjusted daily flows are used as a flow pattern for disaggregating monthly naturalized flow.

CASE STUDY AREA AND DATA SET

Upper Oyster Creek (Figure 1) is located in the Brazos River Basin southwest of Houston, Texas, in northern Fort Bend County. It is identified as segment 1245 and is subdivided into three assessment units: AU01, AU02, and AU03. Segment 1245 extends approximately 86.90 km, and its watershed contains four incorporated areas: Fulshear, Sugar Land, Stafford, and Missouri City. The Upper Oyster Creek watershed covers approximately 277.13 km^2, which is about 12.5% of the area of Fort Bend County. The Gulf Coast Water Authority (GCWA) uses the reach above Dam #3 to supply water for irrigation, industrial, and public drinking to areas southeast of the watershed and retains water for other areas (e.g. GCWA second lift station). The hydrology of the reach below Dam #3 is highly impacted by the presence of the dam and the second lift station. The lower reach contains no retention structures and is characterized by reduced flow composed of small amounts of seepage from Dam #3, contributions from municipal dischargers, natural contributions from the drainage area below the dam, and excess rainfall runoff from the upper reach above the dam (Hauck & Kim 2011).

Daily rainfall data were obtained for the period of 1 January 1991, through 31 December 2004, from the National Oceanic and Atmospheric Administration's National Climatic Data Center website (NCDC 2011). As shown in Figure 1, the five meteorological stations for rainfall data were Clodine, Katy, Richmond, Sugar Land, and Three Rivers. The SWAT input data are the same as the input that includes 30-m topography Digital Elevation Models, soils from the SSURGO database converted into ArcSWAT format, land use and land cover, and point sources for the Upper Oyster Creek watershed used by Du *et al.* (2009). The 1991–1997 naturalized flows, net evaporation minus precipitation depth, and water rights information that are inputs in the WRAP model were downloaded from the Texas Commission on Environmental Quality (TCEQ) website (TCEQ 2012). The 1998–2004 naturalized flow and net evaporation minus precipitation depth developed by Kim & Wurbs (2011b) were utilized for the simulation and analyses procedures. The WRAP model was utilized to compute the monthly regulated flows called gaged flows using the 1991–2004 monthly naturalized flows and water rights information.

Table 1 provides information about the two control points used in the WRAP model and two gage stations used in the SWAT model. Control point 517037 is located below gage station 12090 and directly above gage station 12089. Control point 533601 is located directly above gage station 12077 and below Dam #3. The daily flows at gage station 12089 are used for a daily flow pattern for control point 517037, because gage station 12090 is located far

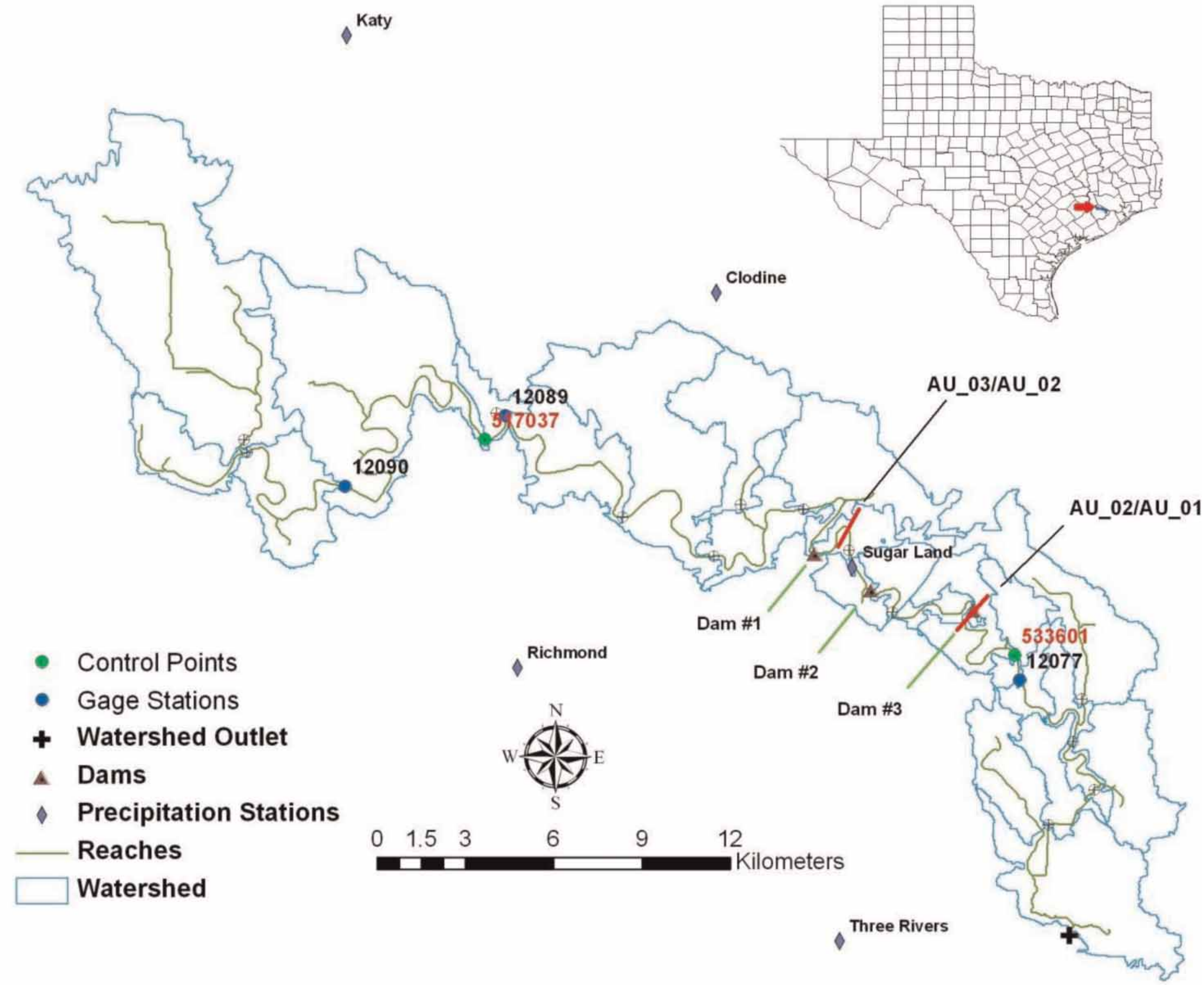

Figure 1 | Gage stations and control points in the Upper Oyster Creek Watershed in Fort Bend County, TX, USA.

Table 1 | Sub-basin information and water rights related to gage stations and control points

		Area (km^2)	Water rights (m^3/sec)	Purposes
Control points	517037	35.16	14.28	Municipal
	533601	8.51	0.63	Irrigation
Gage stations	12089	2.85	–	–
	12077	1.01	–	–

from control point 517031. Some lateral flows are merged into the main stream of Oyster Creek, which leads to the loss of the daily flow pattern characteristics at gage station 12090. Accordingly, the daily flows at gage stations 12089 and 12077 are transferred by the DAR method to each of control points 517037 and 533601, respectively.

Control points 517037 and 533601 have a 14.28 m^3/sec municipal-use water right and a 0.63 m^3/sec irrigation-use water right, respectively. Table 2 provides the characteristics of monthly mean naturalized flow. The lower naturalized flows occurred in July, which leads to the difficulty of monthly naturalized flow disaggregation, and the largest naturalized flows occurred in October. The regulated flows at two control points for the full authorization and current conditions data set (Wurbs 2005) were computed using the WRAP model. The full authorization simulation is used to evaluate applications for perpetual

Table 2 | 1991–2004 monthly naturalized flow average at two control points

	Month (m^3/sec)											
Control points	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
517037	3.90	2.73	2.32	3.02	2.88	3.62	0.92	2.07	2.90	4.18	3.00	3.23
533601	4.14	2.90	2.47	3.20	3.06	3.84	0.97	2.19	3.08	4.44	3.18	3.43

water rights and amendments. The simulation of the current conditions, which includes return flows, is used to evaluate applications for term water rights and amendments (TCEQ 2012).

METHODOLOGY

To use the SWAT daily flow as the flow pattern for monthly naturalized flow disaggregation, the following steps are performed. First, daily flows predicted by the SWAT model are aggregated into the monthly flow and compared with the regulated flow, which can be regarded as gaged flow because all water rights are considered in the WRAP simulation. Flow conversion factors are computed and used to match stream flow characteristics that are not considered in the SWAT model. Second, regression equations between monthly naturalized flow and regulated flow are developed because only monthly flows in the WRAP model are available in this study. These regression equations are used to convert the predicted daily flow into the daily pattern flow. Third, monthly naturalized flows are disaggregated based on the daily pattern flow by using the flow pattern option.

The daily flows for the years 1991–2004 at two gage stations were predicted using the SWAT model (Du *et al.* 2009) in this study. The SWAT daily flows at two stations are transferred to the control points that are used in the WRAP model using a generalized DAR method (Equation (1)), which provides reasonable results if streams have similar flow characteristics (Hirsch 1979). The bias-correction factors (K) and exponent factor (b) parameters in Equation (1) are assumed to be 1 in this study

$$Y_M = K\left(\frac{A_y}{A_x}\right)^b X_M \tag{1}$$

where Y_M is the estimated streamflow at control points, A_y is the drainage area at control points, A_x is the drainage area at gage stations, and X_M is the streamflow at gage stations.

Two kinds of monthly flow conversion factors for the full authorization and current use data set are developed by the WRAP monthly average regulated flow divided by the SWAT monthly average flow. The month conversion factor in July computed for 1991–2004 at control point 517037 is almost zero because of a low naturalized flow that leads all disaggregated daily flow during July to be zero. Accordingly, the July conversion factor is computed by averaging over all conversion factors of the 11 other months. After applying the monthly conversion factors to the SWAT monthly flows, the Nash–Sutcliffe model efficiencies (NSE) (Nash & Sutcliffe 1970), mean relative error (MRE), and correlation coefficient (R^2) are employed for comparing the regulated flow and the converted SWAT monthly flow. By doing this procedure, both the SWAT flow and regulated flow show similar characteristics. As mentioned above, regulated flows are regarded as gaged flow.

These monthly conversion factors are also applied to the SWAT daily flow, and regression equations developed based on the 1940–2007 monthly regulated and naturalized flow are used to convert SWAT daily flows in the daily pattern flow. Finally, two kinds of daily flow patterns developed are used for monthly flow disaggregation using Equation (2)

$$Q_D = \left(\frac{Q_M}{P_M}\right)P_m \tag{2}$$

where Q_M is the monthly flow volume, Q_D is the daily flow, P_M is the monthly total of daily pattern flow, and P_D is the daily pattern flows. Figure 2 provides the detailed procedures for generating the daily flows mentioned above.

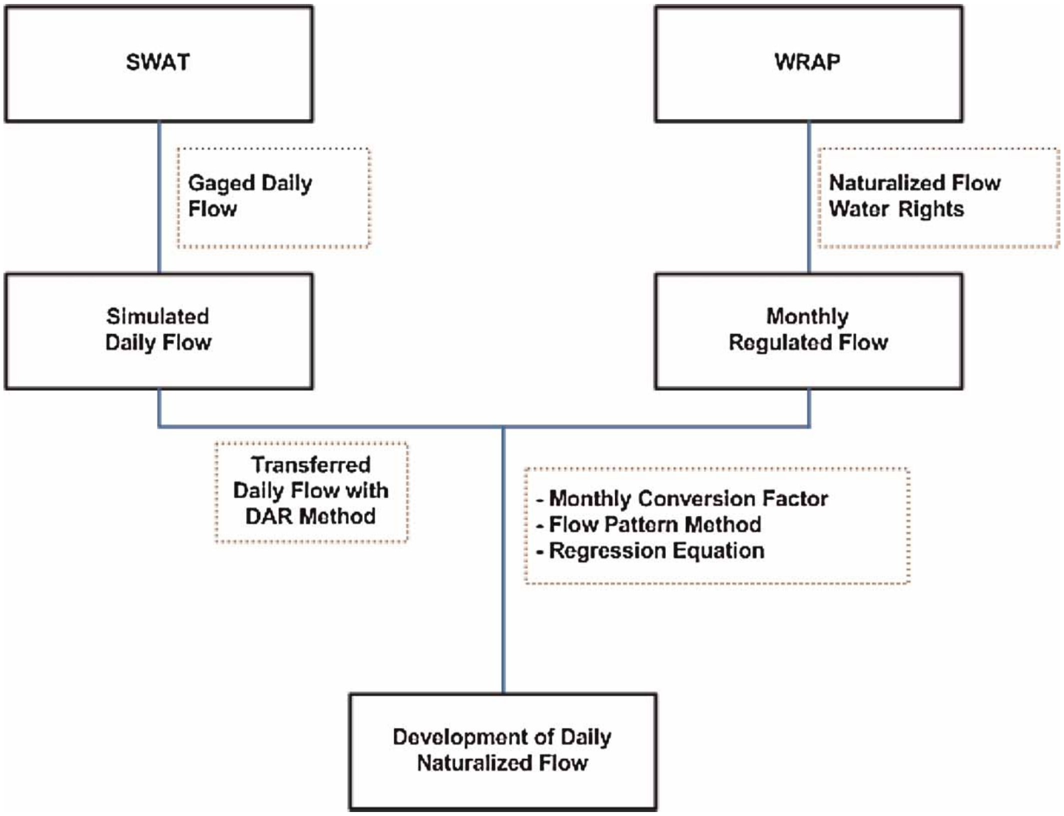

Figure 2 | Flow chart for disaggregating monthly flows.

RESULTS

Table 3 provides comparison results of the average, standard deviation, MRE, NSE, and R^2 values for both WRAP regulated flow and the converted SWAT flow at two control points. For the authorization full data set, control point 517037 shows an overestimation flow of 23%, while control point 533601 shows an underestimation of 9% according to the MRE. Also, NSE and R^2 values for two control points range from 0.38 to 0.45 and from 0.43 to 0.45, respectively. For the current use data set, the results are improved over the authorized data set results. The MRE values at control points 517037 and 533601 are 0.15 and –0.02, respectively. While NSE and R^2

Table 3 | Basic statistical analysis for regulated and converted monthly flows from 1991–2004

			Authorization full		Current use	
			517037 (m^3/sec)	533601 (m^3/sec)	517037 (m^3/sec)	533601 (m^3/sec)
WRAP	Regulated Flow	Mean	1.87	2.02	1.88	2.07
		S.D.	2.96	3.15	2.96	3.16
SWAT	Converted Flow	Mean	2.30	1.83	2.32	2.04
		S.D.	1.51	2.29	1.57	2.46
		MRE	0.23	–0.09	0.15	–0.02
		NSE	0.38	0.45	0.39	0.63
		R^2	0.43	0.45	0.43	0.63

values increase 40% over authorized data set results at control point 533601, NSE and R^2 values at control point 517037 are the same as the full authorization data set values. In conclusion, for both data sets, two kinds of flows at control point 533601 show a more reasonable match than flows at control point 517037.

Figure 3 shows a graphical comparison for WRAP regulated flows and SWAT flows at two control points, both with the full authorization and current use data sets. The peak flow at control point 517037 for the WRAP model is over-predicted by about 29 and 28% compared to the SWAT flow, while the peak flow at control point 533601 for the WRAP model is over-predicted by about 15 and 13% compared to the SWAT flow for the full and current data sets, respectively. Also, most of the SWAT flows at control point 533601 were close to the monthly regulated flows, while those at control point 517031 show little accuracy compared to monthly regulated flows.

Figure 4 shows two kinds of regression equations at each control point developed based on monthly naturalized and regulated flows from 1994–2007. R^2 values of all regression equations range from 0.89 to 0.90, which indicate high correlation relationships between two kinds of monthly flows. Table 4 provides the basic statistics results of monthly naturalized flows and disaggregated daily naturalized flows. The average and minimum values during 1991–2004 at each control point are almost the same, while the standard deviation and maximum values increase due to monthly naturalized flow disaggregation. Figure 5(a) shows a graphical comparison of monthly naturalized flow and daily naturalized flows which are averaged for each month during the 1991–2004 simulation periods at control point 533601 with the current use data set. The daily naturalized flow for July (Figure 5(b)) shows little fluctuation due to a low monthly naturalized flow and a low range of SWAT daily flow fluctuations. For the other 11 months, the daily naturalized flows are

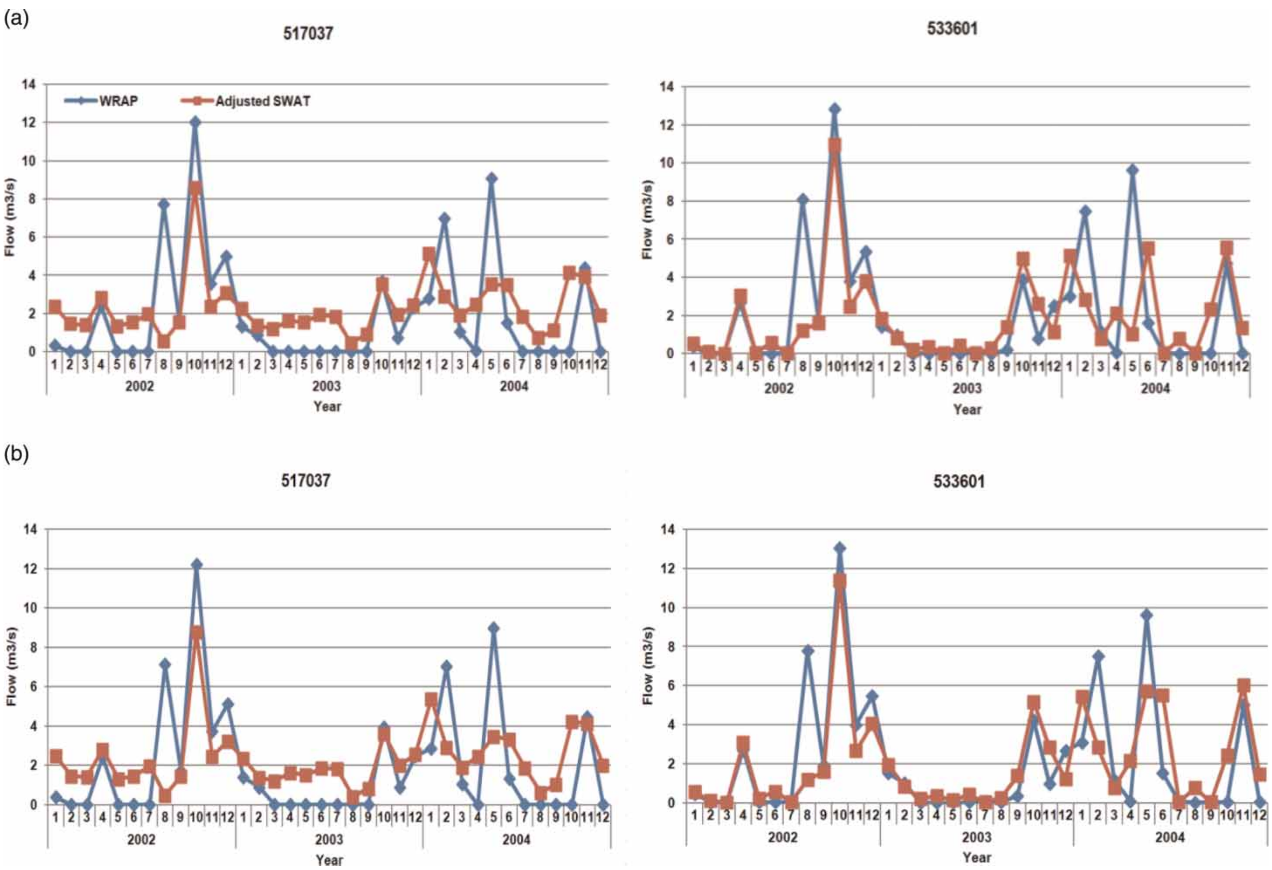

Figure 3 | Converted SWAT and regulated monthly flows comparison. (a) Full authorization; (b) current use.

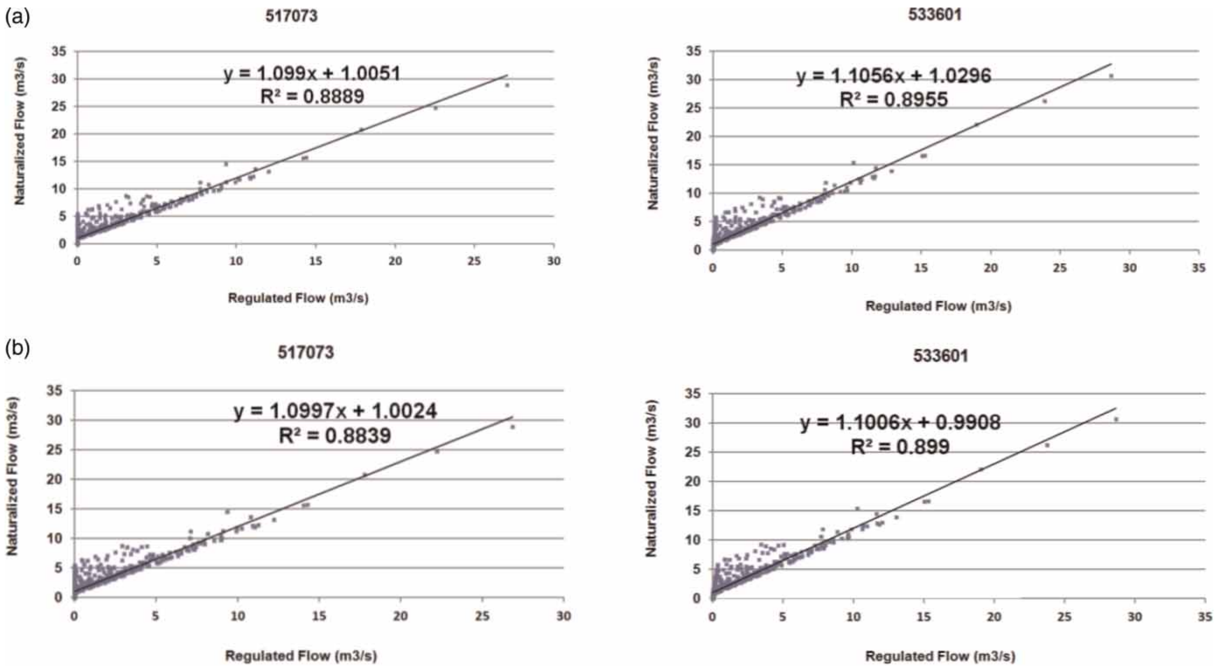

Figure 4 | Regression equation for monthly naturalized and regulated flow with full authorization and current use data. (a) Full authorization; (b) current use.

Table 4 | Comparison results for results for monthly and daily naturalized flows at two control points for authorized and current data set

	Monthly naturalized flow		Daily naturalized flow			
			Authorized		Current	
	517037 (m^3/sec)	533601 (m^3/sec)	517037 (m^3/sec)	533601 (m^3/sec)	517037 (m^3/sec)	533601 (m^3/sec)
Average	2.9	3.1	2.9	3.1	2.9	3.1
S.D.	3.06	3.25	5.92	8.66	5.93	8.99
Skew coefficient	1.32	1.32	6.42	7.43	6.43	7.30
Max	13.15	13.96	91.47	162.49	91.67	163.46
Min	0.02	0.02	0.01	0.02	0.01	0.02

sustained corresponding to daily flow patterns with the same average values.

SUMMARY AND CONCLUSIONS

The development of daily naturalized flow in the WRAP model was imposed on several difficulties that include the limitation of daily flow measurement, water right information, and budget constraints. This study focused on the development of daily naturalized flow using SWAT model, WRAP model, a flow pattern method and the DAR method. The SWAT model was validated with the daily flow measured at gage stations and was used for predicting the daily flow at gage stations. The SWAT daily flow was aggregated into monthly flow and compared with monthly regulated flow computed by the WRAP model for the authorized and current data set with the average, standard deviation, MRE, NSE, and R^2 values. The SWAT daily flow (called the regulated flow) was

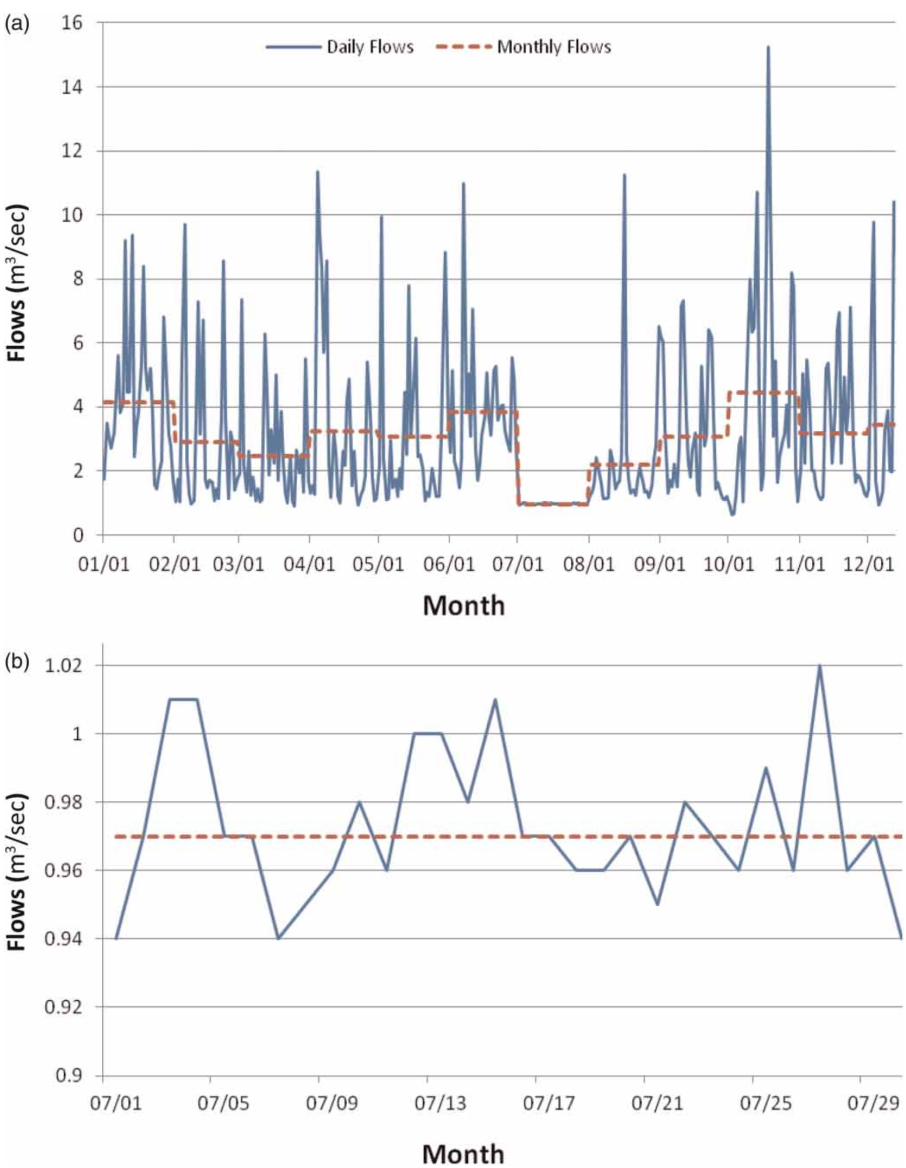

Figure 5 | Monthly average and daily average naturalized flow for 1991–2004 simulation periods. (a) Monthly and daily flows for 1 year; (b) monthly and daily flows for July.

converted using a regression equation into daily naturalized flow and used for the flow pattern at control points. The daily pattern flow at control points 517037 and 533601 was used for disaggregating the monthly naturalized flow. In conclusion, the system application of SWAT and WRAP models reduces the budget for the development of daily flows at primary control points associated with the WRAP model with monthly naturalized flows. Also, the combination of the DAR and flow pattern methods provides alternative ways to transfer and generate daily flows at ungaged stations with daily flow measured at nearby stations.

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