Research Article

Hydrodynamic Modeling of a Tropical Tidal River Using the Dynamic Estuary Model (DYNHYD5): A Case Study in Sibu Laut River, Sarawak, Malaysia

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Received 18 January 2018; Accepted 24 April 2018; Published 3 June 2018

Academic Editor: Jing-song Hong

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Application of the Dynamic Estuary Model (DYNHYD5) in a tropical tidal river is limited. The successfully calibrated and validated hydrodynamic model is valuable in subsequent water quality simulation for environmental management. Hence, a hydrodynamic modeling approach using the DYNHYD5 was conducted in a tropical tidal river in Malaysia. Samplings were conducted in the Sibu Laut River to collect the hydrology data for model simulation. The model was calibrated and validated by comparing the simulated flow and mean depth with the field data at different simulation periods of time. The results showed that the model DYNHYD5 was successfully calibrated with channel flows and mean depths and then reproduced with good agreement in validation. The observed and simulated data were linearly correlated ($R^2 > 0.8$) with values of slope γ ranging from 0.891 to 1.204 in both calibration and validation. The Nash–Sutcliffe coefficient of efficiency (NSE) of more than 0.7 in both calibration and validation also indicated satisfactory comparison between the observed and simulated data. The result indicated that the application of the DYNHYD5 is feasible in a tropical tidal river in Malaysia.

1. Introduction

The Dynamic Estuary Model DYNHYD5 [1] is a one-dimensional hydrodynamic model for simulating water velocities, flows, volumes, and heads using a channel junction (link-node) approach. The DYNHYD5 is the most recent version of the modeling software and is distributed and supported by the USEPA's Center through the WASP5 and WASP6 modeling software [2, 3]. The model utilizes a channel-junction (link-node) model network to perform simulations. Streams, rivers, or estuaries are broken down into a series of channels (links) and junctions (nodes). Each junction is a volumetric unit that acts as a receptacle for the water transported through its connecting channels, while each channel is an idealized rectangular conveyor that transports water between two junctions, whose midpoints are at each end. DYNHYD5 can be applied to river systems with moderate bed slopes as well as to tidally influenced estuaries. The model has the capability of simulating complex

branching river systems with a maximum of six links either leaving or entering a single junction.

The DYNHYD5 has been successfully used in hydrodynamic simulation, but mostly in a subtropical region. The hydrodynamic model has been calibrated to estimate the daily lake volume of Lake Marion, South Carolina Coastal Plain [4], the daily water level of Vistonis Lagoon, North Greece [5], and water levels and currents of the Venice Lagoon, Italy [6]. Besides, the channel flow and velocity variations in the river Mahadayi (Mandovi) and estuarine zone have been predicted for pre- and post-dam construction project scenarios with DYNHYD5 [7]. The successfully calibrated and validated model can be linked with the Water Quality Analysis Simulation Program (WASP) for water quality modeling.

The use of modeling in simulating river flows and water quality is lacking in tropical countries like Malaysia due to lack of data to calibrate and validate the models. The successful application of the models could aid in the environmental

FIGURE 1: Junction network and channel segmentation of the hydrodynamic model of the Sibulaut River and tributaries in Sarawak, Malaysia.

TABLE 1: Summary of hydrodynamic data collected for the calibration and validation of DYNHYD5.

Date	Channel number	1	2	4	5	7	8	9	10	11	12	13	14	15
20.12.10, HT	Time	1543	1535	1441	1432	1359	1332	1255	1230	1033	1206	1147	1118	1055
	Flow (cms)			879.7	476.7		1209.6			127.4	5.8		5.0	
	Mean depth (m)			9.9	8.0		14.1			3.5	3.3		3.1	
20.1.11, HT	Time		1442	1410	1318									
	Flow (cms)		2460.6	1251.7	364.3									
	Mean depth (m)		8.7	9.5	6.4									
24.1.11, LT	Time	918	956	1035	1126	1157								
	Flow (cms)	3006.9	748.1	515.3	63.1	932.2								
	Mean depth (m)	11.1	8.1	8.2	6.0	13.6								
24.1.11, HT	Time	1701						1613	1545	1523	1405	1434	1451	1506
	Flow (cms)	1819.2						2179.8	1346.4	375.8	4.0	7.3	249.4	701.1
	Mean depth (m)	9.9						12.4	12.7	4.6	2.3	4.3	3.3	14.9
22.2.11, LT	Time						913	947	1009		1103	1047	1027	
	Flow (cms)						4168.9	4840.4	4071.9		61.9	125.0	451.5	
	Mean depth (m)						14.0	13.2	13.2		3.1	5.4	5.3	
22.2.11, HT	Time						1428							
	Flow (cms)						845.7							
	Mean depth (m)						14.5							

HT, high tide; LT, low tide.

management as a decision-making tool in Malaysia. Sibulaut River is an important tidal river in Malaysia as it forms the western boundary of the Ramsar wetland and has the potential for the expansion of aquaculture. Thus, in this study, the Dynamic Estuary Model DYNHYD5 is selected for the simulation of the flow of the Sibulaut River. The present study is aimed at calibrating and validating the model by using hydrologic data collected from the field.

2. Materials and Methods

2.1. Study Area and Data Collection. The Sibulaut River, one of the tropical tidally dominated rivers in the northwest of Kuching, Sarawak, was selected in the present study (Figure 1). This river is one of the boundaries of the Kuching Wetlands National Park, a park designated as the Ramsar site (Ramsar site no. 1568) in November 2005 [8]. The length of the river studied was around 10 km, where the whole area was influenced

TABLE 2: Summary of changes (%) of channel flow and mean depth in sensitivity analysis.

Channel	M. coeff. 0.015		M. coeff. 0.055		M. coeff. 0.075		-50% inflow		+50% inflow		-50% SB		+50% SB	
	Flow	Depth	Flow	Depth	Flow	Depth	Flow	Depth	Flow	Depth	Flow	Depth	Flow	Depth
1	-0.3%	-0.2%	0.0%	0.4%	0.0%	0.9%	-50.1%	-0.2%	49.9%	0.2%	0.1%	-43.6%	0.6%	44.3%
2	0.1%	-0.2%	-0.1%	0.3%	-0.1%	0.8%	-50.0%	-0.1%	49.9%	0.2%	-0.1%	-42.0%	-0.6%	42.8%
3	0.2%	-0.4%	-0.3%	-0.1%	-0.3%	0.0%	-50.0%	-0.3%	49.8%	-0.2%	-0.3%	-50.1%	-2.2%	49.0%
4	0.3%	-0.1%	-0.4%	0.2%	-0.4%	0.5%	-49.9%	-0.1%	49.7%	0.1%	0.1%	-44.2%	-4.6%	44.5%
5	0.0%	-0.1%	0.0%	0.1%	-0.4%	-0.2%	-50.0%	0.0%	49.9%	-0.2%	-26.2%	-73.2%	-0.4%	66.8%
6	0.2%	-0.6%	-0.3%	0.1%	-0.4%	0.7%	-49.9%	-0.5%	49.8%	-0.1%	-12.1%	-55.4%	-3.6%	55.8%
7	0.7%	-0.1%	-0.5%	0.3%	-0.5%	0.6%	-49.9%	-0.1%	49.6%	0.2%	-8.4%	-26.8%	-5.2%	27.4%
8	-0.4%	-0.2%	0.3%	0.3%	0.3%	0.7%	-50.1%	-0.1%	50.2%	0.2%	4.4%	-28.3%	3.3%	28.9%
9	-0.5%	-0.2%	0.3%	0.3%	0.3%	0.7%	-50.1%	-0.1%	50.2%	0.2%	3.4%	-32.7%	3.1%	33.4%
10	-0.7%	-0.1%	0.4%	0.2%	0.4%	0.4%	-50.1%	-0.1%	50.3%	0.1%	4.7%	-33.1%	4.8%	33.6%
11	-0.1%	-0.2%	0.0%	0.3%	0.0%	0.8%	-50.0%	-0.1%	50.0%	0.1%	-15.0%	-97.8%	0.2%	114.9%
12	-0.2%	-6.1%	0.2%	6.5%	0.2%	13.0%	-50.2%	-5.6%	50.7%	-1.1%	0.4%	-38.7%	0.9%	216.2%
13	-0.1%	-0.2%	0.0%	0.4%	0.0%	0.9%	-50.1%	-0.1%	50.3%	0.1%	-11.0%	-96.8%	0.6%	110.5%
14	0.1%	-0.1%	0.0%	0.2%	-0.1%	0.4%	-50.0%	0.0%	50.2%	0.1%	-5.1%	-60.6%	0.7%	61.4%
15	-0.5%	0.0%	0.3%	0.1%	0.3%	0.2%	-50.1%	0.0%	50.2%	0.0%	1.2%	-32.3%	3.6%	32.7%

M. coeff., Manning's coefficient; SB seaward boundary.

by tide. Samplings were conducted during high and low tide conditions as summarized in Table 1. Velocity and depth were measured using a flow meter (Geopacks) and a depth finder (PS-7, Hondex), respectively. Flow, mean velocity, and mean depth were calculated according to Chapra [9] for calibration and validation of the hydrodynamic simulation.

2.2. The Dynamic Estuary Model DYNHYD5. The Dynamic Estuary Model DYNHYD5 [1] was used to simulate a one-dimensional hydrodynamic condition of the Sibu Laut River and its principal tributaries in the present study. For the hydrodynamic simulation, 16 junction locations were chosen along the Sibu Laut River and tributaries. The placement of model junctions led to the definition of 15 model channels. Figure 1 shows the junction network and channel segmentation used in the model calibration and validation. The DYNHYD5 employs a junction/channel numbering convention, which starts upstream (junction/channel number 1) and works downstream (junction/channel number N) in the "positive" direction of flow.

All segments have rectangular cross sections and a mean length and width of about 1200 m and 400 m, respectively. Manning's roughness coefficient is the primary calibration parameter in DYNHYD5, where it was adjusted until the simulated data converged upon the observed data. Finally, Manning's roughness coefficient of 0.035 was used for each channel in the model network. Variables were inputted at each corresponding segment. Junction 16 which is the most downstream of the river was designated as the seaward boundary. High and low tide heights versus time were specified for an entire simulation period. However, the Sarawak Marine Department does not operate or maintain a tidal stage recorder near or around Sibu Laut Estuary. As a result, the Sarawak Marine Department tide predictions for the Santubong Estuary [10, 11] were used as the boundary conditions for the downstream seaward boundary.

TABLE 3: Summary of the best-fit criteria used for DYNHYD5 calibration and validation.

Parameter	Calibration		Validation	
	Flow	Depth	Flow	Depth
γ	0.997	0.891	1.204	0.967
R^2	0.949	0.804	0.926	0.904
NSC	0.95	0.77	0.79	0.87
N	20	20	6	6

The model was calibrated and validated based on the flow and mean depth measured previously at different segments of the river. DYNHYD5 calibration simulation runs began on day 1 (1 January 2010) and ended on day 58 (28 February 2010), while validation simulation runs began on day 1 (1 December 2010) and ended on day 31 (31 December 2010). Model junction and channel data remained constant and did not vary between calibration and validation simulation runs. The time step selected for this simulation was 60 seconds. A conventional sensitivity analysis was conducted by varying the values of selected model parameters during simulation. The changes of the output were used to identify the most sensitive parameters of the model.

The model performance was evaluated via two best-fit criteria for hydrological model [12]. The linear regression between simulated and observed data was conducted, where the best agreement between simulated and observed values is achieved when the values of slope γ and R^2 are close to 1.0. The Nash-Sutcliffe coefficient of efficiency (NSE) was also calculated to test the agreement between simulated and observed values where the best value of NSE is 1.0; a NSE value greater than 0.75 indicates good simulation results, and values of NSE between 0.75 and 0.36 indicate satisfactory simulation results [13].

3. Results and Discussion

3.1. DYNHYD5 Calibration. The calibration of DYNHYD5 was carried out by comparing the model outputs with the

FIGURE 2: Calibration chart of channel flow conducted at various channels on (a) 20 January 2011, (b–d) 24 January 2011, and (e, f) 22 February 2011.

measured data in 13 channels of the Sibu Laut River collected in the field work during 1 January to 28 February 2011 (Table 1). Both current and channel mean depth are measured during these periods. The value of Manning's coefficient was maintained for all channels, as sensitivity analysis indicated that the impact of Manning's coefficient on channel flow and mean depth was small (Table 2). In the hydrodynamic modeling of the Venice channels, Umgiesser and Zampato [6] found that the velocity was more sensitive to the variations of Manning's coefficient than elevation. The average error of elevation remained constant, while the average error of current speed ranged from 6.1 to 12.1 cm/s

when Manning's coefficient varied from 0.020 to 0.050. The sensitivity analysis in the present study also shows that the inflow has major impact on the channel flow but has minor impact on the mean depth. On the contrary, the seaward boundary data have profound impact on channel mean depth, but the impact on channel flow is small. The impact of the inflow and seaward boundary data is different on each channel. Table 2 shows that the seaward boundary data have the greatest impact on channels 11, 12, and 13 which were located at the two tributaries of the Sibu Laut River. The mean depth of the three channels increased by 110.5% to 216.2% when the seaward boundary increased by 50%.

FIGURE 3: Calibration chart of mean depth conducted at various channels on (a) 20 January 2011, (b–d) 24 January 2011, and (e, f) 22 February 2011.

The mean depths of the three channels decreased by 38.7% to 97.8% when the seaward boundary decreased by 50%. The impact of the inflow on channel flow was more consistent where a 50% enhancement or reduction of the inflow resulted in approximately 50% increase or decrease of the entire channel flow rate.

The calibration results show an excellent agreement of the simulated hydrodynamic parameters with field data (Table 3). The simulated channel flow and mean depth linearly correlated with the observed channel flow ($R^2=0.949$) and mean depth ($R^2=0.804$). The slope γ obtained for both parameters was close to 1.0. The NSE calculated for the channel flow and mean depth were 0.95 and

0.77, respectively. It can be stated that the channel flow is reproduced with greater accuracy than the mean depth. Most of the simulated channel flow converged upon or were close to the observed data except channels 12, 13, and 14, which were located along Selang Sibu River (Figure 2). The channel flows along the Selang Sibu River was over-estimated. In the hydrodynamic modeling of the Venice channels, the elevation is reproduced with greater accuracy than the velocity during calibration, as the average error of the water level was smaller than the current speed [6]. On the contrary, noticeable discrepancy between simulated and observed mean depth was observed at some of the channels (Figure 3). The model underestimated the mean depth at

FIGURE 4: Validation chart of the channel flow (a, c, e) and mean depth (b, d, f) at various channels on 20 December 2010.

channel 15, which is the most downstream location of the river. The mean depth at channel 14 was simulated closely to observed data during low tide on 22 February 2011 but was overestimated during high tide on 24 January 2011. As can be seen from Figure 3, the model could simulate the mean depth of the channel, but the simulated mean depth either showed a lag compared to the observed data or was simulated one or two hours earlier than the observed data. The result showed that the model tends to simulate the mean depth earlier than the observed data during low tide condition but simulate the mean depth later than the observed data during high tide condition.

3.2. DYNHYD5 Validation. The calibrated model was verified with the field data collected on 20 December 2010 (Table 1). The simulated channel flows and mean depth have been

compared with the observed data measured in six channels. The simulated channel flow and mean depth linearly correlated with the observed channel flow ($\gamma = 1.204$, $R^2 = 0.926$) and mean depth ($\gamma = 0.967$, $R^2 = 0.904$) during validation (Table 3). The NSE value for both parameters was greater than 0.75, which indicated good simulation results. A comparison of model simulation with field data for each segment is presented in Figure 4, conferring that the model reproduces the channel flows and mean depth with good accuracy. The channel flows in most channels are simulated as observed, except that the model overestimated the flow of channel 5 but underestimated the flow of channel 8. Figure 4 shows that the channel mean depth is reproduced better at the upstream of the river than at downstream tributaries. The noticeable discrepancy between the simulated and observed mean depth was observed at channels 11, 12, and 14, which were located at the downstream tributaries and at the river mouth of the river.

In the present study, the model DYNHYD5 was successfully calibrated with mean depths and channel flows and then reproduced with good agreement in validation. The simulated and observed data linearly correlated ($R^2 > 0.8$) in both calibration and validation. Gikas et al. [5] reported the correlation between the predicted and measured water level in the Vistonis Lagoon. The authors showed that the corresponding R^2 values of 0.78 and 0.66 in 1998 and 1999 were a rather satisfactory calibration. In the present study, most of the simulated channel flows and mean depth converged upon the observed data. Some discrepancies were observed where the simulated data were simulated one or two hours earlier or later than the observed data. This discrepancy may be attributed to the use of tide predictions of the Santubong River as a downstream seaward boundary input due to the lack of tidal monitoring data in the Sibulaut River. Discrepancy is not uncommon in hydrodynamic modeling. De Smedt et al. [14] demonstrated that the calculated and measured water levels in the Scheldt estuary agreed well, while calculated velocities and flows are lower than the observed values. The authors attributed the lower agreement between calculated and observed data to the limited measurements of velocities and flows to verify the simulation results.

4. Conclusion

The model DYNHYD5 was successfully calibrated with mean depths and channel flows measured in the Sibulaut River and then reproduced with good agreement in validation. The values of slope γ (0.891 to 1.204), R^2 (0.804 to 0.849), and NSE (0.77 to 0.95) that are close to 1.0 indicate a good agreement between simulated and observed data in both calibration and validation. Some discrepancies in the simulated and observed data were observed, which is most probably due to the lack of tidal monitoring data in the Sibulaut River. The present study revealed that the application of DYNHYD5 is feasible in a tropical tidal river in Malaysia. The successfully calibrated and validated model can be linked with the WASP for water quality modeling in future studies.

Data Availability

Access to the data used to support this study will be considered by the author upon request via email.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors appreciate the financial support provided by the Malaysian Ministry of Science, Technology and Innovation (MOSTI) through E-Science Grant 06-01-09-SF0026 and the Ministry of Higher Education (MOHE) through FRGS Grant FRGS/07(02)/749/2010(35) and the facilities provided by Universiti Malaysia Sarawak.

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