RESULTS AND DISCUSSION

In this section, the results of the application of the CoastalGate model for planning the coastal gate operation schedules of Pak Phanang River Basin are first illustrated. Then the results of utilizing Artificial Neural Networks (ANNs) for deriving coastal gate operation rules for a simplified hypothetical coastal gate that relates to Uthokawiphatprasit water gate, located at Pak Phanang River Basin, Nakorn Si Thammarat province, are presented. The detailed information of each experiment can be described as follows.

1. Application of CoastalGate model to Pak Phanang River Basin

The purpose of this section is to demonstrate the capability and use of the CoastalGate model developed in the present dissertation research for planning coastal gate operations. A hypothetical coastal gate system representing coastal gate system of Pak Phanang River Basin was considered herein as a study case. There are two parts that were conducted in this section. Firstly, the optimal DE's parameters were determined for the considered coastal gate system to obtain the reliable solution. Secondly, the applicability of the CoastalGate model is demonstrated through an example with four cases that analyze the difference of a baseline scenario (BAS) and three full optimization scenarios (FOP), which weighting factor for an area of interest and relative importance of interesting parameters in water subsystem within a particular area are defined with three different data sets. The details of each experiment are described as follows.

1.1 Determination of the optimal DE's parameters

As mentioned previously, the Differential Evolution (DE) needs four parameters: (1) maximum number of generations; (2) population size within each generation (NP); (3) weighting factor (F); and (4) crossover constant (CR). It is time consuming to find "suitable" (not necessarily the "best") parameters for different problems because each applied problem will have different suitable parameters. In present study, the best set will be selected when the highest satisfaction function value is obtained and time taken is not much or over control horizon.

A series of sensitivity were carried out to establish appropriate DE's parameters. Table 4 shows the results obtained from varying the values of number of generations and number of populations (NP) for 10 study cases while fixing F and CR values of 0.8, 0.8, respectively. The satisfaction function values for all cases look similar and close to -4000. However, for choosing the most suitable parameters for this study, test #8 is the best because it has the highest satisfaction function value of -3999. Hence, the suitable number of generations and number of populations equal to 3 and 50, respectively. The test #5, #6, #7, #9, and #10 may not be appropriate for the model application because time taken is over considered control horizon of 1 hour.

Such both suitable parameters for this study case are quite low when compared with other optimization problems since total search space for this study case is quite small (10^5 combinations:- 10 gates and each gate takes 5 possible values). This shows very fast convergence since it used only approximately 200 times for function evaluation. However, the execution time was approximately 50 minutes for one run time step on a 160 MHz Pentium PC. This is because in solving the problem it is necessary to routinely invoke mathematical simulation model several times, especially calling water quality model, which requires rather much computation time. Hence, this developed model is quite appropriate for planning coastal gate operation in advance than using for real-time control tasks, which need making a decision in very short time interval. However, the further development of faster computing equipment and more efficient numerical methods for HQ and WQ models will extend the capability of this proposed methodology.

Table 4 The sensitivity analysis results of maximum number of generations and number of population.

Test no.	Generation	NP	Satisfaction function	Time taken (min.)
1	2	25	-4087	19
2	2	30	-4027	23
3	2	40	-4140	30
4	2	50	-4058	38
5	2	80	-4003	60
6	2	100	-4033	75
7	2	150	-4040	113
8	**3**	**50**	**-3999**	**50**
9	3	100	-4023	100
10	5	50	-4046	76

Table 5 shows the results obtained from varing values of F and CR while fixing values of number of generations and number of populations of 3 and 50, respectively. It was found that when CR equal to 0.4 for varying values of F, all satisfaction function values are very good compared to other cases. However, the suitable values for F and CR parameters in this study case equal to 0.8 and 0.8, respectively since both gave the highest satisfaction function value of -4030. Therefore, it can be concluded that the optimal DE's parameters for this experiment are 3, 50, 0.8, and 0.8 for number of generations, number of populations, weighting factor, and crossover constant, respectively. These optimal parameters will be use in the following section.

The reason why satisfaction function as expressed in equation 32 is the negative for the study case is because the current values of state variables like water levels, salinity concentrations, and dissolved oxygen concentrations at each selected control points are quite deviate from these desired target values. In addition, the exogenous system inputs such as rainfall, upstream discharge, and tide water level limit the model to find the better results.

Table 5 Satisfaction function value on effects of varying F and CR values for Pak Phanang coastal gate system.

F	Satisfaction function									
	CR = 0.1	CR = 0.2	CR = 0.3	CR = 0.4	CR = 0.5	CR = 0.6	CR = 0.7	CR = 0.8	CR = 0.9	CR = 1.0
0.1	-4110	-4110	-4220	**-4100**	-4220	-4220	-4180	-4220	-4220	-4110
0.2	-4190	-4190	-4220	**-4050**	-4220	-4070	-4070	-4220	-4220	-4220
0.3	-4110	-4110	-4220	**-4100**	-4220	-4220	-4070	-4220	-4220	-4220
0.4	-4110	-4190	-4220	**-4050**	-4200	-4200	-4070	-4070	-4220	-4220
0.5	-4190	-4190	-4050	**-4050**	-4210	-4210	-4170	-4200	-4200	-4200
0.6	-4190	-4110	-4050	**-4100**	-4070	-4040	-4200	-4200	-4200	-4170
0.7	-4190	-4190	-4210	**-4100**	-4170	-4170	-4170	-4070	-4170	-4060
0.8	-4110	-4.190	-4050	**-4050**	-4070	-4210	-4190	**-4030**	-4210	-4210
0.9	-4190	-4190	-4210	**-4050**	-4210	-4070	-4070	-4060	-4060	-4070
1	-4190	-4190	-4210	**-4050**	-4210	-4190	-4210	-4060	-4070	-4060

1.2 Simulation results

For the purpose of demonstrating the use of CoastalGate model for planning schedules of coastal gate operations, four study cases were considered. In the first case, since there is presently no a certain rule for controlling water gate located in PPRB, i.e. all gates were generally closed during dry season and opened during rainy season, for this study, it was considered as a baseline scenario (BAS). Therefore, in this experiment, the crest level of Uthokawiphatprasit regulating gate is set at 1.0 meter above mean sea level, and the gate opening of the remaining nine gates: Sua Hueng, Pakrawa, Emergency, Thaphraya, Klong Khong, Chian Yai, Bang Sai, Sukoom, and Praekmueng are zero. In the rest three cases, the operation schedules of the gates in coastal river system guided by the CoastalGate model with three different data sets of weighting factor for an area of interest and relative importance of interesting parameters in water subsystem within a particular area are referred to full optimization scenario#1 (FOP#1), full optimization scenario#2 (FOP#2), and full optimization scenario#3 (FOP#3), respectively.

In fact, the number of different parameter combinations is infinite, and it is not possible to test each of them; therefore, only three case studies are investigated herein. In addition, both factors given to a particular objective plays an importance role in coastal gate operation may vary with space and time depending on the agreement between stakeholders and government agencies. However, for simplicity, such factors are assumed to be constant for all control periods, although these values are easily changed for prioritization of concerning water parameters such as location and time of day.

It should be noted that weighting factor for an area of interest and relative importance of interesting parameters in water subsystem within a particular area given for BAS and FOP#1 are the same. For FOP#2, the effects of changing the relative importance data set are investigated and the effects of changing both weighting factor and relative importance data set are also investigated in FOP#3. The values of weighting factor and relative importance given for FOP#1, FOP#2, and FOP#3 are presented in Tables 6, 7, and 8, respectively. And the desired criteria used for controlling a coastal gate system are presented in Table 9. It shows that at Uthokawiphatprasit, Sua Hueng, and Pakrawa water gates, the values of six state variables, i.e. water levels, salinity concentrations, and dissolved oxygen concentrations at both upstream and downstream control points are considered for controlling the gates. Whereas, for, Emergency, Thaphraya, Praekmueng water gates, the values of three state variables, i.e. water levels, salinity concentrations, and dissolved oxygen concentrations only at upstream control points are used as criteria for gate operations. And the values of four state variables, i.e. water levels at upstream control points, water levels, salinity concentrations, and dissolved oxygen concentrations at downstream control points are considered to operate Klong Khong, Chian Yai, Bang Sai, and Sukoom water gates.

Table 6 The values of weighting factor and relative importance given for FOP#1.

GATE	WF	relative importance					
		WL_US	SAL_US	DO_US	WL_DS	SAL_DS	DO_DS
Uthokawiphatprasit	1.0	0.3	0.1	0.1	0.1	0.2	0.2
Sua Hueng	1.0	0.3	0.1	0.1	0.1	0.2	0.2
Pakrawa	1.0	0.167	0.167	0.167	0.167	0.167	0.167
Emergency gate	1.0	0.4	0.3	0.3	0.0	0.0	0.0
Thaphraya	1.0	0.4	0.3	0.3	0.0	0.0	0.0
Klong Khong	1.0	0.5	0.0	0.0	0.1	0.2	0.2
Chian Yai	1.0	0.5	0.0	0.0	0.1	0.2	0.2
Bang Sai	1.0	0.5	0.0	0.0	0.1	0.2	0.2
Sukoom	1.0	0.4	0.0	0.0	0.2	0.2	0.2
Praekmueng	1.0	0.6	0.3	0.1	0.0	0.0	0.0

Remark WL_US = water levels at upstream gate;
WL_DS = waters level at downstream gate;
SAL_US = salinity concentrations at upstream gate;
SAL_DS = salinity concentrations at downstream gate;
DO_US = dissolved oxygen concentrations at upstream gate; and
DO_DS = dissolved oxygen concentrations at downstream gate.

Table 7 The values of weighting factor and relative importance given for FOP#2.

GATE	WF	relative importance					
		WL_US	SAL_US	DO_US	WL_DS	SAL_DS	DO_DS
Uthokawiphatprasit	1.0	0.4	0.3	0.1	0.05	0.1	0.05
Sua Hueng	1.0	0.4	0.3	0.05	0.05	0.15	0.05
Pakrawa	1.0	0.167	0.167	0.167	0.167	0.167	0.167
Emergency gate	1.0	0.5	0.3	0.2	0.0	0.0	0.0
Thaphraya	1.0	0.5	0.3	0.2	0.0	0.0	0.0
Klong Khong	1.0	0.5	0.0	0.0	0.2	0.1	0.2
Chian Yai	1.0	0.5	0.0	0.0	0.2	0.1	0.2
Bang Sai	1.0	0.5	0.0	0.0	0.2	0.1	0.2
Sukoom	1.0	0.5	0.0	0.0	0.1	0.2	0.2
Praekmueng	1.0	0.6	0.3	0.1	0.0	0.0	0.0

Remark WL_US = water levels at upstream gate;
WL_DS = waters level at downstream gate;
SAL_US = salinity concentrations at upstream gate;
SAL_DS = salinity concentrations at downstream gate;
DO_US = dissolved oxygen concentrations at upstream gate; and
DO_DS = dissolved oxygen concentrations at downstream gate.

Table 8 The values of weighting factor and relative importance given for FOP#3.

GATE	WF	relative importance					
		WL_US	SAL_US	DO_US	WL_DS	SAL_DS	DO_DS
Uthokawiphatprasit	2.5	0.4	0.3	0.1	0.05	0.1	0.05
Sua Hueng	1.0	0.4	0.3	0.05	0.05	0.15	0.05
Pakrawa	0.5	0.167	0.167	0.167	0.167	0.167	0.167
Emergency gate	1.0	0.5	0.3	0.2	0.0	0.0	0.0
Thaphraya	1.0	0.5	0.3	0.2	0.0	0.0	0.0
Klong Khong	0.5	0.5	0.0	0.0	0.2	0.1	0.2
Chian Yai	0.5	0.5	0.0	0.0	0.2	0.1	0.2
Bang Sai	0.5	0.5	0.0	0.0	0.2	0.1	0.2
Sukoom	0.5	0.5	0.0	0.0	0.1	0.2	0.2
Praekmueng	2.0	0.6	0.3	0.1	0.0	0.0	0.0

Remark WL_US = water levels at upstream gate;
WL_DS = waters level at downstream gate;
SAL_US = salinity concentrations at upstream gate;
SAL_DS = salinity concentrations at downstream gate;
DO_US = dissolved oxygen concentrations at upstream gate; and
DO_DS = dissolved oxygen concentrations at downstream gate.

Table 9 The desired criteria used for controlling a coastal gate system located in PPRB.

GATE	WL_US (m)			WL_DS (m)			SAL_US (ppt)			SAL_DS (ppt)			DO_US (mg/l)			DO_DS (mg/l)		
	Max	Min	Target	Max	Min	Target	Max	Min	Target	Max	Min	Target	Max	Min	Target	Max	Min	Target
G1	0.3	0	0.3	0.6	-0.3	0.15	2	0	1	26	20	23	9	3	6	9	3	6
G2	0.3	0	0.3	0.8	-0.3	0.25	2	0	1	26	20	23	9	3	6	9	3	6
G3	0.6	0	0.6	0.6	-0.3	0.15	26	20	23	26	20	23	9	3	6	9	3	6
G4	0.3	0	0.3	N/A	N/A	N/A	2	0	1	N/A	N/A	N/A	9	3	6	N/A	N/A	N/A
G5	0.3	0	0.3	N/A	N/A	N/A	2	0	1	N/A	N/A	N/A	9	3	6	N/A	N/A	N/A
G6	1.0	0	1.0	0.3	0	0.15	N/A	N/A	N/A	0	0	0	N/A	N/A	N/A	9	3	6
G7	1.0	0	1.0	0.3	0	0.15	N/A	N/A	N/A	0	0	0	N/A	N/A	N/A	9	3	6
G8	0.4	0.1	0.4	0.3	0	0.15	N/A	N/A	N/A	0	0	0	N/A	N/A	N/A	9	3	6
G9	0.3	0.1	0.3	0.6	0.3	0.45	N/A	N/A	N/A	26	20	23	N/A	N/A	N/A	9	3	6
G10	0.8	0	0.8	N/A	N/A	N/A	2	0	1	N/A	N/A	N/A	9	3	6	N/A	N/A	N/A

Remark: G1 = Uthokawiphatprasit; G2 = Sua Hueng; G3 = Pakrawa; G4 = Emergency gate; G5 = Thaphraya; G6 = Klong Khong;

G7 = Chian Yai; G8 = Bang Sai; G9 = Sukoom; G10 = Praekmueng;

WL_US = water levels at upstream gate; WL_DS = waters level at downstream gate;

SAL_US = salinity concentrations at upstream gate; SAL_DS = salinity concentrations at downstream gate;

DO_US = dissolved oxygen concentrations at upstream gate; and
DO_DS = dissolved oxygen concentrations at downstream gate.

The hourly operation schedules of coastal gate system located in Pak Phanang River Basin for three full optimization scenarios obtained from running CoastalGate model are shown in Figures 23 to 32 for Uthokawiphatprasit gate, Sua Hueng gate, Pakrawa gate, Emergency gate, Thapraya gate, Klong Khong gate, Chian Yai gate, Bang Sai gate, Sukoom gate, and Praekmueng gate, respectively. These results give the guidelines for operation planning of coastal gate system for 24 hours ahead. It is clearly found that when the different weighting factor and relative importance are given, the different control strategies (see Figures 23 to 32) as well as the different state variables through control horizon (see Figures 34 to 43) are obtained.

Considering the change of gates from run time step to run time step, it is found that there is no occurrence of a sharp change situation since theirs changes do not exceed 2.0 meter, which is the given allowable maximum change of gate settings for this case. Therefore, the preventing in violation of physical bounds on gate operations developed in present research is work.

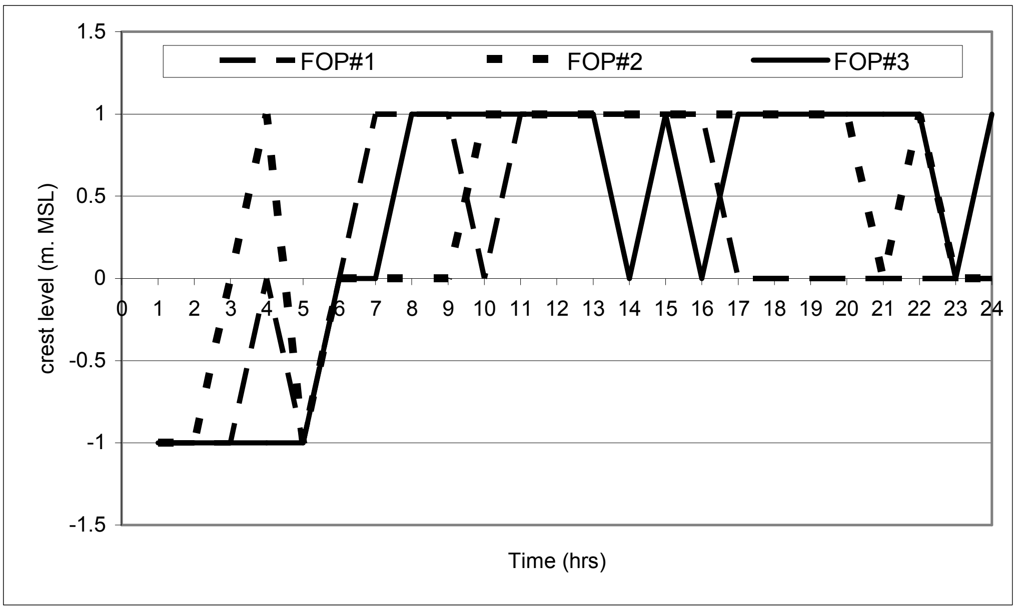


Figure 23 Optimal crest level setting for Uthokawiphatprasit gate.

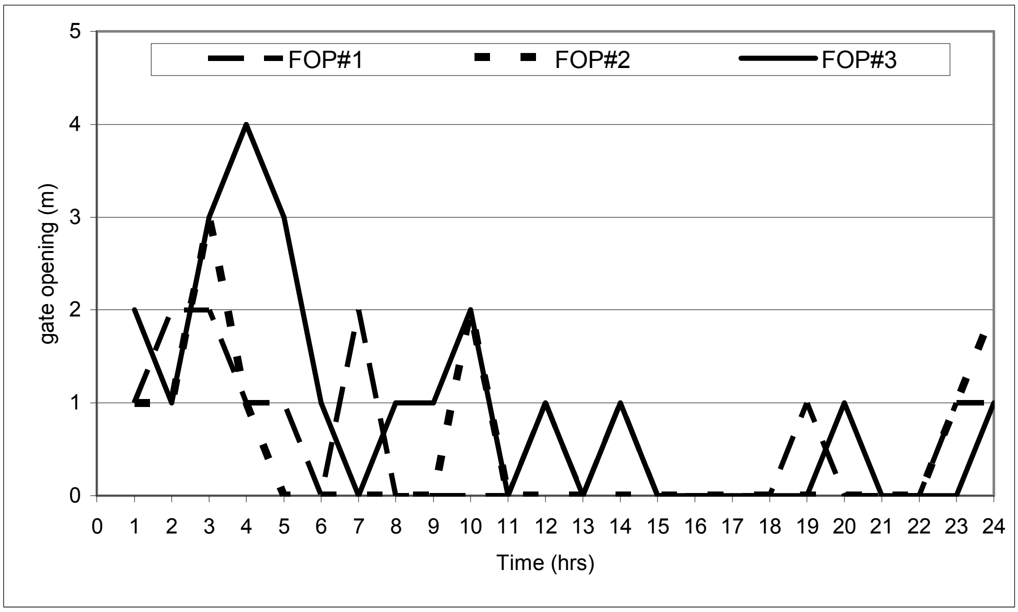


Figure 24 Optimal gate opening for Sua Hueng gate.

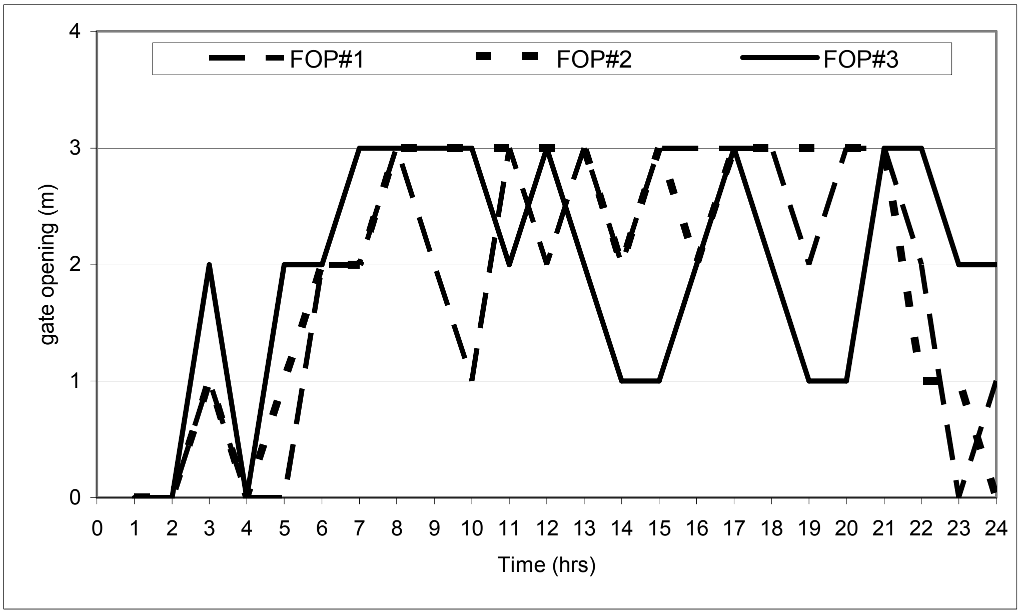


Figure 25 Optimal gate opening for Pakrawa gate.

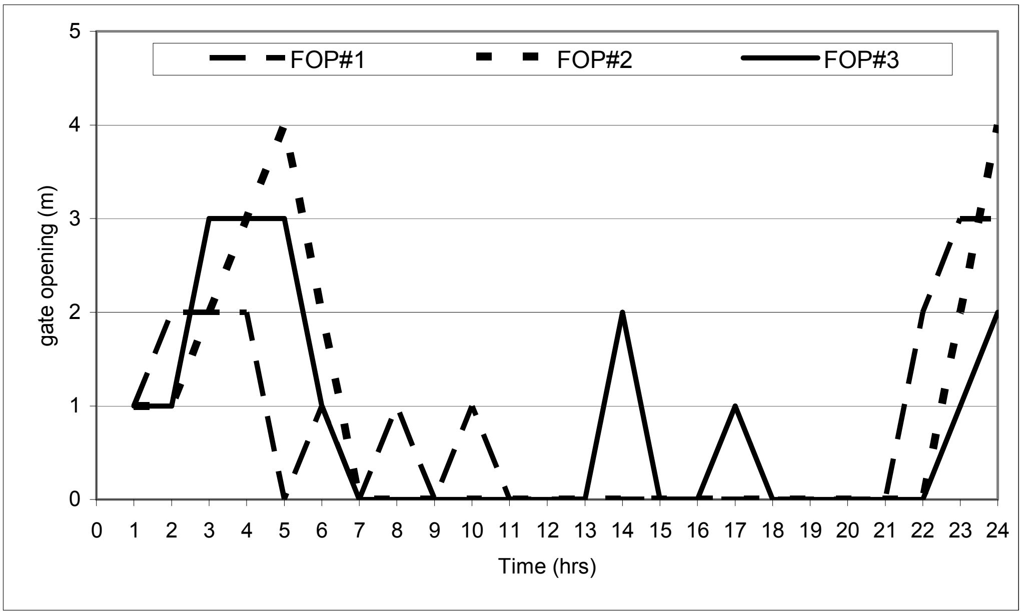


Figure 26 Optimal gate opening for Emergency gate.

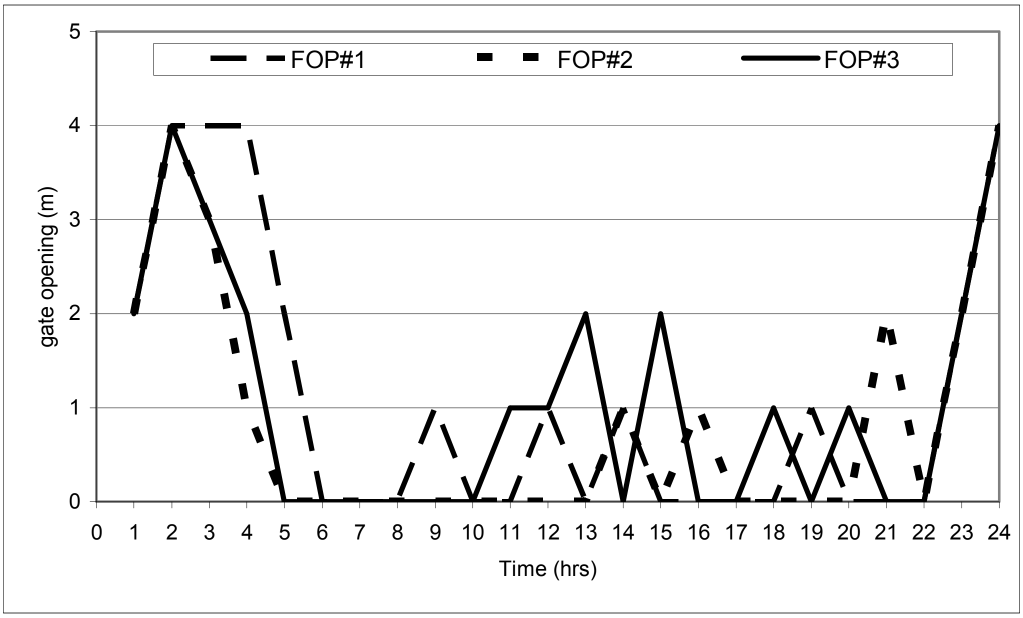


Figure 27 Optimal gate opening for Thapraya gate.

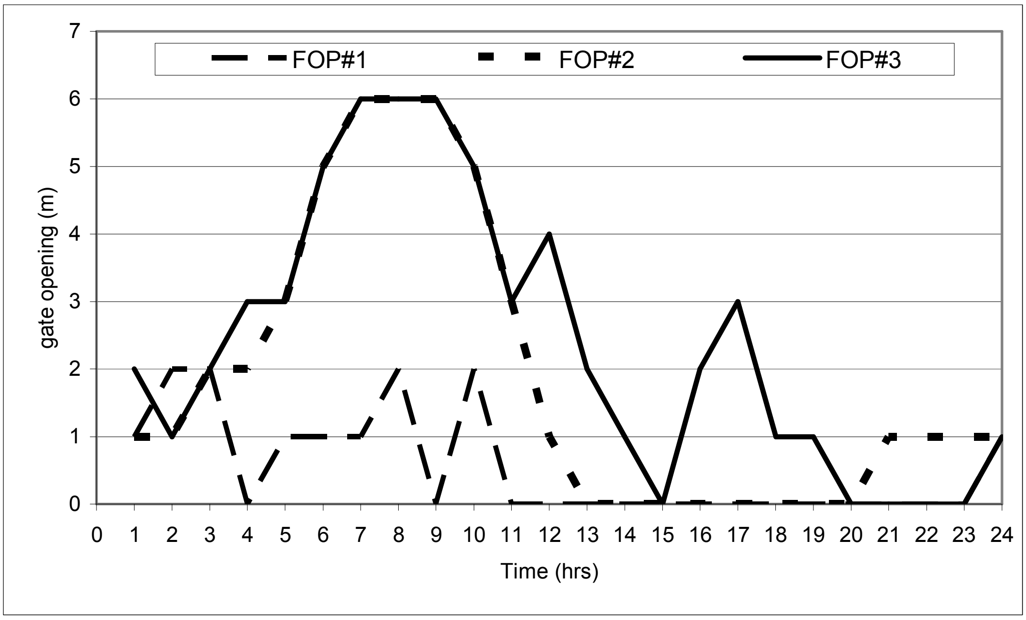


Figure 28 Optimal gate opening for Klong Khong gate.

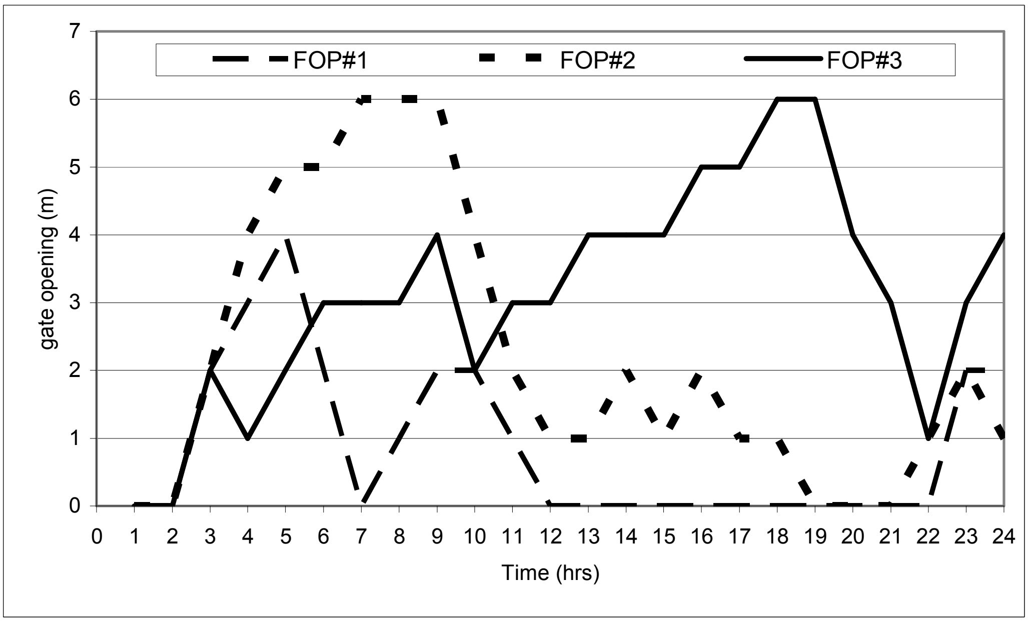


Figure 29 Optimal gate opening for Chian Yai gate.

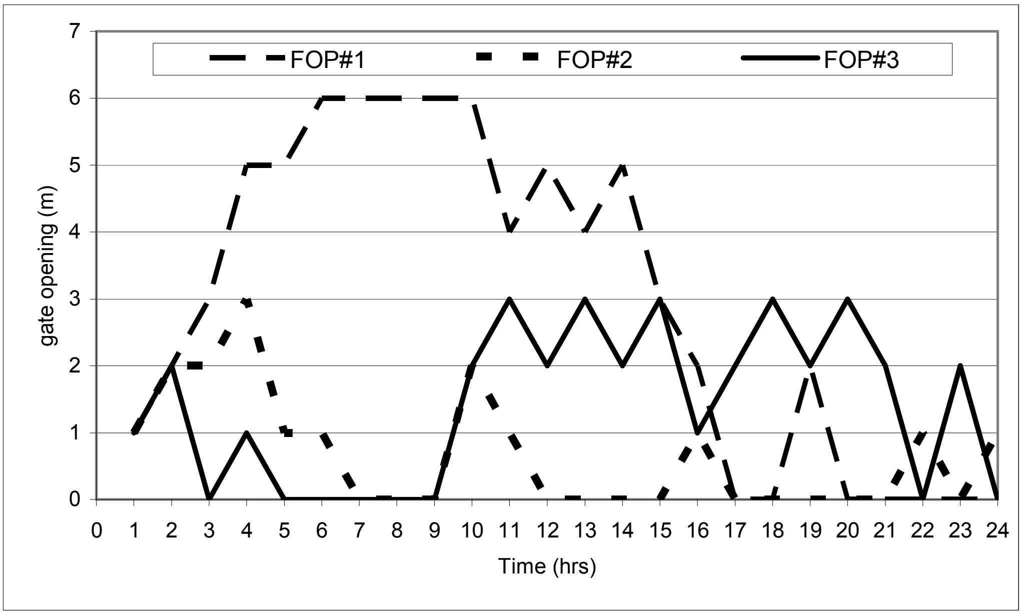


Figure 30 Optimal gate opening for Bang Sai gate.

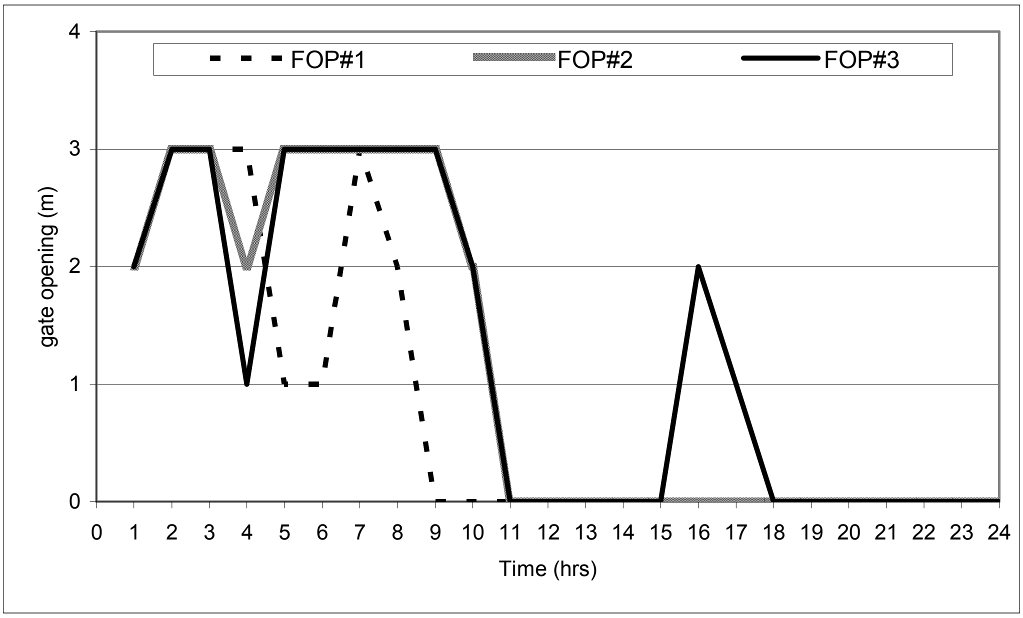


Figure 31 Optimal gate opening for Sukoom gate.

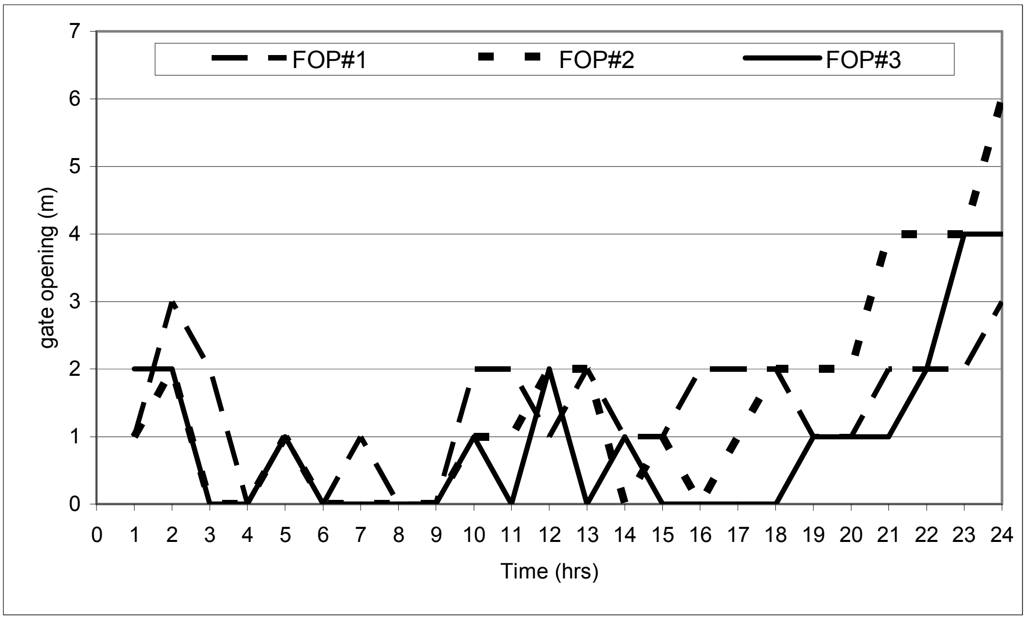


Figure 32 Optimal gate opening for Praekmueng gate.

The results form Table 10 shows comparison of satisfaction function values of each gate as well as gate system for four study cases as described above. As expected, the satisfaction function value of gate system for FOP#1 (-112,201) is higher than that of BAS (-119,610) in spite of the use of the same weighting factor and relative importance data set for both cases. It is clearly seen that FOP#1 give higher performance for coastal gate operations than BAS, with increase of satisfaction function value of 6% over the BAS.

The difference of the satisfaction function value between both cases above may be explained that, for FOP#1, the proposed model tries to find the optimal gate setting by compromising all the desired criteria at all chosen checkpoints simultaneously. Moreover, while the model is running to find the best gate setting, the state variables at all chosen checkpoints for each run time step all through control horizon are adjusted to be or close to the desired state variable as much as possible under several environmental, ecological and hydraulic constraints. On the other hand, for BAS, which all gates are closed all through control horizon, they do not be operated to compromise all the desired criteria at all chosen checkpoints.

Considering the satisfaction value for three full optimization scenarios, it is found that the order of satisfaction function value of gate system is: FOP#1 (-112,201) < FOP#2 (-103,660) < FOP#3 (-90,278). For Uthokawiphatprasit gate, FOP#2 scenario gives the highest satisfaction function value of -7,841whereas FOP#3 gives the lowest satisfaction function value of -16,648. For Sua Hueng gate, FOP#3 scenario gives the highest satisfaction function value of -15,743 whereas FOP#1 gives the lowest satisfaction function value of -19,702. For Pakrawa gate, the satisfaction function value for FOP#1 and FOP#2 are very close but the highest satisfaction function value of -13,789 is obtained for FOP#3 scenrio. Similar to Pakrawa gate, the satisfaction function value of Emergency and Thaphraya gates for FOP#1 and FOP#2 are very close whilst FOP#3 scenario gives the highest satisfaction function value of -4,351 and -3,320 for Emergency and Thaphraya gates, respectively. The highest satisfaction function values are achieved with FOP#3 for Klong Khong, Chian Yai, Bang Sai, and Sukoom gates and the highest satisfaction function value is obtained with FOP#1 for Preakmuenag gate.

Table 10 also presents that the satisfaction function values for all four study cases (i.e. BAS, FOP#1, FOP#2, and FOP#3) for Emergency, Thaphraya, Klong Khong, Chian Yai, Bang Sai are quite well compared to those for the remaining gates. This is because current states of controlled variables are quite close to their desired target, especially Bang Sai gate, which has the highest satisfaction function value. In addition, it can be generally noticed that the more state variables are concerned, the less satisfaction function values are obtained. This may be explained that when several state variables (i.e. water levels, salinity concentrations and DO concentrations at upstream and downstream gates) are considered, it is rather difficult to satisfy all the requirements with only gate operations, but it is just compromising results under present environmental constrains. Hence, to improve water quantity and quality for coastal river system, it should perform other measures as well, such as providing more fresh water storage source, operating optimal waste water release.

Table 10 Comparison of satisfaction function value for four study cases.

Gate	Satisfaction function value			
	BAS	FOP#1	FOP#2	FOP#3
Uthokawiphatprasit	-12,800	-10,967	-7,841	-16,648
Sua Hueng	-18,421	-19,702	-16,958	-15,743
Pakrawa	-26,871	-27,567	-27,957	-13,789
Emergency gate	-4,957	-5,868	-5,527	-4,351
Thaphraya	-4,067	-4,415	-4,056	-3,320
Klong Khong	-7,771	-7,802	-6,323	-2,836
Chian Yai	-8,923	-8,279	-6,010	-2,697
Bang Sai	-3,455	-2,427	-232	-10
Sukoom	-23,033	-13,980	-16,757	-9,764
Praekmueng	-9,312	-11,195	-11,999	-21,120
System	-119,610	-112,201	-103,660	-90,278

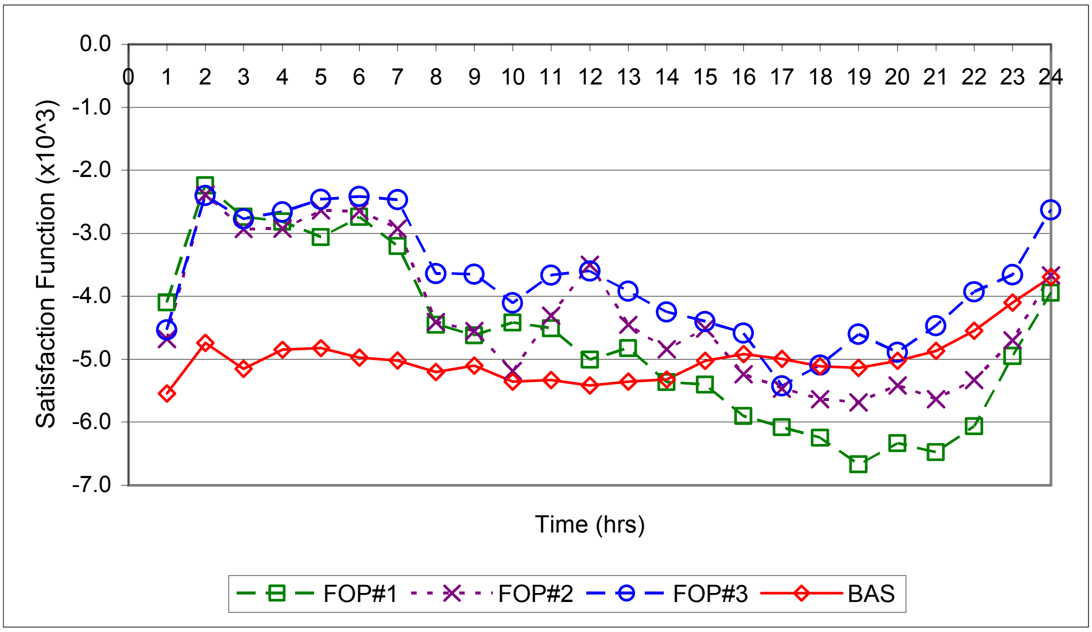


Figure 33 Satisfaction function value for coastal gate system versus control horizon.

Figure 33 also presents comparison of the satisfaction function value for coastal gate system versus control horizon for four study cases. In general, the satisfaction function values all through control period for the case of FOP#3 have the highest values. In the first fifteenth control period, the satisfaction function values for the case of FOP#1 and FOP#2 are more than those for BAS; conversely, in the remaining control period, the satisfaction function values for the case of FOP#1 and FOP#2 are lees than those for BAS. This is because the upstream water levels for all gates are specified to be the first priority level for controlling water gates for the purpose of water storage (i.e. the highest relative importance values are given). Furthermore, as all gates are closed all through control period for BAS, the water levels are accumulated since the beginning of simulation time. This is different from the way of controlling water gates for the case of FOP#1 and FOP#2, which gates are operated under the consideration of compromising all the desired criteria of water quantity and quality at all control points.

Table 11 presents comparison of state variables at control points for all controlled gates obtained from running CoastalGate model for four study cases. Figures 34 to 43 also show the state variables versus control horizon at control points of Uthokawiphatprasit, Sua Hueng, Pakrawa, Emergency, Thapraya, Klong Khong, Chian Yai, Bang Sai, Sukoom, and Praekmueng gates, respectively, for four study cases. Since salinity and dissolved oxygen concentrations at upstream of Klong Khong, Chian Yai, Bang Sai, and Sukoom gates are not state variables to be considered for the present study, they do not be illustrated. Some important information from both Table 11 and Figure 34 to 43 can be concluded as follows.

1. Uthokawiphatprasit gate

The upstream water levels for FOP#1, FOP#2, and FOP#3 (see Figure 34a and Table 11) result from allowing sea water through the upstream river, but those for BAS result from accumulation of fresh water since the beginning simulation time because all gates are closed. The average upstream water level for BAS, FOP#1, FOP#2, and FOP#3 are 0.040, 0,026, 0.060, and 0.076, respectively. This result shows that the average upstream water level for FOP#3 is the closest to its desired target.

Considering water level at downstream control point (see Figure 34b and Table 11), it is found that their values for FOP#1, FOP#2, and FOP#3 scenarios are similar, but those for BAS are a little higher. The reduction of downstream water level is results from allowing sea water through the upstream river as well as the fall of sea level. Although downstream water level for FOP#1, FOP#2, and FOP#3 scenarios rather different from its desired target, it has no an effect on actually desired target since this variable is specified to prevent flooding at downstream gate, which is urban area. It may be seen that the main factor to control downstream water level is the tide.

Although gate operation schedules guided by model allow sea water through the upstream river to raise upstream water level, the level of salinity concentrations at chosen upstream control point for BAS, FOP#1, FOP#2, and FOP#3 scenarios are the same value of 0.0 ppt (see Figure 34c and Table 11). This shows that its operation can satisfyingly control salinity concentrations.

For three full optimization scenarios, the salinity concentrations at chosen downstream control point are similar, i.e. average salinity concentrations for FOP#1, FOP#2, and FOP#3 are 18, 18, and 18.1 ppt, respectively. In addition, they have higher level as well as closer to its desired value (23 ppt) than when using baseline scenario for controlling water gate (16.3 ppt).

As shown in Figures 34e and 34f, the change of dissolved oxygen concentrations at chosen upstream control point for all scenarios have the same trend with gradually increasing level when the run time pass. The maximum of average dissolved oxygen concentrations at chosen upstream control point are found when the gate is controlled by FOP#2 as shown in Table 11. Like dissolved oxygen concentrations at chosen upstream control point, the change of dissolved oxygen concentrations at chosen downstream control point for all scenarios have the same trend and their values are almost the same. However, in this case, gate operated by BAS has the maximum of average dissolved oxygen concentrations at chosen downstream control point.

2. Sua Hueng gate

As presented in Figure 20, Sua Hueng gate does not directly connect the sea due to having Nha Goat gate act like barrier gate. However, at downstream gate, sea water can intrude in the controlled area since Nha Goat gate is opened for the purpose of the dilution of waste water in Klong Hua Sai.

Similar to Uthokawiphatprasit gate, the upstream water levels for FOP#1, FOP#2, and FOP#3 (see Figure 35a and Table 11) result from allowing sea water through the upstream river whilst those for BAS result from accumulation of fresh water since the beginning simulation time because all gates are closed. The average upstream water level for BAS, FOP#1, FOP#2, and FOP#3 are 0.041, 0,026, 0.060, and 0.075, respectively. This result shows that the average upstream water level for FOP#3 is the closest to its desired target.

Considering water level at downstream control point (see Figure 35b and Table 11), which give lesser relative importance value compared to relative importance given for upstream water level, it is found that their values for FOP#1, FOP#2, and FOP#3 scenarios are similar, but those for BAS are higher. It is clearly seen that the reduction of downstream water level is results from allowing salt water through the upstream river as mentioned earlier.

The same as Uthokawiphatprasit gate, gate operation schedules guided by model allow sea water through the upstream river to raise upstream water level. For all scenarios, the level of salinity concentrations at chosen upstream control point equal to 0.0 ppt (see Figure 35c and Table 11). This confirms that gate can control salinity concentration level quite well.

As a result of allowing sea water sea water through the upstream river and having Nha Goat gate, which is buffer gate, for three full optimization scenarios, the salinity concentrations at chosen downstream control point are similar trend and the average salinity concentrations are 9.39 ppt and their concentrations close to those for baseline scenario (9.47 ppt).

As shown in Figures 35e and 35f, the change of dissolved oxygen concentrations at chosen upstream control point for three full optimization scenarios have the same trend but it differs from baseline scenario, which dissolved oxygen concentrations gradually increase level when the run time pass. The maximum of average dissolved oxygen concentrations at chosen upstream control point are found when the gate is controlled by FOP#3. Like dissolved oxygen concentrations at chosen upstream control point, the change of dissolved oxygen concentrations at chosen downstream control point for all scenarios have the same trend However, in this case, gate operated by BAS has the maximum of average dissolved oxygen concentrations at chosen downstream control point. This is possible because the least relative importance is specified.

3. Pakrawa gate

As seen in Figures 36a and 36b and Table 11, the upstream and downstream water levels for three full optimization scenarios are very similar and a litter better than baseline scenario. This is because the environmental constraints limit the model to obtain the better results. In addition, the salinity concentrations at chosen upstream control point for three full optimization scenarios are very similar and have increasing trend after the ninth hour of simulation time. Nevertheless, for baseline scenario, the salinity concentrations at chosen upstream control point is constant of 10 ppt. Due to intrusion of sea water into upstream gate, the salinity concentrations at chosen downstream control point for three full optimization scenarios are lower than those for baseline scenario.

Figure 36e and Table 11 show that the values of dissolved oxygen concentrations at chosen upstream control point for three full optimization scenarios are better than those for BAS. The maximum of average dissolved oxygen concentrations at chosen upstream control point are found when the gate is controlled by FOP#3. The fluctuation of dissolved oxygen concentrations at chosen downstream control point for all full optimization scenarios are the same trend and differ from those for BAS. The maximum of average dissolved oxygen concentrations at chosen upstream control point are found when the gate is controlled by FOP#1.

4. Emergency gate

In fact, the Emergengy gate was constructed to require increase of the number of flood way during flooding. For the present experiment, the operations of this gate are controlled by consideration of state variables of water levels, salinity concentrations, and dissolved oxygen concentrations only at upstream control points.

Similar to Uthokawiphatprasit gate, the upstream water levels for FOP#1, FOP#2, and FOP#3 (see Figure 37a and Table 11) result from allowing sea water through the upstream river whilst those for BAS result from accumulation of fresh water since the beginning simulation time since all gates are closed. The average upstream water level for BAS, FOP#1, FOP#2, and FOP#3 are 0.045, 0,032, 0.066, and 0.082 m, respectively. This result shows that the average upstream water level for FOP#3 is the closest to its desired target.

Considering salinity concentrations at chosen upstream control point (see Figure 37b and Table 11), it is found that their concentrations for BAS, FOP#1, FOP#2, and FOP#3 scenarios are the same value of 0.0 ppt. This shows that the gate operations can control the level of salinity concentrations satisfyingly.

Figure 37c and Table 11 shows that dissolved oxygen concentrations at chosen upstream control point for three full optimization scenarios are higher than those for BAS. The maximum of average dissolved oxygen concentrations at chosen upstream control point are found when the gate is controlled by FOP#2.

5. Thaphraya gate

In the same way, the criteria used for controlling Thaphraya gate are the values of water levels, salinity concentrations, and dissolved oxygen concentrations at upstream control points.

Like Emergency gate, the changes of upstream water levels for FOP#1, FOP#2, and FOP#3 (see Figure 38a and Table 11) result from allowing sea water through the upstream river whilst those for BAS result from accumulation of fresh water since the beginning simulation time since all gates are closed. The average upstream water level for BAS, FOP#1, FOP#2, and FOP#3 are 0.040, 0,027, 0.065, and 0.074 m, respectively. This result shows that the average upstream water level for FOP#3 is the closest to its desired target (0.30 m).

Considering salinity concentrations at chosen upstream control point (see Figure 38b and Table 11), it is found that the gate operations can control the level of salinity concentrations satisfyingly with the same value of salinity concentrations (0.0 ppt) for BAS, FOP#1, FOP#2, and FOP#3 scenarios.

Figure 38c shows the changes of dissolved oxygen concentrations at chosen upstream control point for four scenarios versus control horizon. It is found that dissolved oxygen concentrations at chosen upstream control point for three full optimization scenarios are higher than those for BAS and the maximum of average dissolved oxygen concentrations at chosen upstream control point are found when the gate is controlled by FOP#2 (see Table 11).

6. Klong Khong gate

The changes of water levels at upstream and downstream control points for four scenarios are presented in Figures 39a and 39b, respectively. As presented in Table 11, it is found that the average water levels at upstream control point for FOP#1, FOP#2, and FOP#3 are higher and also closer to the desired water level than that for BAS. Similarly, the average water levels at downstream control point for FOP#2, and FOP#3 are higher and also closer to the desired water level than that for BAS.

The changes of salinity concentrations at chosen downstream control point are shown in Figure 39c. As expected, the levels of salinity concentrations for four scenarios are the same value of 0.0 ppt since this part of river is quite far from the sea.

Figure 39d shows the changes of dissolved oxygen concentrations at chosen downstream control point for four scenarios versus control horizon. It is found that average dissolved oxygen concentrations at chosen downstream control point for three full optimization scenarios are higher than those for BAS and the maximum of average dissolved oxygen concentrations at chosen upstream control point are found when the gate is controlled by FOP#1 (see Table 11).

7. Chian Yai gate

The changes of water levels at upstream and downstream control points for four scenarios are presented in Figures 40a and 40b, respectively. As presented in Table 11, it is found that the average water levels at upstream control point for FOP#1, FOP#2, and FOP#3 are higher and also closer to its desired water level than that for BAS. Similarly, the average water levels at downstream control point for FOP#2, and FOP#3 are higher and also closer to the desired water level than that for BAS.

The changes of salinity concentrations at chosen downstream control point are shown in Figure 40c. As expected, the levels of salinity concentrations for four scenarios are the same value of 0.0 ppt since this part of river is quite far from the sea.

Figure 40d shows the changes of dissolved oxygen concentrations at chosen downstream control point for four scenarios versus control horizon. It is found that average dissolved oxygen concentrations at chosen downstream control point for three full optimization scenarios are higher than those for BAS and the maximum of average dissolved oxygen concentrations at chosen upstream control point are found when the gate is controlled by FOP#2 (see Table 11).

8. Bang Sai gate

The changes of water levels at upstream and downstream control points for four scenarios are presented in Figures 41a and 41b, respectively. As presented in Table 11, it is found that the average water levels at upstream control point for FOP#1, FOP#2, and FOP#3 are higher and also closer to the desired water level than that for BAS. Similarly, the average water levels at downstream control point for FOP#2, and FOP#3 are higher and also closer to the desired water level than that for BAS.

The changes of salinity concentrations at chosen downstream control point are shown in Figure 41c. As expected, the levels of salinity concentrations for four scenarios are the same value of 0.0 ppt since this part of river is quite far from the sea.

Figure 41d shows the changes of dissolved oxygen concentrations at chosen downstream control point for four scenarios versus control horizon. It is found that average dissolved oxygen concentrations at chosen downstream control point for FOP#1 are higher than those for BAS. However, those values for FOP#2 and FOP#3 are higher than those for BAS. This is because this gate operations controlled by FOP#2 and FOP#3 scenarios try to compromise several considered parameters at the same time. Furthermore, the parameter of dissolved oxygen concentrations at chosen downstream control point for this gate may have lower priority level than the others.

9. Sukoom gate

The changes of water levels at upstream and downstream control points for four scenarios are presented in Figures 42a and 42b, respectively. It is clearly seen that the changes of water levels at upstream control points for three full optimization scenarios are different form those for baseline scenario. This is because, for three full optimization scenarios, sea water can intrude in the upstream river but conversely for baseline scenario. Table 11 also shows that the average water levels at upstream control point for three full optimization scenarios are quite higher and also closer to the desired water level than that for BAS. However, the average water levels at downstream control point for three full optimization scenarios are lower than that for BAS. This is because the same reason given above for this gate as well as for Uthokawiphatprasit gate, where is near Sukoom gate (see Figure 20).

The changes of salinity concentrations at chosen downstream control point are shown in Figure 42c. The results from Table 11 and Figure 42c show that the levels of salinity concentrations for three full scenarios are almost the same and are closer to the desired target than that for baseline scenario.

Figure 42d shows the changes of dissolved oxygen concentrations at chosen downstream control point for four scenarios versus control horizon. It is found that average dissolved oxygen concentrations at chosen downstream control point for three full optimization scenarios are lower than that for BAS. This is because, during running model to find the optimal gate settings for full optimization scenario, several parameters are simultaneously considered. Moreover, the parameter of dissolved oxygen concentrations at chosen downstream control point for this gate may have lower priority level than the others.

10. Praekmueng gate

For Praekmueng gate, the criteria used for controlling gate are the values of water levels, salinity concentrations, and dissolved oxygen concentrations at upstream control points like Emergency and Thaphraya gates.

The changes of upstream water levels for FOP#1, FOP#2, and FOP#3 as presented in Figure 43a result from allowing sea water through the upstream river whereas those for BAS result from accumulation of fresh water since the beginning simulation time since all gates are closed. The results from Table 11 show that the average upstream water level for FOP#3 is higher and closer to its desired target than that for BAS.

Considering salinity concentrations at chosen upstream control point as presented in Figure 43b and Table 11, it is found that the gate operations can control the level of salinity concentrations satisfyingly with the same value of salinity concentrations (0.0 ppt) for BAS, FOP#1, FOP#2, and FOP#3 scenarios.

Figure 43c shows the changes of dissolved oxygen concentrations at chosen upstream control point for four scenarios versus control horizon. The results from Table 11 show that average dissolved oxygen concentrations at chosen upstream control point for FOP#2 and FOP#3 are higher than that for BAS. In addition, the maximum of average dissolved oxygen concentrations at chosen upstream control point are found when the gate is controlled by FOP#3.

Table 11 Summary results of state variables at control points of ten controlled gates for four study cases.

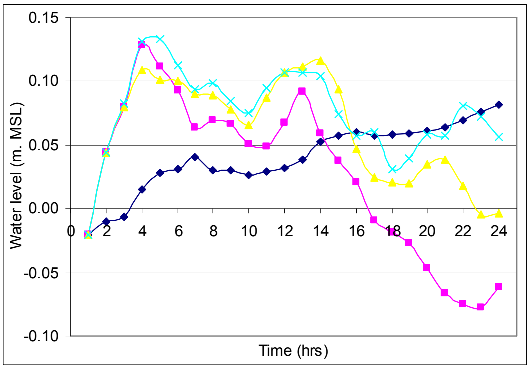
Parameters	Target	BAS			FOP#1			FOP#2			FOP#3		
		Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
<u>1. Uthokawiphatprasit gate</u>													
WL_US (m)	0.30	0.081	-0.020	0.040	0.128	-0.078	0.026	0.116	-0.020	0.060	0.134	-0.020	0.076
WL_DS (m)	0.15	0.358	-0.491	-0.081	0.351	-0.491	-0.119	0.351	-0.489	-0.118	0.351	-0.490	-0.121
SAL_US (ppt)	1.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SAL_DS (ppt)	23.00	20.000	13.590	16.314	20.550	15.740	18.011	20.450	15.720	17.975	20.650	15.830	18.092
DO_US (mg/l)	6.00	2.565	2.000	2.394	2.567	2.000	2.403	2.637	2.000	2.480	2.487	2.000	2.393
DO_DS (mg/l)	6.00	2.054	1.810	1.923	2.000	1.689	1.837	2.000	1.715	1.849	2.000	1.712	1.859
<u>2. Sua Hueng gate</u>													
WL_US (m)	0.30	0.080	-0.008	0.041	0.108	-0.093	0.026	0.124	-0.008	0.060	0.124	-0.008	0.075
WL_DS (m)	0.25	0.360	-0.097	0.100	0.360	-0.115	0.019	0.360	-0.157	0.011	0.360	-0.054	0.064
SAL_US (ppt)	1.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SAL_DS (ppt)	23.00	10.010	9.213	9.472	10.260	9.213	9.396	10.330	9.171	9.387	10.020	9.126	9.393
DO_US (mg/l)	6.00	4.147	4.000	4.085	4.199	3.864	4.064	4.254	4.000	4.130	4.243	4.000	4.145
DO_DS (mg/l)	6.00	4.004	3.437	3.671	4.000	3.447	3.584	4.000	3.373	3.564	4.000	3.493	3.629
<u>3. Pakrawa gate</u>													
WL_US (m)	0.60	0.360	-0.406	-0.164	0.360	-0.427	-0.175	0.360	-0.418	-0.176	0.360	-0.416	-0.176
WL_DS (m)	0.15	0.294	-0.439	-0.194	0.210	-0.427	-0.206	0.210	-0.418	-0.205	0.210	-0.416	-0.202
SAL_US (ppt)	23.00	10.000	10.000	10.000	10.210	10.000	10.056	10.230	10.000	10.061	10.220	10.000	10.060
SAL_DS (ppt)	23.00	16.240	10.000	12.655	14.670	10.000	11.980	14.640	10.000	11.964	14.570	10.000	12.000
DO_US (mg/l)	6.00	4.000	2.881	3.252	4.000	3.057	3.342	4.000	3.267	3.510	4.000	3.473	3.606
DO_DS (mg/l)	6.00	4.238	3.696	3.885	6.000	2.884	3.994	6.000	2.380	3.500	6.000	2.272	3.622

Table 11 (Continued)

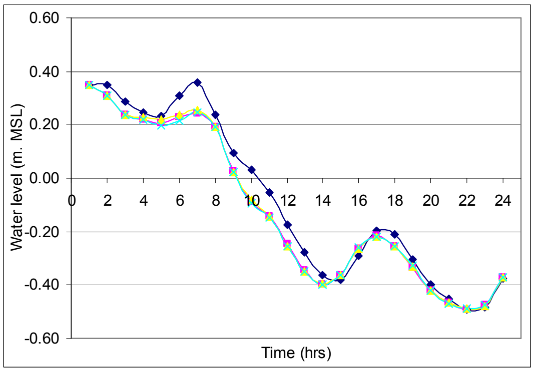
Parameters	Target	BAS			FOP#1			FOP#2			FOP#3		
		Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
<u>4. Emergency gate</u>													
WL_US (m)	0.30	0.210	-0.192	0.045	0.217	-0.147	0.032	0.217	-0.147	0.066	0.220	-0.146	0.082
SAL_US (ppt)	1.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DO_US (mg/l)	6.00	4.040	3.747	3.877	4.247	3.664	3.913	4.238	3.870	4.039	4.245	3.636	3.925
<u>5. Thaphraya gate</u>													
WL_US (m)	0.30	0.082	-0.020	0.040	0.181	-0.087	0.027	0.166	-0.020	0.065	0.167	-0.035	0.074
SAL_US (ppt)	1.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DO_US (mg/l)	6.00	4.190	4.000	4.115	4.501	4.000	4.244	4.576	4.000	4.363	4.542	3.976	4.312
<u>6. Klong Khong gate</u>													
WL_US (m)	1.00	0.100	0.030	0.076	0.103	0.030	0.084	0.120	0.029	0.083	0.124	0.030	0.084
WL_DS (m)	0.15	0.075	-0.002	0.043	0.108	-0.069	0.025	0.120	-0.007	0.059	0.124	0.001	0.075
SAL_DS (ppt)	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DO_DS (mg/l)	6.00	4.083	3.871	4.018	4.452	3.887	4.097	4.311	3.887	4.074	4.214	3.889	4.094
<u>7. Chian Yai gate</u>													
WL_US (m)	1.00	0.063	-0.050	0.027	0.112	-0.050	0.053	0.110	-0.050	0.064	0.108	-0.050	0.066
WL_DS (m)	0.15	0.079	-0.040	0.040	0.124	-0.076	0.023	0.120	-0.040	0.057	0.132	-0.040	0.073
SAL_DS (ppt)	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DO_DS (mg/l)	6.00	4.345	3.830	3.996	4.750	3.947	4.257	5.107	3.945	4.518	5.032	3.955	4.481

Table 11 (Continued)

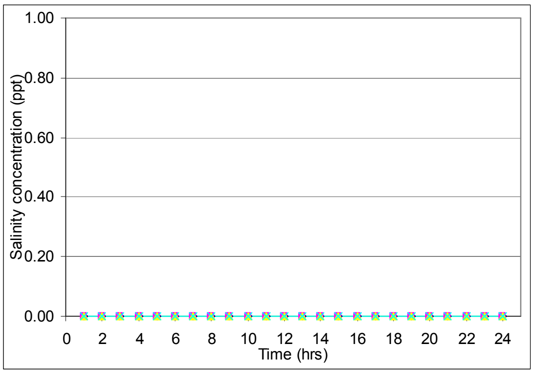
Parameters	Target	BAS			FOP#1			FOP#2			FOP#3		
		Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
8. Bang Sai gate													
WL_US (m)	0.40	0.058	-0.021	0.026	0.108	-0.020	0.051	0.103	-0.020	0.071	0.110	-0.020	0.060
WL_DS (m)	0.15	0.081	-0.020	0.040	0.113	-0.084	0.025	0.121	-0.020	0.059	0.128	-0.020	0.075
SAL_DS (ppt)	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DO_DS (mg/l)	6.00	4.044	3.983	4.004	4.370	3.961	4.113	4.097	3.754	3.924	4.138	3.899	4.001
9. Sukoom gate													
WL_US (m)	0.30	0.057	-0.021	0.026	0.257	-0.020	0.094	0.257	-0.120	0.096	0.258	-0.230	0.071
WL_DS (m)	0.45	0.367	-0.491	-0.081	0.351	-0.488	-0.121	0.351	-0.486	-0.118	0.351	-0.487	-0.119
SAL_DS (ppt)	23.00	20.000	13.590	16.314	20.550	15.740	18.011	20.450	15.720	17.975	20.650	15.830	18.092
DO_DS (mg/l)	6.00	2.054	1.810	1.923	2.000	1.689	1.837	2.000	1.715	1.849	2.000	1.712	1.859
10. Praekmueng gate													
WL_US (m)	0.80	0.076	-0.006	0.044	0.146	-0.220	-0.023	0.209	-0.110	0.035	0.181	-0.001	0.074
SAL_US (ppt)	1.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DO_US (mg/l)	6.00	4.063	3.970	4.028	4.087	3.821	3.965	4.221	3.889	4.034	4.227	4.000	4.085



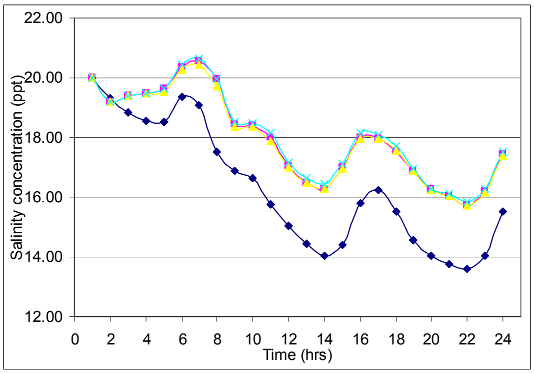
(a) upstream water level



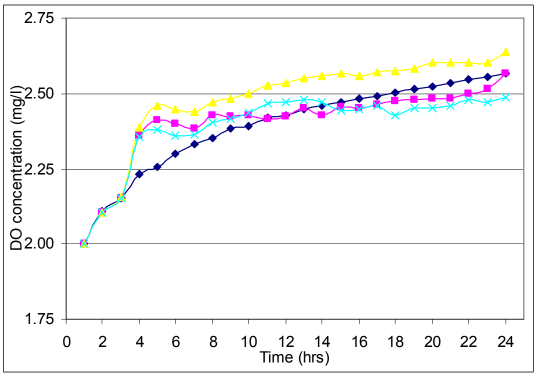
(b) downstream water level



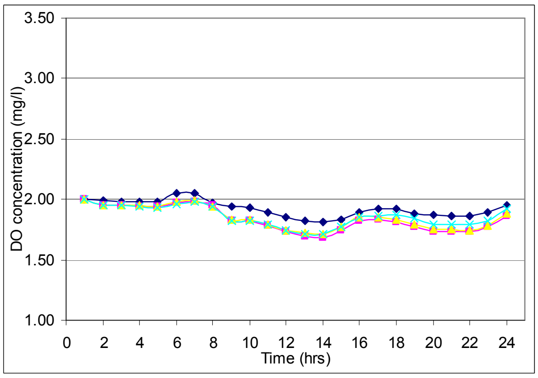
(c) upstream salinity concentration



(d) downstream salinity concentration

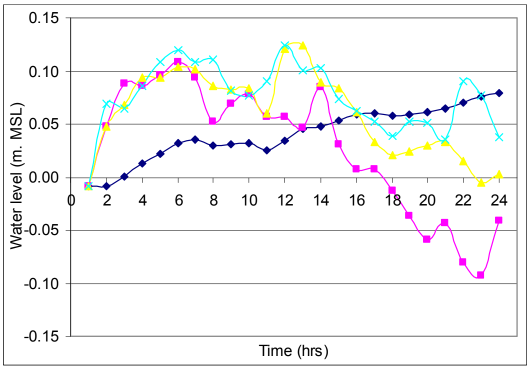


(e) upstream DO concentration

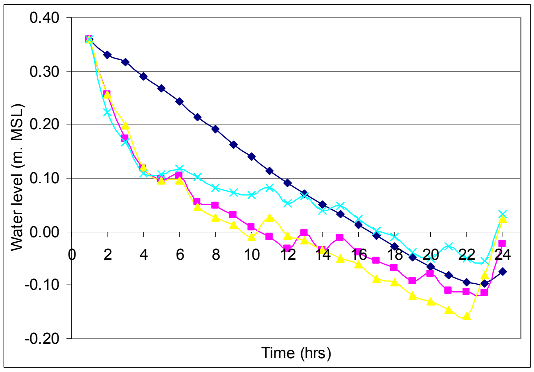


(f) downstream DO concentration

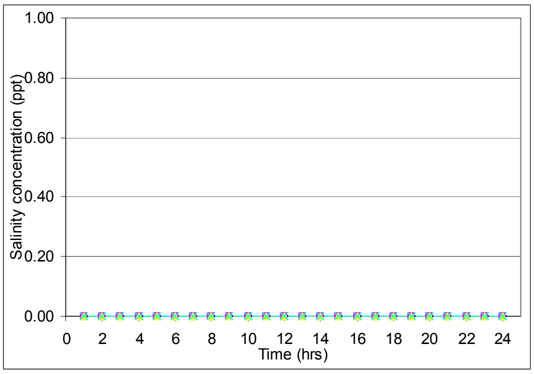
Figure 34 The state variables versus control horizon at checkpoints of Uthokawiphatprasit gate.



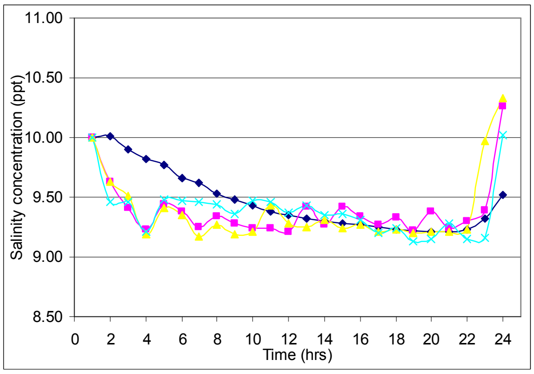
(a) upstream water level



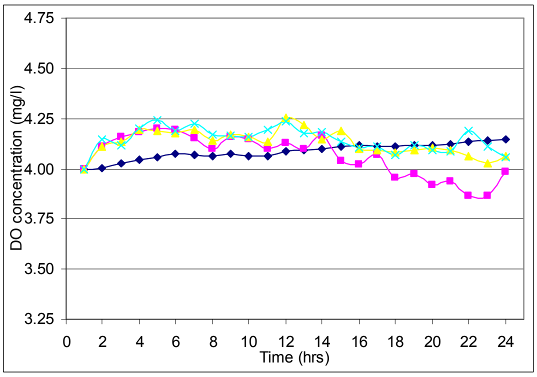
(b) downstream water level



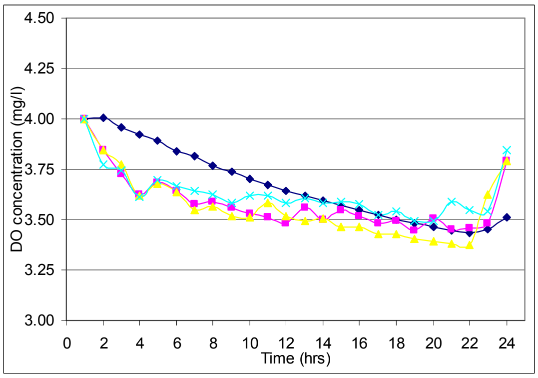
(c) upstream salinity concentration



(d) downstream salinity concentration

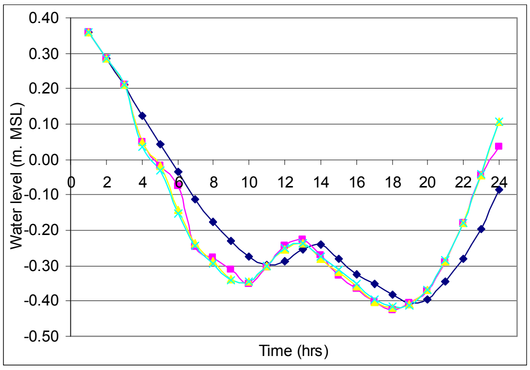


(e) upstream DO concentration

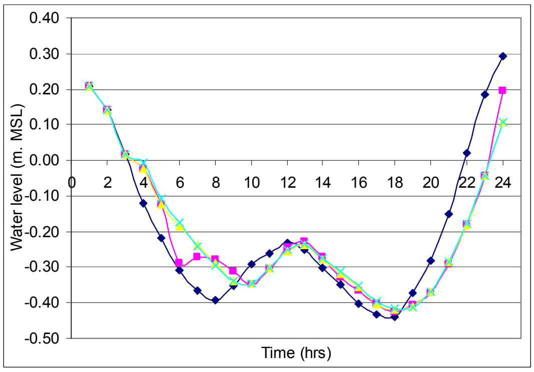


(f) downstream DO concentration

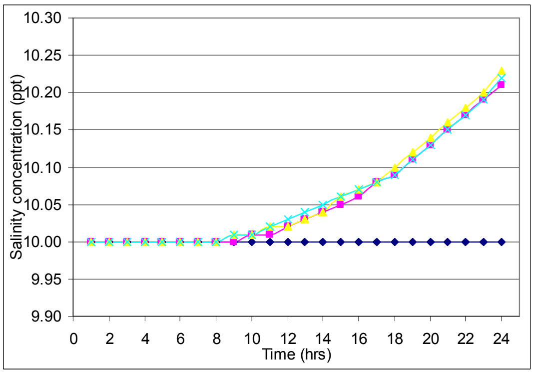
Figure 35 The state variables versus control horizon at checkpoints of Sua Hueng gate.



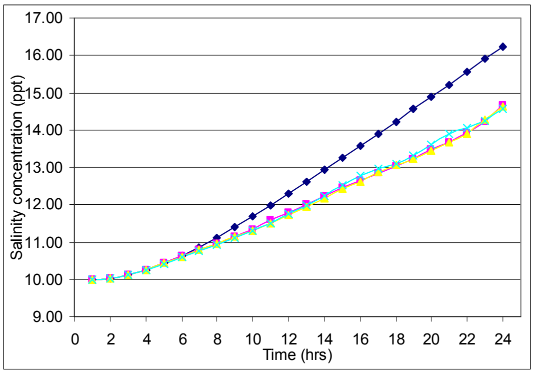
(a) upstream water level



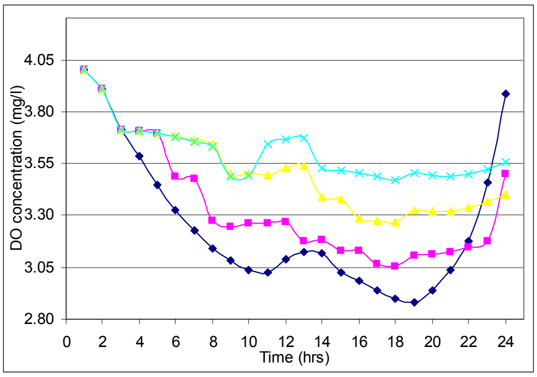
(b) downstream water level



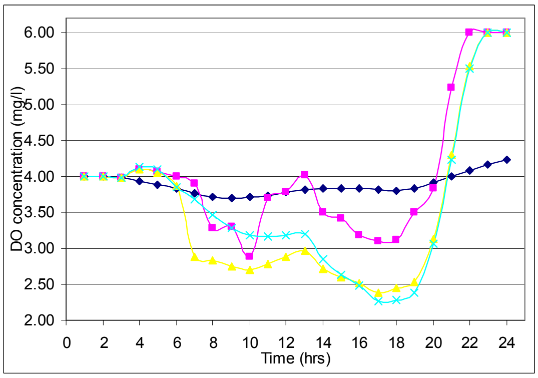
(c) upstream salinity concentration



(d) downstream salinity concentration

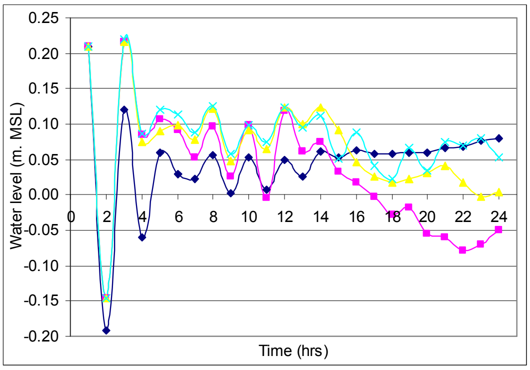


(e) upstream DO concentration

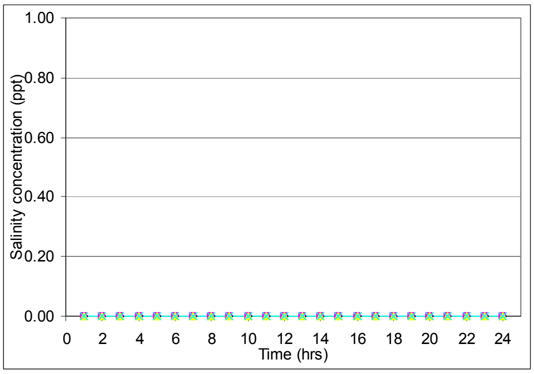


(f) downstream DO concentration

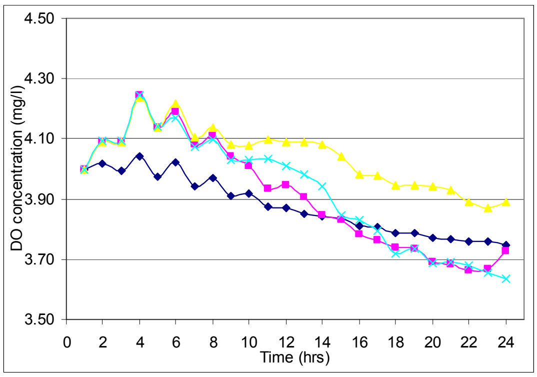
Figure 36 The state variables versus control horizon at checkpoints of Pakrawa gate.



(a) upstream water level

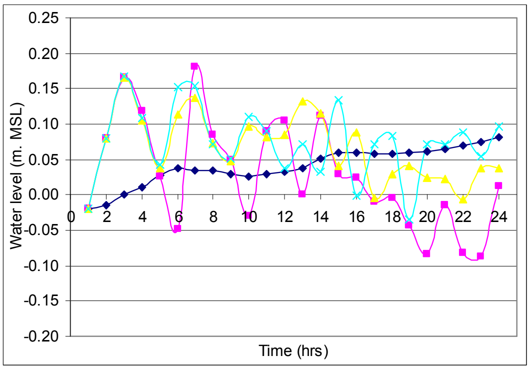


(b) upstream salinity concentration

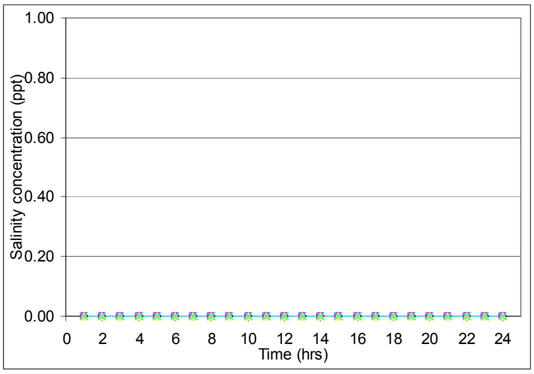


(c) upstream DO concentration

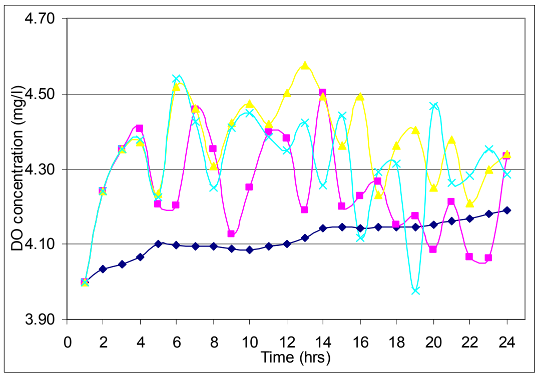
Figure 37 The state variables versus control horizon at checkpoints of Emergency gate.



(a) upstream water level

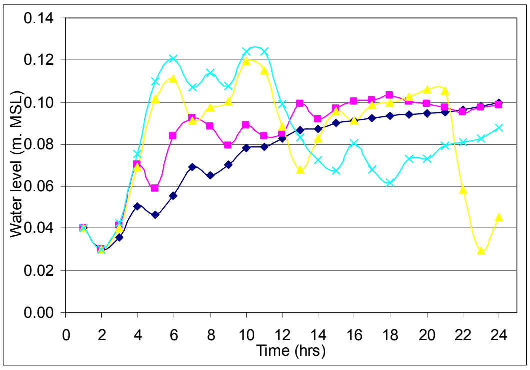


(b) upstream salinity concentration

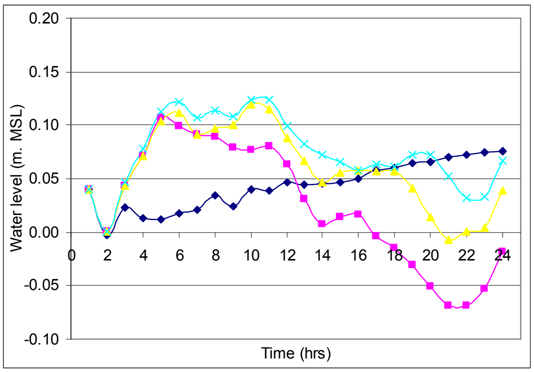


(c) upstream DO concentration

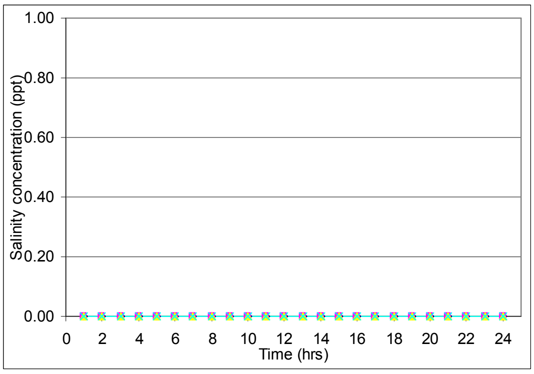
Figure 38 The state variables versus control horizon at checkpoints of Thaphraya gate.



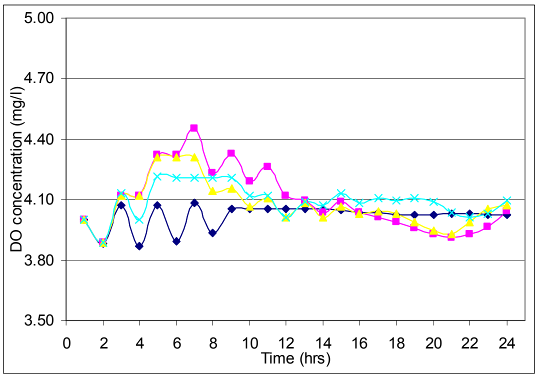
(a) upstream water level



(b) downstream water level

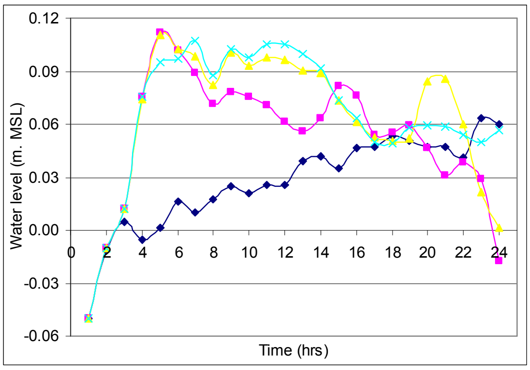


(c) downstream salinity concentration

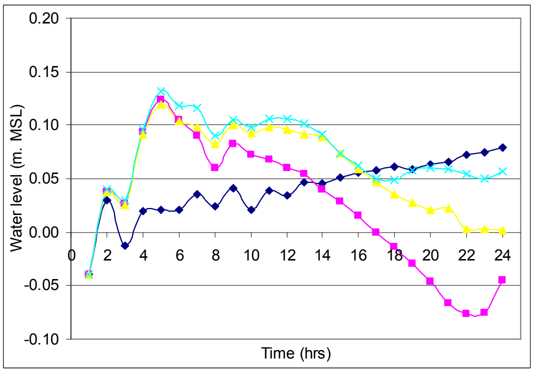


(d) downstream DO concentration

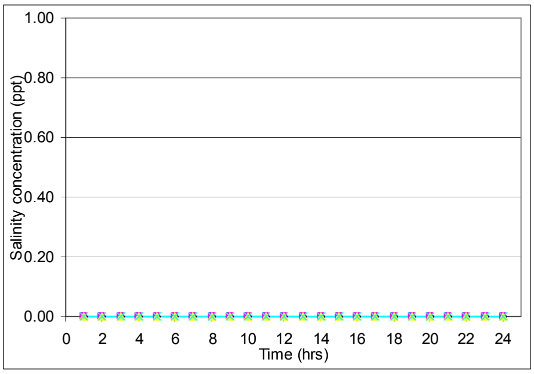
Figure 39 The state variables versus control horizon at checkpoints of Klong Khong gate.



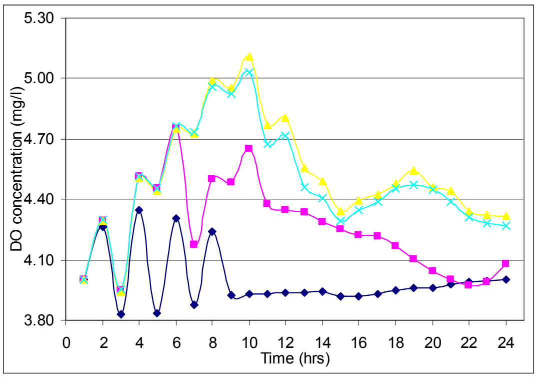
(a) upstream water level



(b) downstream water level

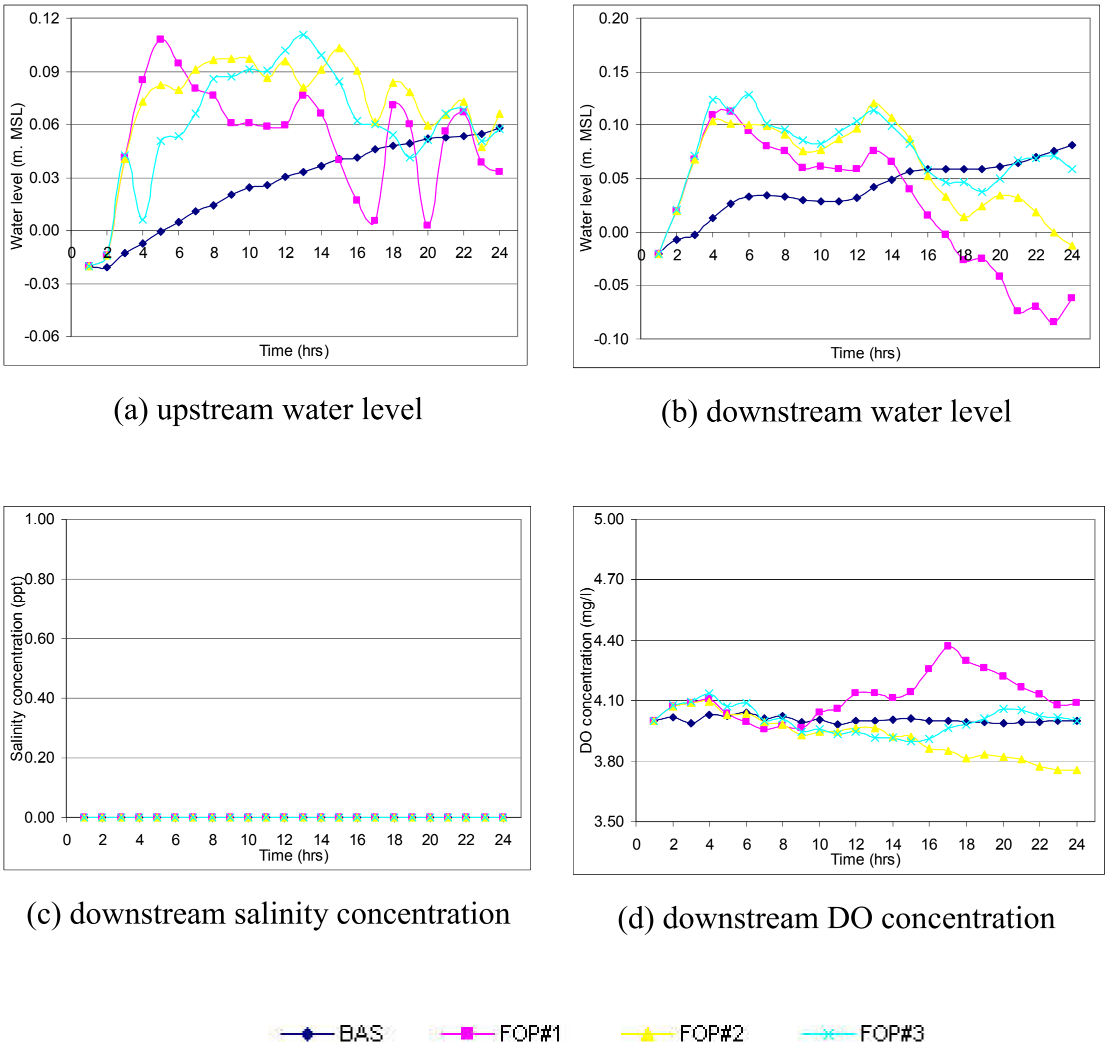


(c) downstream salinity concentration



(d) downstream DO concentration

Figure 40 The state variables versus control horizon at checkpoints of Chian Yai gate.



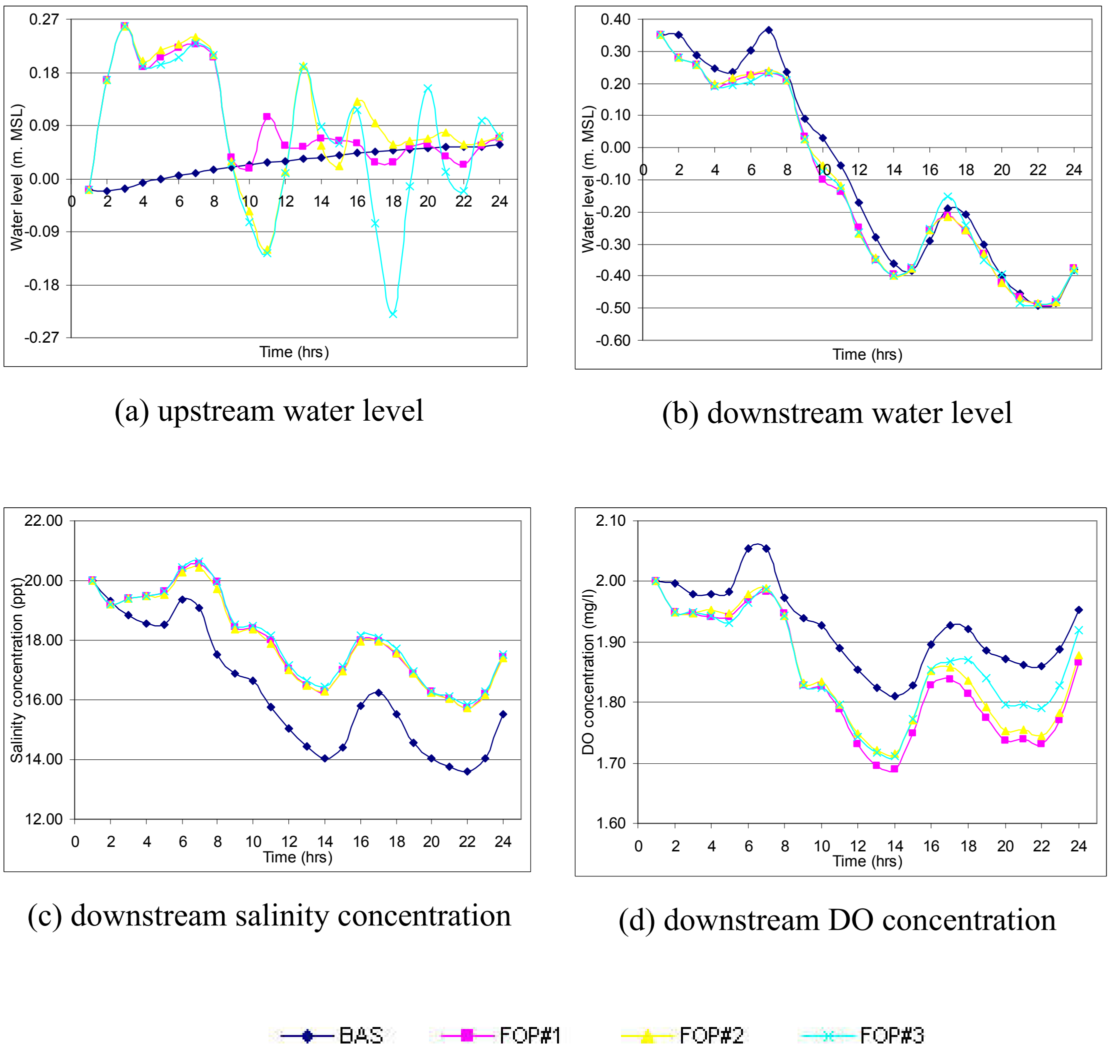
(a) upstream water level

(b) downstream water level

(c) downstream salinity concentration

(d) downstream DO concentration

Figure 41 The state variables versus control horizon at checkpoints of Bang Sai gate.



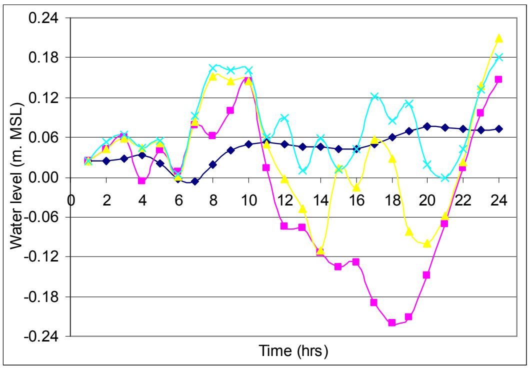
(a) upstream water level

(b) downstream water level

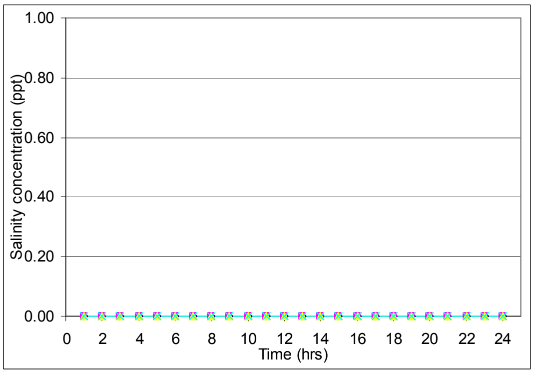
(c) downstream salinity concentration

(d) downstream DO concentration

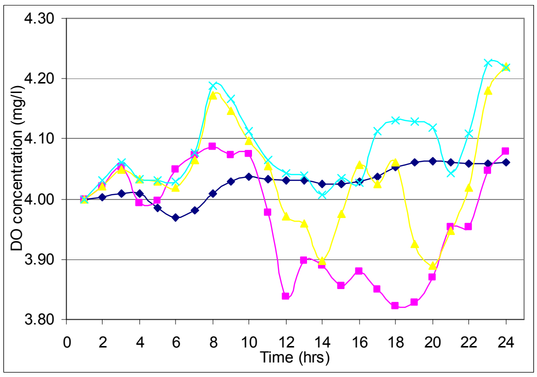
Figure 42 The state variables versus control horizon at checkpoints of Sukoom gate.



(a) upstream water level



(b) upstream salinity concentration



(c) upstream DO concentration

Figure 43 The state variables versus control horizon at checkpoints of Praekmueng gate.

2. Application of Artificial Neural Networks for deriving coastal gate operation rules

As mentioned previously, with execution time and complexity the primary limitation in employing the accurate models (CoastalGate model) necessary for effective real-time control, the application of dynamic or Artificial Neural Networks (ANNs) may provide the analysis speed, generalization ability and fault tolerance needed for effective implementation. The aim of this section is to investigate the possibility of the use of ANNs for deriving coastal gate operating rules, which can be utilized for real time control task.

The advantage of using this approach is no need to rerun CoastalGate model every time for planning the operations of coastal gates. Furthermore, it should save execution time, especially for complex system which requires high execution time due to routinely calling mathematical simulation model several thousands of times.

A schematic presentation of hypothetical coastal gate system that relates to Uthokawiphatprasit water gate is considered as a case study here. There are four parts that were undertaken in this section; namely:- determining the optimal DE's parameters, preparing the training data set for Artificial Neural Networks, comparing learning performance of Artificial Neural Networks, and finally validating of ANNs controller. The details of each experiment are described as follows.

2.1 Determination of the optimal DE's parameters

Due to the fact that a new coastal gate system is considered for this section, it is necessary to find the suitable DE's parameters again. The trial & error approach was used to investigate the optimal values of DE's parameters. Table 12 shows the results obtained from varying the values of the maximum number of generations between 2 and 10 while fixing the number of populations, weighting factor (F), and crossover constant (CR) of 5, 0.8, and 0.8, respectively. It is clearly seen that the maximum number of generations of 2 is quite suitable for the present study case due to the least time taken in spite of the same satisfaction function obtained. Table 13 also shows the results obtained from varying the number of populations between 5 and 10 while fixing the maximum number of generations, weighting factor (F), and crossover constant (CR) of 2, 0.8, and 0.8, respectively. It is clearly seen that the number of populations of 5 is sufficient for this case due to the least time taken in spite of the same satisfaction function obtained.

As expected, due to a very simple case considered here, only two generation with the number of population of 5 is the suitable parameters in this case. The satisfaction function for each test is the same (approximately -2000). It should be noted that time taken as presented in Tables 12 and 13 is time taken for three hour simulation run times.

Table 12 The sensitivity analysis results of maximum number of generations.

Test no.	Generation	NP	Satisfaction function	Time taken (min.)
1	2	5	-2013	4.93
2	3	5	-2013	5.93
3	4	5	-2013	7.21
4	5	5	-2013	8.70
5	6	5	-2013	10.05
6	7	5	-2013	11.43
7	8	5	-2013	12.72
8	9	5	-2013	14.27
9	10	5	-2013	15.52

Table 13 The sensitivity analysis results of the number of population.

Test no.	Generation	NP	Satisfaction function	Time taken (min.)
1	2	5	-2013	4.93
2	2	6	-2013	5.33
3	2	7	-2013	6.17
4	2	8	-2013	6.95
5	2	9	-2013	7.88
6	2	10	-2013	8.65

Table 14 shows the results of finding the values of F and CR with fixing the maximum number of generations and the number of populations of 2 and 5, respectively. It is found that there is no effect of varying the value of F and CR because all cases have the same satisfaction function value of -2013. This is possible because only one decision variable is considered herein. It may be noted that for the problem having very few decision variables, the accuracy of results only depends on the maximum number of generations and the number of populations.

Table 14 Satisfaction function value on effects of varying F and CR values for a hypothetical coastal gate.

F	Satisfaction function									
	CR = 0.1	CR = 0.2	CR = 0.3	CR = 0.4	CR = 0.5	CR = 0.6	CR = 0.7	CR = 0.8	CR = 0.9	CR = 1.0
0.1	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013
0.2	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013
0.3	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013
0.4	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013
0.5	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013
0.6	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013
0.7	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013
0.8	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013
0.9	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013
1	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013	-2.013

2.2 Preparing the training data set for Artificial Neural Networks

This section presents the results of utilizing CoastalGate model, which is a highly accurate but computationally time consuming optimal control model, to provide the training data set for Artificial Neural Networks under a wide range of exogenous input of coastal river system. The 10,500 patterns are provided from 150 events; each event contains 70 patterns. Then, Artificial Neural Networks is applied to determine optimal gate opening as a function of available information. The available information or influencing control parameters considered in this study are water levels, salinity concentrations, and dissolved oxygen concentrations at selected control points as well as discharge at just upstream gate. Table 15 also shows the sample of training data set for Artificial Neural Networks (ANNs).

Table 15 Sample of training data set for Artificial Neural Networks.

WL_US_T	WL_DS_T	SAL_US_T	SAL_DS_T	DO_US_T	DO_DS_T	GATE
0.2306	-0.2162	0	18.69	2.756	1.664	0
0.2431	-0.2673	0	19.16	2.759	1.67	0
0.256	-0.3258	0	19.61	2.782	1.631	0
0.2684	-0.3581	0	20.04	2.795	1.649	0
0.2902	-0.2518	0	20.46	2.823	1.742	0
0.3108	-0.1149	0	20.87	2.842	1.802	0
0.3259	-0.02337	0	21.27	2.856	1.857	1
0.3605	0.2889	0	20.55	3.006	1.942	0
0.3758	0.4415	0	21.04	2.987	2.015	0
0.3784	0.4925	0	21.54	2.988	2.046	0
0.3928	0.4121	0	22.01	2.991	1.956	1
0.3547	0.3274	0	21.61	3.008	1.953	1

Remark: WL_US_T = upstream water level at current time;
WL_DS_T = downstream water level at current time;
SAL_US_T = upstream salinity concentrations at current time;
SAL_DS_T = downstream salinity concentrations at current time;
DO_US_T = upstream dissolved oxygen concentrations at current time;
DO_DS_T = downstream dissolved oxygen concentrations at current time;
GATE = gate opening.

2.3 Comparison of learning performance of Artificial Neural Networks

To investigate the possibility of ANNs for deriving coastal gate operating rules, seven input patterns as presented in Table 16 and two types of supervised neural networks; namely:- back propagation (BP) and general regression neural network (GRNN) are carried out to determine the best structure for the adaptive model. The output data considered herein is the optimal gate opening.

The results obtained from using both supervised neural networks for each input pattern are presented in Table 17 in terms of average absolute error (AAE), and correlation coefficient (R^2). The AAE values of GRNN are in the range of 0.0013 to 0.0052 and 0.1610 to 0.2179 for training and testing data set, respectively. The AAE values of BP are in the range of 0.2668 to 0.3405 and 0.2659 to 0.3428 for training and testing data set, respectively. Therefore, it shows that the application of GRNN gave lower AAE value for both training and testing data set than using BP. Moreover, the AAE ratio values of BP are very close to 1 whereas the AAE ratio values of GRNN are very large number (approximately 100). It may be explained that training by GRNN model gives AAE values of training data set is quite low compared to those of testing data set, but AAE values of BP are almost the same for both training and testing data set. In addition, the use of the sixth input variable pattern gives the lowest AAE value of GRNN for both training (AAE = 0.0013) and testing (AAE = 0.1610) data set and the seventh input variable pattern gives the lowest AAE value of BP for both training (AAE = 0.2668) and testing (AAE = 0.2659) data set.

Table 16 Details of input variables used for training different ANNs controller.

Input variables	Pattern						
	1	2	3	4	5	6	7
WL_US(t-1)	√			√			
WL_US(t)	√	√	√	√	√	√	√
WL_DS(t-1)	√			√			
WL_DS(t)	√	√	√	√	√	√	√
SAL_US(t-1)	√			√			
SAL_US(t)	√	√	√	√	√	√	√
SAL_DS(t-1)	√			√			
SAL_DS(t)	√	√	√	√	√	√	√
DO_US(t-1)	√			√			
DO_US(t)	√	√	√	√	√	√	√
DO_DS(t-1)	√			√			
DO_DS(t)	√	√	√	√	√	√	√
WL_US(t) - WL_US(t-1)			√			√	√
WL_DS(t) - WL_DS(t-1)			√			√	√
SAL_US(t) - SAL_US(t-1)			√			√	√
SAL_DS(t) - SAL_DS(t-1)			√			√	√
DO_US(t) - DO_US(t-1)			√			√	√
DO_DS(t) - DO_DS(t-1)			√			√	√
Q_US(t-1)				√			
Q_US(t)				√	√	√	
Q_US(t) - Q_US(t)							√

Remark: WL_US(t-1) = upstream water level at previous time;
WL_US(t) = upstream water level at current time;
WL_DS(t-1) = downstream water level at previous time;
WL_DS(t) = downstream water level at current time;
SAL_US(t-1) = upstream salinity concentrations at previous time;
SAL_US(t) = upstream salinity concentrations at current time;
SAL_DS(t-1) = downstream salinity concentrations at previous time;
SAL_DS(t) = downstream salinity concentrations at current time;
DO_US(t-1) = upstream DO concentrations at previous time;
DO_US(t) = upstream DO concentrations at current time;
DO_DS(t-1) = downstream DO concentrations at previous time;
DO_DS(t) = downstream dissolved oxygen concentrations at current time;
Q_US(t-1), Q_US(t) = upstream discharge at previous and current time.

The R^2 values of GRNN are in the range of 0.9978 to 0.9994 and 0.6171 to 0.7237 for training and testing data set, respectively. The R^2 values of BP are in the range of 0.6065 to 0.7546 and 0.6026 to 0.7588 for training and testing data set, respectively. For training process, GRNN gives the better R^2 values (approximately R^2 of 0.99) than BP (approximately R^2 of 0.70) for all input patterns. For testing process, on the other hand, BP gives a little better R^2 values (approximately R^2 of 0.70) than GRNN (approximately R^2 of 0.68) for most considered input patterns. Moreover, the R^2 ratio values of BP are very close to 1 whereas the R^2 ratio values of GRNN are more than 0.65. This result also shows that GRNN has R^2 values of training data set quite high compared to those of testing data set, but R^2 values of BP are almost the same for both training and testing data set. In addition, the sixth input variable pattern gives the best R^2 value for both GRNN and BP in both training and testing data set. Figures 44 and 45 shows comparison of learning performance of each selected input patterns and two types of ANNs model in terms of AAE and R^2, respectively.

Table 17 Training and testing results of ANNs model for coastal gate operations.

Case	AAE			R^2		
	Training	Testing	Ratio	Training	Testing	Ratio
pattern1-GRNN	0.0020	0.1963	96.097	0.9991	0.6554	0.6560
pattern1-BP	0.2884	0.2972	1.031	0.7157	0.7040	0.9836
pattern2-GRNN	0.0015	0.2179	144.966	0.9993	0.6171	0.6175
pattern2-BP	0.3405	0.3428	1.007	0.6065	0.6026	0.9936
pattern3-GRNN	**0.0014**	**0.1700**	118.016	**0.9992**	**0.7140**	0.7146
pattern3-BP	0.2779	0.2883	1.038	0.7315	0.7205	0.9850
pattern4-GRNN	0.0052	0.1860	35.898	0.9978	0.6825	0.6840
pattern4-BP	0.2795	0.2776	0.993	0.7243	0.7225	0.9975
pattern5-GRNN	0.0013	0.1902	147.081	0.9991	0.6565	0.6571
pattern5-BP	0.2904	0.3002	1.034	0.7056	0.6887	0.9760
pattern6-GRNN	**0.0013**	**0.1610**	124.227	**0.9994**	**0.7237**	0.7241
pattern6-BP	0.2712	0.2679	0.988	0.7546	0.7588	1.0055
pattern7-GRNN	0.0017	0.1649	96.821	0.9991	0.7112	0.7119
pattern7-BP	0.2668	0.2659	0.997	0.7451	0.7492	1.0056

Remark: pattern1 = input variable pattern 1, AAE =average absolute error,
R^2 = correlation coefficient, Ratio = ration between testing and training.

For choosing the most suitable ANNs structure for the present study, the GRNN is more suitable structure than the BP due to giving lower AAE value and acceptable R^2 value. Considering the suitable input variable pattern, it was found that the third input pattern is the most suitable input structure. This is because its learning performance is very close to that of the sixth input pattern (the best input structure). Furthermore, it requires the number of input data less than that of the sixth input pattern. Hence, the suitable ANN structure selected in this case study is pattern 3-GRNN.

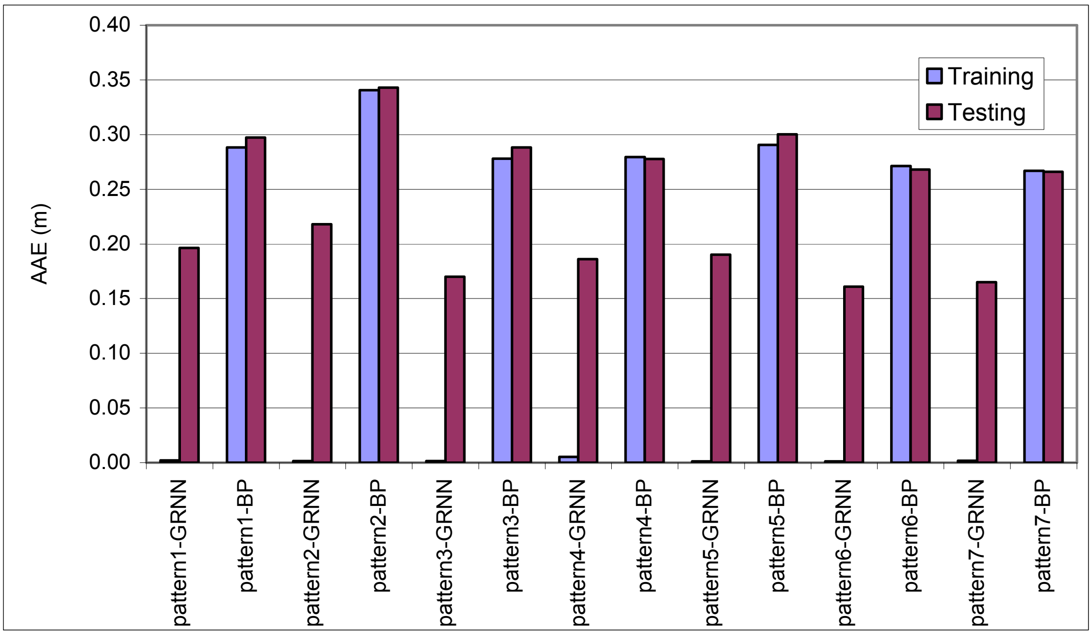


Figure 44 Comparison of input patterns and ANN types in terms of AAE.

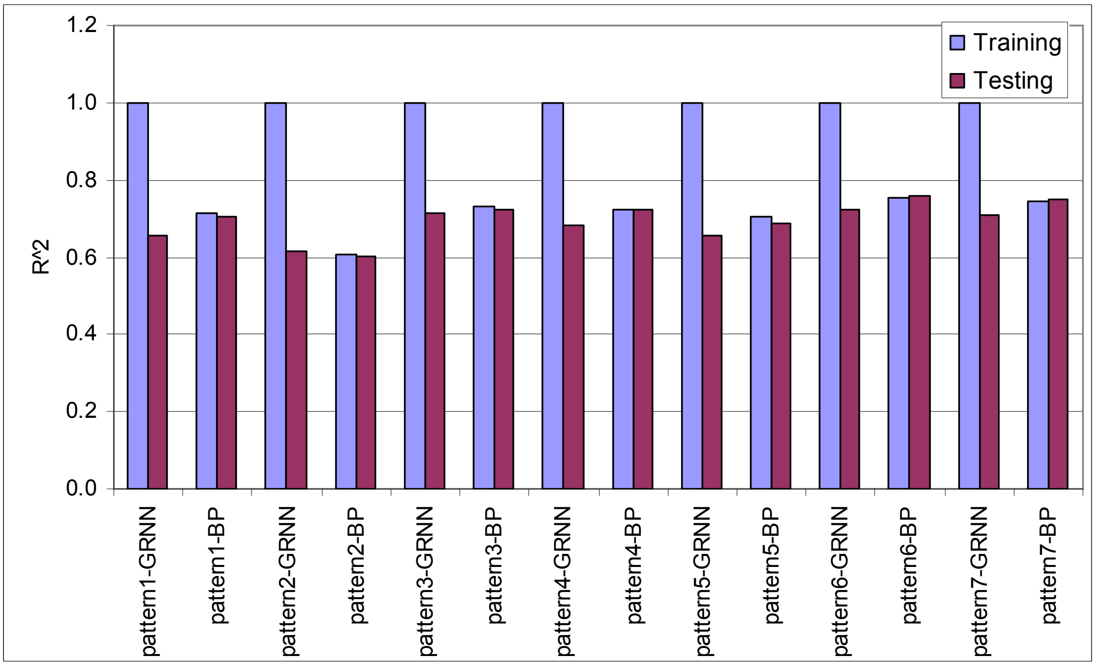


Figure 45 Comparison of input patterns and ANN types in terms of R^2.

2.4 Validation of ANNs as an intelligent controller

The aim of this section is to validate the trained neural networks for controlling coastal gate operations. To deal with this task, the coupling trained neural network and River Operation model is developed as mentioned previously. The performance of the ANNs controller for operating coastal gate is compared with that when reference model (CoastalGate model) is applied. The validation data set, which is not included during both training and testing processes, is used. The ANNs controller is implemented in the control loop as presented in Figure 9, where intelligent controller outputs are used recurrently as input for the next time step. For each time step, the value of gate opening determined by the ANNs controller is and the forecasted exogenous system, e.g. rainfall, upstream discharge, and tide water level are input to River operation Model. Then the state variables, e.g. water level, salinity concentration, and dissolved concentration are computed by River Operation model for the next time step.

Table 18 shows the performance of ANN controller as compared to reference model controller. Figure 46 to 52 depicts the comparison of upstream water levels, downstream water levels, upstream salinity concentrations, downstream salinity concentrations, upstream dissolved oxygen concentrations, downstream dissolved oxygen concentrations, and gate opening, respectively, as function of time under control of ANNs and CoastalGate

Since the gate openings of ANNs controller are not the same moments as for the gate openings of CoastalGate, state variables (e.g. water level, salinity concentration, dissolved oxygen concentration) may encounter phase shift (see Figures 46 to 52). However, the minimum, maximum, and average values of such state variables reached are very similar. Moreover, it should be noted that due to a simplified coastal gate considered herein and the use of NeuroGenetic Optimizer software package, which it cannot generate a computer program code itself, the computation time required for the simulation with the ANNs controller and the CoastalGate model is almost the same. In general, the performance for this study case is comparable to the study of Lobbrecht and D.P. Solomatine (2002), Lobbrecht, *et al.* (2005), and Darsono and Labadie (2007), which applied ANNs for water level control. This result also confirms that ANNs controller work quite well in real-time control.

Table 18 State variables comparison between ANNs and reference model controllers.

State variables	CoastalGate			ANN			Difference		
	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
WL_US	0.225	0.426	0.318	0.177	0.403	0.297	0.048	0.024	0.021
WL_DS	-0.423	0.354	-0.019	-0.424	0.373	-0.022	0.001	0.019	0.002
SAL_UP	0.000	3.142	1.432	0.000	2.877	0.756	0.000	0.265	0.676
SAL_DS	15.110	19.620	17.938	15.110	19.180	17.444	0.000	0.440	0.494
DO_US	2.607	4.134	3.785	2.607	4.162	3.812	0.000	0.028	0.026
DO_DS	1.658	4.991	3.200	1.646	4.626	3.214	0.012	0.365	0.014

Remark: WL_US = upstream water level (m. refer to mean sea level);
WL_DS = downstream water level (m. refer to mean sea level);
SAL_US = upstream salinity concentration (ppt);
SAL_DS = downstream salinity concentration (ppt);
DO_US = upstream dissolved oxygen concentration (mg/l); and
DO_DS = downstream dissolved oxygen concentration (mg/l).

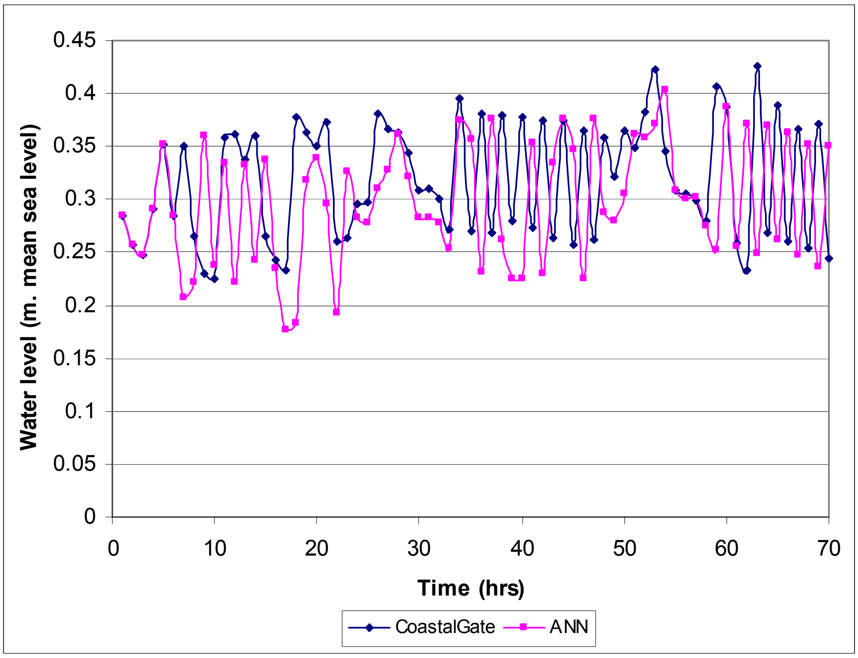


Figure 46 Comparison of upstream water levels under the control of ANNs and CoastalGate model.

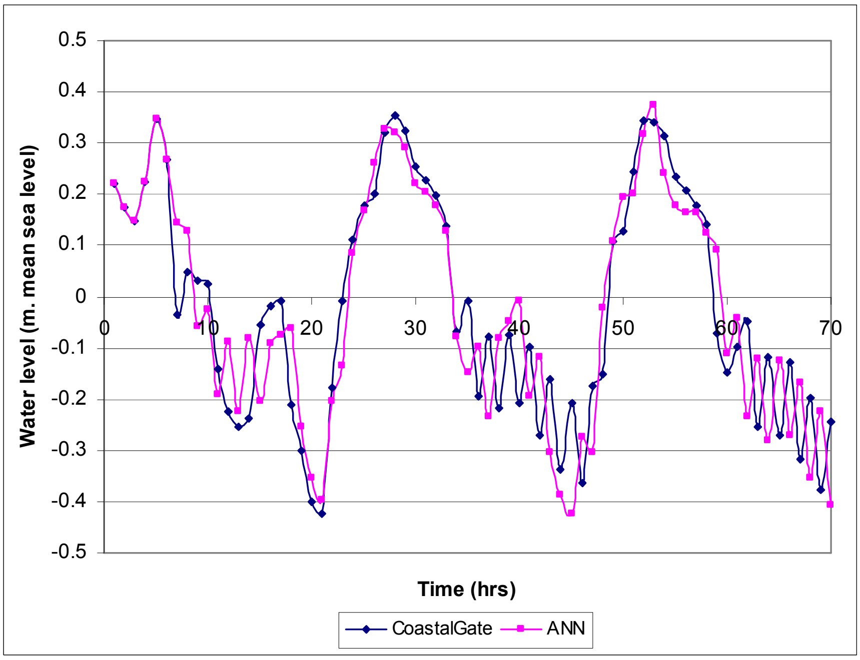


Figure 47 Comparison of downstream water levels under the control of ANNs and CoastalGate model.

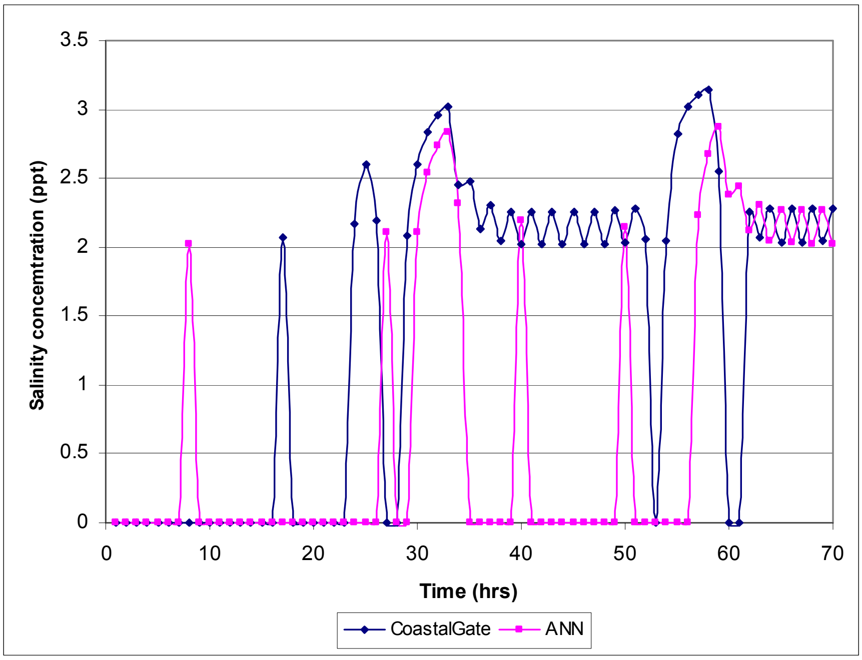


Figure 48 Comparison of upstream salinity concentrations under the control of ANNs and CoastalGate model.

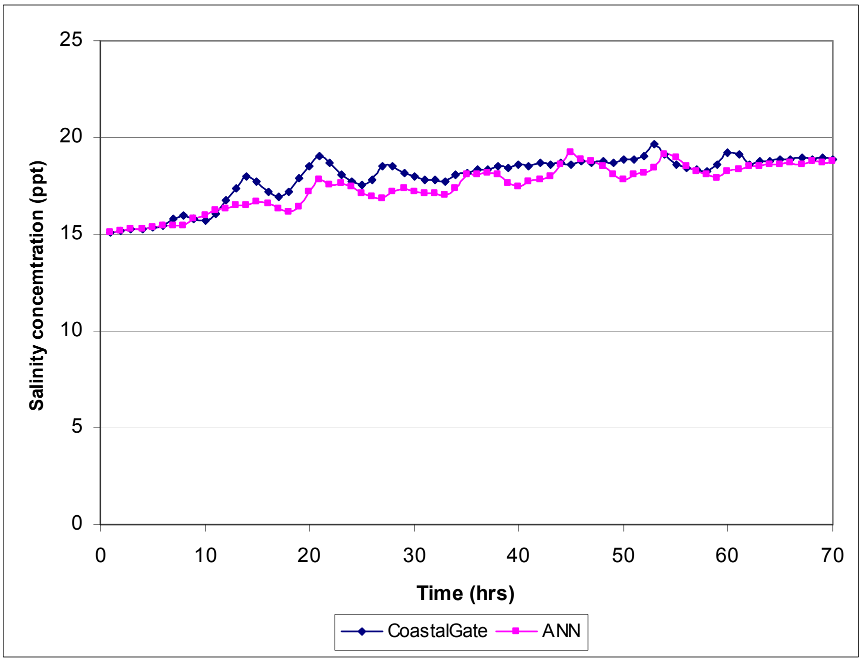


Figure 49 Comparison of downstream salinity concentrations under the control of ANNs and CoastalGate model.

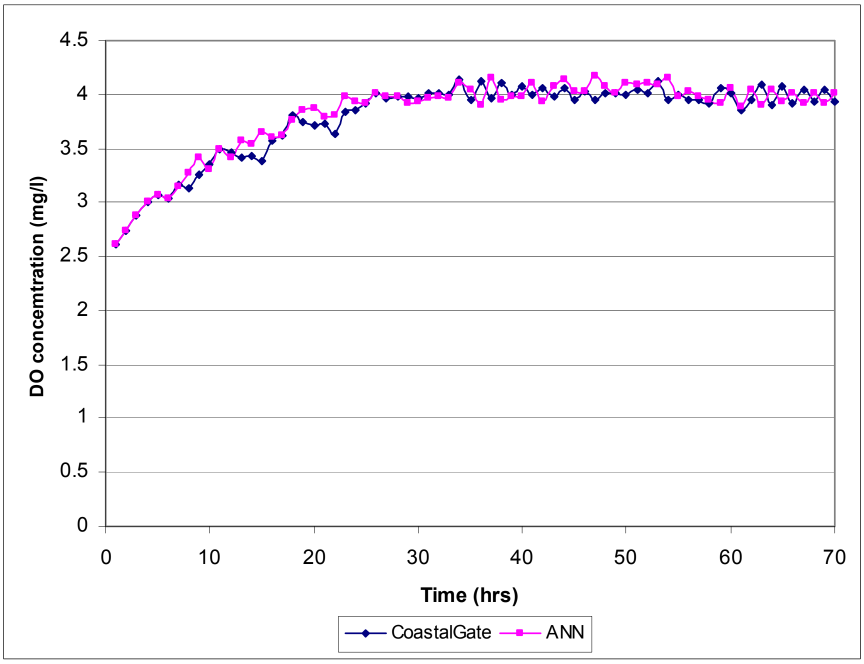


Figure 50 Comparison of upstream DO concentration under the control of ANNs and CoastalGate model.

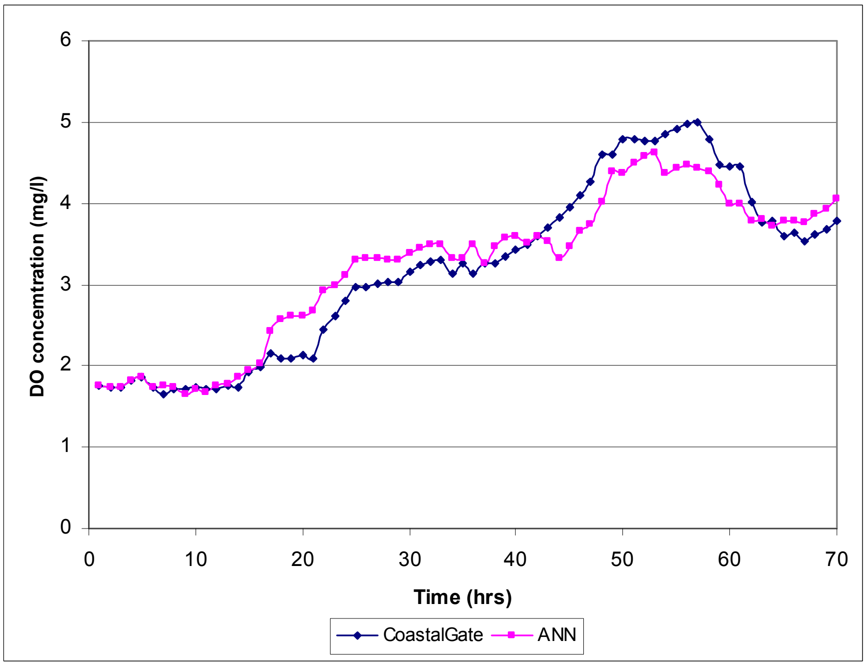


Figure 51 Comparison of downstream DO concentration under the control of ANNs and CoastalGate model.

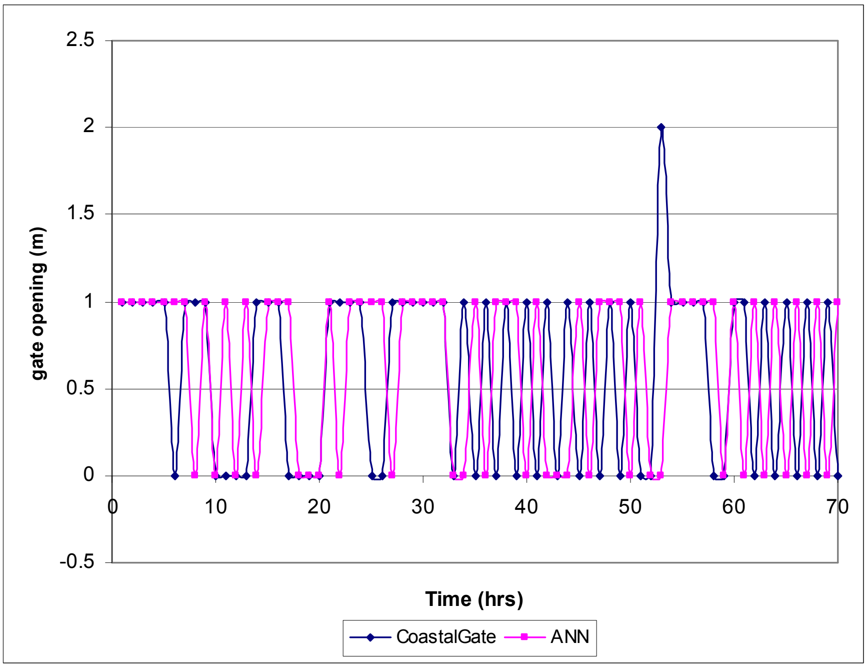


Figure 52 Comparison of gate openings under the control of ANNs and CoastalGate model.