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Optimal Coastal Gate Operation Method through Simulation-Optimization Approach

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ABSTRACT

Coastal gate refers to the water gate constructed in a coastal river basin. Initially, the main purpose of construction of this water control structure is to prevent saline water intrusion into upstream freshwater and also storage freshwater along the water by closing the water gates during the dry season. Nevertheless, the water gate cannot be permanently closed due to the requirement of environmental flow which provides the critical contributions to river health, economic development and poverty alleviation. Therefore, it is necessary to develop a methodology for appropriately operating the coastal gate, which corresponds to various objectives of water resources management system simultaneously. In this paper, the methodology for planning optimal coastal gate opening serving several desired state variables through simulation-optimization approach is presented. The Differential Evolution (DE) approach and River Operation Model (ROM) are applied herein as the optimization and simulation model, respectively. The developed method was then applied to the problem of coastal gate operations in Pak Phanang River Basin (PPRB), which mainly covers the area in Nakhon Si Thammarat province, the southern part of Thailand. The results illustrated that the purposed model can be used as decision support model for management of optimal coastal gate operations under several environmental, ecological and hydraulic conditions.

Key words: coastal gates operation, differential evolution, multi-objective optimization, Pak Phanang River Basin, River Operation Model

INTRODUCTION

The coastal lands are one of the most important areas intensely settled by human beings owing to their fertility and abundance of natural resources. Such areas also support several agricultural activities such as rice farming, aquaculture, horticulture and so forth. At present, all natural resources, especially forests and water sources, have been considerably deteriorated leading to serious adverse effects on environment. For example, during dry season there is inadequate freshwater for agricultural and domestic consumptions and the problem of saline water intruding into upstream freshwater due to tidal effect and low flow in the river. On the contrary, there is the abundance of excessive water in wet season, resulting in inundation and destruction of human's properties and lives. To tackle with these problems, coastal gates, one of widespread construction measures, have been constructed in several countries around the world. Nevertheless,

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the operations of coastal gates to manage such complex problem are not easy task due to the fact that it is necessary to consider multiple objectives (often conflicting objectives) at the same time.

As a result, a number of mathematical models have been developed and used extensively in the recent years as decision support tools for coastal gate management. Gate operators can use these models for planning the coastal gate operations by means of trial and error process to determine gate opening. However, such methods need the considerable experiences of the users, are also very time-consuming process, especially for the complex systems, and do not guarantee to obtain optimal solution. Furthermore, most of gate operation module, which is sub-module in hydrodynamic model, cannot consider both water quality and water quantity criteria simultaneously. Hence, it is necessary to develop the method or the model as the decision support tool for determining optimal coastal gate operations corresponding with multiple objectives.

Differential Evolution (DE) is the stochastic optimization approach used in this study (Price and Storn, 1997a; b). This approach is successfully applied in various optimization problems (Laskari *et al.*, 2003; Hrstka and Kucerova, 2004; Onwubolu and Davendra, 2006) and also in water resource engineering problems, for example the pipe design and the replacement of water distribution system (Charoenongart, 2005; Prempree, 2005), reservoir operation (Thasaduak and Chittaladakorn, 2005; Vasan and Raju, 2005), and water pumping system (Babu and Angira, 2005).

In present article, the novel method for management of optimal coastal gate operations through simulation-optimization model was developed. Firstly, the theory of Differential Evolution (DE) approach and River Operation Model (ROM) used as optimization model and simulation model herein, respectively, are reviewed. Secondly, the development process of simulation-optimization model for coastal gate management is presented. Finally, the method developed was then applied to determine the optimal hourly coastal gate operations in Pak Phanang River Basin (PPRB) as the case study.

MATERIALS AND METHODS

Differential evolution

Differential Evolution (DE) was initially introduced and developed by Price and Storn (1997a) in an attempt to solve the Chebychev Polynomial fitting Problem. DE is the evolutionary optimization technique based on the stochastic approach. This algorithm is the improved version of the Genetic Algorithms (GA) for the simple structure, ease of use, speed and robustness (Babu and Angira, 2005). The principal difference between GA and DE is that GA relies on crossover, which is a mechanism of probabilistic and useful exchange of information among solutions to locate the better solutions; whereas DE uses mutation as the primary search mechanism. DE's algorithm consists of four main processes: initialization, mutation, crossover, and selection (Price and Storn, 1997a; Price and Storn, 1997b; Onwubolu and Dravendra, 2006). The process starts with specifying DE's parameters, namely:- maximum number of generations, population size (NP), weighting factor (F), and crossover constant (CR). Then the four main steps are carried out as follows.

1) Initialization: As with all evolutionary optimization algorithms, DE works with the population of the solutions, not just a single solution for the optimization problem. The population, P, of generation, G, contains the constant population size, NP, solution vectors. In addition, each vector contains D real parameters (chromosome of individuals). Due to no more knowledge available about the location of the global optimum, the initial population is randomly generated from specified boundary constraints using the uniformly distribution random numbers

to cover the entire solution space.

$$P_{G=0} = x_j^{(L)} + rand_j[0,1]\cdot(x_j^{(U)} - x_j^{(L)}), j \in [1, D] \quad (1)$$

where $rand_j[0,1]$ represents a uniformly distributed random value within range [0,1] that is chosen a new one for each j; $x_j^{(U)}$ and $x_j^{(L)}$ is upper and lower boundary of each D real parameters. After generating the initial population, the objective function values of all the individuals are calculated and the best solution is determined.

2) Mutation: DE uses a self-referential population recombination scheme for creating the new generation. From the first generation onward, vectors in the current population, P_G, are randomly sampled and combined to create candidate vectors for the subsequent generation, P_{G+1}. As a result, the population of candidate, or mutant vectors, $P'_{G+1} = V_{i,G+1}$, is generated as follows:

$$V_{i,G+1} = X_{r1,G} + F(X_{r2,3} - X_{r3,G}) \quad (2)$$

where r_1,r_2 and r_3 belongs to set {1,2,3,…, NP} and $X_{r1,G}$, $X_{r2,G}$ and $X_{r3,G}$ represent the three random individuals chosen in the current generation, G, to reproduce the mutant vector for the next generation, $V_{i,G+1}$. The random numbers r_1,r_2 and r_3 should be different from each other and also different from the running index, *i,* and hence *NP* should be at least 4 to allow mutation. *F* is the weighting factor, the real number between 0 and 2; this value is used to control the amplification of the differential variation between the two random vectors.

3) Crossover: This process is performed to increase the diversity of the perturbed parameter vectors. In this step, the trial vector, $U_{i,G+1}$ is produced by duplicating some elements of the mutant vector, $V_{i,G+1}$ or some elements of the target vector, $X_{i,,G}$ with probability equal to CR. For the first generation, the target vector is the best vector of all individuals in the initial population and it is the best vector of all individuals obtained from the selection process for the subsequent generation. The crossover process can be presented in mathematical form as:

$$U_{i,G+1} = \begin{cases} V_{i,G+1} & if\ (randb(j) \le CR)\ or\ j = rnbr(i) \\ X_{i,G} & if\ (randb(j) > CR)\ or\ j \ne rnbr(i) \end{cases} \quad (3)$$

where *randb(j)* is the j[th] evaluation of a uniform random number generator with outcome ∈ [0,1]; *CR* is the crossover constant ∈ [0,1] which has to be determined by the users; *rnbr(i)* is a randomly chosen index ∈ 1,2,3,..,D which ensures that $U_{i,G+1}$ gets at least one parameters from $V_{i,G+1}$. Usually, suitable values for F, CR and NP can be found by experimentation after a few tests using different values. Practical advice on how to select control parameters NP, F and CR can be found in Storn and Price (1997).

4) Selection: On the basis of the target vector of current population, $X_{i,G}$ and the trail vector of next population $V_{i,G+1}$, the child population, $X_{i,G+1}$ is created as follows:

$$X_{i,G+1} = \begin{cases} U_{i,G+1} = U_{j,i,G+1} & \text{if } f(U_{i,G+1}) \text{ better than } f(X_{i,G}) \\ X_{i,G} & \text{otherwise} \end{cases} \quad (4)$$

In equation (4), the trial vector $U_{i,G+1}$ is compared to the target vector $X_{i,G}$ using the greedy criterion. If vector $U_{i,G+1}$ yields a better cost function value than $X_{i,G}$, then $X_{i,G+1}$ is replaced by the trial vector $U_{i,G+1}$; otherwise, the old value of the target vector $X_{i,G}$ is retained. The process of mutation, crossover, and selection is repeated until a termination criterion such as the maximum number of generation is satisfied. The algorithm then terminates proving the best point that has been explored over all the generations.

River Operation Model (ROM)

River Operation Model (ROM), developed by Royal Irrigation Department (RID), was used as mathematical simulation modeling in this work. This model includes five main sub-modules, namely:- Hydrodynamic Model (HD model), Water Quality Model (WQ model), Water Demand Model (WD model), Rainfall-Runoff Model, and Forecasting Model. The HD model based on Saint-Venant equation can be applied to study the behaviors of water level, velocity, and discharge in the river network for both steady and unsteady flow. WQ Model is another sub-module in ROM using to study mass transportation based on the advection-diffusion process in watercourse, for example salinity, dissolved oxygen, biological oxygen demand, and pH. Both HD and WQ models utilize finite difference technique for solving the governing equations. Tank model is adopted herein as rainfall–runoff model to determine upstream boundary data used in HD model. In the case of water management in advance, Auto Regressive & Updating Procedure model (AR model) and harmonic analysis model as two Forecasting models are applied to synthesize upper boundary and lower boundary data, respectively. ROM can be used simulation both event mode for project planning and analysis purposes, and real time mode by using data obtained from telemetering system. In the present study, DE was developed using delphi programming and subsequently linked with two sub-modules: hydrodynamic model and water quality model for determining optimal gate opening corresponding to multiple purposes of integrated water resources management.

Development of simulation-optimization model

1. Design of multiple objective functions

In this study, the multi-objective optimization based on weighting method was used for the model development. The weighting mechanism was used to ensure that if failure cannot be prevented, the least important interests fail first and the most important ones fail last (Lobbrecht *et al.*, 2005). The multiple objectives of operating the coastal gate consist of to keep water level, control salinity concentration, and control dissolved oxygen concentration at any selected control locations along the river (nearby upstream and/or downstream gates) under the desired conditions. The desired conditions are to prevent poor water quality and water scarcity. Hence, the concerning parameters comprise water level, salinity concentration, and dissolved oxygen concentration at selected control points, and control variables or decision variables are gate opening.

The objective function in this study is to maximize satisfaction function. The mathematical formulation of optimization problem for determining coastal gate operations for one time step of the control horizon to simultaneously satisfy the requirement of several interesting parameters can be expressed as follows

$$\text{Maximize } Z = \sum_{i=1}^{m} W_{ai} \sum_{j=1}^{n} R_{di,j} S_{i,j}(\bar{x}, \bar{u}) \quad (5)$$

where $\bar{x}$ = time-dependent state variables; $\bar{u}$ = time-dependent control variables or decision variables; $S_{i,j}(\bar{x}, \bar{u})$= satisfaction function j for water subsystem i; coefficient W_{ai} = weighting factor for an area in the satisfaction function; and coefficient $R_{di,j}$ = relative importance of interesting parameter j in water subsystem i within a particular area. The satisfaction function can be mathematically expressed as follows

$$S_{i,j}(\bar{x}, \bar{u}) = 1 - \frac{|x_{calculated} - x_{desired}|}{0.5(x_u - x_l)} \quad (6)$$

where $x_{calculate}$ is the state variables obtained from calculation results of simulation model while determining optimal gate opening; $x_{desired}$ is the desired state variables; x_u is upper limit on the state variables; x_l is the lower limit on state variables. Considering equation 6, the value of satisfaction function is equal to one when $x_{calculate}$ and $x_{desired}$ are the same value. The satisfaction function is still the positive value until the different value between $x_{calculate}$ and $x_{desired}$ is more than a half of the different value between x_u and x_l, that is, if the different value between $x_{calculate}$ and $x_{desired}$ is more than a half of the different value between x_u and x_l, the value of satisfaction function is the negative value.

The objective function as shown in equation 5 is subject to three constraints: hydraulic, water quality, and physical and operational bounds on the gate operations as follows.

(a) Hydraulic constraint is defined by the Saint-Venant equations for one-dimensional gradually varied unsteady flow and other relationship such as upstream, downstream, and internal boundary conditions and initial conditions that describe the flow in the different components of the river system,

$$H(h,Q,g) \quad (7)$$

where h is the vector of water surface elevations, Q is the vector of discharge, and g is the matrix of gate setting, all given in matrix form to consider the time and space dimensions of the problem.

(b) Water quality constraint is defined by the Advection-Diffusion equation. This model is used in conjunction with hydrodynamic model. The water level elevations and discharge at each space and time are calculated by hydrodynamic model, and then are used as input data in the water quality model. The calculated result of this model is the water quality concentrations at each space and time,

$$W(wq,g) \quad (8)$$

where wq is the water quality parameters such as salinity, dissolved oxygen, biological oxygen demand; g is the matrix of gate setting, all given in matrix form to consider the time and space dimensions of problem.

(c) Physical and operational bounds on gate operations

$$\underline{g} \leq g \leq \overline{g} \quad (9)$$

where $\overline{g}$ and $\underline{g}$ is the upper and lower bounds for gate setting, respectively. The bounds on gate setting are intended primarily to reflect the physical limitations on the gate operations. The allowable maximum change of gate setting, for instance, can be specified through this formulation, as the time-dependent constraint. This particular formulation may be very useful, especially for cases where sharp changes in the gate operations (i.e., sudden opening and closures), are not desirable or physically impossible. It is handled by setting an upper bound to the change of gate opening from one time step to the next (Mays, 1997).

2. Flow diagram of the linked simulation-optimization model

The flow diagram of decision support model for planning coastal gate operations through simulation-optimization model (or CoastalGate model) is shown in Figure 1. The processes of a computer program which is the combination of the simulation and the optimization model start with specifying the parameters, namely, weighting factor (F), crossover constant (CR), population size (NP), and the number of maximum generations. All such DE's parameters must be tested by means of sensitivity analysis for each considered problem to obtain the best optimal solution. The initial population is then randomly generated from specified bound using the uniformly distribution random numbers to cover the entire solution space, which need to be routinely considered in term of violation of physical bounds on gate operations as well. Next, the ROM model is exploited to simulate the behaviors of water flow and mass transportation in terms of water level, salinity concentration, and dissolved concentration. After that, the satisfaction function values of all

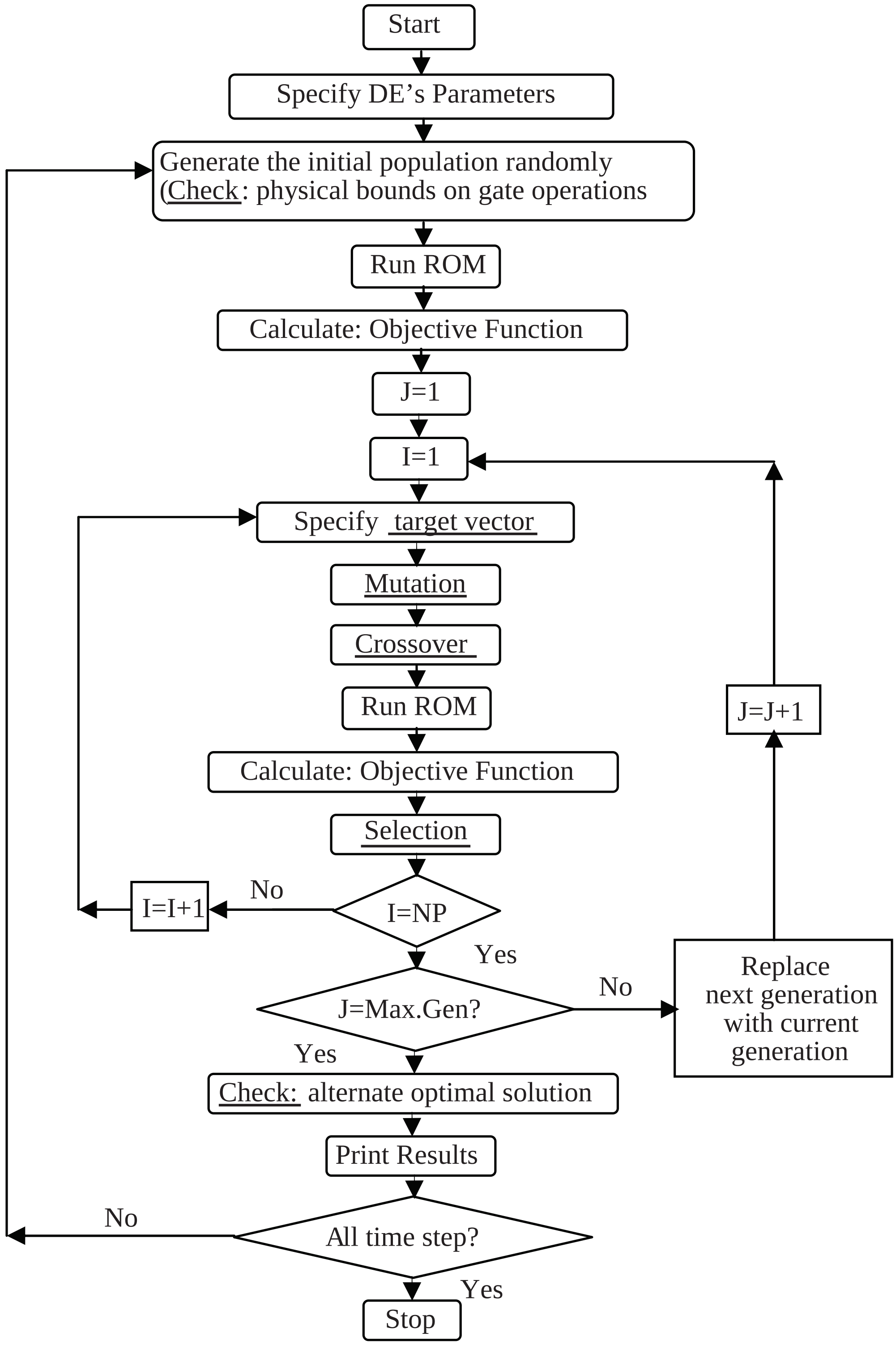


Figure 1 Flow diagram of the main processes in CoastalGate model.

individuals are calculated from such parameters and the best one is determined as a target vector. Then the three main steps: mutation, crossover and selection on the population, are carried out (Price and Storn, 1997a; b). Mutation and crossover operations are performed to diversify the search thus escaping from the local minima, and the selection process is invoked to conduct the best solution into further generations. Between crossover and selection processes, ROM model and calculation of objective function are used again for the purpose of evaluation of new generated control variables (gate openings) of each new population generated from mutation and crossover process. Before printing results, the sub-procedure for checking the alternate optimal solutions, which normally take place when the bottom of the gate is over both the upstream and downstream water surface elevations (nonorifice flow condition), is invoked. Finally, the simulation results, including the values of water level, salinity concentration, dissolved concentration at chosen observation points, and optimal gate openings, are printed in text files form. Such processes are repeated until a termination criterion such as desired simulation time depending on a period of forecasting data are satisfied.

Description of the study area and data used

To demonstrate the applicability of the developed model as described above, it was applied to the problem of planning the gate operations in Pak Phanang River Basin (PPRB) Development Project. This basin covers the total area of 3,100 km^2 or approximately 1,937,500 Rai with the cultivated area over 500,000 Rai. Such project was initiated by his majesty the king Bhumibol Adulyadej to serve the following objectives: 1) to solve the problem of fresh water shortages, saline water intrusion, flood mitigation and acid water; 2) to rehabilitate the agricultural system in the project area; 3) to extinguish the controversy between prawn and rice farm owners; and 4) to raise the standard of living of people in the project area. Eighteen telemetering stations were installed throughout the basin to measure various meteorological, hydraulic, and water quality data, namely:- water level, rainfall, temperature, salinity concentration, dissolved oxygen concentration, pH, and gate opening. Each station cannot measure all of these parameters, but some necessary ones in each location (RID, 2004).

Figure 2 shows schematic diagram of coastal gate system in PPRB considered in this study. The system consists of thirteen gates, namely Uthokawiphatprasit, Sua Hueng, Pakrawa, emergency gate, Thapraya, Klong Khong, Chian Yai, Bang Sai, Sukoom, Praekmueng, navigation gate, Klong Lad, and Nha Goat. The first ten gates were considered as control variables. The eleventh gate, navigation gate, was closed for all planning horizon. The other two gates were controlled by water level at just upstream and downstream gate. Except Uthokawiphatprasit gate, which is the regulating gate (or moving weir), the other nine considered gates are floodgate (or sluice gate).

The data used in this study consist of the input for three different models: hydrodynamic, water quality, and optimization model. The complete list of all data in meteorology, hydraulics, structure, and water quality used in hydrodynamic and water quality model are available from RID (2004). The upstream and downstream boundary data of hydrodynamic model were generated for operation period of 24 hours in advance since 24/03/2005 by using forecasting model in conjunction with database obtained from the existing telemetering system. The input data for optimization model consist of: 1) observation points, which are specified to collect information of state variables (e.g. water level, salinity concentration, and dissolved oxygen concentration); 2) allowable maximum and minimum gate opening; 3) desired criteria (Table 1); and 4) data of weighting factor (WF) and relative importance of interesting parameter. The

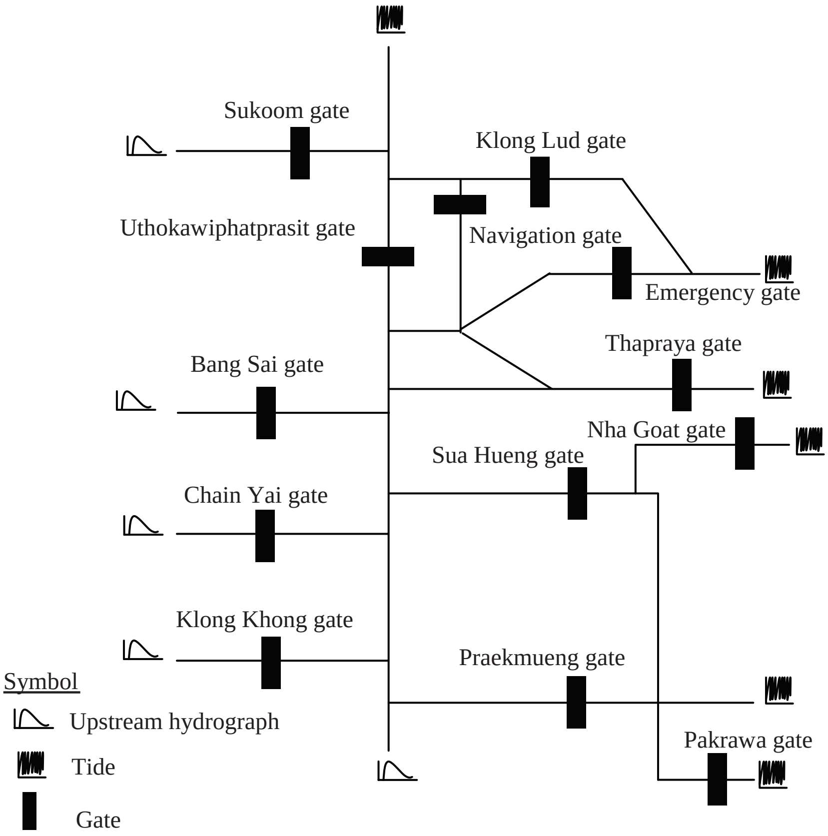


Figure 2 Schematic diagram showing coastal gate system of PPRB.
Source: RID (2004).

values of both factors used in this study were assumed following the priority of controlled gate location and interesting parameters of each gate (Table 2). The gate opening and crest level of moving weir were assumed to be adjusted not exceeding than 2 meters due to gate's speed limit. Gate opening or crest level of moving weir were assumed to be integer (e.g. -2, -1, 0, 1, 2); Hence, there are a total search space of 10^5 combinations:- 10 gates and each gate takes 5 possible values. Since hourly time step of control horizon was considered in present study, the selected control points in the river could not be far from control structures to assure that gate operation has an effect on chosen control locations.

At present, there is no certain rule for gate operations located in PPRB, i.e. all gates were generally closed during dry season and opened during rainy season. Such gate operation is thus referred to a baseline scenario (BAS). On the other hand, the gate operation guided by the CoastalGate model is referred to a full optimization scenario (FOP) in this paper. Both scenarios were compared in terms of the objective function value.

RESULTS AND DISCUSSION

Optimal values of DE's parameters

As mentioned previously, the different evolution needs four parameters: (1) maximum number of generations; (2) population size within each generation (NP); (3) weighting factor (F); (4) crossover constant (CR). The suitable values of each parameter were investigated by using the trial

Table 1 Desired criteria using as water gate control.

GATE	WL_US			WL_DS			SAL_US			SAL_DS			DO_US			DO_DS		
	Max	Min	Target	Max	Min	Target	Max	Min	Target	Max	Min	Target	Max	Min	Target	Max	Min	Target
Uthokawiphatprasit	0.3	0	0.3	0.6	-0.3	0.15	2	0	1	26	20	23	9	3	6	9	3	6
Sua Hueng	0.3	0	0.3	0.8	-0.3	0.25	2	0	1	26	20	23	9	3	6	9	3	6
Pakrawa	0.6	0	0.6	0.6	-0.3	0.15	26	20	23	26	20	23	9	3	6	9	3	6
Emergency gate	0.3	0	0.3	0.6	-0.3	0.15	2	0	1	26	20	23	9	3	6	9	3	6
Thapraya	0.3	0	0.3	0.6	-0.3	0.15	2	0	1	26	20	23	9	3	6	9	3	6
Klong Khong	1.0	0	1.0	0.3	0	0.15	-	-	-	0	0	0	-	-	-	9	3	6
Chian Yai	1.0	0	1.0	0.3	0	0.15	-	-	-	0	0	0	-	-	-	9	3	6
Bang Sai	0.4	0.1	0.4	0.3	0	0.15	-	-	-	0	0	0	-	-	-	9	3	6
Sukoom	0.3	0.1	0.3	0.6	0.3	0.45	-	-	-	26	20	23	-	-	-	9	3	6
Praekmueng	0.8	0	0.8	0.8	0.3	0.55	2	0	1	26	20	23	9	3	6	9	3	6

Note: WL_US = water level at upstream gate; WL_DS = water level at downstream gate; SAL_US = water level at upstream gate; SAL_DS = water level at downstream gate;DO_US = water level at upstream gate; DO_DS = water level at downstream gate

Table 2 The values of weighting factor (WF) and relative importance of interesting parameter.

GATE	WF	Relative importance					
		WL_US	SAL_US	DO_US	WL_DS	SAL_DS	DO_DS
Uthokawiphatprasit	1	0.3	0.1	0.1	0.1	0.2	0.2
Sua Hueng	1	0.3	0.1	0.1	0.1	0.2	0.2
Pakrawa	1	0.167	0.167	0.167	0.167	0.167	0.167
Emergency gate	1	0.4	0.3	0.3	0	0	0
Thapraya	1	0.4	0.3	0.3	0	0	0
Klong Khong	1	0.5	0	0	0.1	0.2	0.2
Chian Yai	1	0.5	0	0	0.1	0.2	0.2
Bang Sai	1	0.5	0	0	0.1	0.2	0.2
Sukoom	1	0.4	0	0	0.2	0.2	0.2
Praekmueng	1	0.5	0.3	0.1	0.1	0	0

& error approach. It was found that the maximum number of generations and the number of population is 2 and 30, respectively. The suitable values of N and CR in this case are both 0.8, which gave the highest value of satisfaction function. This shows very fast convergence since it used only approximately 90 times for function evaluation. However, the execution time was approximately 23 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 WQ model, which requires quite much computational 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.

Simulation results and performance analysis for coastal gate operations

The results of using the developed model for determining optimal hourly coastal gate operation are shown in Table 3. It shows the guideline for planning the gate operations of PPRB for the operation period of 24 hours in advance. These results are based on the given weighting factor and the relative importance of each interesting parameter, and the forecasted exogenous system input.

The performance comparison between BAS and FOP scenarios is presented in Table 4. It shows that the overall performance of FOP is better than BAS, with increase of satisfaction function value of 7.41 over the BAS. Although the difference of this satisfaction function of two scenarios is not much, particularly when considering numerical value, it is quite high value for satisfaction function designed in this study. In FOP scenario, the proposed model tried to find optimal gate setting by compromising all the desired criteria at all chosen checkpoints simultaneously. While model running to find the best gate setting, the state variables at all chosen checkpoints at every run time step of the control horizon are adjusted to be or close to the desired state variable as much as possible under several environmental, ecological and hydraulic constraints.

The reason why satisfaction function value as expressed in equation 6 is negative is because the current values of state variables (e.g. water level, salinity concentration, and dissolved oxygen concentration) at each selected control locations rather deviate from those desired target values. In addition, the exogenous system inputs such as rainfall, upstream discharge, and tide water level limit the model to obtain the better results.

Figure 3 shows the state variables versus time step of control horizon at checkpoints of Uthokawiphatprasit gate for both scenarios as an example case. In the first part of control periods, which is the duration of spring tide, for FOP scenario the weir is set to raise water level as much as possible to approach desired target (0.3 m). The increased upstream water level is a result of allowing sea water to intrude into the upstream river. However, it must be operated in order to control the salinity concentration at selected upstream control point for a value not exceeding desired criteria (1 ppt) and the downstream salinity concentration could be as close as 23 ppt according to target desired. Moreover, the upstream and downstream DO concentrations could be 6 mg/l as much as possible. These compromising results in using FOP scenario were leading to higher values of upstream water level, downstream salinity concentration, and upstream DO concentration in comparison to these of BAS. On the other hand, downstream water level and downstream DO concentration are in opposite direction.

Table 3 The plan of hourly coastal gate operation for 24 hours ahead.

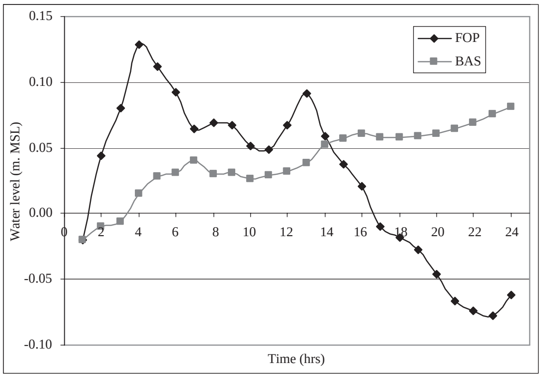
Time (hrs)	Gate opening (m)									
	1[a]	2	3	4	5	6	7	8	9	10
1	-1	1	0	1	2	1	0	1	2	1
2	-1	2	0	2	4	2	0	2	3	3
3	-1	2	1	2	4	2	2	3	3	2
4	0	1	0	2	4	0	3	5	3	0
5	-1	1	0	0	2	1	4	5	1	1
6	0	0	2	1	0	1	2	6	1	0
7	1	2	2	0	0	1	0	6	3	1
8	1	0	3	1	0	2	1	6	2	0
9	1	0	2	0	1	0	2	6	0	0
10	0	0	1	1	0	2	2	6	0	2
11	1	0	3	0	0	0	1	4	0	2
12	1	1	2	0	1	0	0	5	0	1
13	1	0	3	0	0	0	0	4	0	2
14	1	1	2	0	1	0	0	5	0	1
15	1	0	3	0	0	0	0	3	0	1
16	1	0	3	0	0	0	0	2	0	2
17	0	0	3	0	0	0	0	0	0	2
18	0	0	3	0	0	0	0	0	0	2
19	0	1	2	0	1	0	0	2	0	1
20	0	0	3	0	0	0	0	0	0	1
21	0	0	3	0	0	0	0	0	0	2
22	0	0	2	2	0	0	0	0	0	2
23	0	1	0	3	2	0	2	0	0	2
24	0	1	1	3	4	1	2	0	0	3

Note: Gate1 = Uthokawiphatprasit; Gate2 = Sua Hueng; Gate3 = Pakrawa; Gate4= Emergency gate;
Gate5 = Thapaya; Gate6 = Klong Khong; Gate7 = Chian Yai; Gate8 = Bang Sai
Gate9 = Sukoom; and Gate10 = Praekmueng
a = crest level of weir (in meter refers to mean sea level)

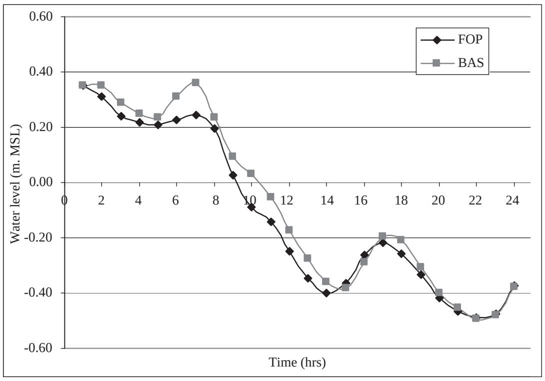
Table 4 Comparison of scenario results.

Satisfaction function value		
Baseline	Full-optimize	Difference
-119.610	-112.201	7.409

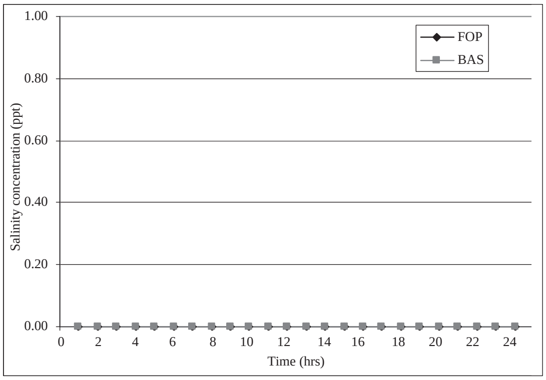
In the rest part of control periods, which is the duration of neap tide, for FOP scenario the weir is raised to prevent the water releasing into the downstream river or to storage the water in the upstream river. However, with the limitation of exogenous inputs, especially tide water level and upstream water flow, and in an attempt to simultaneously compromise several parameters like downstream salinity concentration (the second preferred parameter), the upstream water level could not be increased as desired. On the contrary, for BAS scenario due to an accumulation of water quantity from the beginning run time, the upstream water level in this case is higher than that of FOP



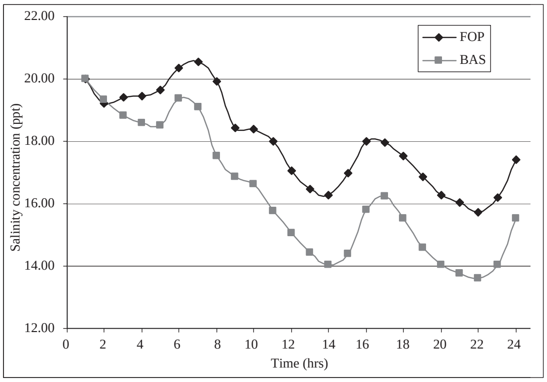
(a) Water level at upstream gate.



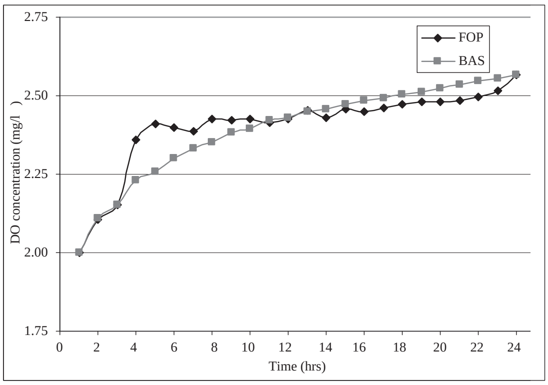
(b) Water level at downstream gate.



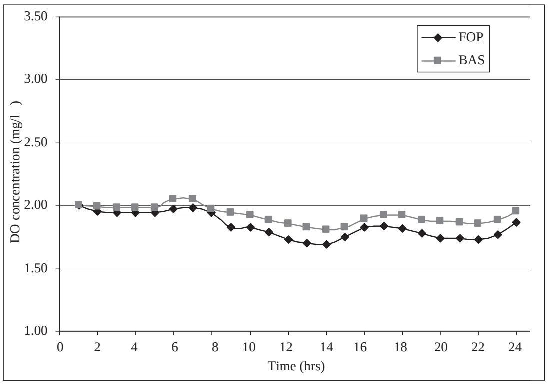
(c) Salinity concentration at upstream gate.



(d) Salinity concentration at downstream gate.



(e) DO concentration at upstream gate.



(f) DO concentration at downstream gate.

Figure 3 The state variables versus time step of control horizon at checkpoints of Uthokawiphatprasit gate under baseline and full optimiuzation scenarios.

scenario. However, other parameters for FOP scenario behave like the first part of control periods. These similar situations occur for all of the gates considered in this system.

The allowing sea water intrude into the upstream part of gate may help to preserve the ecology system of coastal river system as the same manner as that before gate constructed. In addition, the results may indicate that DO parameter is relatively sensitive to gate operations in comparison to other parameters.

The developed model can be used to assist the irrigation operator for making the decision plan for gate operations in the system suitably. Since this is multiple optimization problems, the results depend on the determination of preferred weighting factor and the relative importance of the interesting parameter. It should be noted that when applying this model, the user or gate operator could check the current values of state variables at each control locations to properly determine both factors. In addition, the various combinations of these parameters could be tested to compare the results as well.

CONCLUSION

This article presents the development of methodology for management of optimal coastal gate operations corresponding to several environmental, ecological and hydraulic conditions. The developed methodology consists of two main parts, i.e. 1) design of multiple objective functions and 2) development of computer model, which interfaces between simulation and optimization model. In this study, the River Operation Model and Differential Evolution are utilized as simulation and optimization model, respectively. The developed model was then applied to coastal gate system of PPRB as a case study. The optimal values of DE' s parameters were investigated and the model performance was also evaluated. The proposed method is valuable to help irrigation gate operators to make decision in this complicated task and can be extended to similar situations with suitable modifications.

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