MATERIALS AND METHODS

Materials

The development of decision support modeling which uses for assisting the gate operators in decision-making to plan optimal coastal gate operations required the following materials. The coupling simulation and optimization model, which was subsequently named CoastalGate Model, was developed by using Borland Delphi programming language (version 7.0). The hydrodynamic and water quality modeling (or River Operation model) was used as mathematical simulation model for this research. The developed modeling was tested using personal computers CPU 3.0 GHz with 1 GB of RAM at Walailak University's computer laboratory. In the process of applying Artificial Neural Networks model for deriving general coastal gate operation rules, NeuroGenetic Optimizer, which is Artificial Neural Networks software package, was selected. To validate the performance of operating rules derived from neural network controller, Microsoft Visual Basic programming language (version 6.0), AutoHotkey (Version 1.0.44.13), which is macro windows software package, and Visual basic Application in Microsoft Excel were utilized to develop the linked model between trained neural network and River Operation Model. Finally, several official apparatus such as a printer, paper, etc were also required to complete this work.

Methods

This section presents the development processes of decision support modeling for optimal coastal gate operations in details. In the first part, the development processes of coupling simulation and optimization modeling for determining the optimal gate settings in coastal river system are delineated. The main methodologies are composed of: 1) the formulation of multiple objective functions; and 2) the development of a computer program which links between mathematical simulation of hydrodynamic and water quality models and optimization model of differential evolution approach. Finally, the study area and used data for purpose of demonstration of the developed model applicability are also described in this section.

In the second part, the application of Artificial Neural Networks (ANNs) for deriving coastal gate operation rules is explained. To obtain coastal operating rules, three steps are conducted as follows: 1) generate numerous pair data sets of optimal gate setting and the influencing parameters (e.g. water level, salinity concentration, and dissolved oxygen concentration) at specified control points along the river, from several concerned events by using CoastalGate model, which is a reference model; 2) utilize ANNs to learn the relationship between selected influencing parameters and optimal gate setting; and 3) evaluate the performance of generated operating rules.

In conclusion, in this chapter, the methodologies of developing decision support model for coastal gate operations are divided into two main parts as described above. The more detailed information of each development processes are delineated as follows.

1. Development of coupling simulation and optimization modeling

In the first activity, the coupling simulation and optimization model, which can be used to determine the optimal operation schedules of the gates in coastal river system for a predefined time horizon for water quantity and quality purposes while satisfying the hydraulic, the water quality, and the bound constraints, is designed and developed. The problem is formulated as a discrete time optimal control problem in which gate settings are the control variables and water levels, salinity concentrations, and dissolved oxygen concentrations at specified control points of the coastal river system are the state variables. The specific task in this activity consist of 1) design of multiple objective function or satisfaction function; and 2) development of a computer program that links the existing mathematical simulation model and optimization procedure altogether. Then applicability of the developed model is demonstrated for various study cases with existing coastal river system of Pak Phanang River Basin as a study case.

1.1 Design of multiple objective function

In formulating a discrete time optimal control problem, it is necessary to incorporate all elements of the system that are relevant to system performance. The framework of the problem consists of three components: 1) the control (independent) and state (dependent) variables; 2) the objective function to be minimized or maximized; and 3) a set of constraints which limit the feasible solution space.

In this dissertation research, the multi-objective optimization based on weighting method was applied for model development. This method is a conventional method which multiple objectives are combined to form one objective by using some knowledge of problem being solved. The weighting mechanism was used herein 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 coastal gates are to control water levels, salinity concentrations, and dissolved oxygen concentrations at specified control locations along the river (usually nearby upstream and/or downstream gates) under desired conditions. The desired conditions herein are to prevent poor water quality and water scarcity. Hence, the concerning parameters (or state variables) comprise water level, salinity concentration, and dissolved oxygen concentration at selected control points along the river, and the control variables (or decision variables) are gate setting.

The objective function designed in this study is to maximize satisfaction function. The satisfaction functions as expressed in equation 33 are used to represent an interest in terms of surface water levels, salinity concentrations, and dissolved oxygen concentrations at specified control points along the river. The desired state values of the satisfaction function used herein are assigned as a single value, which is between allowable maximum and minimum of each concerning parameter present in water system. Generally, such values is specified by means of weighting mechanism from their own allowable maximum and minimum. That is, mostly the average values of theirs own allowable maximum and minimum are used.

The mathematical formulation of optimization problem for determining coastal gate operation to simultaneously satisfy the requirement of several interesting parameters can be expressed as follows

$$\text{Maximize Z } = C \times \sum_{i=1}^{m} W_{ai} \sum_{j=1}^{n} R_{di,j} S_{i,j}\left(\overline{x},\overline{u}\right) \tag{32}$$

where $\overline{x}$ = time-dependent state variables; $\overline{u}$ = time-dependent control variables or decision variables; $S_{i,j}\left(\overline{x},\overline{u}\right)$ = satisfaction function j for water subsystem i; coefficient W_{ai} = weighting factor for an area in the objective function; coefficient $R_{di,j}$ = relative importance of interesting parameter j in water subsystem i within a particular area; and C = constant coefficient, which equal to 1,000 for this study case. Both weighting factor and relative importance of interesting parameter are specified by users depending on the priority level of gate locations and concerning parameters in each location. The satisfaction function can be defined as follows

$$S_{i,j}\left(\overline{x},\overline{u}\right) = 1 - \frac{\left|x_{calculated} - x_{desired}\right|}{0.5\left(x_u - x_l\right)} \tag{33}$$

where $x_{calculated}$ is state variables obtained from calculation results of simulation model while determining optimal gate setting; $x_{desired}$ is desired state variables; x_u is upper limits on state variables; x_l is lower limits on state variables. Considering equation 33, it is found that the value of satisfaction function is equal to 1 when the value of $x_{calculated}$ and $x_{desired}$ values are the same. The satisfaction function is still positive value until the deviation between $x_{calculated}$ and $x_{desired}$ values is more than a half of deviation between x_u and x_l values. That is, if the deviation between $x_{calculated}$ and $x_{desired}$ values is more than a half of deviation between x_u and x_l values, the satisfaction function is negative.

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

(a) Hydraulic constraint 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 a river system,

$$H(h, Q, ga) \tag{34}$$

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

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

$$W(wq, ga) \tag{35}$$

where wq are water quality parameters such as salinity, dissolved oxygen, biological oxygen demand, and pH; ga 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

$$\underline{g} \le g \le \overline{g} \tag{36}$$

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 gate operations. Operational constraints other than bounds can be imposed for various purposes. The allowable maximum change of gate setting, for instance, can be specified through this formulation, as a time-dependent constraint. This particular formulation may be very useful, especially for cases where sharp changes in gate operations (i.e., sudden opening and closures), are not desirable or physically impossible. It can be handled by setting an upper bound to the change of gate opening from one time step to the next (Mays, 1997).

The designed objective function is used for optimal control problems which concern a time-series calculation. The optimization problem is composed for each time step for a particular time ahead, called the 'control horizon', denoted by T. The length of the control horizon is at least one time step. Inputs for a problem are current (t=0) state variables $\overline{x}$ (e.g. water levels, salinity concentrations, dissolved concentrations) and control variables $\overline{u}$ (e.g. gate settings) as well as predicted system loads during the control horizon (t = 1 to t = T). Both state and control variables depend on time. The optimized control-variable values for t = 1 are implemented in the time-series calculation. Then, the time-series calculation proceeds one time step, after which the optimization problem is composed again.

1.2 Development of a computer program of coupling simulation and optimization model

In this section, the development of a computer program of coupling simulation and optimization model was described. River Operation model (ROM) and Differential Evolution (DE) were used as simulation model and optimization model, respectively. The main task in this portion is how to develop DE approach for determining the optimal gate operation schedules in coastal river system, and to link the existing mathematical simulation and the developed optimization model together. The development of DE approach involves applying objective function, which are developed in previous section, as the index for selecting optimal gate settings when considering various objectives.

Furthermore, it should consider the subjects of preventing violation of physical and operational bounds on gate operations, and solving the problem of alternate optimal solutions, which usually occur during running mathematical simulation model in case of a non-orifice flow situation. To link simulation and optimization model together, it is necessary to study components of input and output data files for both models.

The overall framework of coupling simulation and optimization model is presented in Figure 13. The working process of such developed model starts with receiving input data for optimization, hydrodynamic, and water quality models (all these input data will be discussed in more details in the subsequent topic). Through this simulator-optimizer formulation, the problem is solved efficiently by incorporating the mathematical simulation model into a procedure when a set of gate settings, g (control vector), is chosen. The simulation model is run, which is subject to the selected control vector, to solve the hydraulic constraint set (H) for the water elevations, discharges, and velocities, and water quality constraint set (W) for the salinity concentrations and dissolved oxygen concentrations (state vector), respectively. Then the multiple-objective function is evaluated, and the bound constraints (physical and operational bounds on gate operations) are checked. These procedures are repeated with an updated data set of gate settings until a convergence criterion is satisfied and no bound constraints are violated.

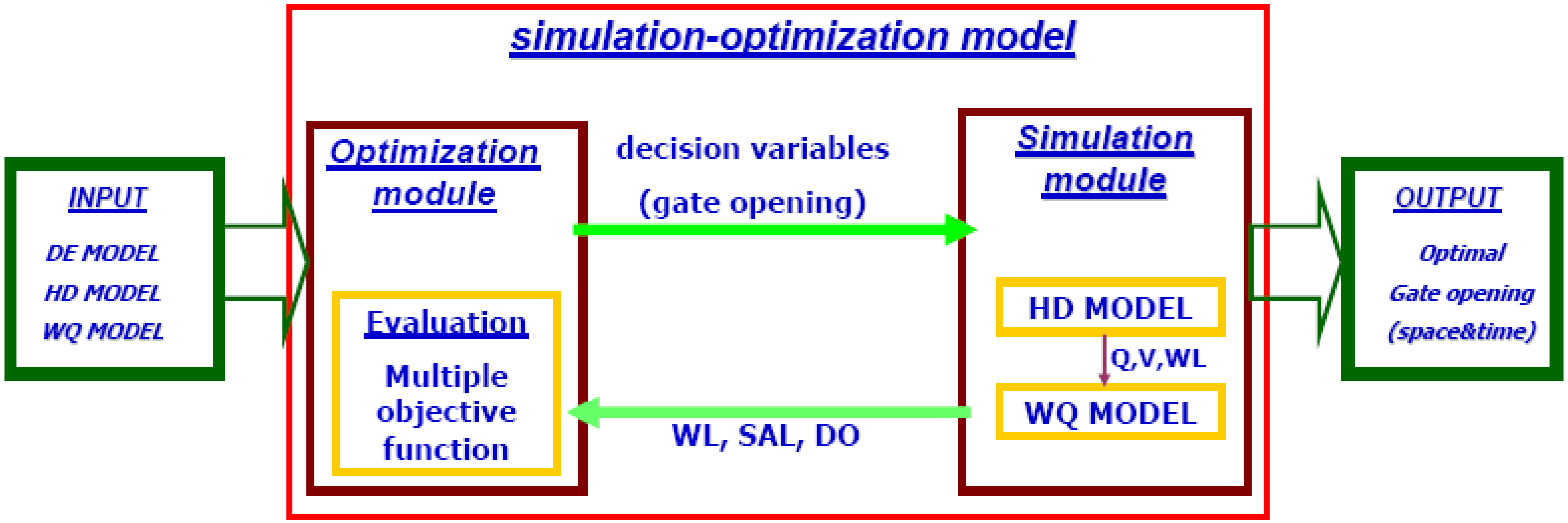

Figure 13 The overall framework of coupling simulation and optimization model.

1.2.1 Preventing in violation of physical bounds on gate operations

As mentioned earlier, in practical gates cannot be operated in sharp change (i.e., sudden opening and closures) due to speed limit of gate. On the contrary, in mathematical analysis, particularly when using River Operation Model (ROM), it is possible to obtain this undesired incident. This is because ROM has no function for solving this subject matter. Hence it is necessary to develop subroutine process embedded in Differential Evolution approach based on optimization model to figure out this problem. The idea for solving this problem is determination of the possible upper and lower boundary of search space for gate settings in the current run time step related to those in the previous run time step. The processes of this developed procedure consist of: 1) specify the allowable maximum change of gate settings; 2) specify of the allowable maximum and minimum of gate settings; and 3) check on the possible upper and lower boundaries of search space for gate settings in current run time step. Hence, the gate settings for each run time step are controlled by those in the previous run time step, the allowable maximum change of gate setting, and the allowable maximum and minimum of gate settings. A code fragment for this subroutine process is shown in Figure 14.

```
If CountTime > 1 then
begin
      AllowGateOpening:=StrToFloat(FrmMain.EditSpeedControl.Text);
      for i:=0 to (D-1) do
      begin
         max[i]:=StrToFloat(FrmMain.StringGrid_Constraints.Cells[2,i+1]);
         min[i]:=StrToFloat(FrmMain.StringGrid_Constraints.Cells[3,i+1]
      end;

     for i:=0 to (D-1) do
      begin
          ibound[0,i]:=bestit[i]-AllowGateOpening;
          if ibound[0,i]<min[i] then ibound[0,i]:=min[i];
          ibound[1,i]:=bestit[i]+AllowGateOpening;
          if ibound[1,i]>max[i] then ibound[1,i]:=max[i];
      end;
end;
```

Figure 14 Sample code fragment from routine to prevent violation of physical bounds on gate operations.

1.2.2 Preventing the problems of alternate optimal solutions

When applying the coupling simulation and optimization model for determining optimal coastal gate opening, it is generally occurrence of the problem of alternate optimal solutions. Such problem results from a non-orifice flow situation, which the gate bottom is set at the level higher than both the upstream and downstream water surface elevations. As a result, in this situation, each state vector (e.g. the water levels, discharges, velocities, salinity concentrations, and dissolved oxygen concentrations) obtained from running mathematical simulation model are the same whether gate settings are the same or not.

This problem may not be directly effect on mathematical solution, but it can affect on the violation of physical bounds on gate operations as mentioned in the previous topic. This is because the proposed methodology for preventing violation of physical bounds on gate operations is necessary to know the exact gate position in the previous run time step, not arbitrary gate positions, to be able to determine the possible gate positions in the current time step. Therefore, after determining the gate settings through optimization process, it could check whether this impending situation occurs or not before dispatching the optimal gate settings into mathematical simulation model to calculate state vectors in repeated routine.

The idea for solving this problem is to check if a non-orifice flow situation occurs or not. If a non-orifice flow situation occurs, the gate settings, which are guided by optimization model, have to be changed to be appropriate settings according to the current water surface elevations. On the contrary, if a non-orifice flow situation does not occur, the gate settings, which are guided by optimization, will be directly used for the calculation state vectors. A sample code fragment for this function is shown in Figure 15.

```
J:=1.0;

for i:=0 to (D-1) do
begin
  MaxGateSetting:= StrToFloat(FrmMain.StringGrid_Constraints.Cells[2,i+1]);
  MinGateSetting:= StrToFloat(FrmMain.StringGrid_Constraints.Cells[3,i+1]);
  GateSillEle[i]:= StrToFloat(FrmMain.StringGrid_Constraints.Cells[4,i+1]);
end;

for i:=0 to (D-1) do
begin
  If WL_UP_T1[i]>=WL_DS_T1[i] then MaxWL:=WL_UP_T1[i];
  If WL_UP_T1[i]<=WL_DS_T1[i] then MaxWL:=WL_DS_T1[i];

  While (MinGateSetting+J) <= MaxGateSetting do
  begin
    If ((MaxWL>= GateSillEle[i]) and (MaxWL< GateSillEle[i]+1)
        and (BESTIT[i]>= MinGateSetting+J)) then BESTIT[i]:= MinGateSetting+J;
    GateSillEle[i]:= GateSillEle[i]+1;
    J:=J+1;
  end;
end;
```

Figure 15 Sample code fragment from routine to prevent alternate optimal solution.

1.2.3 Input and output data files for coupling simulation and optimization model

The main process of developing a computer program of coupling simulation and optimization model for determining optimal coastal gate operation schedules concerns the study of interface between their input and output data. In this research, the interface between both models was implemented through text file owing to unavailable source code of mathematical simulation model. Hence it is to understand the components of input and output data files for these models. The data files of three models: hydrodynamic, water quality, and optimization models are discussed in the following paragraph.

The input data files for hydrodynamic model are divided into seven files to be comfortable for writing computer program:

a) *Geometry.DAT* contains details of configuration of river network (linking between nodes and branch), cross-section, length of river reach, roughness coefficient, area elevation of floodplain, and types and dimensions of control structures.

b) *GateOperation.DAT* contains details of conditions of gate operations.

c) *UpstreamBoundary.DAT* contains details of time-series data of discharge at upstream boundaries and also includes details of lateral discharge.

d) *DownstreamBoundary.DAT* contains details of time-series data of tide level at downstream boundaries.

e) *FlowDirection.DAT* contains details of flow directions. These values don't be used for running simulation model, but they are defined to specify the direction of flow using index of Direction Value (DV). DV is a value defined at node to specify flow direction. Flow direction is from node which has higher DV to node which has lower DV. If the simulated discharge (or velocity) has plus sign, it means that the simulated flow direction is the same as the direction of DV. On the contrary, if simulated discharge (or velocity) has minus sign, it means that the simulated flow direction is opposite to the direction of DV.

f) *InitialDischarge.DAT* contains details of initial values of discharge at branches in river network. Some of these values may be collected from telemetering system and the rest values are generated by River Operation Model (ROM) using steady state module.

g) *InitialWaterLevel.DAT* contains details of initial values of water level at nodes in river network. Similar to initial discharge value, some of these values may be collected from telemetering system and the rest values are generated by River Operation Model (ROM) using steady state module.

The input data files required for water quality model comprise two modules based on the selected water quality parameters: salinity module, and Biological Oxygen Demand (BOD) and Dissolved Oxygen (DO) module as follows:

The input data files for salinity module can be divided into three files as follows.

a) *NodeAndBoundary.SAL* contains details of types of nodes: common node, junction node, and boundary node; types of boundary: closed boundary, specified value boundary, and upstream water mixing. For specified value boundary, the time-series boundary values are specified in model.

b) *InitialSalinity.SAL* contains details of initial value of salinity concentration at nodes in river network. Some of these values may be collected from telemetering system and the rest values are approximated by interpolation technique.

c) *Diffusion.SAL* contains details of salinity's diffusion coefficient at nodes in river network. These values must be calibrated and validated before running CoastalGate Model.

In a similar manner of salinity model, the input data files of BOD&DO module comprise four files.

a) *NodeAndBoundary.BOD* contains details of types of nodes: common node, junction node, and boundary node; types of boundary: closed boundary, specified value boundary, and upstream water mixing. For specified value boundary, the time-series boundary values are specified in model.

b) *InitialBOD&DO.BOD* contains details of initial value of BOD and DO concentration at nodes in river network. Some of these values may be collected from telemetering system and the rest values are approximated by interpolation technique.

c) <u>*Diffusion&Parameters.BOD*</u> contains details of BOD's diffusion coefficient and DO's diffusion coefficient at nodes in river network. In addition, it contains details of BOD and DO parameters such as decaying rate (K_1), settling rate (K_3), sediment oxygen demand (SOD), reaeration rate (K_2), temperature, and dissolved oxygen saturation (DOS). Such values must be calibrated and validated before running CoastalGate Model.

d) <u>*PolutionLoad.BOD*</u> contains details of pollution loads: discharged BOD, discharge DO, and discharge of waste water. These values are observed from the considered system.

The output data file for hydrodynamic and water quality model consisting of only one file is '*Results.DAT'* file. It contains details of the computed discharges and water levels at branches and nodes in along the river network, and also includes the computed water quality parameters: salinity concentrations, biological oxygen demand (BOD) concentrations, and Dissolved Oxygen (DO) concentrations. During running mathematical simulation model, the computed discharge and water level data at branches and nodes in river network are used as input file for water quality model as well.

Based on input data files mentioned above, they can be classified into two groups: static files and transaction files. The static files are the files in which the data are fixed during simulation run. These files maintain the same data as run time pass. Generally, they show the river network's properties. There are nine static files, which are consist of *'Geometry.DAT', 'UpstreamBoundary.DAT', 'DownstreamBoundary.DAT', 'FlowDirection.DAT', 'NodeAndBoundary.SAL', 'Diffusion.SAL', 'NodeAndBoundary.BOD', 'Diffusion&Parameters.BOD',* and '*PolutionLoad.BOD'*, respectively. Conversely, the transaction files are the files, which are continuously changed data while running simulation model. There are five transaction files, which consist of *'GateOperation.DAT'*, *'InitialDischarge.DAT'*, *'InitialWaterLevel.DAT', 'InitialSalinity.SAL'*, *'InitialBOD&DO.BOD*', respectively.

The *'GateOperation.DAT'* file is a file which is continuously updated data while running simulation model. The updated data are control vector (or gate settings) obtained from optimization model. The *'IntialDischarge.DAT'*, *'InitialWaterLevel.DAT'*, *'InitialSalinity.SAL'*, and *'InitialBOD&DO.BOD*' files are initial data set used for running mathematical simulation model. These files are altered to become the new data set for running in the next time step by using the data obtained from *'Results.DAT'*, which is hydrodynamic model and water quality model's output data file.

However, prior to replacing the new initial data set for all models, the optimization model is repeatedly invoked to determine optimal gate opening. This means that if optimization model doesn't meet termination criterion, the mathematical simulation models (hydrodynamic and water quality models) still use the old initial values for running simulation model at current time step. On the other hand, if optimization model meet termination criterion, these new updated data are respectively used as initial data of discharges, water levels, salinity concentrations, BOD concentrations, and DO concentrations for the next run time step. Before running hydrodynamic, salinity, and BOD&DO models, all input files as mentioned above are merged to be three files: *'Input.DAT'*, *'Input.SAL'*, *and 'Input.BOD*'. These three merged files are used as input files for hydrodynamic, salinity, and BOD/DO models, respectively. The components of input and output files for hydrodynamic and water quality models are presented in Figure 16.

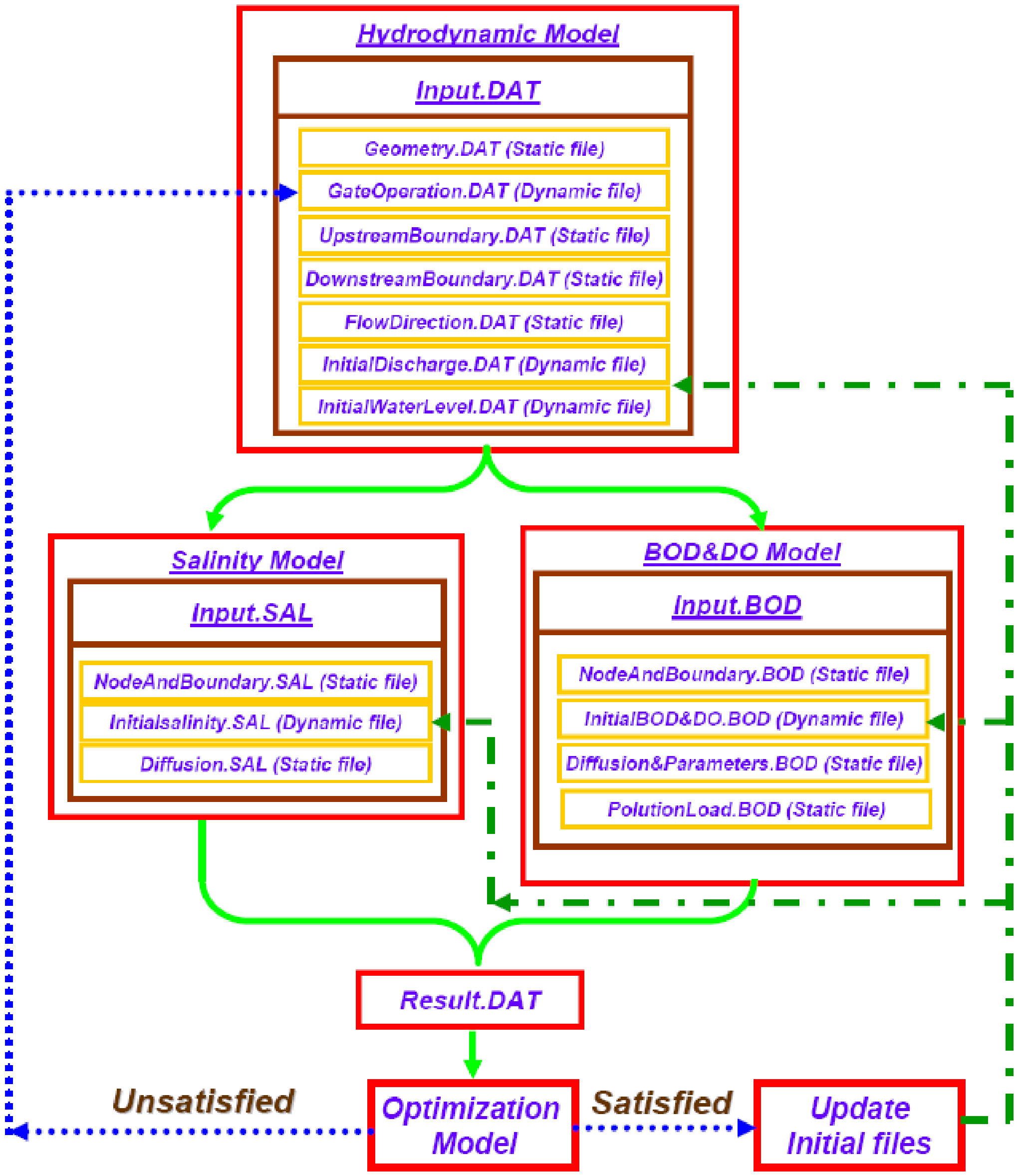

Figure 16 The components of input and output file for hydrodynamic and water quality model.

1.2.4 Flow diagram of the coupling simulation and optimization model

The Flow diagram of decision support model for planning coastal gate operations through the simulation and optimization model (or CoastalGate model) is presented in Figure 17. The processes of a computer program start with specifying the Differential Evolution (DE)'s parameters, namely weighting factor (F), crossover constant (CR), population size (NP), and the maximum number of generations. To obtain the reliable solution, all such DE's parameters must be investigated for each considered problem. The well known technique which use for determining such parameters when applying population-based optimization algorithm based on stochastic approach like DE are sensitivity analysis.

In the next step, the initial population is randomly generated from specified bound by using the uniformly distribution random numbers to cover the entire solution space, which need to be routinely considered in terms of violation of physical bounds on gate operations as well. The ROM model is exploited to simulate behaviors of water flow and mass transportation in terms of water levels, salinity concentrations, and dissolved concentrations. The objective function values of all 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, 1997; Srinivas and Rangaiah, 2006). 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. More details of each step have been already described in the previous chapter. Between crossover and selection processes, the ROM model are used and the objective function are evaluated for the purpose of selecting new generated control variable vector (gate settings) of each new population generated from mutation and crossover processes.

Finally, before printing results, the sub-procedure for checking the alternate optimal solutions is invoked. The simulation results, which include the values of water levels, salinity concentrations, dissolved concentrations at chosen control points, and the optimal gate settings, are printed in text file, which is named *'Results.txt'*. Such processes are repeated until a termination criterion such as desired control horizon is satisfied.

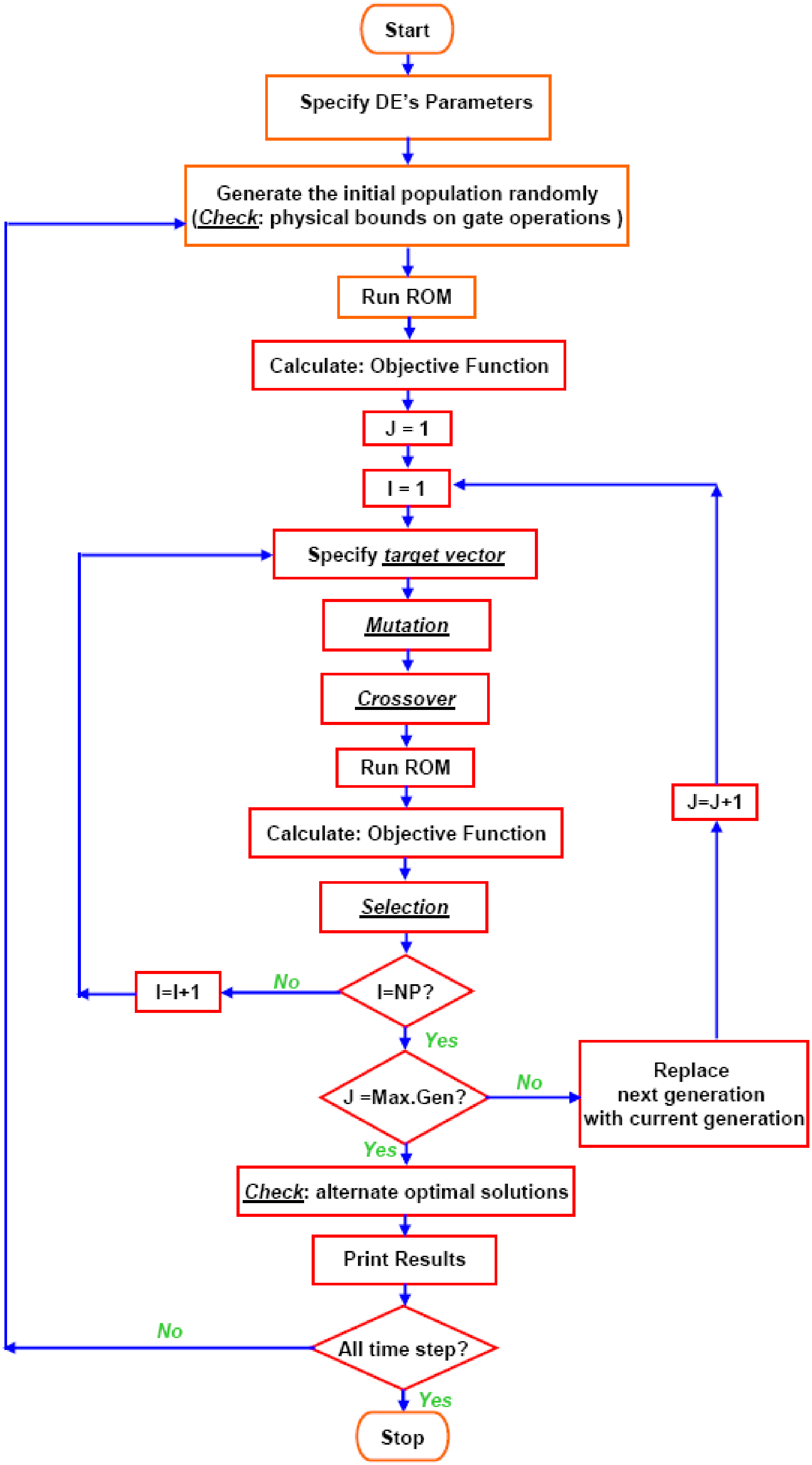

Figure 17 Flow diagram of the main processes in CoastalGate model.

1.3 Demonstration of the CoastalGate model applicability

In this study, the existing coastal gate system of Pak Phanang River Basin (PPRB), Nakorn Si Thammarat province, are chosen for the purpose of demonstrating applicability of CoastalGate model. The details of this study area and used data can be described as follows.

1.3.1 Description of study area

The Pak Phanang River Basin (see Figure 18) located along the east coast of southern Thailand covers parts of three provinces: (1) the districts of Pak Phanang, Chian Yai, Hua Sai, Cha-Uat, Ron Phibun, and Chulaporn, including parts of Lan Saka and Muang Districts, as well as Phra Phrom Sub-district in Nakorn Si Thammarat province; (2) parts of Khuan Khanun District in Patthalung Province; and (3) parts of Ranot District in Songkhla Province. The total area of this basin is 3,100 km^2 or approximately 1,937,500 Rai with the cultivated area over 500,000 Rai. The Pak Phanang River Basin was once named as “Rice Bowl of the South” due to its fertility, abundance of natural resources, and firm economic status of the people.

The Pak Phanang River, a major river in this basin, originates from the Kuan Hin Kaew and Kuan Hin Tan, which is a part of Nakhon Si Thammarat Mountain and boundary area among three districts: Huai Yot, Trang; Pa Payom, Phatthalung; and Cha-Uat, Nakorn Si Thammarat. The flow direction is approximately from the southern to northern part of area. The length of the Pak Phanang River (from the origin to the Pak Phanang Bay) is approximately 147 kilometers. The flow direction of most branch rivers (the main water sources) of the Pak Phanang River, namely Klong La Mai, Huai Thum Pra, Klong Kok Yang, Klong Kong, Klong Chian Yai, etc are from Nakhon Si Thammarat Moutain (western part of basin) to the Thai sea (the eastern part of basin). In addition, the eastern branch rivers which is southern part of Chian Yai district; namely:- Klong Tha Phraya, Klong Hua Sai, Klong Bang Phru, Klong Bang Sai, etc can help to drain the excess water during monsoon season (RID, 2004; Panpiampoth, 1996). There are nine principal subcatchment areas in Pak Phanang River Basin as presented in Table 2.

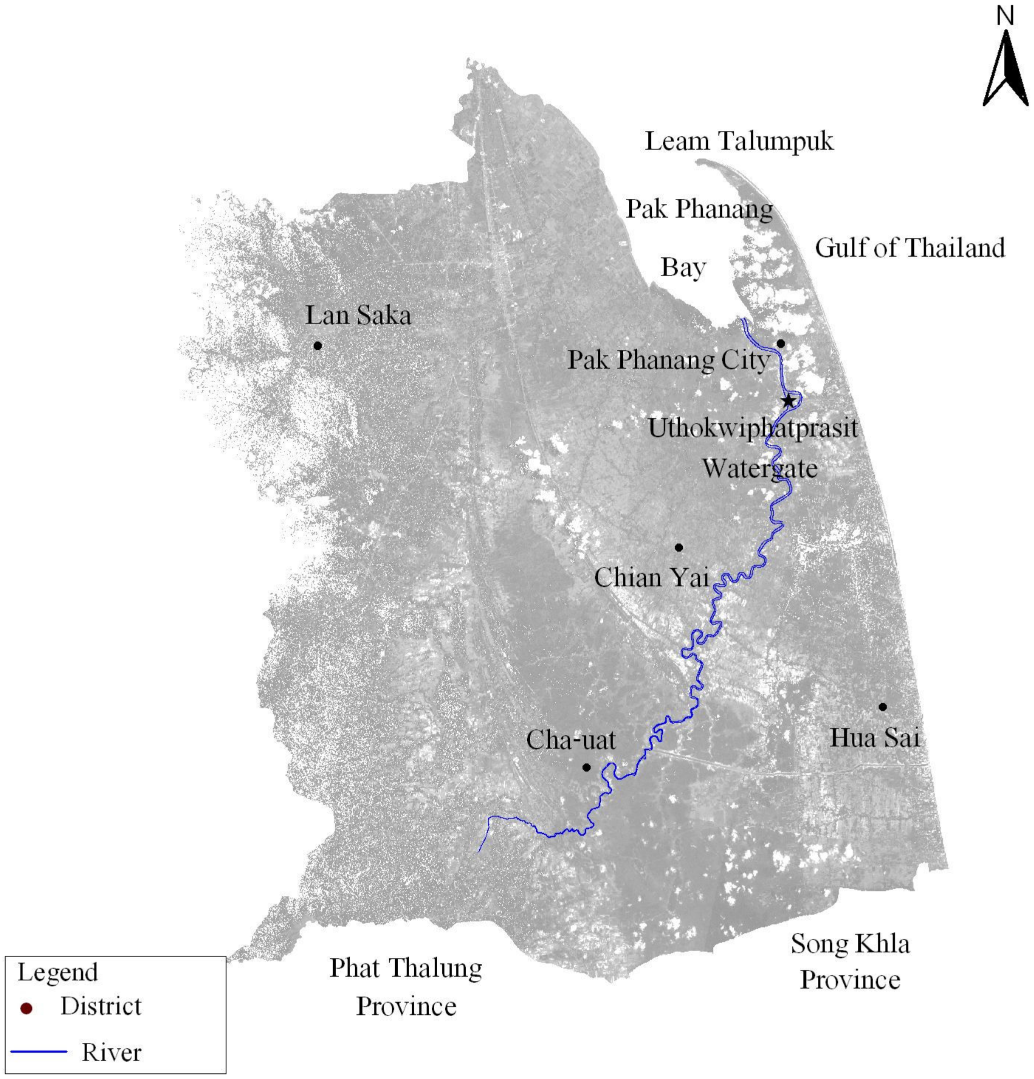

Figure 18 A satellite image showing the boundary of the Pak Phanang River Basin.

Source: Prabnarong and Kaewrat (2006)

Table 2 The principal subcatchment areas of Pak Phanang River Basin

Principal Sub-basin	Watershed area (km^2)
Sao – Tong canal	459.9
Kok –Yang canal	438.4
Tham – Phra canal	347.7
La-Mai canal	134.0
Mai-Siap canal	173.9
Tung-Tao canal	87.0
Hua-Krut	97.9
Pak Phanang river bank	1,174.0
Phru Khuan Khreng	82.9
Total:	2,995.3

Source: Panpiampoth (1996)

At present, the Pak Phanang people have been facing with three water problems: freashwater shortage, saline water intrusion, and acid water occurrence. As a result, His Majesty the King Bhumibol Adulyadej initiated the Pak Phanang River Basin Development Project to render assistance to his people. This project includes the construction of saline barrier, flood gate, drainage canal and so forth. The main objectives of such a project are the following: to solve the problem of freshwater shortage, saline water intrusion, flood mitigation and acid water, to rehabilitate the agricultural system in the project area, to extinguish the controversy between shrimp and rice farm owners, and to raise the standard of living of people in the project area.

In addition to constructing the hydraulic structures as mentioned above, seventeen telemetering stations were installed throughout the basin to measure various meteorological, hydraulic, and water quality data (e.g. water level, rainfall, temperature, salinity concentration, dissolved oxygen concentration, pH, and gate opening) in every fifteen minute interval. Table 3 shows the details of meteorological, hydraulic, and water quality parameters that can be observed for each telemetering station (RID, 2004). Figure 19 also shows the location of telemetering stations.

Table 3 The details of telemetering stations installed in Pak Phanang River Basin

No.	Station	WL0	WL1	RF	TE	SA	DO	pH	GO
1	Uthokawiphatprasit	√							√
2	Song Pi Nong	√		√					
3	Bang Sai	√	√	√					√
4	Pak Praek	√		√					
5	Hua Sai	√		√	√	√	√		
6	Chain Yai	√	√	√					√
7	Cha Mou	√		√					
8	Sao Tong	√		√					√
9	Klong Khong	√	√	√					√
10	Ban Toon	√		√					
11	Mai Seap	√	√	√					√
12	Emergency gate								√
13	Praekmueng	√	√	√					√
14	Pak Nakhon	√							
15	Pak Phanang				√	√	√	√	
16	Karaket				√		√	√	
17	Nha Goat				√	√	√		

Remark WL0 = downstream water level, WL1 = upstream water level, RF = Rainfall,
TE = temperature, SA = salinity, DO = dissolved oxygen,
GO = gate opening

Source: RID (2004)

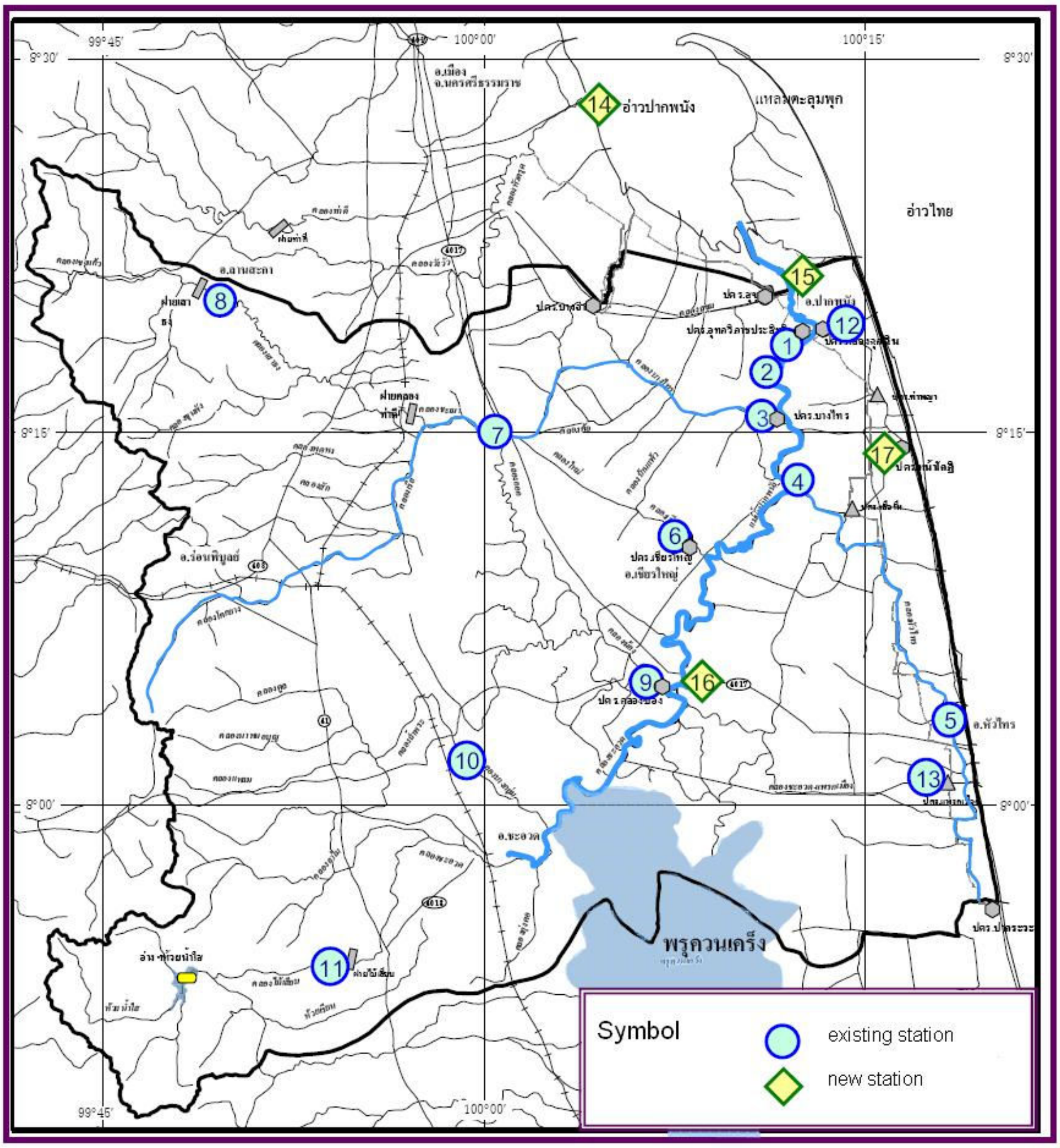

Figure 19 Map showing the location of telemetering stations installed in PPRB
Source: RID (2004).

1.3.2 Data used

Figure 20 shows schematic diagram of coastal gate system located in PPRB, which includes 248 cross section and 269 river reach, and also shows the locations of water gates used for controlling water quantity and water quality with respect to the desired control criteria of PPRB. The entire water gates installed in PPRB are of 20, i.e. Uthokawiphatprasit, Klong Lad, Sua Hueng, Pakrawa, Navigation gate, Emergency gate, Thapraya, Nha Goat, Klong Khong, Chian Yai, Bang Sai, Sukoom, Bangjak, Mai Siap, Jung Hoon, Ban Bangputtra, Ban Pia, Ban Bangluek, Klong Nhong Nhon, and Praekmueng. However, in the course of developing and testing the proposed methodology, only ten main coastal gates consisting of Uthokawiphatprasit, Sua Hueng, Pakrawa, Emergency gate, Thapaya, Klong Khong, Chian Yai, Bang Sai, Sukoom, and Praekmueng are considered for a case study. Except for Uthokawiphatprasit gate, which is the regulating gate (or moving weir), the other nine considered gates are floodgate (or sluice gate).

This means only ten decision variables are considered in this study. The other gates are operated by the standard operating policy. That is, gates are closed for all planning control horizon during dry season except for Klong Lad and Nha Goat, which are controlled by using water level at just upstream gate and downstream gate as control parameters. For example, if the water level at just upstream gate is higher than that at just downstream gate, the gates are opened. Otherwise the gates are closed. The reasons to select such simplified gates in this study are that the optimization process involves calling the mathematical simulation model several thousands of times. This leads to the requirement of a significant amount of the computational time, especially calling water quality modeling, which needs a tiny run time interval on account of numerical stability. Thus, based on regular computer performance at the present day, it may not be appropriate to apply the developed methodology for the very large and complicated river network system.

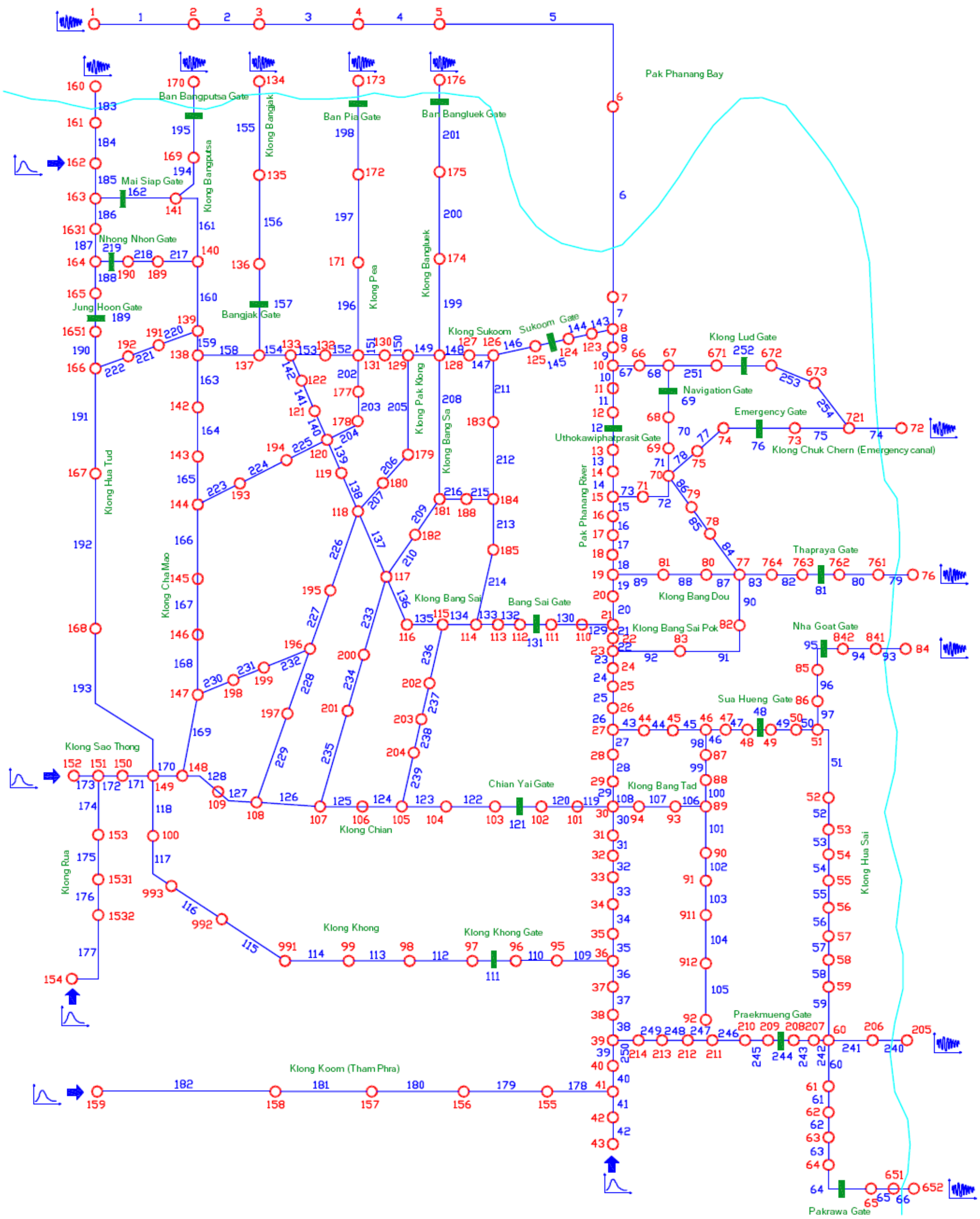

Figure 20 Schematic diagram showing coastal gate system of PPRB.

Source: RID (2004).

The data used in this study include the input data for three models: hydrodynamic, water quality, and optimization models. The details of input data for hydrodynamic and water quality models have already been described in the previous topic (input and output data files for coupling simulation and optimization model). The complete lists of all data in meteorological, hydraulic, structure, and water quality used in hydrodynamic and water quality model, which are available from RID (2004), are shown in Appendix Table A1 to Appendix Table A23. The upstream and downstream boundary data of hydrodynamic model are prepared for operation period of 24 hours in advance of 24/03/2005 by using forecasting model in conjunction with database obtained from the existing telemetering system.

The input data for optimization model consists of: the DE's parameters; the general information about river network system; the criteria for controlling speed of gate opening; required run time; observation point data, which are specified to collect information of state variables (e.g. water level, salinity concentration, and dissolved oxygen concentration); allowable maximum and minimum gate opening; upper boundary and lateral discharge data; lower boundary data; point source information; file management information; desired criteria used for controlling water gate including the maximum and minimum values of water level, salinity concentration, and dissolved oxygen concentration at selected nodes; and the data of weighting factor (WF) and relative importance of interesting parameter.

The values of both factors used in this study were assumed following the priority level of controlled gate location and interesting parameters of each gate. 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). Therefore, 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 the control structures to assure that gate operation has an effect on the chosen control locations.

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

As mentioned in literature review, Artificial Neural Networks (ANNs) can satisfactorily learn the relationship between dependent and independent variables, especially for determination of complicated relationship. In addition, this kind of technique has been ever used for deriving reservoir operation rules (Raman and Chandramouli ,1996; Cancelliere *et al.*, 2002; Chandramouli and Raman , 2002; Chandramouli and Deka, 2005) and intelligent controllers (Lobbrecht and Solomatine, 2002; Lobbrecht *et al.*, 2005; Darsono and Labadie, 2006). The study aim in this section is to investigate the possibility of the application of ANNs for deriving optimal coastal gate operation rules. Instead of using CoastalGate model for determining the plan for operations of coastal gate system in advance, the trained ANNs can be used as intelligent controller for costal gate operations in real time control. That is, water gates can be operated in very short time period corresponding to environmental changes.

The specific task in this activity consist of 1) preparation of data set between optimal gate setting and the influencing parameters; 2) use of ANNs for deriving coastal gate operation rules; and 3) evaluation of neural network controller's performance. The neural-optimal control algorithm was demonstrated in a simulated real-time control experiment for the Uthokawiphatprasit water gate, which is the main controlled gate of Pak Phanang River Basin. The details of development processes in this part are described as follows.

2.1 Preparing data set of optimal gate settings and the influencing parameters

In this step, the CoastalGate model as developed in previous step is employed as a tool to generate numerous data sets, which show the relationship between gate settings and the influencing parameters. As the first step of developing and testing the proposed methodology, the hypothetical data sets representing a simplified coastal gate are considered for a case study. A schematic presentation of hypothetical coastal gate system relates to Uthokawiphatprasit water gate, which is located at Pak Phanang River Basin, Nakorn Si Thammarat province, as shown in Figure 21. Such a controlled gate consists of 6 sluice gates. Each gate is 9.0 meters high and 20.0 meters wide. To simplify a problem and prevent eddy current at downstream gates due to imbalanced gate opening, which is the situation that cannot be analyzed through ROM, all gates were assumed to operate simultaneously. That is, there is only one decision variable in this study case. A search space or possible set of gate opening is integer between 0.0 and 9.0 meters, which is the allowable minimum and maximum gate opening, respectively. For CoastalGate model, this example is very simple case due to consideration of only one decision variable. However, it is preliminary example used for study the possibility of the application of ANNs for deriving coastal gate operations corresponding to various purposes at the same time.

The configuration of river includes 43 cross sections and 42 reaches with no bifurcation and confluence of river. The value of river's roughness coefficient is between 0.03 and 0.035. The diffusion coefficient of salinity, BOD, and DO is 2000, 25 to 50, and 25 to 50 m^2/s, respectively. All these values were available from RID in 2004. Since there is no observed inflow data for considered gate, the upstream inflow hydrographs were randomly generated in the range of 70 and 90 m^3/s. This selected range is sub-range, which RID (2004) have ever used for generating rule curves for this gate. However, such rule curves were separately developed for each controlled parameter, not for all controlled parameters simultaneously. As a result of these developed rule curves, it is rather difficult in practice to apply for operating coastal gate with the consideration of several parameters at the same time.

The downstream water level hydrographs, which cover both spring and neap tide during dry season events (during March to July) of 2002 to 2006, were collected from Pak Nakhon station. These prepared data are used as upstream and downstream boundary of hydrodynamic model. The initial data of hydrodynamic model, which correspond to each upstream and downstream hydrographs, were generated by using steady flow analysis mode of River Operation Model. The initial and boundary data of water quality modeling were specified using the data collected from Pak Phanang River. The complete lists of all data in meteorological, hydraulic, structure, and water quality used for hydrodynamic and water quality model as well as the data used for optimization model are shown in are shown in Appendix Table B1 to Appendix Table B25.

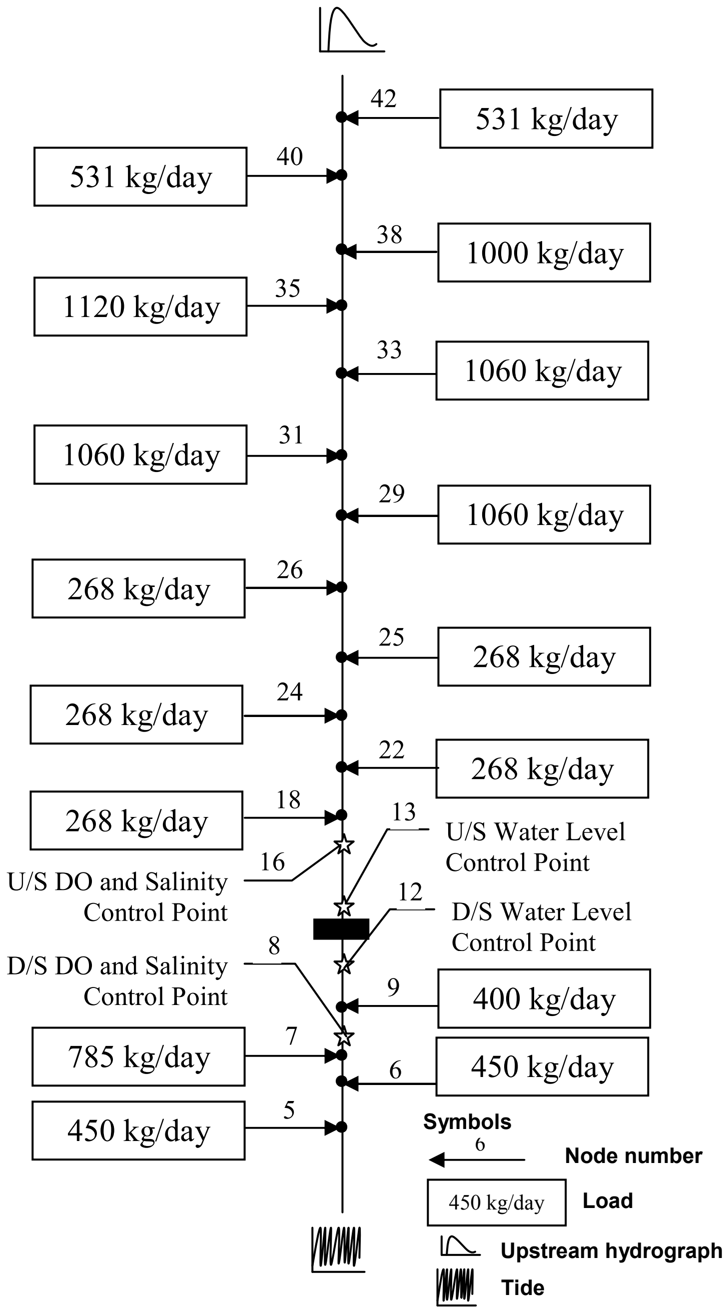

Figure 21 Schematic diagram of hypothetical coastal gates system.
Source: RID (2004).

2.2 The use of Artificial Neural Networks for deriving coastal gate operation rules

In this section, the Artificial Neural Networks model was applied for deriving general coastal gates operation rules for real time control task. By using data set generated from CoastalGate model as input data of artificial neural network model, ANNs can learn the relationship between selected influencing parameters and optimal gate opening for several prepared situations. In training and testing processes, such data sets are randomly divided into two parts: 70% of the records for training and using the remainder, 30% of the record, for testing. After training and testing process, ANNs can be used to represent the reference model (CoastalGate model) for operating coastal gate. This step may be called generating rule curve. In this study, NeuroGenetic Optimizer (NGO), a software package developed by BioComp System, Inc., is chosen for development of neural network controller. There are two interesting topic concerning this experiment. Firstly, the learning performance comparison between two supervised neural network types: back propagation and general regression neural network, are investigated. Secondly, the effects of various selected input data to learning performance are examined. Two statistical indices are used for evaluation of learning performance: Average Absolute Error (AAE), and Correlation Coefficient (R^2).

2.2.1 Average Absolute Error (AAE)

Average Absolute Error is calculated between the expected and actual neural outputs and is averaged across all output neurons, if more than one is employed. Average Absolute Error is calculated using the formula:

$$AAE = \frac{\sum \left| Y_{desired} - Y_{predicted} \right|}{N_d} \tag{37}$$

where $Y_{desired}$ is desired output, $Y_{predicted}$ is predicted output, and N_d is number of data.

2.2.2 Correlation Coefficient (R^2)

Correlation Coefficient is calculated between the expected and actual neural outputs and is averaged across all output neurons, if more than one is employed. If R^2 is equal to 1, it shows that both data sets have the perfect positive linear association. On the other hand, if R^2 is equal to 0, it shows that there is no linear relation. R-squared is calculated using the formula:

$$R^2 = \left(\frac{N_d \left(\sum Y_{desired} Y_{predicted} \right) - \left(\sum Y_{desired} \right) \left(\sum Y_{predicted} \right)}{\sqrt{N_d \left(\sum Y_{desired}^2 \right) - \left(\sum Y_{desired} \right)^2} \sqrt{N_d \left(\sum Y_{predicted}^2 \right) - \left(\sum Y_{predicted} \right)^2}} \right)^2 \tag{38}$$

where $Y_{desired}$ is desired output, $Y_{predicted}$ is predicted output, and N_d is number of data.

2.3 Performance evaluation of Artificial Neural Networks controller

To evaluate the learning capability of a trained neural network, an event, which differ from all the events used for training and testing of the ANN, are applied herein, i.e. different exogeneous input is used. Additionally, a computer program which links between a trained neural network and River Operation Model, is necessary to be developed. Consequently, it was named NGO-ROM model. Figure 22 shows the overall framework of such linked model. The working processes of NGO-ROM model starts with invoking ROM to simulate current event. The output results from running ROM are the values of water levels, salinity concentrations, and dissolved oxygen concentrations at selected control points along the river. Then such three parameter values are sent into the trained neural network. The neural network controller performs the calculation and then the optimal gate opening is obtained. This gate setting is used to be input data for ROM in subsequent run time step. This procedure is repeated until control horizon is satisfied. It should be noted that NeuroGenetic Optimizer (NGO) is software package working on Microsoft Windows based computers. Thus, the way to link both models (NGO and ROM models) can be performed through the development of several computer programming languages altogether, i.e. Macro Windows software, Visual Basic Application embedded in Microsoft Excel, and Delphi computer programming language. The functions of Macro Windows software and Visual Basic application embedded in Microsoft Excel are: 1) to receive data of influencing parameters (e.g. water levels, salinity concentrations, and dissolved oxygen concentrations) obtained from running ROM; 2) to invoke NGO software and then input data of such three parameters into NGO software; 3) to order NGO software make processing; and 4) to sent data of the optimal gate opening into ROM. The Delphi computer programming language was written to control the overall process. That is, it performs to invoke macro windows code, visual basic application code, and ROM.

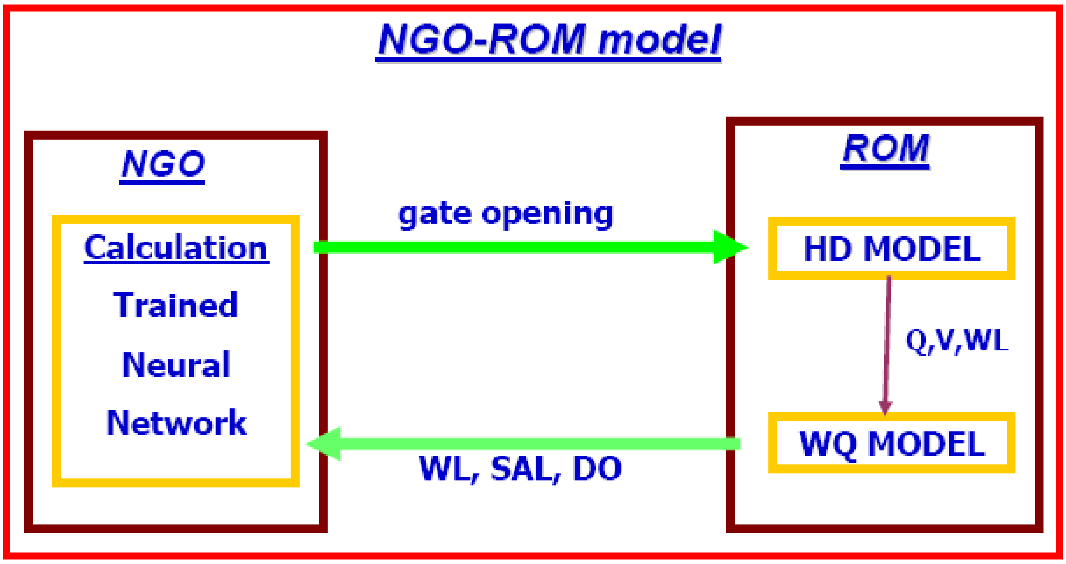

Figure 22 The overall framework of NGO-ROM model.