Salinity control on Saigon river downstream of Dautieng reservoir within multi-objective simulation-optimisation framework for reservoir operation

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Abstract

This research proposes a modelling framework in which simulation and optimisation tools are used together in order to obtain optimal reservoir operation rules for the multi-objective Dautieng reservoir on the Saigon River (Vietnam), where downstream salinity control is the main objective. In this framework, hydrodynamic and salinity transport modelling of the Saigon River is performed using the MIKE 11 modelling system. In the first optimisation step this simulation model is coupled with the population simplex evolution (PSE) algorithm from the AUTOCAL optimisation utility (available as a part of MIKE 11) to estimate to estimate the discharge required to meet salinity standards at the downstream location of Hoa Phu pumping station for public water supply. In the second optimisation step, with the use of MATLAB optimisation toolbox, an elitist multi-objective genetic algorithm is coupled with a simple water balance model of the Dautieng reservoir to investigate how the optimised discharges obtained from the first optimisation step can be balanced with the other objectives of the reservoir.

The results indicate that optimised releases improve the performance of the reservoir especially on controlling salinity at Hoa Phu pumping station. In addition, the study demonstrates that use of smaller time steps in optimisation gives a closer match between varying demands and releases.

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1 Introduction

Most reservoirs are designed and constructed for multiple tasks including water supply for agriculture and industry, hydropower production, flood control, navigation etc. These objectives sometimes conflict with each other so the operation and management of the reservoir system becomes more complicated for decision makers and reservoir operators. As it has been pointed out by many experts, there is a problem of ineffective operation of existing reservoirs mainly due to highly subjective management practices (Chen, 2003; Hejazi et al., 2008). Hence, there is a continuous need for methodologies to optimise the reservoir operation in order to obtain satisfactory results in terms of meeting each demand from the reservoir (Labadie, 2004; Le Ngo et al., 2007).

This particular study investigates the optimal operation of a reservoir located in Vietnam where it is necessary to have many multi-objective reservoirs due to highly variable rainfall caused by tropical monsoon climate. In Vietnam, the reservoirs are used to manage different water requirements that occur both during the rainy and the dry season. While there are many reservoirs mainly used as flood control pools during the wet season, meeting irrigation and other water demands are major tasks of the reservoirs during the dry season. However, 'many difficulties are encountered in reservoir operation due to too much water in the wet season and too little water during the dry season' (Ngo et al., 2006). Whilst, there is a risk of flooding (and sometimes even dam break) in the rainy season, water levels in the reservoirs drop considerably in the dry season with the higher demands of the water users. Sea level rise, triggers the salinity intrusion in coastal areas. Based on the report prepared by UNEP (2009), sea level along the coastline of Vietnam has risen by about by 20 cm and it is expected to rise by 65-100 cm by the year 2100 (VCAPS-Consortium, 2013). Especially during the dry season, due to decreased natural discharges of rivers and low releases from reservoirs, salinity penetrates more in upstream direction. This migration decreases the quality of freshwater, which brings serious problems for the ecosystem and the other users of freshwater, e.g. public water supply intakes. In this context, although there are structural measures such as building control structures at river mouths to control the salinity intrusion, operational changes of existing upstream reservoirs are considered as alternative solutions such that more discharge is released in order to push back the salinity towards the sea.

In analysing a reservoir system for setting operating policies, simulation and optimisation are the most commonly used tools. In simulation models, the behaviour of the catchment together with the operation of the reservoir system are analysed given many variable conditions. On the other hand, optimisation algorithms are applied to obtain optimal operating rules for the reservoir system by using different objective functions and constraints.

One of the earlier application of this simulation-optimisation approach to control salinity intrusion was of Waite (1980), who developed a mathematical model of salt water intrusion in conjunction with a model of reservoir operation for water control scheme on the River Abary, Guyana. It was proved that the levels of salinity in the estuary can be decreased during the dry season by controlling the releases from the reservoir. Le Ngo et al. (2007) developed a framework for adaptive management which combines simulation model with optimisation model to obtain trade-off solutions between flood control and hydropower generation objectives of Hoa Binh Reservoir, Vietnam. MIKE 11 hydrodynamic model was applied to simulate the reservoir releases. It was demonstrated that coupling of simulation with optimisation gave optimum solutions in this multi-objective task.

Dhar and Datta (2008) proposed a GA-based linked simulation and optimisation methodology to determine the optimal releases for controlling water quality at downstream locations. They used CE-QUAL-W2 model developed by US Army Corps of Engineers (USACE) to simulate the hydrodynamics and water quality downstream. This simulation model was linked externally to an elitist GA.

Abdullah et al. (2018) developed a methodology based on coupled simulation-optimisation approach for setting water allocation strategies, given the salinity from estuary into Shat el Arab river.

Given the recent successful applications of use of simulation and optimisation models together, this approach is adopted in the present research in order to obtain optimum operational policies for the

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Dautieng Reservoir which is located on the upstream part of Saigon River, Vietnam. The main objective is to provide optimum amount of discharge from the reservoir to keep the balance between sea water intrusion and fresh water allocations, especially during the dry season when the salinity in the river exceeds the fresh water salinity standards.

2 Case Study Description

The Dongnai River basin is the largest national river basin in southern Vietnam (see Figure 1), with a total surface area of 48471 km^2 within Vietnam, which constitutes 15% of country's total land surface area (Ringler et al., 2002). The basin includes Dongnai, Saigon and Vamco rivers. The lower part of the basin covers one of the most important economic development zones including Ho Chi Minh City, which contributes more than half of total GDP of the country (ADB, 2009). At the same time, this basin plays a large role in the agricultural sector of the country, producing coffee, fruits, and vegetables. The economy of this productive basin highly depends on proper management of water resources for different uses (Ringler et al., 2002).

Figure 1: Dongnai River Basin

There are two main seasons in the basin, namely wet and dry season. The wet season lasts from May to December, causing serious flooding problems, while the dry season takes place between December and May, bringing water scarcity.

Saigon River, is one of the main water suppliers for towns and industries and need a careful salinity control management. It is the second largest river in the Dongnai River basin. It originates in south-eastern Cambodia and after flowing 280 km in southeast direction it joins in Dongnai River 40 km from the East Sea.

The largest irrigation reservoir of Vietnam, Dautieng Reservoir, was completed in 1983 with the support of World Bank. This reservoir is located on the Saigon River, 120 km from the confluence point with the Dongnai River, and has a reservoir capacity of 1050x10^6 m^3 .

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The existing rule curves for the reservoir operation are given in Figure 2. Among these curves, crest level represents the highest level of the reservoir (28 m), whereas dead storage level (17 m) is the level below which the reservoir does not operate. Flood control curve is formed by the maximum water levels above which the water has to be spilled in order to control flooding. On the other hand, critical operation curve is the minimum operation level of the reservoir below which the operation of the reservoir is restricted.

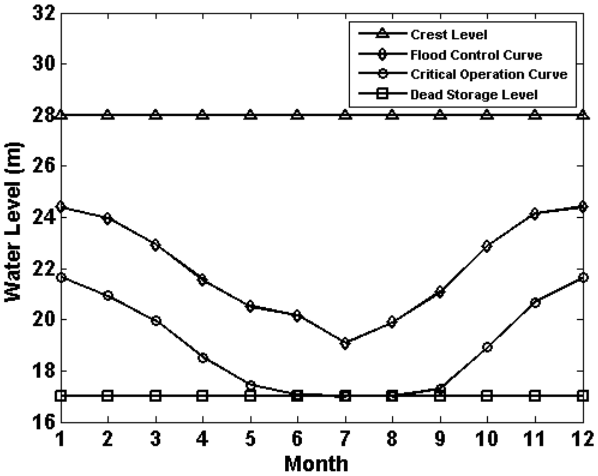

Figure 2: Rule operation curves for Dautieng Reservoir

The objective of the reservoir was set to achieve food grain self-sufficiency by developing 42000 ha of irrigated area mainly for rice and groundnuts in the first stage, and ultimately to provide water for irrigation of 172000 ha (WorldBank, 1989). Resulting from the tropical climate characteristics and the tides, the basin faces serious problems, namely flooding, drought and salinity intrusion. Next to the hydro-meteorological drivers, the dense population and the intensive industrial-agricultural activities in the region require large amount of water especially during the dry season, which results in a significant decrease of water levels in Saigon River and also in Dautieng Reservoir. In addition, the water quality in the river is highly affected by the discharges from the industrial and agricultural zones.

Apart from heavy pollution due to industrial and agricultural wastes in Saigon River, higher salinity levels threaten the downstream communities located in lower lying reaches of Saigon River. In addition to different demands from the river, Saigon River is one of the major sources of public water supply for Ho Chi Minh City.

A pumping station located in Tan Hiep, Hoa Phu, used for domestic water supply is taken as a control point to check salinity levels in this research. This station is located along Saigon River about 70 km from the Dautieng Reservoir and about 90 km from the sea (see Figure 1).

The competition between agriculture, industry and other water demands is causing salinity intrusion further upstream, especially during the dry season. Exceeding the salinity limits would cause suspension of operation of the pumping station and water treatment will not be performed, which could result in a shortage of clean water for Ho Chi Minh City. This is why there is an urgent need for operational strategies that will keep salinity levels under a certain limit.

In this present study, operational changes for Dautieng reservoir are explored in order to control salinity at the Hoa Phu pumping station, which will prevent the shortage of drinking water for the region. All data used in this research were obtained from Ho Chi Minh University of Technology, Vietnam.

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3 Methodology

This study searches for an optimal operation of an existing reservoir by using simulation and optimisation techniques together. In the simulation part, hydrodynamic and salinity transport modelling of Saigon River is performed. For the optimisation process, a two step approach is adopted. The first step optimisation is carried out to determine the optimal/minimal discharges in Saigon River to control the salinity at Hoa Phu pumping station. The hydrodynamic simulation and salinity intrusion model of the river is linked with a generic tool, normally used for parameter optimisation. Here, the optimisation problem is formulated with river discharge as a decision variable and only one objective function, namely minimisation of the difference between the actual and target salinity at the location of Hoa Phu pumping station. In the second step optimisation, a multi-objective optimisation is performed by considering the other demands from the reservoir next to salinity control, together with additional constraints regarding the reservoir operation. At the end of this step, optimal reservoir releases with respect to each objective are obtained. The final step is to evaluate the level of satisfaction of the individual demands with these releases.

MIKE 11 modelling system developed by Danish Hydraulics Institute (DHI) is chosen to simulate hydrodynamics and salinity intrusion in Saigon River. The schematics of the model is represented in Figure 3. In order to select a critical year for salinity control, out of the years with available data, HD and AD modules are run simultaneously and the salinity levels at the control point are simulated. The criterion for selecting the critical year is the extent at which salinity exceeds the permissible limit, which is set as 0.3 PSU. This analysis shows that the only year in which salinity at the control point above the limit is 2001, with a maximum value of 0.510 PSU. Simulation of flow for the year 2001, indicates that salinity has significant values and variations only during the dry period between January and May, whereas it is low during the rest of the year. Salinity exceeds the critical value only for the months March and April, which is reasonable since these are the driest months of the dry season when the natural discharge in the river reaches its minimum values, triggering the salinity migration upstream. Since salinity exceeds the limit only in March and April in 2001, the optimisation is performed for these two months.

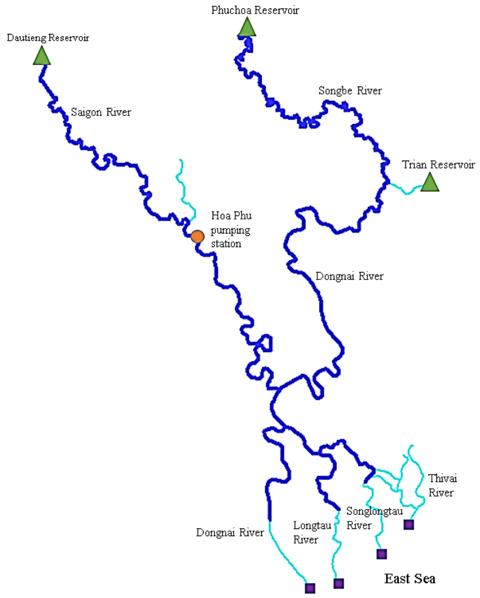

Figure 3: Mike 11 schematisation of the river, with location of reservoirs and the salinity control point at Hoa Phu

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3.1 First Step Optimisation

The aim of the first step of optimisation is to obtain optimal/minimum discharge to keep the salinity under the permissible limit of 0.3 PSU at Hoa Phu pumping station. To achieve this objective, the MIKE 11 model is coupled with a parameter optimisation tool available in Mike 11, the AUTOCAL. In this step the hydrodynamic and advection dispersion models are executed together with optimisation algorithms for determining optimal parameter sets.

AUTOCAL is mainly used for the purposes of automatic calibration, parameter optimisation and sensitivity analysis of MIKE 11 models. Parameter optimisation option of this tool is applied by Le Ngo et al. (2007) in order to obtain optimised rules curves for Hoa Binh Reservoir, Vietnam. In this particular study, a kind of parameter optimisation option is performed as well.

AUTOCAL includes two different parameter optimisation methods, namely Shuffled Complex Evolution (SCE) and Population Simplex Evolution (PSE). Out of these two methods, PSE is chosen since it is especially suited for simultaneous simulations that take place in AUTOCAL (DHI, 2014).

The objective function in this first step optimisation aims to minimise the maximum squared difference between simulated salinity at the control point and permissible salinity limit, which is formulated as:

$$F = MIN[\, Max\,\{\, S, S\ \varepsilon\ [0,T]\} - Target\,]^2 \qquad (1)$$

with S= Simulated salinity at Hoa Phu pumping station

$Target$ = 0.3 PSU (permissible salinity limit)

$[0,T]$ = Simulation period,T = 30 days for monthly optimisation;

T = 10days for ten-daily optimisation

The decision variables are the discharges of Saigon River, which are modified during the optimisation process in order to obtain the best value of the objective function. Once one of the stopping criteria is met, the optimal discharge, corresponding to the best (minimum) objective function is obtained. With this optimal discharge, MIKE 11 model is executed one more time using AUTOCAL in order to simulate the final salinity at the control point. The chosen population size is 100 and optimisation is run for a simulation period of 30 days for purposes of monthly optimisation in the second step (see next section) and 10 days for ten-daily optimisation (also in the second step). This leads to 2 monthly and 6 ten-daily results in terms of critical salinity discharge.

3.2 Second Step Optimisation

In the second step of the optimisation next to salinity control purpose, the other objectives of the reservoir are taken into account to perform a multi-objective optimisation. The aim is to meet all the demands as much as possible during the optimisation period. This second step optimisation is performed for monthly and ten-daily time steps during the two months; March and April.

The general form of the objective function is defined as follow:

$$F = MIN\ [\textstyle\sum_{t=1}^{N}(Rt - Dt)^2] \qquad (2)$$

where Dt = Demand for a specific purpose of the reservoir during time *t*

Rt = Reservoir release to meet a specific demand during time *t*

N = Number of time steps for the optimisation process

The main objective of Dautieng reservoir is to supply enough water for the agricultural areas. Next to this, the reservoir release should control the salinity at Hoa Phu pumping station, which is the key interest of this research and this is taken as the second objective for the reservoir operation. In addition to these two objectives, domestic and industrial water supply are also objectives for the reservoir operation. On the other hand, since the optimisation is carried out only during the dry season of the year, flood control objective is not taken into account.

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The objective functions for this second step optimisation are defined as follows:

$$F(I) = MIN\ [\textstyle\sum_{t=1}^{N}\left(R_{I_t} - D_{I_t}\right)^2] \tag{3}$$

$$F(S) = MIN\ [\textstyle\sum_{t=1}^{N}\left(R_{S_t} - D_{S_t}\right)^2] \tag{4}$$

$$F(Ind) = MIN\ [\textstyle\sum_{t=1}^{N}\left(R_{I_{ndt}} - D_{Ind_t}\right)^2] \tag{5}$$

$$F(Dom) = MIN\ [\textstyle\sum_{t=1}^{N}\left(R_{Dom_t} - D_{Dom_t}\right)^2] \tag{6}$$

The terms given in Equations 3to 6 are explained in Table 1.

$\boldsymbol{F(I)}$: Irrigation objective function	$\boldsymbol{F(S)}$: Salinity control objective function	$\boldsymbol{F(Ind)}$: Industry objective function	$\boldsymbol{F(Dom)}$: Domestic water objective function
$\boldsymbol{R_{I_t}}$: Irrigation release during time *t*	R_{S_t}: Salinity control release during time *t*	R_{Ind_t}: Industry release during time *t*	R_{Dom_t}: Domestic water release during time *t*
$\boldsymbol{D_{I_t}}$: Irrigation demand during time *t*	D_{S_t}: Salinity control demand during time *t*	D_{Ind_t}: Industry demand during time *t*	D_{Dom_t}: Domestic water demand during time *t*

$\boldsymbol{N}$: Number of time steps for the optimisation process (2 for monthly, 6 for ten-daily optimisation)

Table 1: The terms in objective function equations

The demands for salinity control, in monthly and ten-daily forms, are taken from the results of the first step optimisation. Since the irrigation, domestic and industrial water demands are defined as monthly average values, for both monthly and ten-daily optimisation the same average values are used.

The reservoir continuity / mass balance equation which is used in the optimisation process is given by Equation 7.

$$S_{t+1} = S_t + I_t - R_t - E_t \tag{7}$$

where S_{t+1} = Final storage at time t+1
S_t = Storage at time t
I_t = Inflow to reservoir during time *t*
R_t = Outflow from reservoir during the time *t*
E_t = Evaporation loss from reservoir during time *t*

The constraints include storage and release constraints as follows:

- Storage constraints: $S_{min} \leq S_t \leq S_{max}$ (8)

  where S_{min} = Allowable minimum storage in the reservoir
  S_t = Storage in the reservoir at time *t*
  S_{max} = Allowable maximum storage in the reservoir

- Release constraints :$0 \leq R_t \leq D_t$ (9)

  where R_t = Reservoir release for a specific objective during time *t*
  D_t = Demand for a specific objective during time *t*

In order to calculate the storage at time *t* by using water balance / continuity equation given in Equation 7, there is a need for assessing the inflow values for the reservoir. However, there is a lack of observed inflow data for the last 25 years. Therefore, it is decided to use the measured inflows from the available data on monthly average inflows in the period of 1960 - 1984, for three characteristic years, dry, average and wet, which are given in Table 2.

	Month											
Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1982 (dry)	16.2	12.8	11.2	13.7	12.3	32.5	41.3	80.5	171	107	69.9	25.6
1979 (average)	25.9	23.4	20.2	19	23.8	26.6	68.5	117	170	185	73.1	38
1966 (wet)	34	32.8	26.1	21.9	25.9	26	36.1	134	173	161	92	43.5

Table 2: Monthly average inflow data for dry, average and wet year

The average monthly average inflows from the year of 1982, which is the driest year in terms of observed inflows, are chosen to be used as representative for the most critical scenario analysed during the optimisation process. In addition to the problem of not having the real inflow discharges in the reservoir for the period of interest, the operation rules of the reservoir releases couldnot be obtained. Therefore, instead of building a reservoir operation model, the already defined critical reservoir operation curve below which water supply restricted, is taken as the lowest water level/ storage target for the reservoir operation (Figure 2). Since optimisation is performed for the dry season only, the flood control curve which specifies the maximum water levels that can be reached is not taken into account.

Next to this most critical scenario in which the inflow data of the driest year is used as input for the reservoir, reservoir operation is tested with the monthly inflow data of the average year and the wet year, namely 1979 and 1966 (Table 2).

Reservoir optimisation was carried out to fulfil the two objectives, irrigation and industry, where the following constraints are defined for meeting the salinity control and domestic water demands:

$$R_{S_t} \geq D_{S_t} \tag{10}$$

$$R_{Dom_t} \geq D_{Dom_t} \tag{11}$$

With these hard constraints, it is ensured that salinity control and domestic water demands are always fully met.

The optimisation is carried out by applying an elitist multi-objective genetic algorithm using the genetic algorithm solver available in the Matlab optimisation toolbox. This elitist multi-objective genetic algorithm, a variant of NSGAII, searches for a Pareto front which is a subset of feasible solutions for multi-objective minimisation. It favours the individuals even if they have a lower objective function value in order to increase the diversity of the population. In this research, a population of 1000 is specified and the number of generations is taken as 350 for each run.

Among all the points on the Pareto set, best option for each objective and the trade-off solution between the objectives are analysed in terms of their effects on meeting demands. The best option for each objective is the point which makes the value of objective function minimum. However, there are different techniques in choosing a particular trade-off solution between the objectives. In this research, the Pseudo-Weight Approach proposed by Deb (2001) is adopted to select a trade-off solution, as in the Equation 12 below:

$$w_i = \frac{(f_i^{max} - f_i(\mathrm{x}))/(f_i^{max} - f_i^{min})}{\sum_{m=1}^{M}(f_m^{max} - f_m(\mathrm{x}))/(f_m^{max} - f_m^{min})} \tag{12}$$

f_i^{max} = Maximum value for the i^{th} objective function

f_i^{min} = Minimum value for the i^{th} objective function

The summation of all the weight vectors for a particular solution is equal to one. A 100 % weight for objective function 1 (f_1) and 0% for objective 2 (f_2) gives the best option for f_1 and vice versa. In this research three points from the Pareto set are selected for further analysis, of which two are such extreme points and one is the trade-off solution that gives 50% weight to both objectives.

4 Results and Discussions

The initial average releases from the reservoir for the months March and April in 2001 are given in Table 3.

Month	Irrigation Release (m^3/s)	Salinity Control Release (m^3/s)	Industry Release(m^3/s)	Domestic Water Release(m^3/s)
March	62.75	2	Not known	Not known
April	51.55	2	Not known	Not known

Table 3: Initial releases from the reservoir in 2001

As a result of initial releases from the reservoir to control the salt water intrusion, the salinity at the control point exceeds the limit of 0.3 PSU for *800 hours* in the two months period considered. On the other hand, by looking at the irrigation demands and irrigation releases for the months March and April, the irrigation deficit is calculated as *32.40 %* for March and *28.60%* for April 2001, where the deficiency describes the percentage of demand (in m^3 of water) that cannot be met by the current release.

4.1 First step optimisation

The optimisation process aimed to determine river discharges to keep the salinity under 0.3 PSU at the control point. First, the monthly average releases for March and April where observed to have salinity exceeding the limit. These two month duration is divided in six ten-daily operation periods to perform the optimisation with ten-daily time steps. In order to keep the salinity under 0.3 PSU during March, monthly average river discharge of the Saigon River is considerred between 01/03/2001 and 01/04/2001. As a result, the optimal/minimum river discharge obtained is 9.21 m^3/s, which has the minimum objective function value of zero. With this optimal discharge, MIKE 11 model is run and the salinity at the Hoa Phu pumping station is simulated (Figure 4).

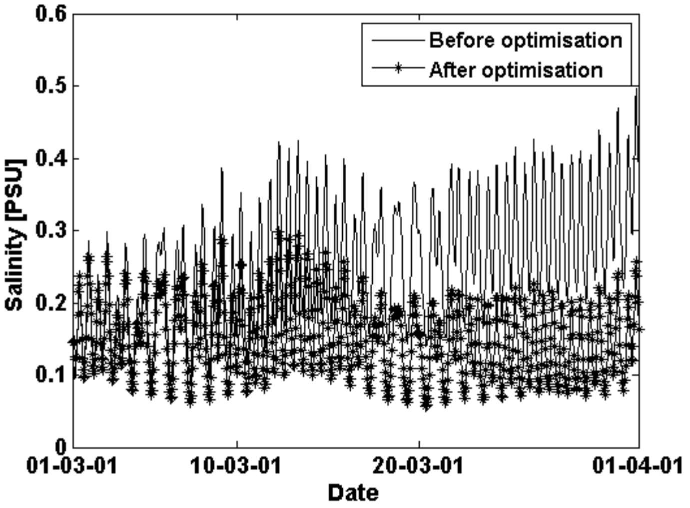

Figure 4: Simulated salinity before and after optimisation in March

Monthly average discharge of the Saigon River for April is optimised in a same way as the previous case. The simulation date is defined between 01/04/2001 and 01/05/2001. The results in terms of

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hydrodynamics and advection-dispersion from the previous optimisation process in March are provided as initial conditions for the optimisation in April. In this optimisation, the optimal river discharge is obtained as 5.79 m^3/s, which gives minimum objective function value of zero.

As a next step, optimisation of the river discharges to control salinity is performed for ten-daily intervals. In order to keep the salinity under 0.3 PSU during the first ten days of March, ten-daily average river discharge for this period is considered over dates between 01/03/2001 and 11/03/2001. This optimisation gives an optimum discharge as 8 m^3/s. With this optimal discharge, MIKE 11 model is run and then the salinity at the control point is simulated. Figure 5 compares the salinity before and after the optimisation in March.

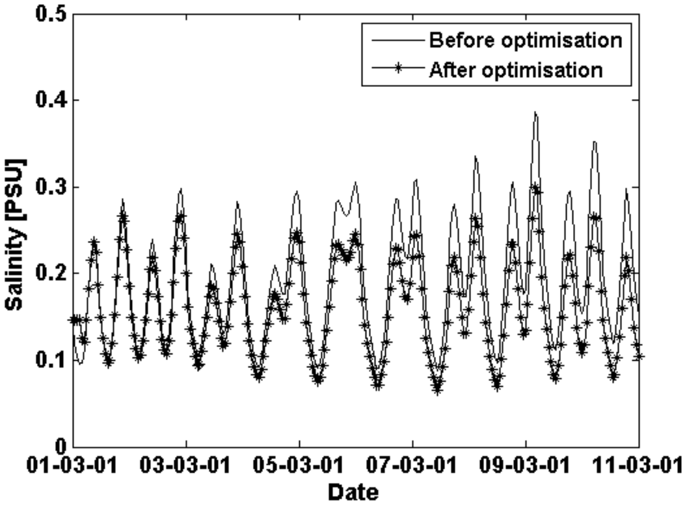

Figure 5: Salinity before and after optimisation for the period 01/03/2001 – 11/03/2001

The same process is repeated for each ten day interval and the optimised river discharges which provide the minimum objective functions are obtained (Table 4).

Simulation period	Optimal river discharge (m^3/s)
01 March - 11 March	8.00
11 March - 21 March	9.10
21 March - 31 March	7.52
01 April - 11 April	5.62
11 April - 21 April	7.24
21 April - 30 April	6.43

Table 4: Optimal river discharges in each ten-daily period

In comparison to the initial case of 2001 in which the average discharges for the salinity control is 2 m^3/s for both March and April, both monthly and ten daily time-step simulations give optimal discharges with higher values, which ensures that salinity is below than 0.3 PSU at the Hoa Phu pumping station. It is important to note that for both simulation time-step, salinity before and after optimisation follows the same pattern, there is only a a difference in the discharges of the river.

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4.2 Second step optimisation

The results of the second step optimisation are presented here only for the ten-daily time step. The obtained Pareto front is presented in Figure 6 and the obtained deficits for the three characteristic points are represented in Figure 7.

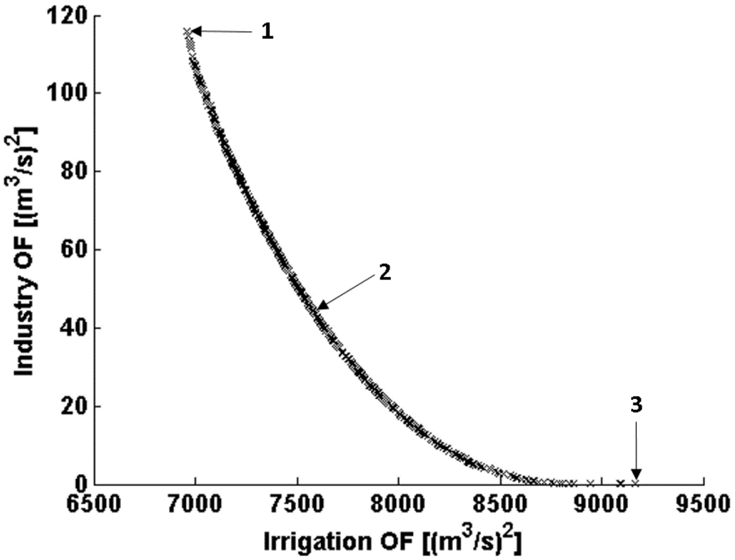

Figure 6: Pareto set for the irrigation and industry objectives,

The demands for salinity control and domestic water are always satisfied in this case since they are introduced as hard constraints.

4.3 Sensitivity Analysis with Different Inflow Scenarios

The optimisation results were further tested for two other inflow scenarios namely the inflows of average year (1979) and the inflows of wet year (1966).

Average year (1979)

The year 1979 is a year with average inflows, hence an average volume between the curves of critical reservoir operation and flood control is assigned as an initial volume. An initial check is performed to see if all the demands can be met without compromise between the objectives of the reservoir. Once all the inflows and outflows, which refer to irrigation, salinity control, industrial and domestic water demands, are inserted in reservoir continuity equation, the water levels at the end of each ten-daily period are computed. The obtained calculated water levels in the reservoir are greater than the critical operation curve, which means that there is no need for an optimisation in case of an average year if the initial water level is assumed as the average of flood control curve level and critical operation curve level. However, it is important to check the reservoir operation if the initial water level is at the critical operation level. Such a check shows that the calculated water level drops under the critical operation curve, which means that not all the demands can be fully supplied, hence the need for reservoir releases optimisation.

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The best option for Irrigation (Point 1), trade-off solution (Point 2) and the best option for Industry (Point 3) are chosen from the Pareto set. Corresponding to these points, irrigation and industry deficits are calculated as presented in Figure 7.

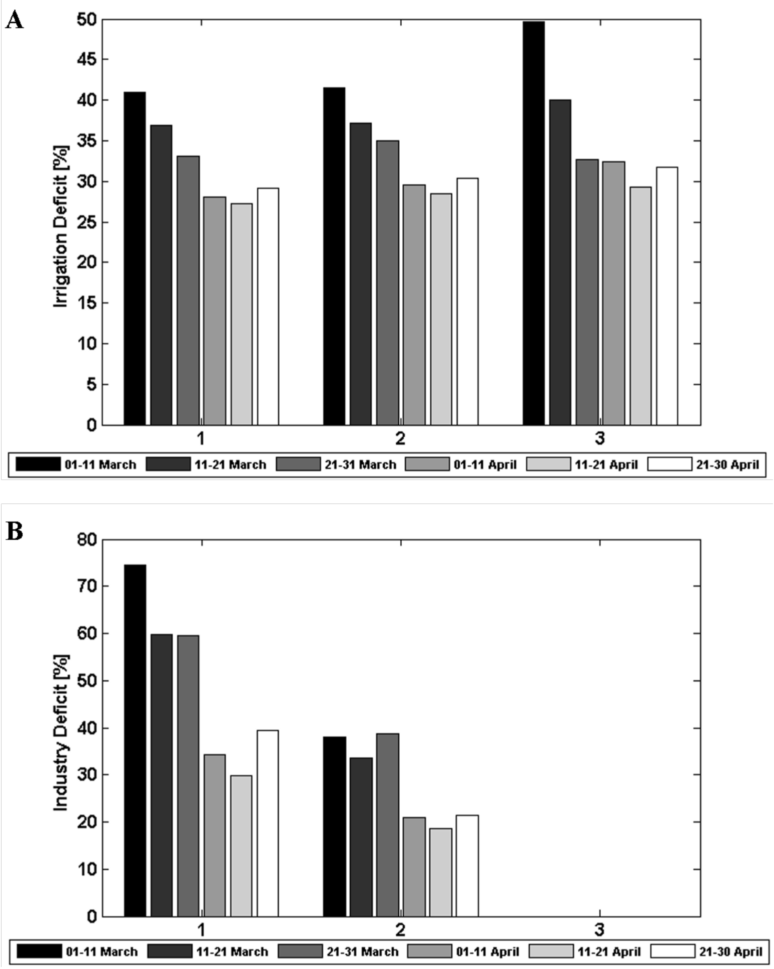

Figure 7: Irrigation deficits (A) and industry deficits (B) for Point 1, Point 2 and Point 3

Wet year (1966)

For a wet year there is a need to check the situation if the initial water level is at the critical level. Same as in the average year case, the inflows to the reservoir and outflows, which refer to irrigation, salinity control, industrial and domestic water demands, are inserted in reservoir continuity equation. The calculated water level drops under the critical operation curve, which indicates that not all demands from the reservoir can be satisfied completely and reservoir optimisation is required also for wet year case if the initial water level is at the critical level. Irrigation and industry deficits regarding the best option for irrigation (Point 1), trade-off (Point 2) and the best option for industry (Point 3) are assessed as shown in Figure 8.

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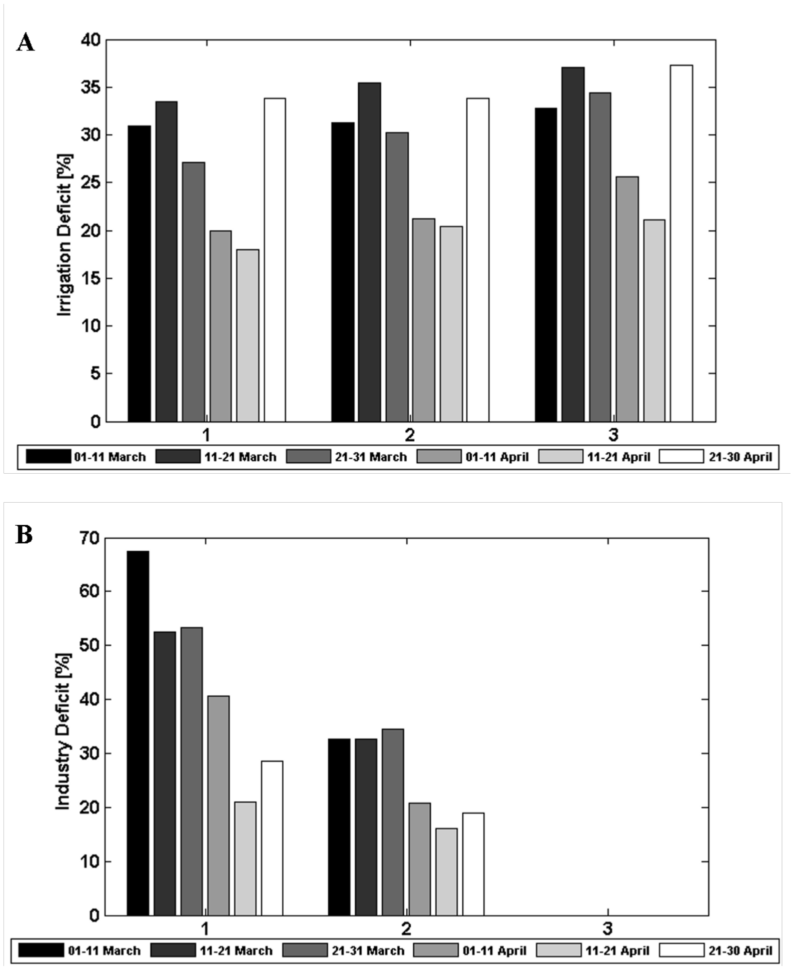

Figure 8: Irrigation deficits (A) and industry deficits (B) for Point 1, Point 2 and Point 3

The results obtained for average year and wet year demonstrate that with the increase in inflows to the reservoir, more satisfactory results are obtained on satisfying the demands from the reservoir..

5 Conclusions

The main objective of this research was to find an optimal reservoir operation strategy for downstream salinity control in Saigon River Basin, Vietnam. Therefore, it is proposed to develop a simulation-optimisation framework for finding the optimal solutions to control salinity by satisfying the other objectives of the reservoir as much as possible. The final outputs of the multi-objective optimisations are the Pareto sets which give a chance for decision makers to negotiate on possible trade-off solutions. Therefore, the developed approach can be used for decision making purposes in an integrated water resources management. It has been demonstrated that regardless of the inflow scenarios (dry, average and wet years) if the initial water level (in the beginning of March) is at the critical level, there is a need for reservoir optimisation since not all water allocation needs can be satisfied simultaneously. Although it has been observed that altering the inflow data affects the operational capacity of the reservoir, initial condition (initial water level) plays the most important role on satisfying the demands from the reservoir.

This research demonstrates that coupling of simulation and optimisation models for smaller time steps better match varying demands. However, because considered demands during simulations are constant it is recommended that this work is extended using additional data on time-varying demands and inflows, which is combined with even smaller optimisation time steps can provide better results.

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