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PREDICTION MODEL OF INUNDATION IN PUMPED-FIELD LOWLANDS AND SCENARIOS FOR IMPROVING ITS PERFORMANCE

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ABSTRACT: During the rainy season, frequent flooding by storm water is one of the most serious problems in lowland areas, causing heavy effect on transportation, agriculture, industry and economic activities. As a result, the required drainage water levels in this area are generally lower than the water levels of the boundary rivers. Under such circumstances, pumping systems should be designed from a viewpoint of integrated control floods. The Nam Ha lowland, in Vietnam, bounded by four surrounding rivers, is selected as a case study. The operation scheme in this area is a key factor for drainage and flood protection. The developed mathematical model can be used as a tool to evaluate the present drainage system as well as scenarios to improve its performance, considering the released water from agricultural areas. The results show both the flooding processes in the field as well as inundation areas and water levels along drainage channels. It is found that the proposed model can be applied to evaluate integrated flood control systems for pumped-field lowland. Such an operating system provides an effective tool by means of which the drainage system can be operated appropriately taking into account of tidal effects, rainfall intensity, and reaching time of the rainwater.

Key words: Pumped-field lowland, unsteady flow model, inundation area, gate operational scenarios

INTRODUCTION

The Study Area

The Ha Nam area located at about 20°36' North and 106°10' East is the relatively flat and low-lying land area of the Red River delta, Vietnam, as shown in Fig. 1. The interior land is protected by banks and dykes system and bordered by 4 surrounding rivers, the Chau River and the Red River in the North, the Day River and the Dao River in the South. The hydraulic network systems with a total length of 105 km, which perform both as irrigation systems in the dry season and drainage systems in the rainy season, consist of many other canals and pumping stations. There are six large pumping stations, namely Coc Thanh, Co Dam, Huu Bi, Nhu Trac, Vinh Tri and Nham Trang, for draining purpose. They were planned in the 1960s then orderly built in the period of 1962-1972. The total pumping capacity is of 220 m3/s and the drainage coefficient is q=2.89 l/s/ha. The current condition is caused by the limit of gravity drainage capacity due to high water level in the boundaries, and insufficient pumping capacity. Moreover, drainage canal systems and on-canal control structures have not been completed, causing many difficulties in draining water. Canals heavily suffer from sedimentation leading to the reduction of the system's drainage capacity. During the rainy season, frequent flooding by storm water is one of the most serious problems of this area, strongly affecting transportation, agricultural, industrial and economic activities. The required drainage water levels in this area are lower than the water level of the bounded rivers. Under such circumstances, excessive water cannot be drained out of the area by gravity flow; therefore, it must be pumped out. In the development of this area, conventional functional drainage systems have been built, including channels, sluiceways, gates, regulators, pumping stations, etc. In operation, the drainage system should be operated appropriately taking into account tidal effect, rainfall intensity, and reaching time of the rainwater. Such an operating system has not yet been established in the region. At present, the development of agriculture is extensive and intensive, based on diversified crop patterns, two or three cropping seasons in a year, and high yielding crop varieties with high demands for irrigation and drainage and the level of management. However, after 30 years in operation and having been exploited for a long time, most of the drainage systems have become heavily deteriorated, with uncompleted canals and control structures. Generally, the drainage system in this area is no longer suitable for the present stage of the agricultural land use. For these reasons,

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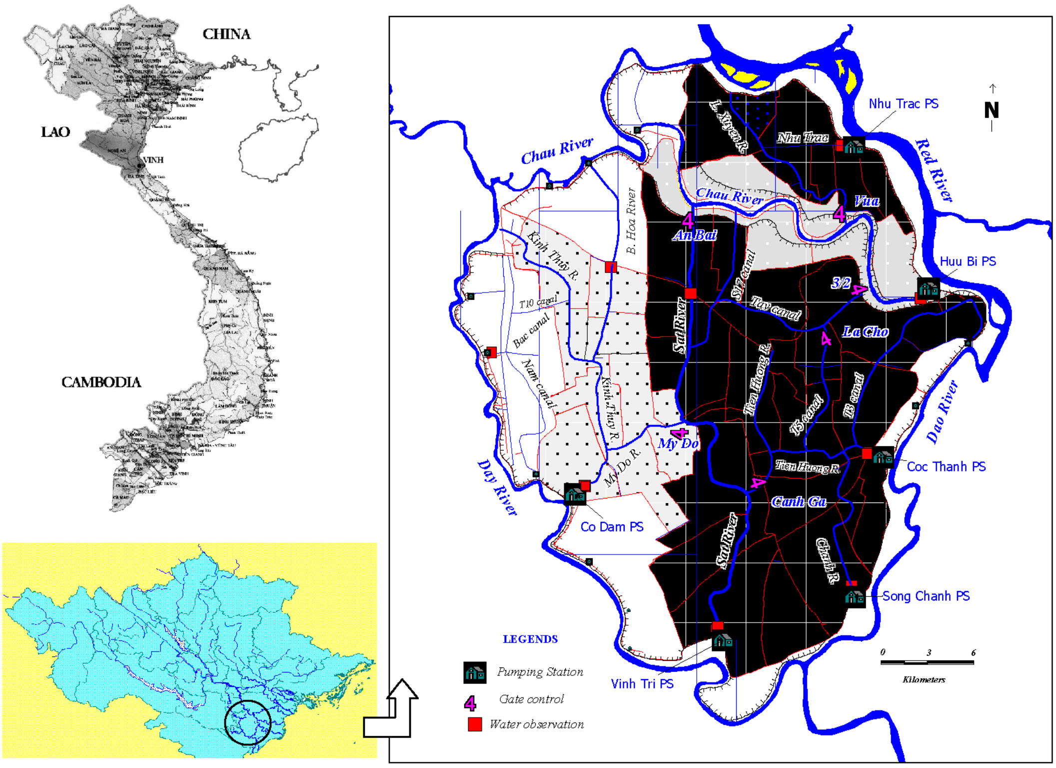

Fig. 1 Map showing the study area

the improvement of the drainage system's operation is now very necessary. In order to solve these existing problems, it is necessary to understand the characteristics of the complicated unsteady flow regime in the drainage canal systems. Simulation approach is the best way to estimate the unsteady flow and to determine the most suitable measures for improving these drainage systems (Don 2002).

Rainfall

The annual rainfall of the region, as given in Table 1, is about 1800 mm with about half this amount falls during July to September, the rainy season. Rainfall pattern for the model is given in Fig. 2.

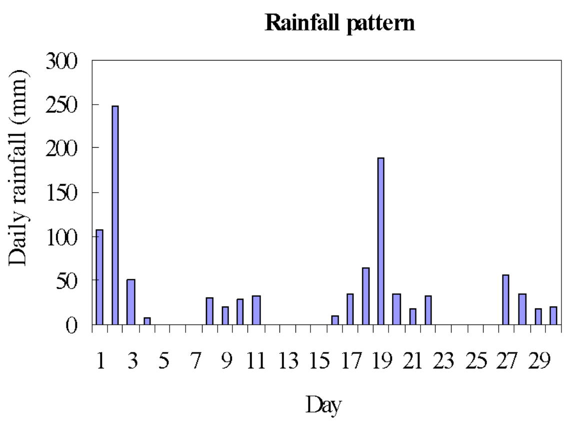

Fig. 2 Areal rainfall pattern

Drainage Condition

The total drainage area is 85,326 ha. The latitude of this area ranges from +0.75 to +2.50 m above mean sea level. The area can be divided into 5 sub-basins with key pumping stations and channels. Surface water is collected by the open channel network systems and is finally pumped out at the downstream end of the drainage channels.

MATHEMATICAL MODEL

Flow in an open channel is governed by the equations of motion and conservation of mass. The basic equations are expressed in the partial differential form as follows,

Movement equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial (Q^2/A)}{\partial x}+g\cos(i)A\frac{\partial h}{\partial x}=-g\frac{n^2 Q|Q|}{R^{4/3}A}+gA\sin(i) \quad (1)$$

Continuity equation:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \quad (2)$$

where:

v: velocity [L/T]; t: time [T]; i: channel slope [L/L];
R: hydraulic radius [L]; q: lateral inflow [L3/(T.L)];

Table 1 Monthly rainfall at selected gauging stations *(Unit: mm)*

Station	Jan	Feb	Mar	Apr	May	Jun	*Jul*	*Aug*	*Sept*	Oct	Nov	Dec	Total
Phu Ly	29.9	29.3	50.2	103.6	177.3	254.1	*251.3*	*312.0*	*325.8*	233.4	86.1	36.0	1,889.0
Nam Dinh	27.8	35.0	50.8	81.6	174.7	192.7	*230.2*	*325.2*	*347.7*	194.6	67.5	29.2	1,757.0
Ninh Binh	23.7	35.6	46.0	82.7	166.8	224.1	*227.2*	*301.5*	*381.8*	235.2	69.8	34.1	1,828.5
Van Ly	25.8	34.0	37.6	70.1	131.5	185.4	*211.3*	*339.5*	*339.2*	226.7	86.6	22.1	1,759.9

A: wetted cross section area [L2];
x: distance measured along the channel [L];
g: acceleration due to gravity [L/T2];
n: the flow resistance coefficient (Manning coefficient).

Numerical Approach

The numerical solution of the governing equations is executed through two basic steps (Cung et al. 1980). In the first step, the partial differential equations are approximated by algebraic finite difference equations.

Among finite difference explicit and implicit schemes such as Lax's, Lax-Wendroff's and Crank-Nicholson's, the linear implicit four points scheme first proposed by Preissmann (1961) is one of the most widely applied in the numerical modeling of unsteady flow, because this scheme has the following advantages (Don 1998):

- It is compact. Its compactness allows the modeler to space grid points (or river cross sections) non-uniformly along a river system.
- It is implicit, as the scheme has a wide region of stability allowing the modeler to choose the time step to suit the time scales of physical flow rather than being restricted by a limit on a Courant number.
- Values at boundaries are very easily calculated.
- Interior boundary can be treated in the same manner as another part of the reach.

According to the Preissmann formulation, a function *f(x,t)* is discretized by,

$$\begin{aligned} f(x,t) &= \frac{\theta}{2}\left(f_{j+1}^{n+1}+f_j^{n+1}\right)+\frac{(1-\theta)}{2}\left(f_{j+1}^{n}+f_j^{n}\right) \\ \frac{\partial f}{\partial x} &= \theta\,\frac{f_{j+1}^{n+1}-f_j^{n+1}}{\Delta x}+(1-\theta)\frac{f_{j+1}^{n}-f_j^{n}}{\Delta x} \\ \frac{\partial f}{\partial t} &= \frac{f_{j+1}^{n+1}-f_{j+1}^{n}+f_j^{n+1}-f_j^{n}}{2\Delta t} \end{aligned} \tag{3}$$

where θ is the weighting factor; j and n represent space and time steps, respectively. When θ =1, the scheme is fully implicit, and when θ = 0, the numerical scheme reduces to the explicit method. The difference will be central if θ=0.5. And for 0.5≤θ ≤1, the implicit scheme will be unconditionally stable. The recommended value of θ is 0.55 since such a value minimizes the loss of accuracy and moreover avoids instability under some transient conditions.

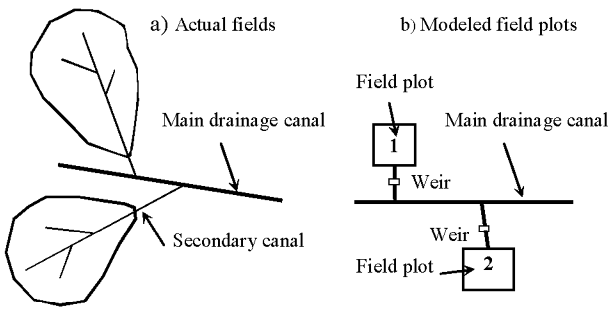

Fig. 3 Modeling field plot

Applying this difference scheme, the basic equations are discretized. In the second step, the Newton-Raphson method is then used to solve the non-linear algebraic equations obtained from the first step. Non-linear terms in the equation are linearized with a Taylor series expansion in which second-degree higher order terms in the equation are neglected. Finally, the double sweep method is applied in order to solve the system of linear simultaneous equations.

Interior Boundaries

The applicability of the unsteady flow model depends considerably on the diversity and availability of the boundary condition. As is well known, there are two types of boundaries: exterior and interior. The former is posed on the edge of a channel system; the later is posed on the inner special part of a channel system where flow movement described by the original Saint-Venant equations is not applicable. Interior boundary conditions are more influential on the model's applicability. If they are utilized effectively, the potential of the unsteady flow model will be increased significantly (Kubo and Don 2000). In this study, typical interior boundaries including channel junction, sudden expansion, weir, gate, siphon, and pump are considered. All of them are important elements to compose a channel system.

Modeling Field Plot

The gravity fields that drain water to secondary canals are modeled as field plots, directly exchanging water with main drainage canals as seen Fig. 3. The fields drained by

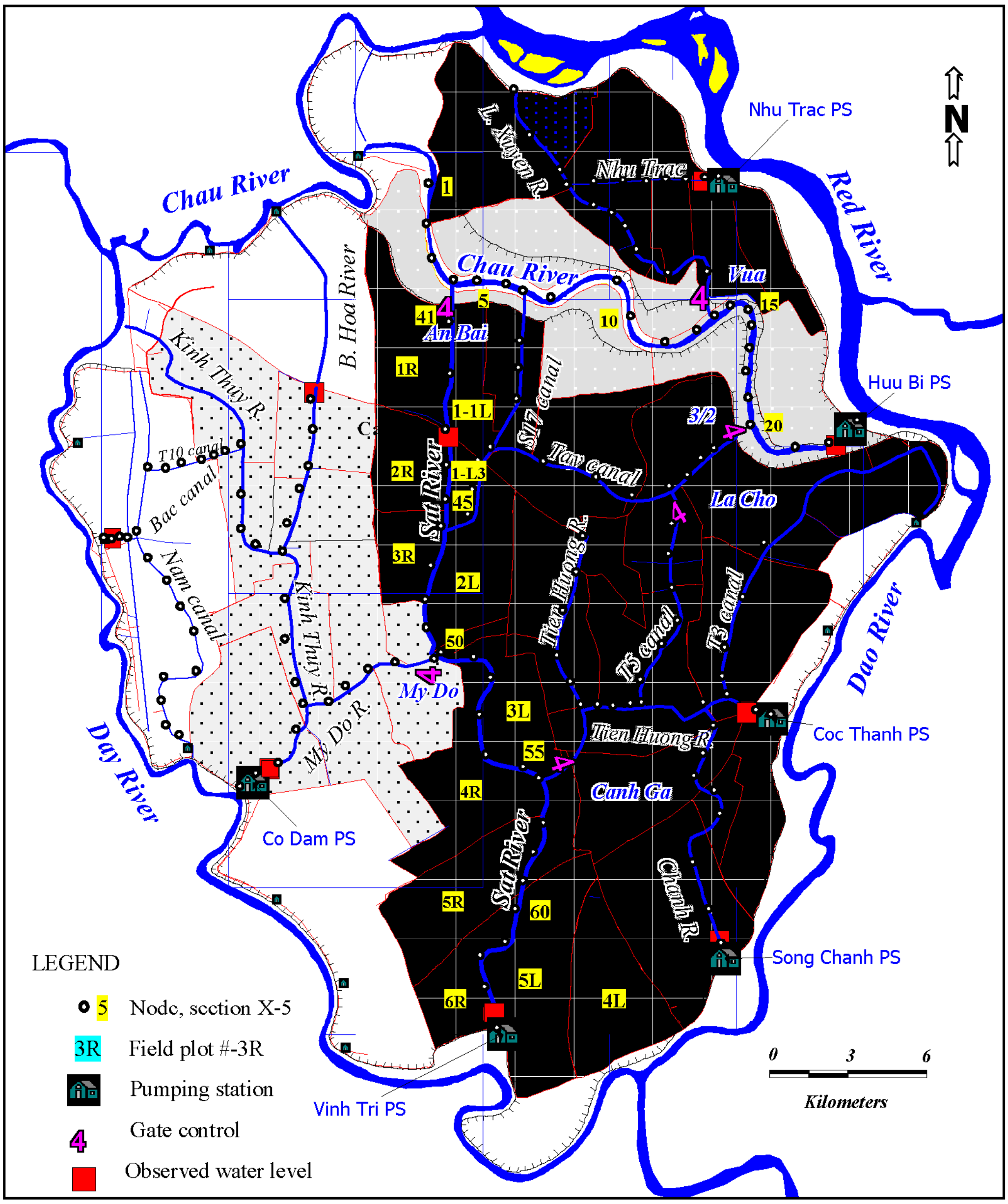

Fig. 4 Schematic diagram of the drainage systems showing nodes, links and field plots

pumping are modeled as the pumped-field plots that discharge water at nodes of the canal system. The process of discharge depends on the actual operation of the pumps.

Estimating the flooding of the field plot

Estimation of the flooding in each field plot is based on the crops' tolerance to flooding, which is determined by two factors:

- Submerged water depth in a crop field;
- Time duration of water flooding without affecting crop yield, normally three or five days with the yield reduction not excess of 10%.

MODEL APPLICATION

The unsteady flow model is applied to simulate the flow regime and evaluate the existing capacity of the drainage system and the operating systems. The model is also used as a tool to simulate the discharge in the drainage channels and the submerged floodwater depth in inundated areas. The purpose of this study is to introduce mitigation scenarios for improving the drainage system and operation of gates and pumps.

Figure 4 shows a schematic diagram, nodal points, and some selected field plots of the drainage systems. There are 13 drainage channels, 6 regulators, 6 main drainage

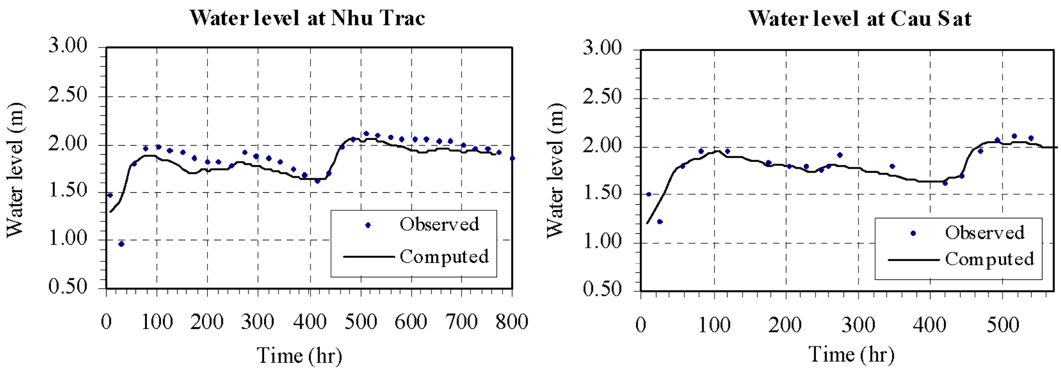

Fig. 5 Water levels at Nhu Trac (model calibration) and at Cau Sat (model validation)

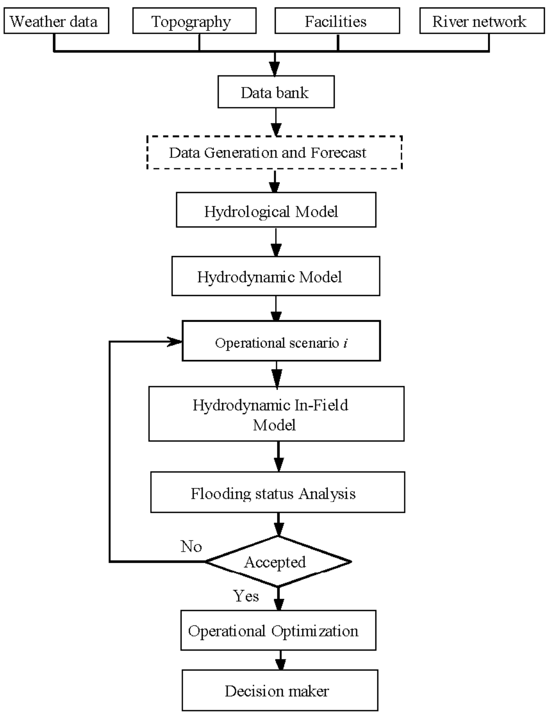

Fig. 6 Integrated operational model

pumping stations, 25 secondary in-field pumps, and 64 field plots. The rainfall and water level at some regulators were recorded during 28th Aug to 27th Sept, 1994. Water levels in the study area were measured at hourly intervals in the same period for the sake of model calibration.

The input data include the time series of 4 heavy storms, the geometric data of the river network and facilities, the water level at the boundaries, and the area of each field plot by elevation. The calibration procedure was carried out in order to estimate the acceptable value of the roughness coefficient n. The model calibration was carried out through fitting of peak water levels as well as the shape of the water level curves, based on the adjustment of the roughness coefficient. The model calibration showed that computed and observed values agreed very well, as shown

Table 2 Scenarios based on gates operation

Gate / Case	Vua	An Bai	3/2	La Cho	Canh Ga	My Do
1	o	o	o	o	o	o
2	x	x	x	x	x	x
…						…
…						…

(Note: x = Closed; o = Opened)

in Fig. 5. The calibrated model was successfully verified for another flooding year of 1995 for the same period, by running the model with new time series data while keeping all the parameters unchanged (Fig. 5).

Figure 6 shows the integrated operation model for the system. On the basis of data collection, a data processing procedure is used to prepare all kinds of data (weather, topographic, geometric data) to supply for other models as the input values. The hydrological model is applied for storm design and forecast based on frequency analysis. Usually, each rainfall occurs over several days producing a certain amount of rainfall. Hence, the rainfall pattern over a certain duration is needed for design calculation. The hydrodynamic model will then be used for predicting water level at the boundaries. If the water levels at the boundary rivers are higher than "alarming water levels" (these values are decided by the dyke protection law according to the level of the dyke's importance and grade), all pumping stations must be stopped working because floods in the bounded rivers have reached dangerous levels. The hydrodynamic in-field model, the main one, is applied after each scenario of drainage operation has been specified, in order to predict the flooding process and inundation area in the field and flooding in the river network system. Through these processes, flooding analysis will be made based on the crops' tolerance to flooding, taking into account the type of crops, ponding time, excess water-logging stress, etc. The computation process will be repeated by changing the operation scenario until the flooding control criteria are

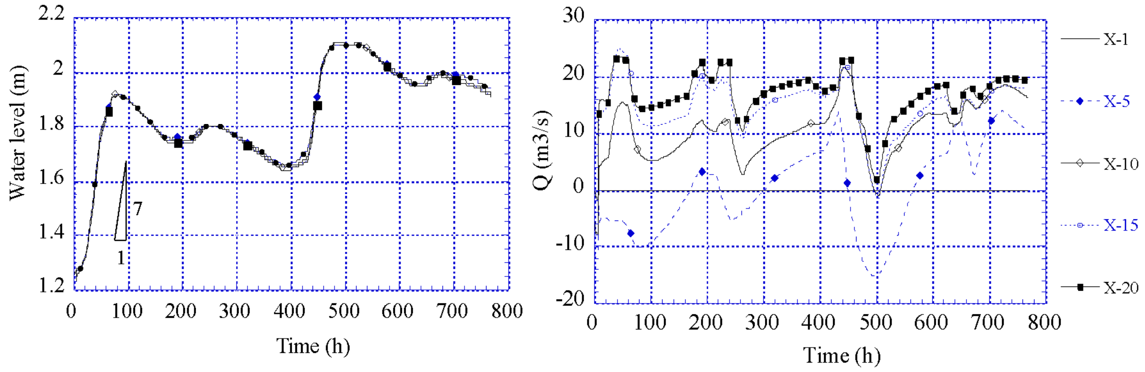

Fig. 7 Variation of water level and discharge at selected cross-sections of the Chau River

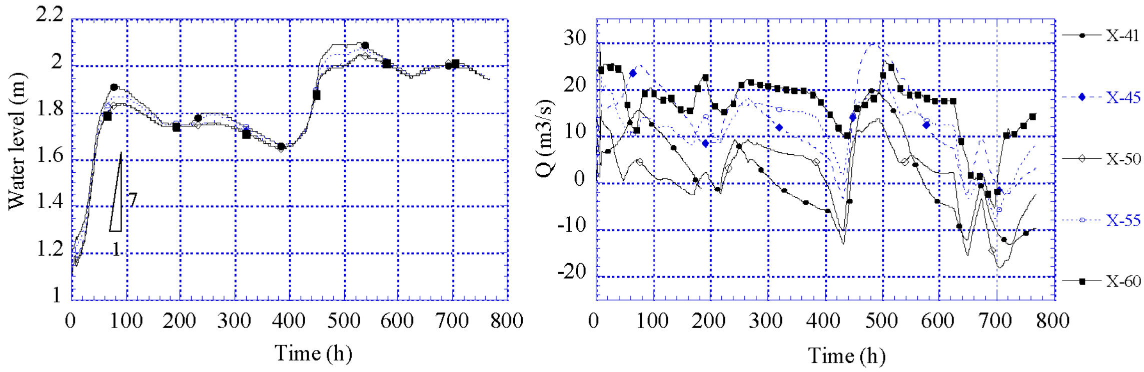

Fig. 8 Variation of water level and discharge at selected cross-sections of the Sat River

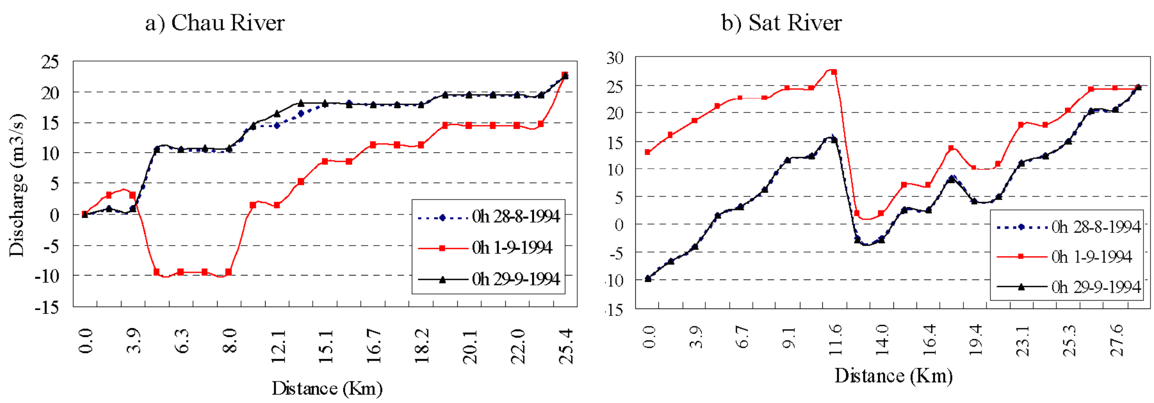

Fig. 9 Fluctuation of discharges along the rivers

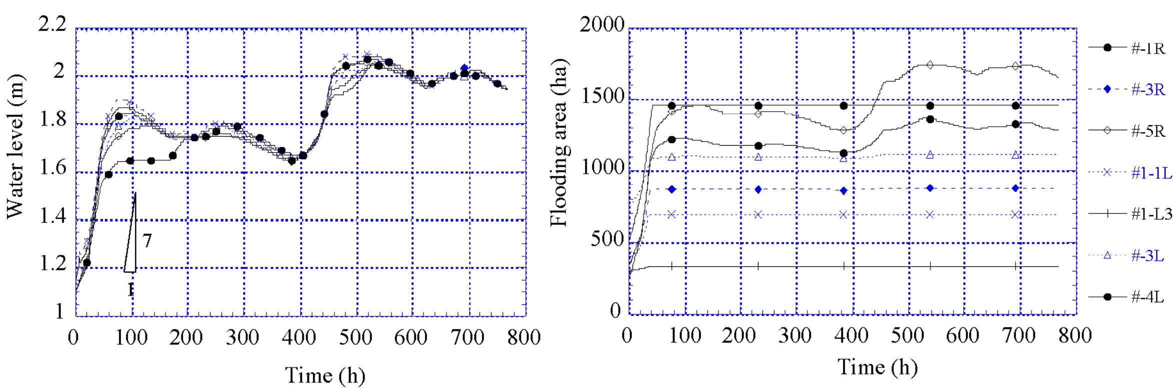

Fig. 10 Variation of water level and flooding process at selected field plots in the Vinh Tri basin

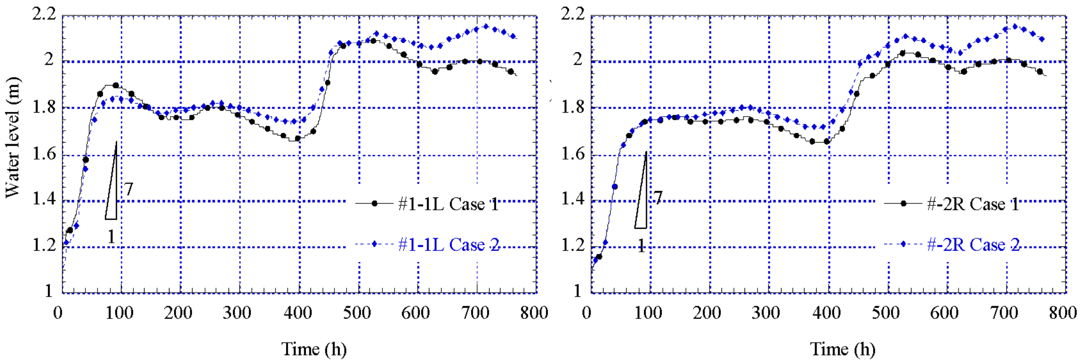

Fig. 11 Comparison of water level at selected field plots in the Vinh Tri basin

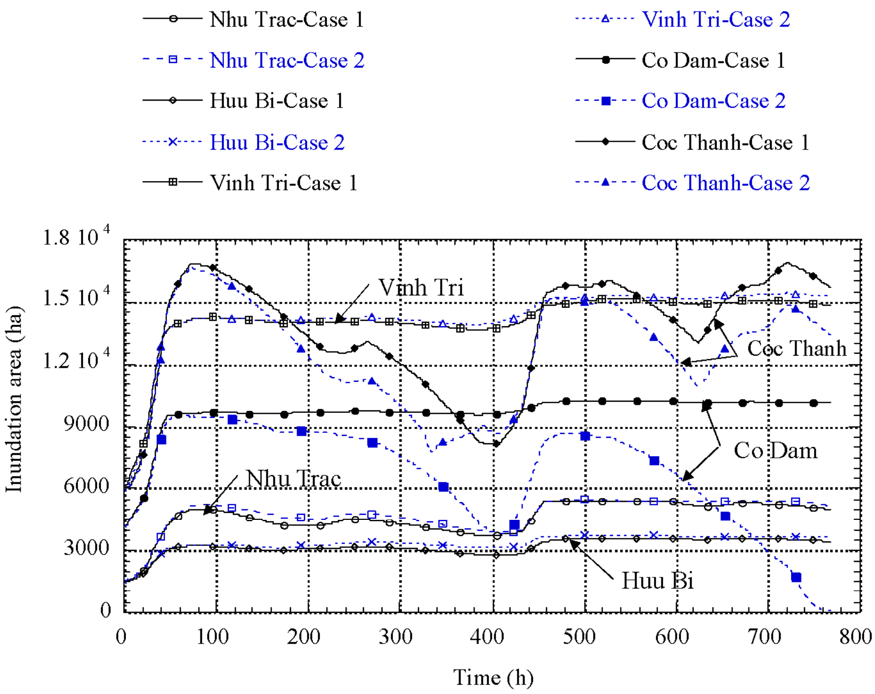

Fig. 12 Comparison of inundation area in the sub-drainage basins

satisfied. In this study, only the results obtained from the hydrodynamic in-field model are presented.

In order to improve the present drainage capacity, the conceptual idea can be formulated based on gate combination since the large drainage basin is composed of five sub-basins which are connected through channels provided by gates. The regulators, namely, Vua, An bai, 3/2, La cho, Canh Ga, and My Do can be closed or opened in order to divide the area into 5, 4, 3, 2, or 1 polder(s). In this paper, the two main operational scenarios as listed in Table 2 are examined.

Case 1- System operation: all regulators are open. Because of the topography of the area, water only can flow down from upper basin to lower basin. The lower ones will receive more water from the upper ones. This reasoning is applied when rainfall is unevenly distributed in the area.

Case 2- Individual operation: each of five drainage basins, namely Nhu Trac, Huu Bi, Coc Thanh, Vinh Tri, and Co Dam, works independently as all regulators are closed. This case can be applied when heavy rain or evenly distributed rain falls in the area.

Case 1 - All Gates Open (1 polder)

The simulated results for all the cases are presented in Figs. 7 to 12. Figures 7 to 9 display the variation of water levels and discharges at some cross-sections along the Chau River and the Sat River, respectively. In these figures, the river hydrographs show that river flow is increased as water discharging from the fields accumulates and flows downstream the river. This variation is much dependent on the size and the altitude of the field plot. The Chau River at

27 km long, and the Sat River, 38km long, collect drainage water for the Huu Bi and Vinh Tri stations with pumping capacities of 22.6 m3/s and 30.7 m3/s, respectively. It is clear from these figures that, at many periods, the river flow capacity is much lower, at about 70%, than the pumping capacity. This flow capacity is too small due to friction loss and small flow cross sections, consequently which cause the flooded water slowly accumulates at the pumping stations. As a result, the suction water levels at the pumping stations are not as high as required, finally cause low pump efficiency. It can be supposed that the water conveyance capability of the drainage system is somehow limited and drainage facilities are not fully operational. It would be possible to improve the drainage system performance by installing more pumps and by dredging drainage channels, and by widening the cross-sections of channel and drainage facilities.

The flooding depths at each field plots were calculated using water levels data and land levels' contours by subtracting land levels from water levels. The flooding area under each depth category, 0.5 m interval each (0.0, 0.5, 1.0, 1.5, 2.0, 2.5m, 3.0, 3.5m) was calculated using the contour flooding depth.

Figure 10 shows the flooding process at selected field plots located in the Vinh Tri basin, along the Sat riverbanks. It can be seen that the water levels in the fields were increased and reached their maximum values on the 3rd day and 20th day since the storms had come, and then gradually decreased as all of the pumping stations were in operation. The results also indicate that the rate of increase in water level is very high. From this figure, it appears that at some selected field plots in the Vinh Tri basin, namely the plots numbered 1R, 3R, 5R, 1-1L, 1-L3, 3L, 4L (here, R and L stand for ones located at the right side and the left side of the drainage channel), after 3 days of flood, almost all areas had remained submerged as result of high water level remaining in the field. The total flood area with respect to time is easily calculated by summing up the accumulated inundation area of every field plot. The computed results show that the total inundation area at a specific time, for instance at 0h, 30th Aug 1994, is about 48,200 ha, accounted for 56% of the total area and is 49,200 ha at 0h, 17th Sept 1994, or 58% of the total area.

From the computed results, it is found that, a minor part of 14% of the study area was under non-flooding zones, 3% were under depth category 2.5 to 3.5m. The remaining major part of 83% of the study area was under depth category 0.0 to 2.5m. This indicates that the study area has very lowland levels. The results also indicate that the rate of rise in water level is high so that the flood can quickly spread over a large area with time and consequently the water level increases too much (Figs. 10, 11). Theses results are useful for developing hazard map and

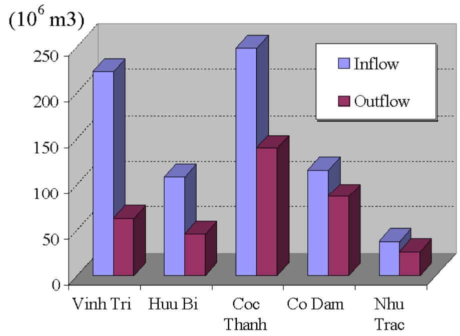

Fig. 13 Water balance of closed drainage basins

categorizing flood hazard, hazard zones, and hazard factors for different land units, which have been doing in a further study.

By observing the flooding process hydrograph, we can easily locate the long-lasting flood period at a certain submerged water depth as well as determine the maximum water level at any field plot and how long the crops have remained submerged. Furthermore, together with information regarding kind, excess water-logging stress/tolerance of crops and so on, flood damage to crop production can be estimated. Similarly, flood damages to other economic activities can also be evaluated.

Case 2 - All Gates Close (5 polders)

This alternative will divide the area into 5 separate polders. The advantage of this alternative is that each polder can operate independently, requiring less co-ordination.

The behaviors of the same system are illustrated in Fig. 11, showing the comparison of computed water levels at some selected field plots, namely 2R and 1-1L, in the Vinh Tri basin for the two cases. It shows the rising tendency, which is about a 0.2 to 0.3 m increased water level at peak, compared to the previous case. The same increment can be observed in the Nhu Trac and Huu Bi basins, which could cause more than 500 ha to be inundated in each basin. As shown in Fig.12, inundation area of the field plots of the Nhu Trac, Huu Bi, and Vinh Tri basins in case of all gates being closed is much higher than that in the case of all gates being opened. However, in the case of a basin having high pumping capacity as in the case of Co Dam (42.8 m3/s) and Coc Thanh (43.10 m3/s), the inundation area would therefore diminish. This is simply because of, as expected in this case, the systems' standalone function; the flooding process in each drainage basin depends significantly on its pumping rate and rainfall inflow. For a closed basin, the larger the pumping capacity and or the smaller the rainfall intensity, the smaller inundation area.

The surface water balance for the closed sub-basins during specific time duration was then calculated. Some of the components such as rainfall and pumping rate could be measured. Infiltration and evaporation taking place during short flood period were negligible. With a closed basin, no water exchanging between basins was considered. As given in Fig. 13, the total amount of water pumped out in 32 days since 28th Aug. was only 358 million m3, where as the amount of rainwater causing flood fell in the region was as much as 730 million m3. Therefore, after that time, about 372 million m3 of excessive water still remained in the region. Consequently, more time was required to operate the drainage system.

Besides the two main operational scenarios discussed earlier, the operation of the drainage system allows many options depending on various combinations of gate operating condition. Therefore an operational optimization problem for the system should be formulated based on minimizing the flooded area, subjected to the continuity equation and a set of constraints regarding the pumping rate, the conveyance capacity of the channel, the discharge passing through gate, the allowable water level at the boundaries, etc.

The feasibility of applying real time control to lowland drainage systems should also be carried out, utilizing existing capacity of the drainage system or to operate existing gates and pumps more efficiently in order to reduce or prevent flooding. The model concept may also be used to optimize future improvement and analyze performance with respect to the expansion of the drainage system in order to cope with the population growth.

CONCLUDING REMARKS

This study presents the development of an integrated model for predicting the inundation area, water movement, and the flooding process in pumped-field lowlands. The model is aimed at properly operating the drainage system by integrating series data such as the river network, facilities, hydrology, weather data, etc. The simulation results, briefly selected, show the flooding process at every field plot, location in the drainage channel including water level, discharge, inundation area, and submerged water depth as well. As discussed earlier, the channel network systems that convey storm water from a particular area to the pumping stations need to be fully operational with sufficient flow capacity.

The flood damage in the area finally depends on the drainage system for storm water and the control system. Real time control (RTC) should be carried out by improving operational conditions. The aim of RTC is to maximize the effective use of the facilities in order to achieve various goals, such as reducing overflows, reducing or eliminating flooding, and optimizing energy use. The study demonstrates two main operational scenarios based on gate operating conditions. If all regulators are kept closed, the pumping systems will work independently. This case can be applied when heavy rain or evenly distributed rain falls in the area. In the case in which all regulators are open, the pumping systems should be run in conjunction with others. This procedure should be applied when rain is unevenly distributed over the area. Besides, there are many possible combinations of controlling the system in regard to individual operation or system-wide operation, depending on which gates are manipulated.

The model provides an effective tool for river network modeling through which we can study and gain an understanding of hydraulic phenomena, select and design sound engineering operations, and predict extreme situations so as to provide advance warning of their occurrences in nature.

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