Flood Management Scenarios Based on Hydrodynamic Modeling

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Abstract

This paper describes the scenarios developed to assist in the understanding of possible future situations of the complex river system as a part of knowledge acquisition process. Due to complexity of river system, knowledge acquisition is a major bottleneck to develop an expert system for forecasting flood. Operation of flood control gates has a very important role in flood alleviation. With what-if scenarios development including positions of flood control gates and slackers, the hydrologic behavior of the river system is assessed based on simulated water level and discharge hydrographs at the flood forecast points of interest. A case study was carried out based on the position of the existing gates and slackers by using Anglian Flow Forecasting modeling System (AFFMS) in the Welland and Glen catchment, UK. AFFMS was developed by DHI based on Mike 11 Hydrodynamic model. Under Mike11 model runs, water levels and flows at the flood forecast points of interest were simulated based on three scenarios of fully open, half open, and fully closed for gates and slackers' position. To evaluate the model performance and arrive at decisions that reduce flood damage, two criteria were employed to analyse the simulation results: percent difference between peak observed value and peak simulated value, and difference between times of observed and simulated peaks in hour.

Keywords: *Flood Management, Mike11 model, Flood Control Gate, What-if Scenario, Welland and Glen Catchment*

Introduction

Flood management is surrounded by a variety of uncertainties. The key points are: given the uncertainties related to flood control gates' states, what is the best strategy of flood management? what if a rapid rise in river water level occurs whilst the manually operated gates are not raised quickly enough. Generally speaking, existing flood control structures' conditions need to be taken into account when evaluating flood management scenarios. This raises the necessity for suitable scenarios that consider possible futures in a consistent way. In the present paper, a case study was carried out in which hydrodynamic modeling has dealt with the existing gates and slackers in the Welland and Glen catchment. The focus of the study was on development of three scenarios: fully open, half open, and fully closed. Existing flood forecasting points have been used to simulate water levels and discharges for each of states of gates and slackers.

According to Booch et al. (1999), a model is a simplification of reality. Hydrological models vary from conceptual rainfall-runoff models such as GR4 (Edijnato, 1984) to distributed physically based models such as SHE (Abbot et al., 1986) within a large range of complexity (Ledoux et al. 2002). Each hydrological or hydraulic model comprises independent variables, dependent variables, relationships between these quantities, and also parameters whose actual values are not known precisely, but may vary within some ranges that reflect out incomplete knowledge or uncertainty regarding them (Cacuci, 2003). For this purpose, the model needs to be well calibrated and verificated against several data sets covering the events of interest such high flow, low flow and flood. The Main issue in distributed models is the determination of model parameters for the various areal units distinguished that this cannot be done by calibration. The best solution is to use land surface characteristics available in GIS based maps of land use, vegetation and soil type, topography, and hydrogeology (Becker et al. 2002). Analysis and understanding of observed floods phenomena, and testing of different hypotheses and scenarios are the major objectives of modeling and simulation. In any successful study of a complex river system using modeling tools, it is critical to identify how the model is to be used, and focusing the model development on the simulation of the associated key processes. Depending on the extent to which these two kinds of knowledge are exploited, three basic levels of model synthesis can be defined (Ljung, 1999):

- White Box: The model is completely constructed from a priori knowledge and physical insight. Here, empirical data are not used during model identification and are only used for validation. Complete a-priori knowledge of this kind is very rare, because usually some aspects of the distribution of the data are unknown.
- Gray Box: An incomplete model is constructed from a priori knowledge and physical insight, and then available empirical data are used to adapt the model by finding several specific unknown parameters.
- Black Box: No a priori knowledge is used to construct the model. The model is chosen as an exible parameterized function, which is used to fit the data.

The hydrologic response of catchments is not constant in space and time, as characterised by fluctuations of water levels and discharges, with major and minor peaks in the hydrographs across space and over time. With the availability of sophisticated, fast and robust tools and easy access to high performance desktop computers today, the simulation of catchments' responses is no longer so difficult. Two key issues which must always be addressed are the selection of a suitable model and selection of parameters so that the model closely simulates the behavior of the catchment (Sorooshian and Gupta, 1995).

In hydrologic simulation and modelling, there are some types of analyses that are essential to identify constraints and bottlenecks, produce graphical output under various hypotheses, and evaluate future situations and scenarios. These include 'what-if' Analysis and 'if-what' Analysis. One way to understand the behavior of the river system is to conduct what-if scenarios by entering different values for parameter of interest and then examining the values that are generated as output. 'What-if' analysis is carried out by characterised possible scenarios and hypothetical situations. 'What-if' analysis is an essential part of modelling under the scenarios and situations of interest. In this study, several scenarios were employed to assess future situations and prove various hypotheses. The analysis aimed to see the possible reasoning behind each scenario and run 'What-if' scenarios to see how chosen scenario affects final output of the model. One can change all or some of the conditions (i.e., rainfall boundary conditions, options of flood control gates operations) and compare the results of the various 'What-if' simulations. 'If-what' analysis that is less familiar than 'what-if' Analysis, refers to backward reasoning from desired outcomes to proposed alternatives for their attainment (Barnett, 2005).

This study aims at showing the role of hydraulic structures such flood control gates and their affects in decreasing or increasing peak water levels and flows to varying degrees depending on the flood control gates' positions based on three positions of 'fully closed', 'half open', and 'fully open'. Although the reports of the Welland and Glen catchment hydrodynamic modeling (AFFMS) and supplementary field surveys and data from Environment Agency, UK, provided significant detail of the river system in the catchment, detailed information for flood control gates were still incomplete. Therefore, some of these control structures were not included in the prototypes due to lack of critical information such as control logical rules for control gates and operation situation of them (offline or online).

Study Area

The study area is the Welland and Glen catchment located in the Anglian Region (Fig. 1) which covers an area of some 27500 square kilometres, stretches from the Humber in the north to the Thames in the south. The Environment Agency is divided into eight regions and the Anglian Region is one with 58% of the most productive agricultural land and a population of some five millions persons. The sustainable use of water is crucial given the competing demands for it, particularly because this region is also the driest in the UK. The Anglian Region has experienced two severe drought periods resulting from periods of exceptionally low rainfall in ‘October 1988-February 1992’, and ‘April 1995-September 1997’ characterised as ‘groundwater’ and ‘surface water’ droughts respectively. In some summers, irrigation can make up 50% of total water use. In the summer, water is diverted from the rivers to the drains whence it is distributed to the fields to maintain high water tables for irrigation pumping (Merrett, 2004). The main river is the River Welland, which flows into the River Glen that has its outflow in the Wash. The river Welland is 130 km long with a catchment area of 1750 square kilometres. The Welland extends from its headwaters near Market Harborough in Leicestershire to the Wash Estuary. The Glen rises in the Lincolnshire Limestone ridge east of Grantham and joins the Welland north east of Stamford. Major towns within the catchments include Oakham, Stamford, Spalding, Market Harborough and the northern fringes of Peterborough. There are a large number of complex control and dynamic structures such as gates and pumps in the Welland and Glen catchment as shown in Fig. 2. Many flow control structures and pumps have been built in the Welland and Glen catchment in order to regulate the discharge for the purpose of water conservation, flood alleviation and irrigation. Almost all of these structures operate manually given that they strongly influence hydraulic Conditions in the lower Welland and Glen catchment. All the pumps are located in the lower Welland and this is illustrated in Fig. 2.

Figure 1. The Anglian Region

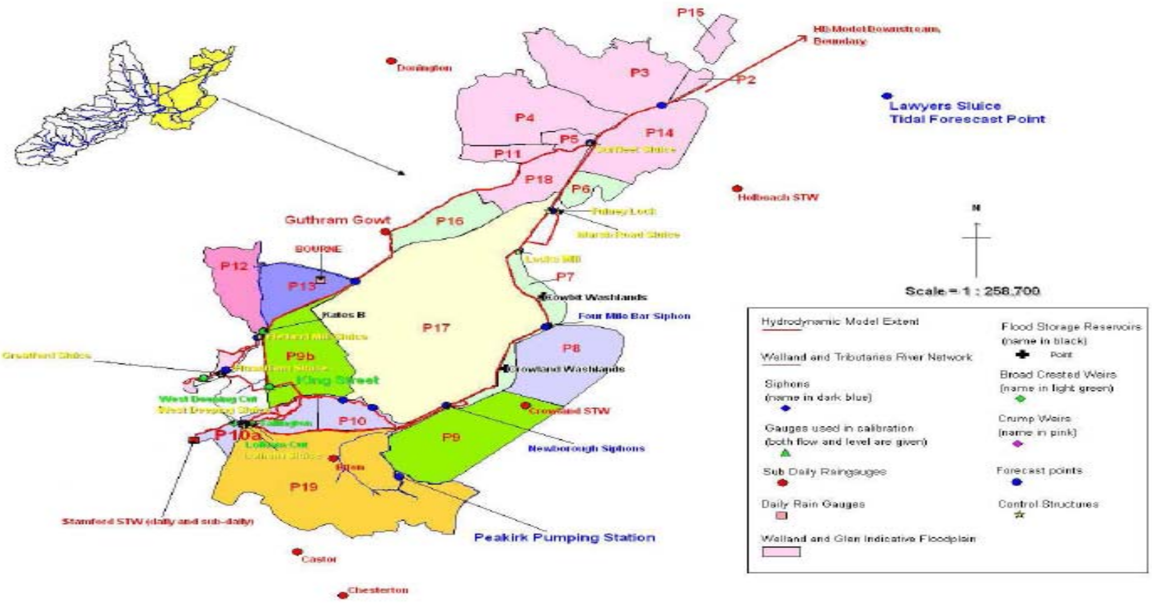

Figure 2. Lower Welland catchment and the existing static and dynamic structures.

Sluice Gates and Slackers

Sluice gates (photo. 1) within the river network of the Welland and Glen catchment have been modelled explicitly using a control structure in MIKE 11 that allows the modeller to specify discharge through the structure as a function of upstream or downstream head, a function of head difference across the gate, and a defined value for a given water level. Flow control is achieved by a range of vertical sluice and radial sector gates, and fixed weirs. For high flows, these structures are fully open, allowing maximum outflow. Also weirs are in most cases drowned and artificial influences have only a minimal effect on the system. Slackers are used to provide irrigation. Tab. 1 lists the gates and slackers located in the Welland and Glen catchment. The gates in the set-up of the Welland and Glen model are operated automatically in the sense that the model decides the gate position (or discharge through it) based on water levels or discharges in some control point in the vicinity of the gate. Exceptions are the slackers, where the gate position is governed by timeseries (with annual variation).

Photo 1. View looking downstream in Duddington Mill Sluice2&3.

As can be shown in Tab. 1, the sluice gates and slackers operate automatically or manually, mainly influenced by water levels immediately upstream of the structures so that small changes in water levels upstream can result in a big change in the opening of the sluice gate, and hence a big change in discharge through the structure. Tab. 2 represents the rules governing the operation of the gates and slackers. In the Welland and Glen model, in the control structure tab of the network file of the Mike 11 model, the flow control at each gate uses one or more 'if-then' rule(s) with relevant priorities.

Table 1: Characteristics of flood control gates of the Welland and Glen catchment.

ID	Branch	Chainage(m)	Type	No.	Automatic	Manual
FSR flap gate	Little Bowden Outlet	5	Underflow	1		✓
FSR flap gate	Braybrook Outlet	5	Underflow	1		✓
Caldecott sluices	Eyebrook d/s	2208	Underflow	3		✓
SCOU	Reservoir-Sections	3005	Underflow	1		✓
Duddington Sluice	Welland T-S	3160	Underflow	1	✓	
Duddington Mill Sluice1	Duddington	200	Underflow	1	✓	
Duddington Mill2	Duddington	200	Underflow	1	✓	
Sluice	Side Channel A	1100	Underflow	1	✓	
Kett	Chater	2040	Underflow	2		✓
SL0	Slack0	50	Underflow	1		✓
SL6	Slack6	50	Underflow	1		✓
SL5	Slack5	50	Underflow	1		✓
SL4	Slack4	50	Underflow	1		✓
SL3	Slack3	50	Underflow	1		✓
SL1	Slack1	50	Underflow	1		✓
SL2	Slack2	50	Underflow	1		✓
High locks	Welland A15S	953	Underflow	1	✓	
Low Locks	Welland A15S	2800	Underflow	2	✓	
Fitzwilliam Sluice	Glen u/s SS	460	Underflow	1	✓	
Greatford Sl	Greatford Ct	50	Underflow	2	✓	
W Deeping Sl	W Deeping Ct	55	Underflow	1		✓
Surfleet	Glen u/s SS	29060	Underflow	2	✓	✓
Fulney Lock	Welland SFL	3000	Discharge	1		✓
MRS1	CoronationFC	3400	Underflow	1	✓	
MRS2	CoronationFC	3400	Underflow	1	✓	
MRS3	CoronationFC	3400	Underflow	1	✓	
Fletland Mill Sluice	Glen u/s SS	3937	Underflow	1	✓	

Table 2: Gates and slackers operations.

Name	Description	Control Rules
Caldecott Sluices	Width:1.0 m Invert:50.91 m AOD	If siphons at Eyebrook are primed, Then fully open.
Eyebrook Scour Valve	Width:1.5 m Invert=63.24 m AOD	Timeseries data allowing the gate to open at specific time intervals.
Duddington Mill Sluices	Widths:(2.5,1.8,2.8 m) Inverts:(29.17,29.06,29.67 m AOD)	To retain u/s level= 30.5 m AOD.
Ketton Sluice	Width:1.25 m Invert:38.81 m AOD	Fully open at all times.
Sluice in Side Channel A	Width:2.1 m Invert:21.639 m AOD	Fully open at all times.
West Deeping Sluice	Width:3.9 m Invert:12.45 m AOD	Opened by 0.1 m at all times. (Water level maintained at 0.1 m above crest.)
Fletland Mill Sluice	Width:3.8 m Invert:6.8 m AOD	Fully open with u/s level=8.22 m AOD. Fully close with u/s level=8.1 m AOD.
High locks Sluice	Width:5.6 m Invert:5.0 m AOD	Open with u/s level=5.9 m AOD. Fully open by 6.2 m AOD.
Low locks Sluice	Width:4.25 m Invert:3.771 m AOD	Open with u/s level=5.3 m AOD. Fully open by 5.5 m AOD.
Surfleet Sluice	Width:3.1 m Invert:-0.268 m AOD	Retention level=2.7 m AOD. If flow at Kates Bridge >15 cumecs, Then fully open. Summer retention level=2.9 m AOD Winter retention level=2.6/2.7 m AOD
Marsh Road Sluice	Width:19.59 m Invert:-0.29 m AOD Amount each gate opens may be generated from a regression analysis of gate position against water levels at various points through the network. Gate full travel time=347 secs	Retention level=2.9 m AOD. If flow at Tallington >43 cumecs, Then fully open. Winter retention level=2.9 m AOD Summer retention level=3.1 m AOD If water level<12.9 m AOD, If 13.04<water level<13.1 m AOD, Then maintain their respective positions.
Fulney Lock	Width:9.4 m Invert:1.5 m AOD	Discharge control Rules: 0.01 cumecs @ u/s level=1.5 m AOD, increasing to 0.1 cumecs @ u/s level=15 m AOD.
Greatford Sluice	Width:3.504 m Invert:12.139 m AOD A 10-second dealy on gate operation to prevent gate opening due to wind or wave action.	Open in increments when u/s level equals 13.2 m and rising. If water level>13.63 m AOD, Then fully open. If water level<13.1 m AOD, If 13.1<water level<13.2 m AOD, Then maintain their respective positions.
Fitzwilliam Sluice	Width:2.6 m Invert:12.395 m AOD A 10-second dealy on gate operation to prevent gate opening due to wind or wave action.	Open in increments when u/s level equals 13.1 m and rising. If water level>13.25 m AOD, Then fully open. If water level<12.9 m AOD, If 13.04<water level<13.1 m AOD, Then maintain their respective positions.

Model description

The model described in this paper is the Mike 11. Mike 11 is based on an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries. This model is a commercial one-dimensional model for the detailed simulation, management and prediction of behavior of both

complex and simple rivers systems. The model uses an implicit finite difference scheme for computation of unsteady flow based on the Saint Venant Equations.
The hydrodynamic module (HD), which is the core of MIKE 11, uses an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries. The module can describe subcritical as well as supercritical flow conditions through a numerical scheme that adapts according to the local flow conditions (in time and space). Advanced computational modules are included for description of flow over hydraulic structures, including possibilities to describe structure operation. The formulations can be applied to looped networks and quasi two-dimensional flow simulation on flood plains. The computational scheme is applicable for vertically homogeneous flow conditions extending from steep river flows to tidal influenced estuaries. The system has been used in numerous water engineering studies. The Welland and Glen model was fully calibrated to observed data for the period July 1996 to June 1998 including the Easter 1998 flood and the 1996 drought, and validated using data for the subsequent year, from July 1998 to June 1999.

Methodology

Control strategy of Mike 11 model is intended to determine the way that the gate level is calculated. It describes how the gate level depends on the value of a control point based on a list of 'if'-statements. For each of these statements it is possible to define an arbitrary number of conditions that all must be evaluated to 'TRUE' if the 'if'-statement is to be evaluated to TRUE. It is hereby made possible to use different operating policies depending on the actual flow regime, time etc. From above it is concluded the conditions that must be fulfilled for the control strategy to be executed and the control strategy itself, are two factors required to define a control strategy. The control strategy itself is a relationship between an independent variable (the value of the control point) and a dependent variable (the value of the target point). Under control strategy definitions, it is possible to make Mike11 choose between an arbitrary numbers of control strategies. These control strategies are organised using a list of 'if' statements. The control strategy belonging to the first of these statements that are evaluated to TRUE will be executed. It is thus of importance for the user to define which 'if'-statement that are evaluated first, second, third and so on. This is enabled by the priority field that the user defines the priority of the 'if'-statement by writing an integer number. By default the first line in the table will have priority equal to one; the second line will have priority equal to two and so on. Note that the 'if'-statement with the lowest priority always will be evaluated to TRUE. This is because this statement is connected to the default control strategy that will be executed when all other 'if'-statements are evaluated to FALSE. The following is an example of the control strategy definitions at Fulney Lock with three priorities:

1st: 'IF the water level difference immediately up and downstrem is positive (dH (2999, 3001) ≥ 0) AND the water level difference at som points farther away (dH(2900, 3100)) is in the interval -10m to 0' THEN 'control the discharge as a function of the level difference dH (2900, 3100)), that is, the control point'. The strategy for controlling is that whichever value of dH (2900, 3100) takes in the interval -10m to 0m the discharge through the structure is zero.
2nd: 'IF the water level difference (dH (2999, 3001)) is positive (and so is dh(2900, 3100), otherwise priority 1 was entered)' THEN control the discharge as a function of the discharge in Welland SFL 2900. The strategy for controlling is that as long as Q in Welland SFL 2900 is below 1.49 cumecs then the discharge through the structure is 0. From 1.49 cumecs to 1.5 cumecs, the discharge increases from 0 cumecs to 0.01 cumecs. From 1.5 cumecs to 15 cumecs, the discharge increases linearly from 0.01 to 0.1'.
3rd: (The trap catching cases not covered by the above). Control the discharge through the structure as a function of the level at Welland SFL 3100(downstream level). The strategy is that the discharge through the structure is zero no matter what the level at Welland SFL 3100 is (assuming that -15m to 20m covers all physically possible levels). If the washes are used in flood, the floodwater is evacuated from the washes through Locks Mill sluice at Spalding once the river levels have receded.

In this study, it was assumed that the model is almost well-calibrated, then under scenarios different than what historically happened and what ideally happens, when the flood control gates have different positions operationally, it can be a good tool to simulate decisions by the model, and also the postulation of the river system's response in different scenarios will be possible. A numerical and graphical comparison has been made on the flood peak value and time computed by the model at the forecast points under consideration where historical recorded timeseries are available. The following two criteria were employed to analyse the results of the model runs under various scenarios of flood control gates' positions:

- Percent difference between values of observed and simulated peaks (ΔP).
- Difference between times of observed and simulated Peaks (ΔPT, in hour).

Tab. 3 represents the brief results of comparison of water levels at the forecast points under consideration the based on current flood control gates' position changes to three positions of fully closed, half open, and fully open. As shown in the table, there are no significant differences among simulated water levels in three states of gates at Ashley GS forecast point. What this table shows is that at Kates Bridge GS forecast point keeping the gates fully closed will result in maximal ΔP and minimal ΔPT of water level (about 45% and -3.375 hours, respectively) , while fully opening the gates will result in minimal ΔP and maximal ΔPT of water level (about 2% and 0.531 hours, respectively). By contrast, at Tallington GS forecast point keeping the gates fully closed will result in minimal ΔP of water level (about -0.5%) and also ΔPT of water level is equal to 0.125 hours, while fully opening the gates will result in maximal ΔP and minimal ΔPT of water level (about 16% and -0.063 hours, respectively).

Table 3: Comparison of simulated water levels at the forecast points based on gates' positions.

Forecast Point Name	Fully Closed		Half Open		Fully Open	
	$\Delta P(\%)$	$\Delta PT(\text{hr})$	$\Delta P(\%)$	$\Delta PT(\text{hr})$	$\Delta P(\%)$	$\Delta PT(\text{hr})$
Ashley GS	-0.339	-0.167	-0.339	-0.167	-0.333	-0.177
Kates Bridge GS	45.399	-3.375	7.733	-0.031	2.232	0.531
Market Harborough GS	0.387	0.044	0.387	0.042	0.387	0.042
Tallington GS	-0.491	0.125	4.153	0.438	15.668	-0.063

Also Tab. 4 represents the brief results of comparison of discharges at the forecast points under consideration based on the various scenarios of the flood control gates' position. What this table represents is that at Kates Bridge GS forecast point keeping the gates fully closed will result in maximal ΔP and minimal ΔPT of discharge (about 898% and -3.875 hours, respectively), while fully opening the gates will result in minimal ΔP and maximal ΔPT of discharge (about 11% and -0.073 hours, respectively). By contrast, at Tallington GS forecast point keeping the gates fully closed will result in minimal ΔP of discharge (about -7%) and also ΔPT of discharge is equal to 0.177 hours, while fully opening the gates will result in maximal ΔP and minimal ΔPT of discharge (about 166% and 0.01 hours, respectively).

Table 4: Comparison of simulated discharges at the forecast points based on gates' positions.

Forecast Point Name	Fully Closed		Half Open		Fully Open	
	$\Delta P(\%)$	$\Delta PT(\text{hr})$	$\Delta P(\%)$	$\Delta PT(\text{hr})$	$\Delta P(\%)$	$\Delta PT(\text{hr})$
Ashley GS	10.254	-0.167	10.254	-0.167	10.506	-0.177
Kates Bridge GS	898.029	-3.875	182.540	-0.813	11.120	-0.073
Market Harborough GS	-32.677	-0.052	-32.677	-0.052	-32.677	-0.052
Tallington GS	-6.935	0.177	65.434	0.490	165.862	0.010

Fig. 3 shows graphically variation of statistical indicators employed in this study; ΔP and ΔPT of water levels and discharges at Tallington GS forecast point.

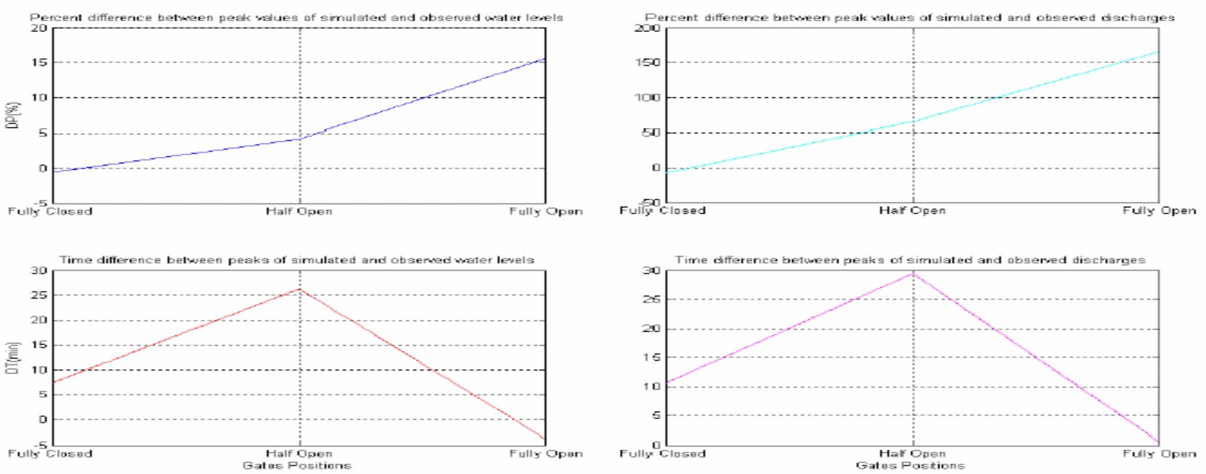

Figure 3: Comparison of statistical criteria for simulated and observed water levels and discharges at Tallington GS forecast point.

The Welland and Glen model has been developed specifically to forecast flow and level at the locations marked as shown in Tab. 5. The Environment Agency has three colour codes (yellow, amber and red), to the flood warning severity categories of Flood watch, Flood warning and Severe flood warning, respectively.

Table 5: Threshold levels of forecast points currently in use by the Environment Agency.

forecast point	Flow(cumecs)			Stage(m AOD)		
	Flood Watch	Flood Warning	Severe Flood	Flood Watch	Flood Warning	Severe Flood
Ashley GS	NA	NA	NA	58.07	58.15	NA
Kates Bridge GS	11.5	15	27.6	6.37	6.52	6.98
Market Harborough GS	11.7	NA	NA	76.35	76.75	77.3
Tallington GS	43	80	95	14.16	14.55	14.72

A graphical comparison represents among simulated water level and discharges hydrographs against observed water level and discharges hydrographs based on the Environment Agency thresholds (water level and discharge) at Tallington GS forecast point as shown in Fig. 4 and Fig. 5. According to Fig. 4, there is no peak over threshold for water level hydrographs simulated in all states of gates at Tallington GS forecast, but it can be seen in Fig. 5 that there are two peaks over severe flood thresholds for discharge hydrographs simulated in two states of fully open and half open gates at this forecast point.

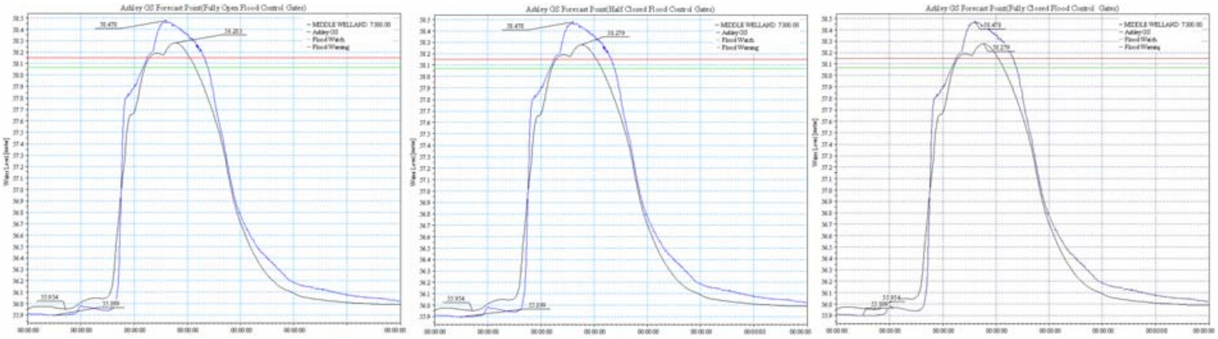

Figure 4: Comparison of hydrographs of simulated and observed water levels at Tallington GS forecast point under what-if analysis of gates.

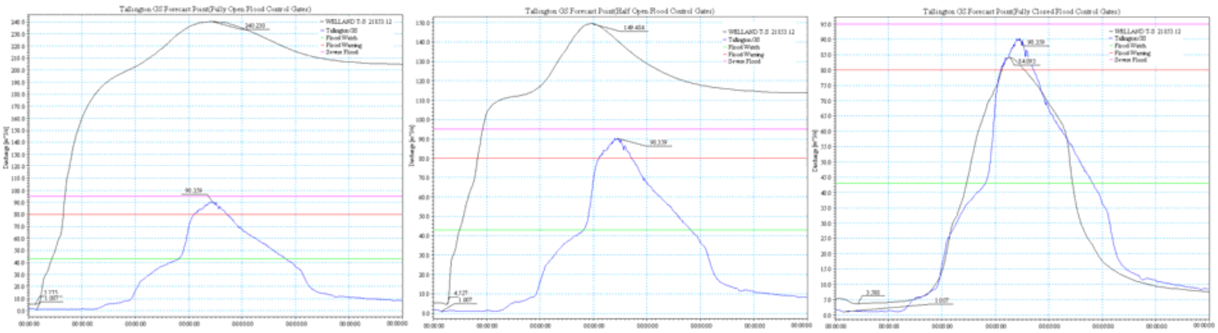

Figure 5: Comparison of hydrographs of simulated and observed discharges at Tallington GS forecast point under what-if analysis of gates.

Discussion

In the present study, flood structural management is investigated by taking account of flood control gate positions under three scenarios of fully open, fully closed, and half-open flood control gates. The scenario analyses demonstrate that - at the scale of the entire Welland and Glen catchment - the influence of gates' positions changes on extreme floods is very useful for understanding behavior of river system and interaction of control structures and catchment response. Even though, influence of land use changes needs to be studied that may be much stronger than influence of gates' positions.

Conclusions

Results show simulated scenarios for flood management, each representing a different view of the future of the gates and slackers, together with the corresponding flood management strategy. Using a hydrodynamic modeling tool like MIKE 11 HD, the simulations of each scenario for the flood management were evaluated. Finally, a comparison of different flood management strategies under different possible futures was made, showing the risk, cost and benefits of different strategies. Flood management under scenarios of 'control gates position' was performed to characterise possible future situations as a key challenge in decision making process. The scenarios were developed to assist in the understanding of possible future situations of the complex river system as a part of knowledge acquisition process. In addition, the developed scenarios are of importance for either extracting operational actions that can be incorporated into the knowledge base of a decision support system in order to support decision maker (s) when flooding as one of flood management measures.

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