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REAL-TIME CONTROL OF FLOODS ALONG THE DEMER RIVER, BELGIUM, BY MEANS OF MPC IN COMBINATION WITH GA AND A FAST CONCEPTUAL RIVER MODEL

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ABSTRACT

Today, retention reservoirs along the Demer River in Belgium are controlled by means of adjustable gated weirs based on fixed rules. To improve the regulation of these weirs, this paper investigates a method for real-time flood control. Because of the excessive calculation time of detailed hydrodynamic models, a conceptual model was used. This model combines the Model Predictive Control (MPC) technique with a Genetic Algorithm (GA). For several scenarios, MPC controls the future state of the river network by changing the positions of the adjustable weirs. The GA generates these positions. Damage functions depending on water levels, were introduced to evaluate the efficiency of each scenario, based on flood damage minimization. The influence of the most important parameters of the MPC-GA-algorithm is investigated by means of a sensitivity analysis. Simulation results show that the algorithm manages to reduce the total flood volume during the historical event of September 1998 by 46% in comparison with the current regulation based on fixed rules.

Introduction

All over the world periods of extreme rainfall cause flooding with huge environmental, economic and human damage. Floods and storms are the natural disasters with the highest economic damage. The Intergovernmental Panel on Climate Change [1,2] has shown that the frequency of extreme rainfall events has increased during the last decades. This trend will continue in the 21st century and will lead to an increase in the amount of floods. Another trend is the rising urbanization which causes faster surface runoff and thus higher peak discharges in rivers [3].

Temporary storing water in retention reservoirs is one of the measures to limit floods. These reservoirs can be filled during periods of high rainfall to store large amounts of water. Adjustable weirs regulate the inflow and outflow of water in the reservoirs. The difficulty is to determine when and how fast the reservoirs should fill. Different techniques to control river systems have been developed. An overview can be found in Malaterre *et al.* [4]. Model Predictive Control (MPC) is a promising technique whereby a model of the river system is used to simulate potential future states based on scenarios. This technique has been applied by Rutz *et al.* [5] for set-point control in a river reach and by Negenborn *et al.* [6] to control irrigation canals. Barjas-Blanco *et al.* [7] has listed the advantages of MPC and stated that it can be used for flood control as well. Other techniques such as PI controllers and heuristic controllers [4,8,9] are not applicable for this purpose, because they cannot cope with non-linear response behavior of river systems, which typically occurs during flood periods. This research combines the MPC technique with a genetic algorithm (GA) and investigates its efficiency for flood control.

The paper is structured as follows. The next section will explain in more details the MPC technique and the genetic algorithm. Thereafter the efficiency of the MPC-GA-technique will be discussed by means of the case study of the Demer River in Belgium. The last section formulates some conclusions and future work.

MPC-GA technique

Principle of MPC

Model Predictive Control (MPC) is a technique whereby control variables in a system are determined after optimization over a prediction horizon in such a way that given simulated state variables evolve towards a desired reference value. To calculate these state variables, a model of the system is used. Due to uncertainties (rainfall predictions, model uncertainty, …) the real state variables may differ from the model based ones. Therefore in real time control the state of the model will be updated after each optimization step by making use of observations available for state variables at some locations along the system. Through this feedback the algorithm can adjust the control during the next optimization step and take the observed present situation into account. This process is repeated in every optimization step and determines the optimal input for the next optimization step.

For flood control of river systems, the simulated state variables (model outputs) are the river water levels at flood-prone locations. They are limited to a maximum value being the flood level. The control variables are the positions of the adjustable weirs.

Principle of MPC-GA

The MPC-GA algorithm is based on the research by Chiang [10]. In that algorithm, a series of gate levels is generated for each adjustable weir. Secondly, these series of gate levels are applied to a river model, together with catchment rainfall-runoff simulation results of incoming discharges as a result of forecasted rainfall. The model now calculates the water levels at the desired locations over the prediction horizon. By means of a damage model, which will be discussed later on, the total flood damage corresponding to these water levels is calculated. This process (generating series of gate levels, applying them to a river model and calculating the total damage) is repeated several times during one optimization step. The total damage of each such case is compared and the series providing the lowest amount of damage is selected. The gate levels corresponding to this optimal case are passed on to the river system, where they will be applied during the next optimization step. This process is repeated for each control time step.

The quality of the results will improve when a wider range of gate levels are considered during the optimization process. However, the available time to calculate these cases is limited in real time control. Simulations with detailed hydrodynamic models, solving the Saint-Venant equations explicitly, are too slow for this purpose. Therefore this research makes use of much faster conceptual models that simplify the dynamics of the river system. This approach is investigated by Barjas-Blanco *et al.* [7], Wolfs [11] and Meert [12].

Despite the use of conceptual models, only a finite number of cases can be considered during one optimization step, due to limited computational capacity. Therefore it is important to consider sufficient variation in the tested series of gate levels. To achieve this goal the series are generated in a semi-random way, making use of a genetic algorithm (GA), as discussed in the next section. To guarantee that in every optimization step at least a small amount of good solutions are found, the default procedure in GA is to reuse the best cases from the previous time step. The series of gate levels are therefore shifted over one time step. For the last time step in the prediction horizon, the previous gate levels are kept constant.

Genetic algorithm: generating series of gate levels

As stated before, the series of gate levels are generated in a semi-random way based on a GA. Each series starts with the current gate position. The next gate position is the sum of the previous position and a semi-randomly generated change, whereby the maximum movement rate of the gate is taken into account as well as the upper and lower limit of the gate position. This process is repeated over the full prediction horizon.

For the determination of the gate change of the GA, a gen consisting of three numbers is randomly generated. The first number determines the direction of the gate movement (up or down), the second one if there is a movement or not and the last one determines a random number between zero and 63. The gate level change is then defined as the product of the ratio of this number and 63 and the maximum movement step. That parameter depends on the maximum movement rate of the gate and the time between two gate movements.

During each optimization step a new gate level position is determined for the next time step. Thus the time between two gate movements is equal to the time between two optimization steps. Given that the optimization step is similar to the time by which the algorithm receives the river level observations (15 minutes in our case study), new gate levels will show strong temporal fluctuations. This is not desirable. It is operationally to have slight changes in the series of gate positions. Therefore the time step by which semi-random gate levels are generated is set to six hours. In this way the series show a smooth trend over the prediction horizon and the gate position does not show strong temporal fluctuations, hence does not cause unstable behavior.

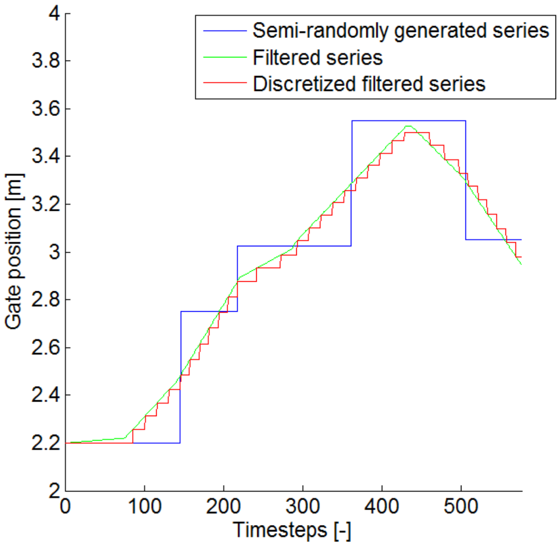

Figure 1. Example of a semi-randomly generated series of gate positions

Figure 1 shows an example for the series of gate positions generated with a time step of six hours over a prediction horizon of two days. It is however desired to have a smoother temporal variation of the gate positions. Therefore a Savitzky-Golay filter [13] is applied to smoothen the gate levels. The result of that filter is also shown in Figure 1. Finally, the series needs to be discretized, according to the optimization step. Thereby the gate level will only change if the change is higher than five centimeters, to overcome several small movements of the gate. Also that result is shown in Figure 1.

Objective functions

To assess the river flood damage, considered as objective function for the optimization, damage functions across the river network are required. These will couple the simulated water levels to the damage that would occur during floods. When the river level is below the flood level, the flood damage is zero but the objective function is set such that it keeps the water level at a certain reference level when there is no risk of flooding, to empty and fill the retention reservoirs and to follow the control priorities.

More specifically, the objective function makes use of three reference levels: the flood level (FL) at which flooding will occur, the Reference Level (RL), which is the desired water level when there is no flooding, and the Warning Level (WaL). This last one indicates that the water level is high and that flooding may occur in the near future when the water level would further rise. Of course, the damage will be dependent of the location. This distinction is made by adding weighting factors Q for the different zones of the objective function, bordered by the reference levels, see Table 1. To make sure the retention reservoirs will not overtop during floods, which may cause the dikes to collapse, a penalty cost (PC) is added for these locations. To incorporate the difference in importance of floods at different locations in the network, each of the locations has its own set of weighting factors.

Table 1. Configuration of objective functions

Zone	Objective function
WL > FL	2 [Q_RL + Q_WaL] + [WL - FL] Q_FL (+ PC)
FL > WL > WaL	Q_WaL [WL - WaL] / [FL - WaL] + Q_RP
WaL > WL > RL	Q_RL [WL - RL] / [WaL - RL]
WL < RL	0.8 Q_RL [RL - WL]

Case study: The Demer basin (Belgium)

To investigate whether the developed MPC-GA technique succeeds to reduce floods and evaluate its efficiency, it was implemented for a case study. The study area is one of the eleven river basins in the Flanders region of Belgium: the Demer basin. It was selected because it is flood-prone and several regulation structures and flood control reservoirs were installed during recent years as part of the flood management strategy. The results using the MPC-GA technique are compared to the results obtained with the current control strategy. During this case study rainfall forecasts were assumed to be perfect; hence historical rainfall series were considered instead of forecasts.

Demer basin

In the Demer basin, adjustable weirs and two large retention reservoirs (Schulensmeer and Webbekom) were installed by the Flemish Environment Agency (VMM) to reduce the risk of flooding in the region. These structures assisted in reducing the number and total damage cost of recent floods, but extreme rainfall on September 1998, January 2002, November 2010, …

still resulted in major floods. The control of the weirs is to date based on fixed regulation rules based on up- and downstream water levels, set by the VMM. Because of the complexity of the system, it is expected that the current flood regulation based on these expert-based fixed rules is suboptimal. Improvements are necessary: a more advanced way to control the gate levels should be developed.

Conceptual model

A full hydrodynamic model of the Demer basin, implemented in the InfoWorks^{TM}-RS software, was available for the river network in the Demer basin. The model is currently applied on the basis of the operational flood forecast system of the VMM (www.waterinfo.be). Meert [12] has identified and calibrated to the detailed model a simpler and much faster conceptual model in Simulink®. In the Simulink® model the floodplains are not explicitly modeled. Both models, however, implemented the two flood control reservoirs Schulensmeer and Webbekom, and their subregions. In this research, the conceptual model is integrated with the MPC-GA technique in Simulink®.

Current control strategy

Nowadays, the reservoirs are controlled by fixed logical rules based on experience. These are based on if-then-else conditions that depends on the current state of the system. This means that they do not anticipate on forecasted rainfall. A second problem lies in the fact that they only take the up- and downstream water levels or discharge over the adjustable weir into account. So the control strategy is only local and the influence of the regulation of the other structures is not taken into account. To tackle the problem in a more intelligent way, the flood damage over the whole study area and over the whole prediction horizon is minimized, taking the future rainfall conditions into account, by means of the MPC-GA technique.

Damage functions

Damage functions were defined for the twenty most flood-prone locations in the study area, and reference levels set for these locations. The weighting factors for the different locations were determined based on the building density, the damage in the past and the control priorities.

Sensitivity study of the algorithm parameters

The influence of the most important parameters of the MPC-GA algorithm was investigated. These parameters are: the number of simulated cases during each optimization step, the time step between two gate movements, the number of selected best cases for the next optimization and the prediction horizon. For this sensitivity study different simulations were carried out for the most severe recent historical flood event of September 1998. This was done based on local sensitivity analysis, where one of the parameters was changed at the time while the others were kept constant.

The efficiency of the MPC-GA results were found highly dependent on the number of simulated cases during each optimization step. When only a small number of cases is used (less than 200), the efficiency is quite uncertain. This result can be expected because the series of gate levels are generated in a semi-random way and the algorithm thus finds good series of gate levels ‘by coincidence’. The more cases are simulated during each optimization step, the higher the chance of finding a good case. This is clearly visible in Figure 3 were the range of the total damage cost decreases with increasing number of cases. Also the mean damage cost decreases with increasing number of cases. Hereby, it can be noticed that the total damage cost of the worst simulation in Figure 3 is even better than the result obtained with the current fixed regulation (10.6×10^5). This indicates that the MPC-GA technique succeeds in reducing the flood risk.

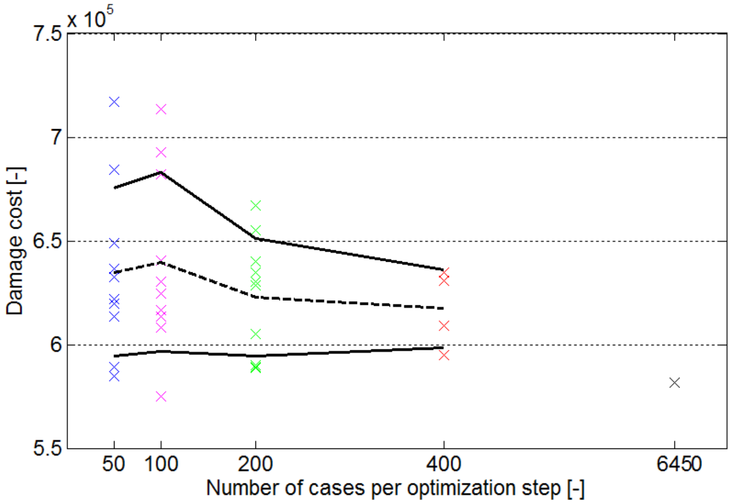

Figure 3. Total damage cost in function of the number of cases per optimization step

For the number of best cases that should be taken into account during each optimization step, it was found that keeping the four best cases is sufficient to guarantee good results. The prediction horizon should be at least 48 hours, because otherwise the algorithm cannot sufficiently anticipate on the future rainfall conditions. For larger prediction horizon, the uncertainty in the rainfall forecast would become very large; hence the use of a longer horizon is questioned. This is however not investigated in this research. Finally, the range of the total damage and the mean damage decreases when the optimization step decreases.

Evaluation of the efficiency

To check the efficiency of the MPC-GA algorithm the obtained results are compared with the results obtained for the current fixed regulation. Table 2 shows a comparison between these two regulation strategies for the twenty selected locations in the network for the historical storm of September 1998.

This table shows that the highest exceedance of the flood level is lower when MPC-GA is applied at all locations. Also the duration of the flood is always shorter with the MPC-GA control strategy. This can also be seen in Figure 4 where the exceedance of the flood level over time is shown for two locations. Another indicator for the good results obtained by the MPC-GA algorithm is the total flood volume, which is reduced by 46% for the flood event of September 1998. For other events similar gains are achieved.

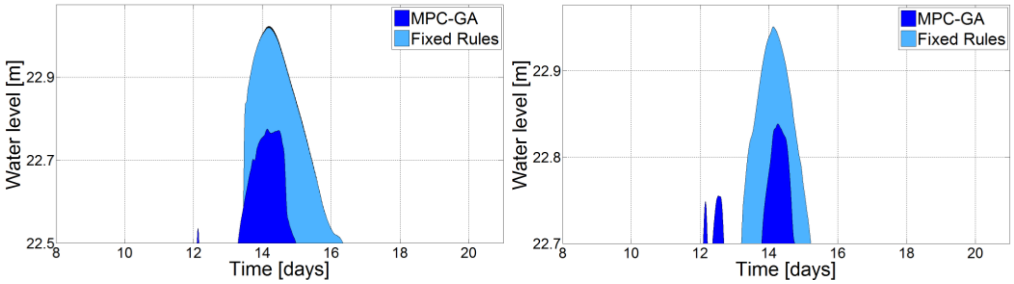

Figure 4. Comparison of the exceedance of the flood level over time for both control strategies at two locations for September 1998

Table 2. Comparison of the results obtained by MPC-GA with these by the current fixed regulation strategy for September 1998

Locations	Highest exceedance of flood level [m]		Duration of flood [h]	
	Fixed rules	MPC-GA	Fixed rules	MPC-GA
DemOpw	-	-	-	-
Velpe	-	-	-	-
BegOpw	-	-	-	-
HerkOpw	-	-	-	-
Resch1	0.03	-	10.50	-
Resch2	0.03	-	10.33	-
Resch3	-	-	-	-
Resch4	-	-	-	-
ReWeb1	-	-	-	-
K7afw	-	-	-	-
MondGete	0.25	0.14	48.50	33.92
MondVl	0.07	-	19.83	-
K31Opw	-	-	-	-
ZwaOpw	0.51	0.48	89.25	88.83
Vlootgr	0.60	0.28	69.58	41.75
K31Afw	-	-	-	-
Begijnenb	0.05	-	15.67	-
Leugeb	-	-	-	-
Leigracht	0.13	-	34.92	-
DemAfw	0.33	0.29	74.58	74.58

Conclusions and future works

This research has shown that the developed and implemented MPC-GA technique may be efficient for use in flood control. This conclusion is based on the case study of the Demer basin in Belgium, assuming perfect rainfall forecasts for a time horizon of 48 hours. The results show that not only the flood volume, but also the duration of floods and the peak river water level exceeding the flood level can be reduced by the intelligent control algorithm.

The main advantage of MPC-GA in comparison with other control strategies is that the technique is able to deal with complex, non-linear, interactions between the different hydraulic structures and river segments. By making use of a river model and rainfall forecasts, the algorithm can anticipate on future rainfall events, taking the mutual influence of the different gate movements into account. Due to the fact that during each optimization step different cases can be simulated independently, parallel computing is applicable. Thanks to that, far more cases may be calculated during each control step.

One critique one can have on the MPC-GA-algorithm is that it is quite “naïve” because it is not really goal-oriented. However, the case study has already shown that major improvements can be achieved by just a limited number of cases. In future work, the efficiency of the algorithm will be investigated and improved in a way that larger basins with more adjustable weirs can be handled as well. Also for statistical analysis and longtime simulations this could provide large benefits. Another topic for future work is consideration of the uncertainty in rainfall forecasts, which can have an important influence on the real-time control results and efficiency.

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