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Flood control in an urban drainage system using a linear controller

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Abstract

Effective management of floods in densely populated urban areas poses a great challenge. Computer modeling plays an important role in appropriate management of urban drainage systems. In this study an effort has been made to develop an efficient urban drainage model in which hydraulic results obtained from the developed SWMM model have been linked with a Proportional Integral Derivative (PID) controller for controlling floods. The resulting model can optimize flood levels substantially in urban water bodies and hence can be used as an effective tool to mitigate urban flooding.

Key words: flood, linear controller, PID, SWMM, urban drainage

INTRODUCTION

Flooding can occur for various reasons in urban areas, including river overflow (fluvial), flash flooding arising from short duration heavy rainfall, and coastal floods. Flash floods arise mainly in urban areas because of the relatively extensive impervious surfaces, and are very variable in time and space. High rates of infrastructure development and corresponding declines in infiltration have resulted in increased runoff (El Alfy 2016), often exceeding the capacity of existing storm-water drains and causing flooding. Implementation of the various traditional structural flood control measures, e.g., source or collection system controls, etc. is difficult because of the lack of space in densely populated urban areas. Therefore, a practical and financially viable option would be to use the existing drainage network, introducing control structures like gates at suitable locations. These gates need to be controlled and operated in a planned manner, but the control process can depend only on the response characteristics of the drainage system under different flow scenarios, including extreme rainfall events. Thus, it is crucial to consider all variables to enable efficient and effective control.

Since the mid-1960s there have been studies on the implementation of optimal control algorithms on complex canal systems (Levin 1969; Liu *et al.* 1995; Schuurmans *et al.* 1999; Clemmens & Wahlin 2004; Litrico & Fromion 2004), and algorithms have been developed for determining gate scheduling based on linear, non-linear or dynamic programming.

The application of automatic control techniques to urban drainage systems is one means of managing the problem of urban-floods. It is difficult, however, to choose any relatively accurate automatic control technique because of the complexities of the hydraulic systems, e.g., non-linearity, stochastic rainfall patterns, etc.

Papageorgiou & Messmer (1985) suggested some easily applicable design rules for a fairly broad class of water flow and water level problems on the basis of linear control theory. In a subsequent study (1989), they designed a proportional integral (PI) regulator on the basis of a dynamic model of a long river for the control problem of a natural stream. Gutman (1986) demonstrated the utility of linear programming techniques for the control of regulators, while Begovich & Ortega (1989) studied the feasibility of adaptive control of the head of an open hydraulic channel with an upstream control configuration. This study also involves examination of the feasibility of linear Proportional Integral Derivative (PID) controllers for meeting water level targets quickly and efficiently in an urban water body.

From past experience in developing countries, existing drainage systems cannot accommodate the excess runoff generated during heavy storms, because of rapid urbanization. Computer modeling is needed to identify the critical flooding locations. The aim of this study is to develop a methodology that will minimize flooding by linking the SWMM program, used for the hydraulic results, with a PID Controller for efficient operation of an urban drainage system.

STUDY AREA

Delhi is in northern India between latitudes 28°24′17″ and 28°53′00″ North, and longitudes 76° 50′24″ and 77°20′37″ East. It has an average elevation of 233 m (range 213 to 305 m) above the mean sea level. The study area is a small catchment in the Najafargarh basin, which lies below the Aravalli Hills in the western part of Delhi (see Figure 1).

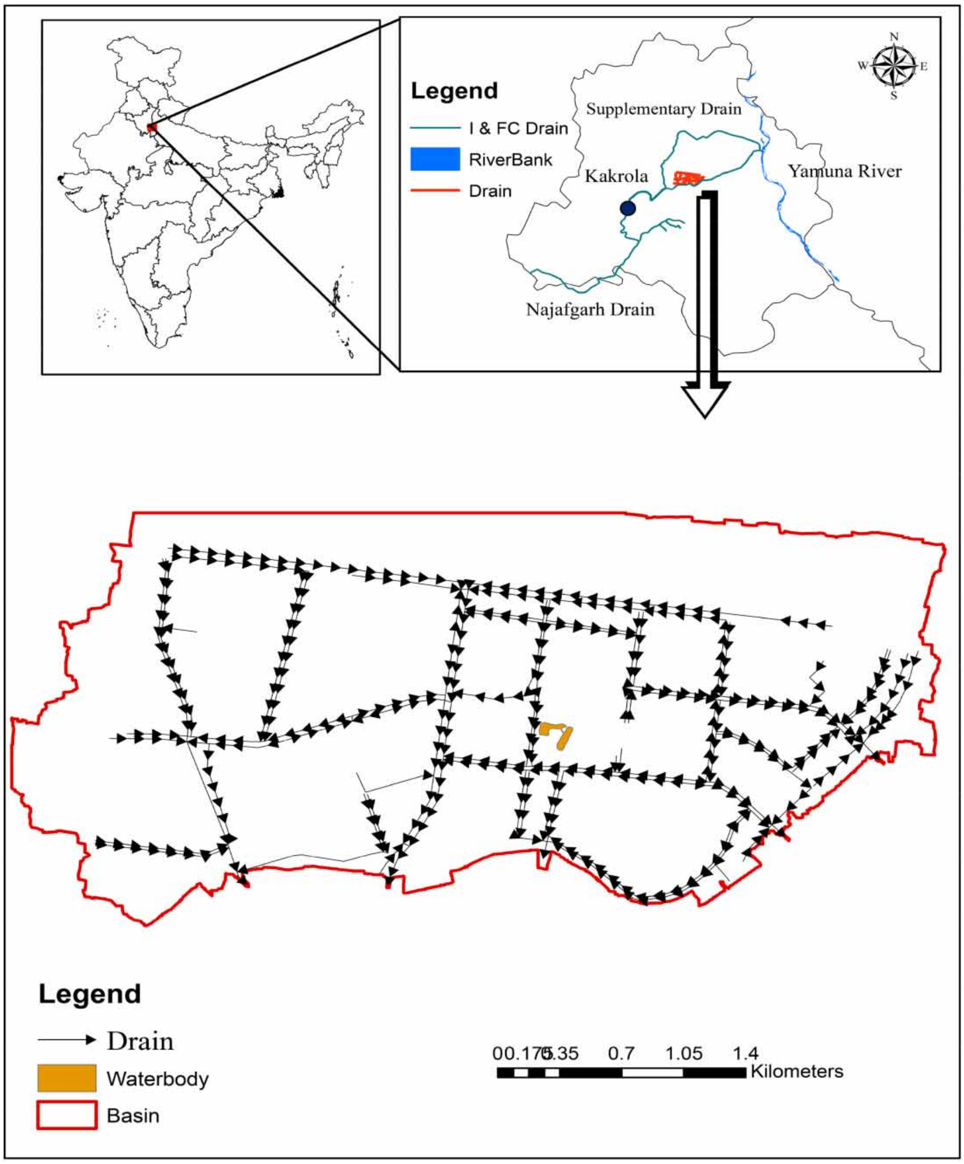

Figure 1 | Study area.

METHODOLOGY

Control system

Control systems have become an important and integral part of modern manufacturing and industrial processes. The first step in their design consists of establishing the system goals e.g., perhaps accurate control of the flow or level in an open channel. The second is to identify the variables to be controlled (for example, orifice setting and water body level), and the third to write the specifications in terms of the accuracy required. The latter will then lead to identification of a sensor to measure the controlled variable. Here, the concept of trade-off comes into the picture, involving the need to determine the level of compromise acceptable between criteria, which are both desirable but are also in conflict. The design process requires an efficient compromise in circumstances such as overshoots, settling time or error convergence. After that a controller can be selected. Proportional Integral Derivative (PID) controllers play an important role in flow and level control in process industries (Wong & Rad 1994; Campisano & Modica 2002). Although there are many studies reporting on the application of controls in irrigation canals (Balogun *et al.* 1988; Sawadogo *et al.* 1995), few report on its application to urban drainage networks.

PID controllers have been the most common form in process industries since the 1960s, even though significant development has been made in advanced control theory (Dong & Brosilow 1997). PID controller calculation (algorithm) involves three separate parameters, the proportional, integral and derivative values, hence their name. The proportional value determines the reaction to the current error, the integral value determines it based on the sum of recent errors and the derivative determines it against the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element such as the orifice settings.

In civil engineering, control theory has been applied to a variety of problems including gate operation in irrigation canals (Reddy 1991). Eker *et al.* (2003) designed a level controller using the $H\propto$ optimization method that regulates water flow and heads for a sequential pumping system involving many reservoirs.

Control system concepts

Continuous control systems typically need a target value, called a *set point*, for example water levels and flow in drainage systems, and should be designed with an objective in mind. Requirements may be very diverse, e.g., small tracking errors, good disturbance attenuation, reasonably small control effort, low sensitivity to measurement noise, and robustness to modeling errors, small overshoot and fast settling time, and yet all must be squeezed into a small number of design specifications that can be handled by available design methods.

Control systems configurations

There are two control system structures, closed and open loops. Closed loop control systems (see Figure 2) have a feedback mechanism, in which the output from the control system is taken as

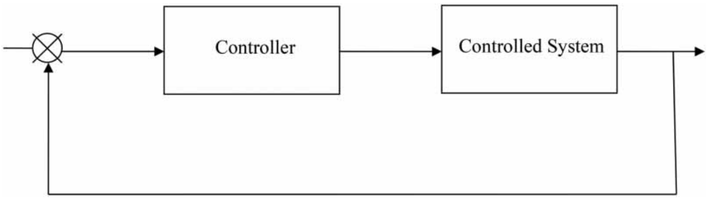

Figure 2 | General architecture of a closed loop control system.

Figure 3 | General architecture of an open loop control system.

input to controller, which uses it to generate control commands for the next cycle. As shown in Figure 3, open loop control systems have no feedback from the system's output but generate output commands as a function only of input. Open loop controllers are most commonly used to control servo-motors (Ogata 2002). In the water sector, open loop systems have been used to control irrigation canals (Bautista & Clemmens 1998; Begovich *et al.* 2002), but most of the sector's control applications involve closed loop systems (Reddy 1991).

Controller parameter selection criteria

The controller parameters proportional gain, integral gain and derivative gain are derived on the basis of three criteria:

1) **Steady-state error:** the difference between the input and output of a system in the limit as time goes to infinity (i.e. when the response has reached the steady state).
2) **Overshoot:** the percentage by which the final output value is exceeded at first oscillation.
3) **Settling time:** the time in which the output settles to within 1% of its final value.

These three parameters are explained in Figure 4 (Ogata 2002).

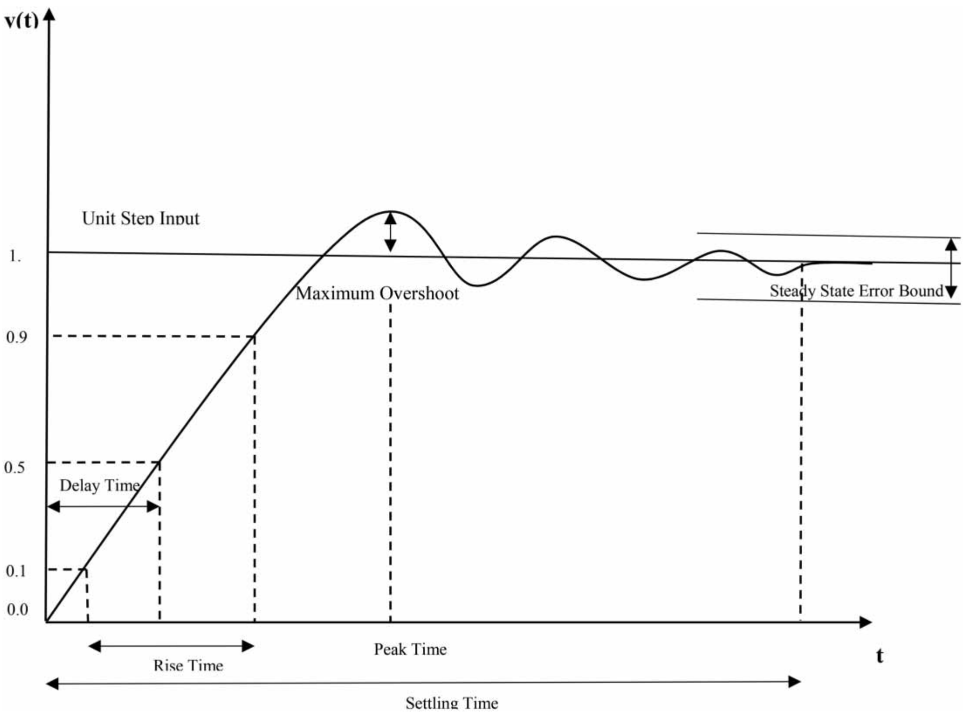

Figure 4 | Performance Criteria.

PID controller

The PID controller is a generic control loop feedback mechanism. Such a unit attempts to correct the difference in value between a measured process variable and a desired set point, by calculating and issuing a corrective action to adjust the process. The PID algorithm involves the proportional, integral and derivative actions.

Proportional action

The control signal is proportional to the instantaneous value of the error, and the proportional action controller is simply a constant gain multiplied by the error (e). Proportional action output is expressed as;

$$u = K_p e \tag{1}$$

The error e is the difference between the actual (or simulated) and target values. The proportional part of the control law multiplies the error at each time by a fixed value of K_p to determine the modified output.

Integral action

The controller's output is proportional to the accumulated error – the error is accumulated from the time of initialization, and the integral increases or decreases the output when there is an error that lingers for some time. Integral action output is expressed as;

$$u = K_i \int_0^t e\,dt \tag{2}$$

Derivative action

Control is proportional to the rate of change of the error. This increases the control system's speed of response, since the derivative action is anticipatory or predictive. Derivative action is given by;

$$u = K_d \frac{de}{dt} \tag{3}$$

Combining the three control actions gives Equation (4):

$$u = K_p e + K_i \int_0^t e\,dt + K_d \frac{de}{dt} \tag{4}$$

where the terms on the right hand side are the expressions for proportional, integral and derivative actions, respectively. The constants K_p, K_i and K_d are the gains (parameters) of the PID controller. The controller treats the error signal with three different multiplication constants or gains, thus justifying its name.

Effects of proportional, integral and derivative actions

a. The Proportional gain, K_p, is multiplied by the error signal and the result sent to the output. The proportional gain dictates the band over which the controller's output is proportional to the error signal and is responsible for making the controller react to the current value of the error signal.

b. The Integral gain, K_i, is multiplied by the integral of the error signal over a (usually short) period of time, and added to the Proportional output. K_i denotes the steady state error of the system, and is intended to remove errors that have persisted in the system for some time.

c. The Derivative gain, K_d, is used to adjust the controller's response to changes in the system. The rate of change of the error signal (i.e. its first derivative) is multiplied by K_d and added to the sum of the two outputs above. The larger the derivative gain, the faster the controller responds to changes in the system.

RESULTS AND DISCUSSION

Development of SWMM model for virgin flow conditions

The SWMM model was developed for the urban drainage system shown in Figure 5, starting with virgin flow conditions. The results show flooding at few nodes (Figure 5).

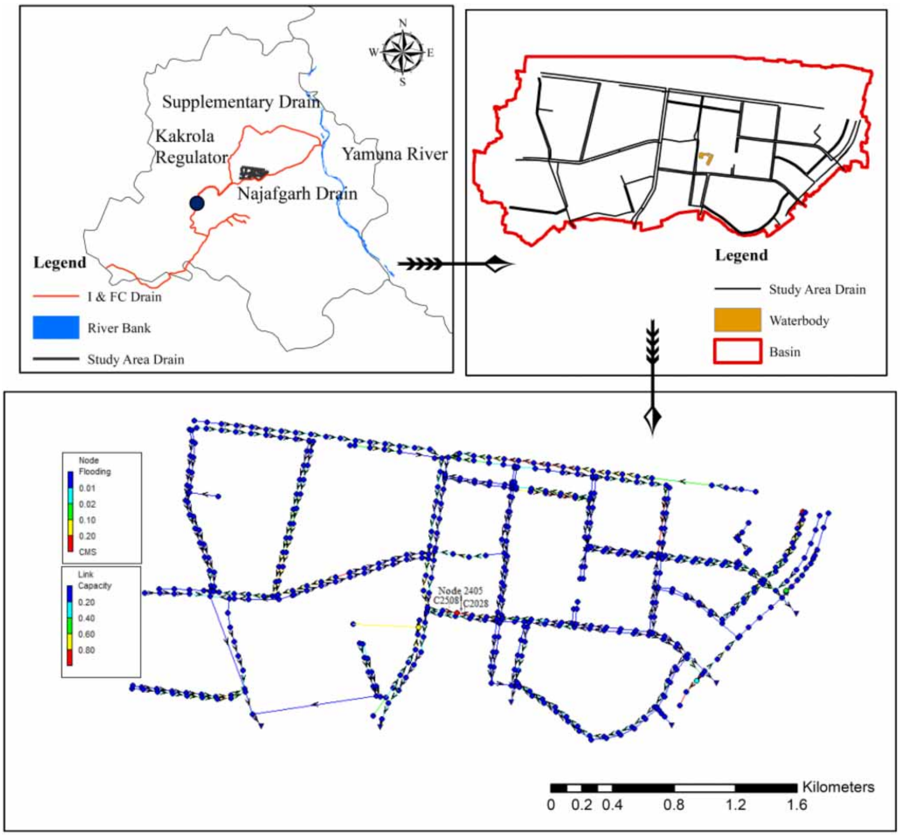

Figure 5 | SWMM Model virgin flow results.

Analysis reveals that node 2405 becomes flooded. Upstream, however, the conduit at 2028 is flowing normally, while the downstream conduit, i.e. 2508, is at full capacity. Due to the full capacity flow in the latter, the runoff flowing from upstream conduit 2028 cannot move on and hence causes flooding at node 2405 (see Figure 6).

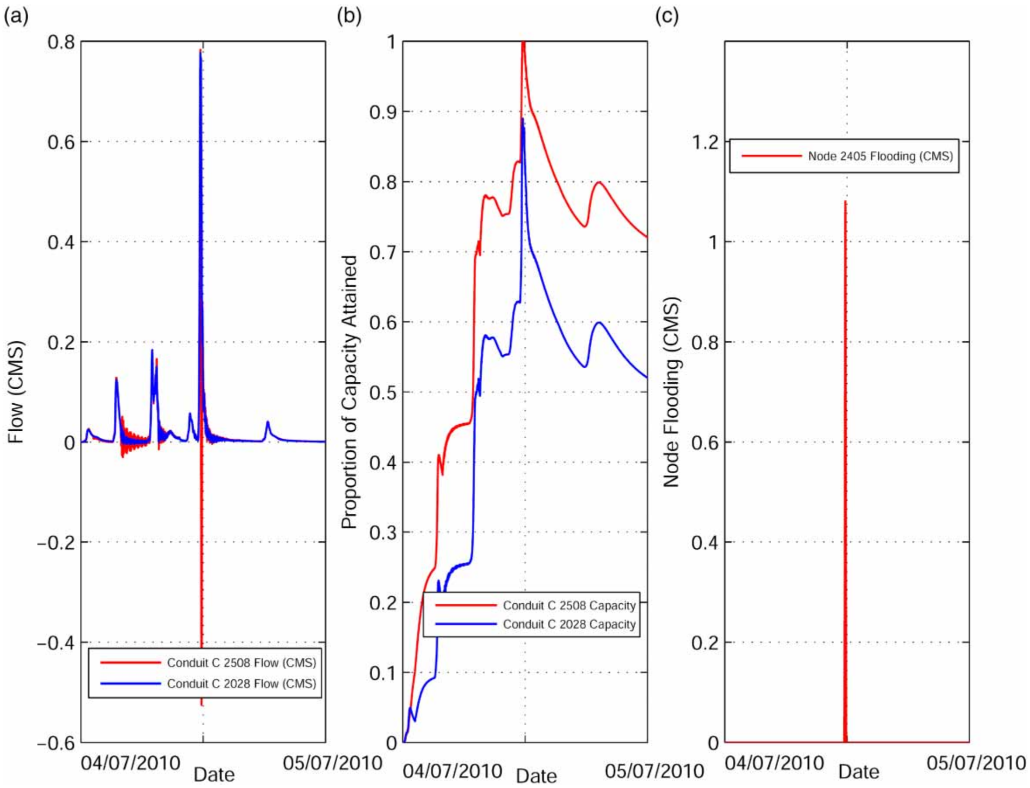

Figure 6 | SWMM simulation results (a) Conduit flows, (b) Conduit capacity and (c) Node flooding.

Flooding can be minimized in different ways, including interlinking the drains with nearby water-bodies like lakes, ponds, etc., which can play a major role. In this study, to minimize the flooding, a water-body was identified upstream of node 2405 and the drainage network was linked to it, while information on it, e.g., its depth-area curve, was put into the SWMM Model.

Depth-area curve of water-body

The water-body's depth v/s cumulative area relationship was defined as shown in Figure 7. The body's maximum area comes from the Digital Elevation Model (DEM) cells, which have an elevation of about 212 m.

The depth-area curve information was fed into the SWMM model to develop a modified version, which was then used with all parameter values the same. The results are shown in Figure 8 flooding is minimized at node 2405 when the water-body is linked into the drains.

Figure 9(a) shows the flow profile in conduit C6, connected to the water-body. Initially, flow is from the conduit to the water-body until the peak is achieved. Then, as the level falls, the flow moves back towards the drain (see Figure 9(a)). Figure 9(b) shows the water head profile variations in the water-body.

Head control in the water-body using PID controller

It is possible that the water-body may not be able to accommodate the flow coming from the drain, thereby flooding the nearby areas, e.g., during heavy storms. To avoid this, an automatic control system is required and so, in the study, a PID control technique was adopted for head control in the water-body using an orifice.

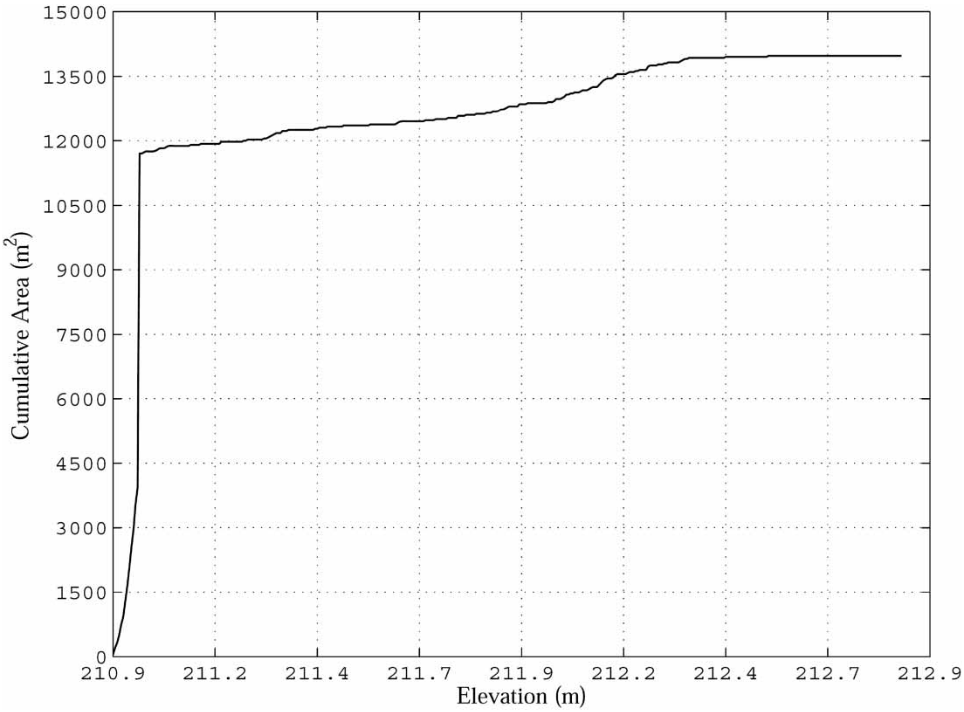

Figure 7 | Water-Body Depth-Area Curve.

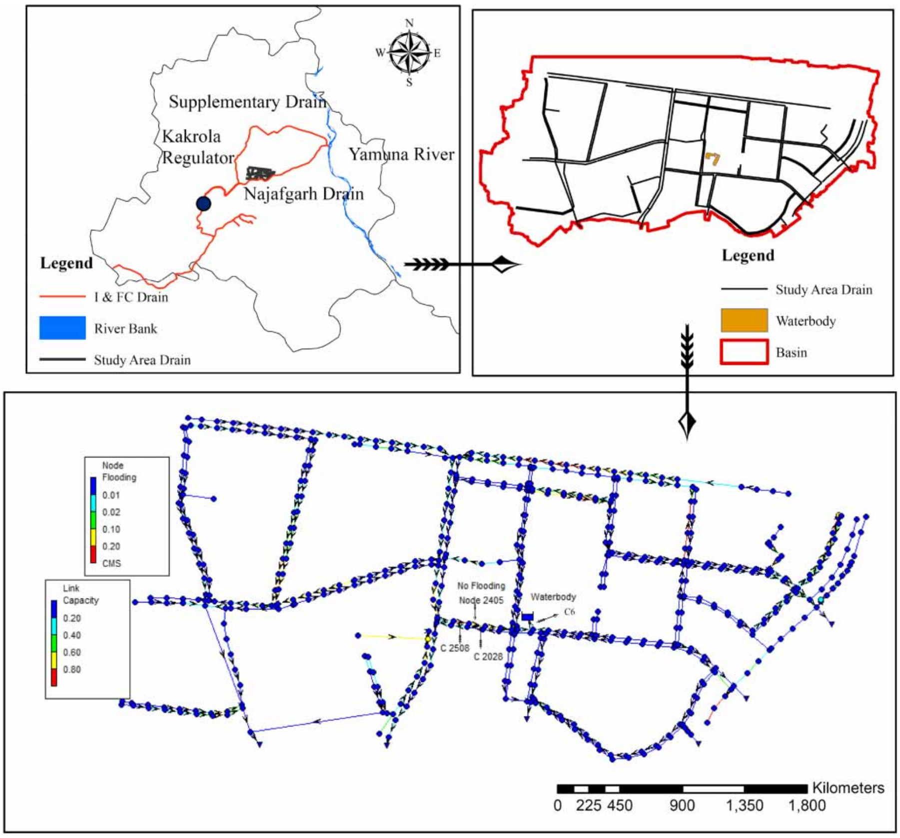

Figure 8 | Results from modified SWMM model.

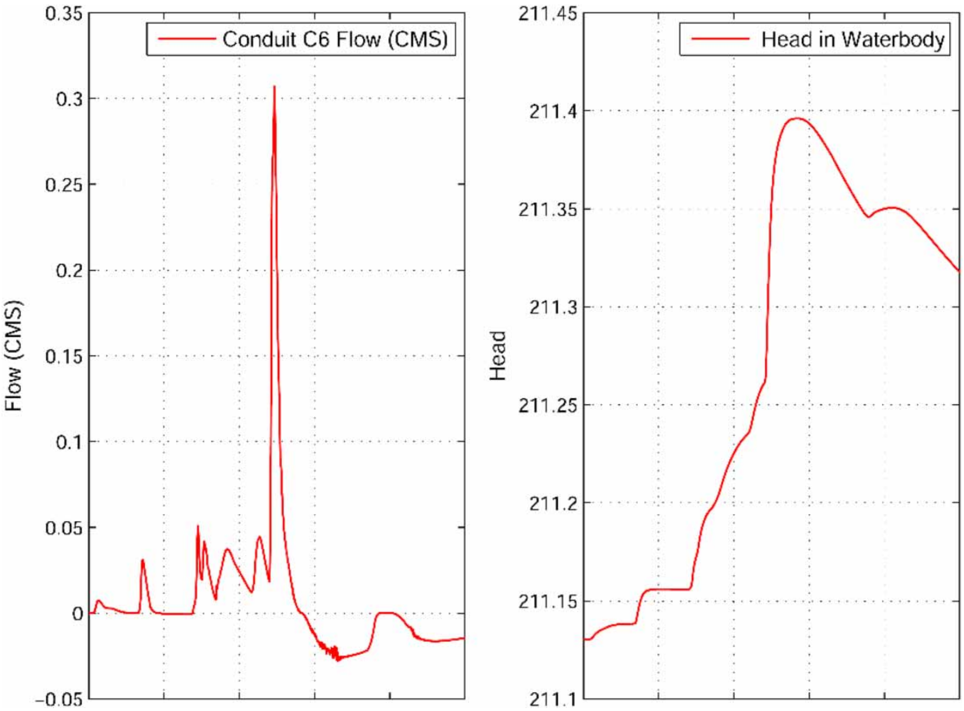

Figure 9 | SWMM model output (a) flow profile in conduit C6, and (b) head profile variation in the water-body.

In this study, a PID controller has been used to adjust the opening of an orifice to maintain the target flow rate. A rectangular, close sided orifice 0.94 m wide (width of the upstream conduit) was used to transfer flood water from the conduit to the nearby water body by adjustment the orifice height (Figure 10). Initially, the orifice is fully open and free flow is allowed in the network. These flows and nodal heads are the initial values in the simulation. The PID controller reached target slowly for this level control problem. Figure 11(a) shows the level in the water-body, while 11(b) shows the variation in the orifice setting.

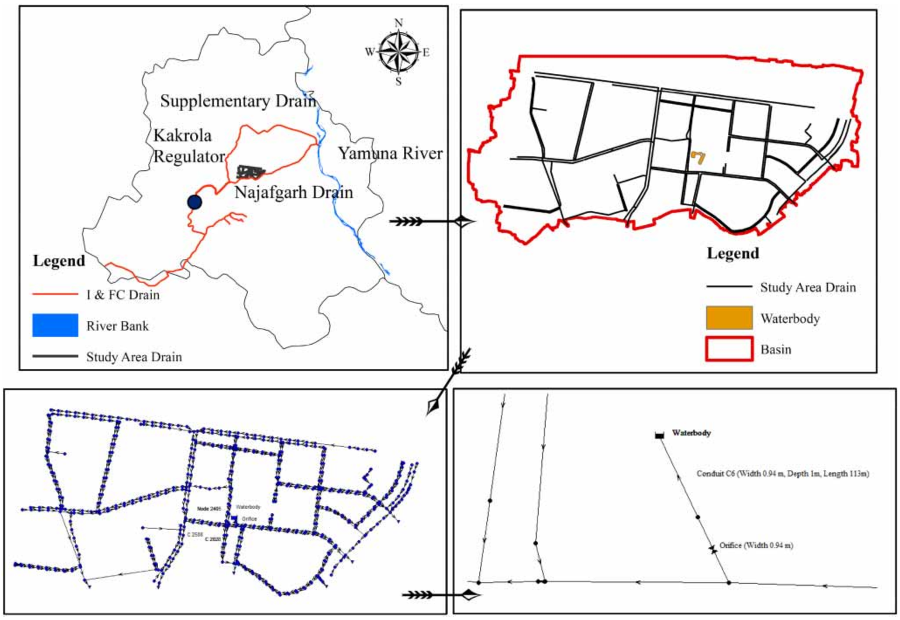

Figure 10 | Location of orifice connecting drain to water-body.

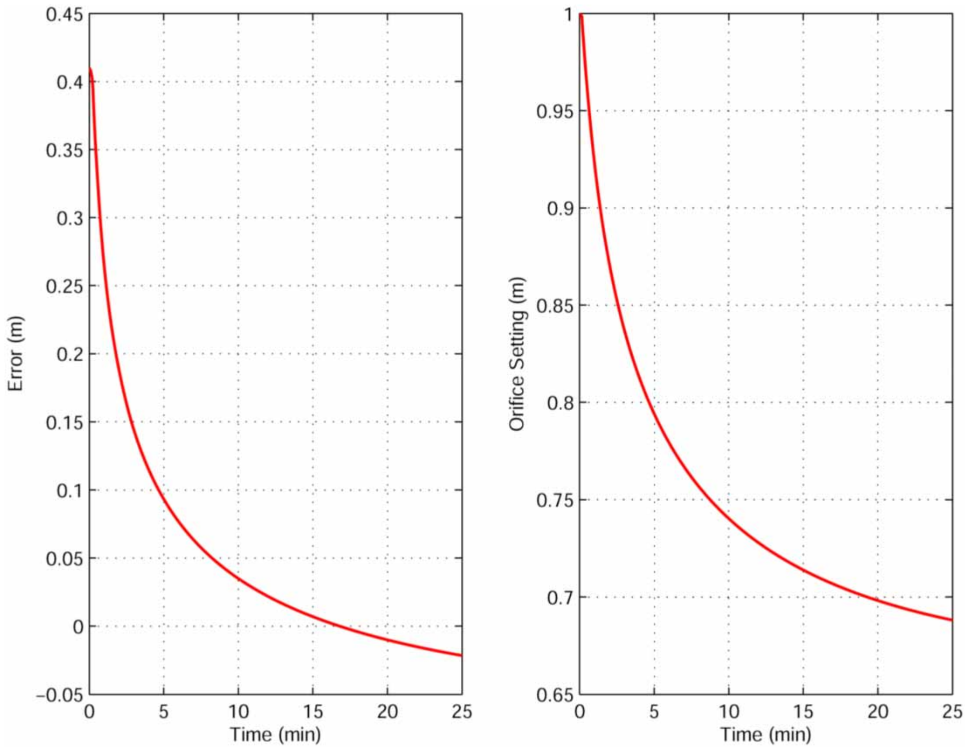

Figure 11 | PID Controller Results (a) level in the water-body, and (b) variation in orifice setting.

CONCLUSIONS

A broad view of current control systems has been presented and the concepts underlying them discussed. Linear control is discussed using urban drainage system examples with real-time field data. A PID controller has been designed to test water level control in a water-body and it has been shown that it can achieve the target water level slowly.

The developed system can be implemented in the field using a Supervisory Control and Data Acquisition (SCADA)/telemetry system. Such systems collect information from the field, transfer it to a central control site, do the necessary analyses and then display the results. The data are transferred using telecommunication systems like satellite communication.

The main components of SCADA/telemetry systems are: (a) field instrumentation and control equipment (b) remote station (c) communication network, and (d) central monitoring station.

The data are collected by the field instrumentation and control equipment. These include sensors connected directly to the manholes or conduit, which record the data and transfer them to remote stations. The remote station is located at a suitable point in the drainage network. The telemetry communication network transfers the data collected through the field instruments within the SCADA system, and may depend on telephone lines, radio, and cable or satellite terminals. The data are transferred to the central communication station, which is equipped with computers where they are processed automatically and the output is generated for use by drainage engineers. The output consists of real-time water levels in the conduit, and helps in proper regulation and management of the drainage network. This easy and rapid dissemination of information can help in controlling flooding.

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