SIMULATION AND CONTROL OF FLOODING IN RIVER AND URBAN SYSTEMS

PAWAN KUMAR RAI

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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SIMULATION AND CONTROL OF FLOODING IN RIVER AND URBAN SYSTEMS

by

PAWAN KUMAR RAI

Department of Civil Engineering

Submitted

in fulfillment of the requirements for the degree of Doctor of Philosophy

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Dedicated to

My grandfather

Late Shree. Badri Narayan Rai

CERTIFICATE

This is to certify that the thesis entitled **"Simulation and Control of Flooding in River and Urban Systems",** being submitted by **Mr. Pawan Kumar Rai** to the Indian Institute of Technology, Delhi (India) for the award of the degree of **Doctor of Philosophy** in Civil Engineering, is a bonafide research work carried out by him under our joint supervision. The thesis work, in our opinion has reached the standard, fulfilling the requirements for the said degree. Further, we certify that this submission is Mr. Pawan's own work and that, to the best of our knowledge and belief, it contains no material previously published or written by another person which to a substantial extent has been accepted for the award of any other degree or diploma of any University or Institute, except where due acknowledgment has been made in the text.

(Dr. Dhanya C.T.)
Assistant Professor
Department Of Civil Engineering
Indian Institute of Technology Delhi
New Delhi-11001

(Prof. B.R Chahar)
Professor
Department Of Civil Engineering
Indian Institute of Technology Delhi
New Delhi-11001

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Abstract

Floods in India are one of the most common natural disaster due to the irregularities in monsoon. The water generated from these floods causes huge damage to the lives and property, and, hence optimal water management has emerged as a major issue that concerns every member of our society. Over the past few decades, water professionals have made tremendous efforts towards management of different water resource systems like rivers, urban drainage, water distribution systems, etc. Since, the river system is one of the major source to cater various water demands, the management of river water is utmost important.

River flooding has been causing extensive losses to life and property. Although flooding cannot be completely avoided, its ill-effects can be minimized conventionally by two approaches: firstly, through flood protection works by designing and constructing river banks, dams and flood storages to guard the inundation susceptible areas apart from regulating the reservoir discharges, and secondly, by developing a flood warning system which can assist in evacuation of people, property and livestock.

In the recent times, there is ever-increasing emphasis on the development of flood warning systems as they offer a relatively cheaper option as compared to the costlier flood protection works. Storm Water Management Model (SWMM) has been an effective tool for simulating floods in urban areas, but has been seldom applied for river systems. In the current research, SWMM model has been successfully employed as an effective flood modelling tool for a river catchment. The developed model may be used as a tool for effective planning and management of natural disasters such as floods.

Though 1D models can be easily developed to obtain bulk information about the discharge features, they lack in providing comprehensive floodplain flow information. On the other hand, a pure 2D model applied on the same river basin takes longer computational time. To overcome these drawbacks, a hybrid approach consisting of 1D river flow models coupled with 2D floodplain flow models has been used in this doctoral work. A well-known 2D river hydrodynamic model iRIC was coupled with 1D SWAT and SWMM models to simulate and visualize flood scenarios, and to identify the flood prone areas. The developed hybrid approach has shown great benefits in terms of reduced computational time and enhanced details of the floodplain flow during the simulation of flood events.

Effective management of floods in densely populated urban areas poses a great challenge. Computation modelling plays an important role in appropriate management of urban drainage system. In the present study an effort has been made to develop an efficient urban drainage model where hydraulic results obtained from the developed SWMM model have been linked with Proportional Integral Derivative (PID) controller for controlling floods. The developed model is able to substantially optimize the flood levels in the urban water bodies and hence can be used as an effective tool to mitigate urban flooding. Also for the nonlinear control applicability in urban drainage system, derivation of nonlinear controller have been derived using collocation technique.

From the above discussion, it can be said that the present doctoral research explores the application of computational modelling and automatic control systems to resolve the water related issues in critical sectors like river flooding and urban inundation.

सारांश

मॉनसून में अनियमितताओं के कारण भारत में बाढ़ सबसे आम प्राकृतिक आपदाओं में से एक हैं । इस बाढ़ से उत्पंन पानी जीवन और संपत्ति के लिए भारी नुकसान का कारण बनता है, और इसलिए इष्टतम जल प्रबंधन एक प्रमुख मुद्दा है जो हमारे समाज के हर सदस्य की चिंताओं के रूप में उभरा है।

पिछले कुछ दशकों में जल पेशेवरों ने नदियों, शहरी जल निकासी, जल वितरण जैसे विभिंन जल संसाधन प्रणालियों के प्रबंधन की दिशा में जबरदस्त प्रयास किए हैं । चूंकि नदी प्रणाली विभिन्न जल मांगों को पूरा करने के लिए प्रमुख स्रोत में से एक है अतः नदी जल का प्रबंधन अत्यंत महत्वपूर्ण है।

नदी के बाढ़ से जीवन और संपत्ति को व्यापक नुकसान होता है। हालांकि बाढ़ से पूरी तरह से नहीं बचा जा सकता है परन्तु इसके दुष्प्रभावों को सबसे पहले दो पारंपरिक तरीकों से कम से कम किया जा सकता है। प्रथम बाढ़ संरक्षण कार्यों के माध्यम से जैसे नदी के किनारे के निर्माण द्वारा, बांधों और बाढ़ के भंडार के निर्वहनों को नियंत्रित करने के साथ ही साथ अतिसंवेदनशील क्षेत्रों को सुरक्षित रखने के द्वारा और दूसरा एक बाढ़ चेतावनी प्रणाली विकसित कर के जो लोगों संपत्ति और पशुओं को निकालने में सहायता कर सकती है। हाल के दिनों में बाढ़ चेतावनी प्रणालियों के विकास में लगातार बढ़ोतरी हुई है क्योंकि वे महंगे बाढ़ संरक्षण कार्यों की तुलना में अपेक्षाकृत सस्ता विकल्प प्रदान करते हैं।

तूफान जल प्रबंधन मॉडल (एसडब्ल्यूएमएम) शहरी इलाकों में बाढ़ का अनुकरण करने के लिए एक प्रभावी उपकरण रहा है लेकिन शायद ही कभी नदी प्रणालियों के लिए लागू किया गया है । वर्तमान शोध में, एसडब्ल्यूएमएम मॉडल को सफलतापूर्वक बाढ़ के जल निकासी के लिए प्रभावी बाढ़ मॉडलिंग उपकरण के रूप में नियोजित किया गया है। विकसित मॉडल को प्राकृतिक आपदाओं जैसे कि बाढ़ के प्रभावी नियोजन और प्रबंधन के लिए एक उपकरण के रूप में इस्तेमाल किया जा सकता है।

हालांकि 1 डी मॉडल आसानी से निर्वहन सुविधाओं के बारे में थोक जानकारी प्राप्त करने के लिए विकसित किया जा सकता है, लेकिन वे बाढ़ के व्यापक प्रवाह की जानकारी प्रदान नहीं कर पाते है। दूसरी तरफ समान नदी पर लागू एक शुद्ध 2 डी मॉडल लम्बा कम्प्यूटेशनल समय लेता है। इन कमियों पर काबू पाने के लिए, एक हाइब्रिड दृष्टिकोण जिसमे युग्मित 1 डी और 2 डी नदी प्रवाह मॉडल इस शोध के काम में इस्तेमाल किया गया है।

एक प्रसिद्ध 2 डी नदी हाइड्रोडायनामिक मॉडल आईआरआईसी, 1 डी एसडब्ल्यूएटी और एसडब्ल्यूएमएम मॉडल के साथ युग्मित किया गया है ताकि बाढ़ के परिदृश्यों को अनुकरण और दृश्यित

किया जा सके और बाढ़ के प्रकोप वाले क्षेत्रों की पहचान की जा सके। विकसित हाइब्रिड दृष्टिकोण ने कम कम्प्यूटेशनल समय में बाढ़ की घटनाओं के अनुकरण के दौरान बाढ़ के प्रवाह के विस्तार के संदर्भ में महान लाभ दिखाए हैं।

घनी आबादी वाले शहरी इलाकों में बाढ़ का प्रभावी प्रबंधन एक बड़ी चुनौती बन गया है। अभिकलन मॉडलिंग शहरी ड्रेनेज सिस्टम के उचित प्रबंधन में एक महत्वपूर्ण भूमिका निभाता है । वर्तमान अध्ययन में एक कुशल शहरी जल निकासी मॉडल विकसित करने का एक प्रयास किया गया है जहां विकसित एसडब्ल्यूएमएम मॉडल से प्राप्त हाइड्रोलिक परिणाम को बाढ़ को नियंत्रित करने के लिए पीआईडी नियंत्रक के साथ जोड़ा गया है। विकसित मॉडल शहरी जल निकायों में बाढ़ के स्तर को पर्याप्त रूप से अनुकूलित करने में सक्षम है और इसलिए इसे शहरी बाढ़ को कम करने के लिए प्रभावी उपकरण के रूप में इस्तेमाल किया जा सकता है। इसके अलावा शहरी जल निकासी प्रणाली में गैर रेखीय नियंत्रण प्रयोज्यता के लिए गैर रेखीय नियंत्रक की व्युत्पत्ति को स्थानान्तरण तकनीक का उपयोग करके प्राप्त किया गया है।

उपर्युक्त चर्चा से यह कहा जा सकता है कि मौजूदा अनुसंधान में नदी के बाढ़ और शहरी बाढ़ जैसे महत्वपूर्ण क्षेत्रों में पानी से संबंधित मुद्दों के समाधान के लिए गणनात्मक मॉडलिंग और स्वचालित नियंत्रण प्रणालियों के आवेदन की पड़ताल की गयी है।

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Symbols

τ_b -Bed shear stress

c_1 and c_2 = learning rates

D = diameter of pipe (m)

$e(t)$ = error (m)

f = Darcy-Weisbach coefficient (dimensionless)

F = nonlinear state dynamic function

g = acceleration due to gravity (ms^{-2})

G = nonlinear control distribution function

h = scalar function

H_{D1}, H_{D2} and H_{D3} = reservoirs variable heads of reservoirs 1, 2, and 3, respectively (m)

h_p (m) = head developed by the variable-speed pumps (m)

H_{SH1}, H_{SH2}, H_{SH3}= reservoirs static heads of reservoirs 1, 2, and 3, respectively (m)

H_{SH4} = static head of pipe 4 (m)

HWC = Hazen-Williams roughness coefficient ($m^{0.37}s^{-1}$)

ISE = integral of the square error (m^2s)

K_p, K_i and K_d = Proportional, Integral, and Derivate gains, respectively ($m^{-1}s^{-1}$, $m^{-1}s^{-2}$ and m^{-1} respectively)

L_{pipe1}, L_{pipe2}, L_{pipe3} and L_{pipe4} = lengths of pipes 1, 2, 3 and 4 respectively (m)

N = pump speed (s^{-1})

N_1, N_2 *and* N_3 = pump speeds of pump 1, 2 and 3 respectively (s^{-1})

n_p = number of pumps running in parallel

$P_g(t)$ = best particle found up to time t

p_{gD} = global best position

$P_i(t)$ = best positions of every particle

p_{iD} = best historical position of particle i itself

Q = flow in the pipeline (m^3/s)

Q_1, Q_2, Q_3 *and* Q_{out} = water flow rates through pipes 1, 2, 3 and 4 respectively (m^3s^{-1})

Q_{out}^* = target outflow from the third reservoir (m^3s^{-1})

Qp = pump flow rate (m^3s^{-1})

$rand_1()$ and $rand_2()$ = uniformly distributed random numbers

T_i = time of integration (s)

u = control variable (s^{-1})

V = volume of a particular reservoir (m^3)

$V_i(t)$ = velocity vector of the particles

v_{iD} = velocity of particle i

w = inertia weight

x = state variable (If used for the flow, the unit is m^3s^{-1} and if used in case of the head, then the unit is m)

$x_{des}(t)$ = desired response (m)

$X_i(t)$ = position vector of the particles

x_{iD} = position of particle i with objective value fitness

$y(t)$ = system output (m)

z -Invert level

z_b -Bed elevation

α_{tc} - Fraction of daily rainfall that occurs during the time of concentration

ν -Eddy viscosity;

ρ -Water density

$\dot{x}_{des}$ = rate of the desired states (ms^{-1})

h_{loss} = total loss in a pipe section (m)

$h_{loss-friction}$ = friction loss of a pipe (m)

$h_{loss-local}$ = local losses of a pipe (m)

A_R = area of reservoir (m^2)

A_{pipe}= Cross-sectional area of pipe (m^2)

H_D = variable head of particular reservoir (m)

L_{pipe} = length of pipeline (m)

Q_0= reservoir output water flow rate (m^3s^{-1})

Q_i = reservoir input water flow rate (m^3s^{-1})

Δh = head difference between two ends of a pipeline (m)

A - Subcatchment area

A_0, B_0 and C_0 = pump constants (ms^2, s^2m^{-2} and s^2m^{-5} respectively)

a-Weir exponent, *3/2* for transverse weirs and *5/3* for side flow weirs

C_0 -Coefficient of discharge

C_f -Bed friction coefficient

CN -Curve number for the day

cncoef -Weighting coefficient used to calculate the retention coefficient for daily curve number

C_w-Coefficient of discharge

D - Cell size.

d - Depth of water

d_p - Depression storage depth

E_a - Potential evapotranspiration for the day (mm/day)

E_a -Amount of evaporation on day i (mm)

F - Cumulative infiltration volume

f -Rate of infiltration

f_0 - Maximum or initial value of f_p.

f_c - Minimum or ultimate value of f_p,

f_p = Soil infiltration capacity

f_p -Capacity of infiltration

F_s-Cumulative infiltration volume required to cause surface saturation

g - Gravitational constant

h - Driving head on the weir

h -Depth of water

H -Stage height

h-Water depth

I -Intensity of rainfall

i^* -Excess rainfall

IMD-Initial moisture deficit for this event

k- Karman constant

K_s-Hydraulic conductivity of saturated soil.

L_w -Length of weir (transverse to overflow)

n - Coefficient of Manning’s roughness,

n - Manning’s roughness coefficient

n = total observations.

P_i - Amount of precipitation on day *i* (mm)

Q - Runoff

Q_{gw} -Amount of groundwater flow on day *i* (mm).

q_{peak} - Peak runoff rate (m^3/s)

Q_{surf} -Amount of surface runoff on day *i* (mm)

Q_{surf} -Excess rainfall (mm)

Q_{surf} -Surface runoff (mm)

Q_{surf} -Surface runoff (mm)

R = hydraulic radius

R_{day} - Rainfall depth for the day (mm)

R_{day} -Rainfall depth for the day (mm)

S - Retention parameter (mm)

S - Slope of the subcatchments

S_f -Friction (energy) slope.

S_{max} -Maximum value retention parameter can achieve on any given day (mm)

S_{max} -Maximum value that the retention parameter can have on any given day (mm)

S_{prev}-Retention parameter for the previous day (mm)

S_u_Average capillary suction at the wetting front

SW -Soil water content of the entire profile excluding the amount of water held in the profile at wilting point (mm)

SW_o-Initial content of soil water on day *i* (mm)

SW_t -Final content of soil water (mm)

t -Time (days)

t_{conc} -Time of concentration for the sub basin (hr) *u* -Shear velocity.

u, *v* - Depth averaged velocity components

V -Approach velocity

V-Water volume on the subarea

W - Width of the subcatchment,

w_1 and w_2 - shape coefficients.

W_{seep} -Amount of water entering the vadose zone from the soil profile on day *i* (mm)

x -Distance along the pipe/channel, and *t* = time.

x, *y* -Spatial coordinate components in the Cartesian system.

Abbreviations

1D – One Dimensional Model

2D – Two Dimensional Models

Decay constant - Decay constant for the Horton infiltration curve (/hr−1)

DEM- Digital Elevation Model

Des-imperv - Depth of depression storage on impervious area (mm)

Des-perv - Depth of depression storage on pervious area (mm)

FLC - Fuzzy-logic control

IMD - Indian Meteorological Department

IMD-Initial moisture deficit for this event

India WRIS – India Water Resources Information System

ISRO - Indian Space Research Organisation

LQR - Linear-quadratic regulator

LU/LC - Landuse/ Land Cover

Max. Infilt - Maximum rate on the Horton infiltration curve (mm/hr)

Min. Infilt - Minimum rate on the Horton infiltration curve (mm/hr)

MPC - Model predictive control

NBSS-LUP - National Bureau of Soil Survey & Landuse Planning

N-imperv - Manning’s roughness coefficient for impervious areas

N-perv - Manning’s roughness coefficient for pervious areas

NSE - Nash-Sutcliffe Efficiency

PBIAS - Percent Bias

PI - Proportional Integral

PID - Proportional Integral Derivative

PPU - % parameter uncertainty range

r_CN2.mgt - Curve number

RBC - Rule-based control

RMSE - Root Mean Square Error

RSR - RMSE-Observations Standard Deviation Ratio

SRTM - Shuttle Radar Topography Mission

v_ALPHA_BF.gw - Base flow alfa factor

v_CH_K2.rte - Effective hydraulic conductivity

v_CH_N2.rte - Manning roughness for main channel

v_GW_DELAY.gw - Groundwater delay time

v_GW_REVAP.gw - Groundwater ‘revaporation’ coefficient

v_GWQMN.gw - Threshold depth of water in shallow aquifer

Zero-Imperv - Percent of impervious area with no depression storage (%)