REAL TIME FLOOD FORECASTING AND FLOOD INUNDATION MAPPING FOR BAGMATI RIVER SYSTEM OF BIHAR, INDIA

NARENDRA KUMAR TIWARY

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

NARENDRA KUMAR TIWARY

Department of Civil Engineering

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DEDICATED

TO

MY PARENTS,

TO MUKUNDA MADHAV, SREE & GOPI

AND MOSTLY TO MY WIFE ANJALI

CERTIFICATE

This is to certify that the thesis entitled **"REAL TIME FLOOD FORECASTING AND FLOOD INUNDATION MAPPING FOR BAGMATI RIVER SYSTEM OF BIHAR, INDIA"** being submitted by **Mr. Narendra Kumar Tiwary** to the **Indian Institute of Technology, Delhi** for the award of the degree of **Doctor of Philosophy**, is a bonafide record of research work carried out by him under our guidance and supervision. The thesis work in our opinion, has reached the requisite standard, fulfilling the requirements for the said degree. The research report and results presented inn this thesis have not been submitted, in part or in full, to any other university or institute, for the award of any degree or diploma.

Prof. A. K. Gosain

Supervisor

Department of Civil Engineering

Indian Institute of Technology Delhi

New Delhi -110016.

Prof. A. K. Keshari

Co-Supervisor

Department of Civil Engineering

Indian Institute of Technology Delhi

New Delhi -110016.

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NARENDRA KUMAR TIWARY

ABSTRACT

Flood is one of the most recurring, wide spread, frequent natural disasters like earthquakes, cyclones, landslides, drought and volcanic eruptions. Flood is associated with a serious loss of life, property and damage to utilities. More than 520 million people are affected by flood per year in the world. It gives annual deaths of 25,000, extensive homelessness, disaster induced disease, crop and livestock damage and other serious harm. Children, women and old age people suffer most during the flood. An accurate flood forecast well in advance can help the water managers in taking emergent actions to mitigate some of the adverse effects of flooding. Real-time flood forecasting is an important non-structural method which forms the basis of decision pertaining to flood warning, flood control or river regulation.

Developments in computer technology have revolutionized the methodology of real-time flood forecasting. Several computer-based models have been developed for real-time flood forecast applications. In present scenario real-time flood forecasting models can be classified as GIS-based models and stand alone computer aided models. Distributed parameter models have large input data requirements. Geographic information systems (GIS) aid the efficient creation of input data files required by such models. Soil and Water Assessment Tool (SWAT), is a distributed parameter GIS-based model developed by the United States Department of Agriculture. In its present form SWAT model is a continuous time model, i.e. a long-term yield model. The model is not designed to simulate detailed, single-event flood routing. The study describes some modifications made in the SWAT model for its use as real-time flood forecasting model. Two new subroutines have been developed and integrated into SWAT model for enabling

it for hourly simulation and forecasting flows at outlet points of different sub-basins. Other related subroutines have been modified to capture the final conditions of the catchment at any desired instant. Thus capability of event modeling has been introduced in SWAT model. Time series analysis of errors in hourly forecasts has been carried out. An ARIMA model for forecasting error has been developed as an error updating technique. Integration of simulation capability of SWAT model and error forecasting capability by time series analysis has been done for enhancing the accuracy of real-time flood forecasts.

Modified SWAT model has been applied for simulating hourly flows and real time flood forecasting of Bagmati river basin of Bihar, India. The SWAT model requires data on terrain, land use, soil, and weather for assessment of inflows and outflows of reaches. SRTM – DEM (90 m resolution), landuse of global USGS (2 M), Soil of FAO Global soil (5 M), rainfall of rain gauges of IMD and stream flows of stream gauges of CWC have been used for setting up of SWAT model. For calibration and validation of model observed data have been collected from CWC, WRD and IMD. Seventeen parameters were selected for sensitivity analysis, calibration, validation and uncertainty analysis to be carried out by SWAT-CUP4 using SUFI algorithm. On the basis of global sensitivity analysis it can be concluded that most sensitive parameter is curve number followed by groundwater delay time, Manning's coefficient, soil evaporation compensation factor, average slope steepness, threshold water level in shallow aquifer for base flow, aquifer percolation coefficient and SURLAG. P-factor and r-factor for calibration were found to be 0.74 and 0.44 respectively, which are very much within the range recommended for a perfect model. Seventy four percent observed and simulated values lie in 95PPU. P-factor and r-factor for validation period are 0.63 and 0.36

respectively which are satisfactory. Nash-Sutcliffe coefficient for calibration of model for Hayaghat gauge station was found to be 0.95 which indicates the best performance of the model. Nash-Sutcliffe coefficients for validation of the model for daily simulation for years 2004 and 2010 were found to be 0.93 and 0.91 respectively. Criteria for evaluation of performance of the model have been summarized into four categories for stream flow: (1) very good (0.75<NSE <1.0), (2) good (0.65<NSE <0.75), (3) satisfactory (0.50<NSE <0.65), and (4) unsatisfactory (NSE <0.5). According to this classification, performance of our model lies in category 1 i.e. very good. For hourly simulation for years 2004, 2005, 2010, 2011 Nash-Sutcliffe coefficients were found to be 0.65, 0.84, 0.74, and 0.64 respectively which are within the range for good performance. Real time forecasting for flood events of year 2004 and 2010 were also carried out using modified SWAT model. Forecasted values were found very close to observed values. Errors in hourly simulated flows and forecasted flows have been successfully corrected by error forecasting ARIMA model developed in the present study.

Expected flood inundation maps are another most important information products needed by the policy makers and water resource managers. There is a need to deploy hydrological modelling by SWAT and hydrodynamic modelling by HEC-RAS for solving the problem of real time flood forecasting and inundation mapping.

In the present study, maximum expected water levels at different cross sections, critical reach at maximum risk, and expected inundation area for different flood events in Bagmati river basin have been assessed using HEC-RAS model in conjunction with HEC-Geo-RAS. Cross sections data have been incorporated at 2-3 km interval using SRTM data. Measured cross sections are in agreement with SRTM based cross sections. Average percentage error is about 2-5%.

Simulated flow hydrographs generated by SWAT were used as boundary conditions for running unsteady flow analysis by HEC-RAS model for obtaining longitudinal water surface profile, water surface at each cross section and forecasted flood inundation mapping. Water levels at different cross sections of the study reach, and inundation areas were compared with the observed values obtained from CWC and inundation maps derived from satellite imageries obtained from NRSA. Results were found in agreement with observed values for most of the cross sections.

The performance of the model can be improved in future by using high resolution DEM and land use derived from CARTOSAT satellite imageries. Telemetry network installation in the study area is under process and efficiency will be increased because of the enhanced spatial coverage of the catchment. By setting up real time data acquisition system in the study area, higher accuracy can be achieved.

The lead time can be further increased by incorporating rainfall forecast of IMD or other agencies. Sub-hourly simulations will be very useful for estimating urban flooding, which has become a major problem these days. Inundation maps generated by the methodology developed in present study can be used for flood hazard characterization.

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LIST OF SYMBOLS AND NOTATIONS

Abbreviation	Expansion	Units
αgw:	ALPHA_BF Baseflow recession constant .gw	
BIRSAC	Bihar Remote Sensing Application Centre	
CWC	Central Water Commission	
CGWB	Central Ground Water Board	
D	Day	Day
DEM	Digital elevation model	
DL	Danger level	
e_z^0	Saturation vapour pressure of air at height ‘z’	kPa
e_z	Water vapour pressure of air at height 'z'	kPa
ET	Evapotranspiration	
Et	Maximum evapotranspiration rate	mm per day
$f_{t,ly}$	Soil temperature factor in layer 'ly'	
FAO	Food and Agriculture Organization of the United Nations	
FC	Water present at field capacity of soil	
FIG	Watershed configuration file in SWAT	
FILE.CIO	Control input/output watershed level file in SWAT	
FMISC	Flood Management Information Support Centre, Bihar	
FMC	Flood Control Planning and Monitoring Circle	
G	Soil heat flux	MJ per m^2 per day
GIS	Geographical Information System	
GW	Groundwater input file in SWAT	

GW_DELAY	Groundwater delay time	Days
GWQMN	*aqshthr,q*: Threshold water level in shallow aquifer for base flow (mmH_2O)	mm
GWHT	Initial groundwater height	m
GW_RCHG	Recharge to shallow aquifer	mm
GW_REVAP	Groundwater revaporation coefficient	
GW_SPYLD	μ: Specific yield of the shallow aquifer (m/m)	mm
HFL	High flood level	m
H_{net}	Net radiation	MJ per m^2 per day
K_{eq}	Equivalent hydraulic conductivity for aquifer	m per day
Lakh	A numerical unit (One lakh = 100000 = 10^5)	
MIKE SHE	See SHE	
MINARS	Monitoring of Indian National Aquatic Resources Series	
NRSA	National Remote Sensing Agency	
NSE	Nash-Sutcliffe Efficiency /coefficient	
NCMRWF	National Centre for Medium Range Weather Forecast	
PCPD(mon)	Number of wet days in a month	
PCP	Precipitation data input file of SWAT	
PCPMM	Mean monthly precipitation	mm
PCPSIM	Rainfall input code. Identifies the method the model will use to process rainfall data. The variable is equal to 1 if measured data is to be read for each sub-basin. Else 2: data generated using weather generator	
P-factor	Percentage of measured data bracketed by 95 percent prediction uncertainty	
PR_W (1, mon)	Probability of wet day following a dry day in a month	

PET	Potential evapotranspiration	mm
95PPU	95Percent Prediction Uncertainty	
PR_W (2, mon)	Probability of a wet day following a wet day in a month	
$Q_{lat,ly}$	Water discharged from layer by lateral flow	mm
Q_{surf}	Surface runoff generated on a given day	mm
R	Soil drainage property	
r_a	Aerodynamic resistance	s per m
r_c	Plant canopy resistance	s per m
R	Recharge into the aquifer	m per day
Rc	Total inflow into the aquifer including recharge	m per day
R_{day}	Amount of rainfall on a given day	mm
rnd_1	Random number in weather data generator of SWAT	
rnd_2	Random number in weather data generator of SWAT	
RCHRG_DP	Deep aquifer recharge fraction	
R-factor	Average thickness of the 95PPU band divided by the standard deviationof the measured data	
REVAPMN	*aqshthr,rvp*: Threshold water level in shallow aquifer for revap or percolation to deep aquifer (mm H_2O)	
RFILES	Daily precipitation files (.pep)	
RETEDAT	Sub-basin routing input data file (.rte)	
ROTO	Routing outputs to the outlet	
ROUTIN	Watershed ROUTing commands in configuration file of SWAT	
SAND	Sand content in soil	
SAR	Synthetic aperture RADAR	

SCS	Soil Conservation Service	
SBS	HRU output file generated by SWAT	
SILT	Silt content in soil	%
SHE	SystemeHydrologique European	
SLR	Solar radiation input file of SWAT	
SLRSIM	Solar radiation input code. Same as PCPSIM	
SLSUBBSN	Average slope length in HRU	$m\ m^{-1}$
SOL	Soil input file for physical properties in SWAT	
SOL_K	Soil hydraulic conductivity	$mm\ hr^{-1}$
SOL_AWC	Available water capacity of the soil layer	mm
SRTM	Shuttle RADAR topography mission	
SUB	Sub-basin input file of SWAT	
SWAT	Soil Water Assessment Tool model	
SUBDAT	Name of sub-basin general input data file	
SUFI	Sequential uncertainty fitting	
SURLAG	Surface flow time lag	
TFILES	Temperature FILES (.tmp)	
TMP	Temperature input data file of SWAT	
TMPMX	Average daily maximum temperature for a month	Degree Celsius
TMPMN	Average daily minimum temperature for a month	Degree Celsius
TMPSIM	Temperature input code. Same function as PCPSIM	
TMPSTDMN	Standard deviation for daily maximum air temperature in a month	Degree Celsius
TMPSTDMX	Standard deviation for daily minimum air temperature in a month	Degree Celsius
$T_{soil,ly}$	Soil temperature for layer 'ly'	Degree Celsius

USGS	United States Geological Survey	
WGNDAT	Name of sub-basin weather generator data file (.wgn)	
WL	Water level	(m)
WND	Wind speed input file of SWAT	
WP	Water content at soil layer wilting point	mm
Wperc,ly	Water percolating to underlaying layer on a given day	mm
a	Angle (degrees)	Degrees
P_{air}	Air density	Kg per m^3
P_w	Density of water	G per cm^3
γ	Psychrometric constant	kPa per degree Celsius
Δ	Slope of saturation vapour pressure-temperature curve	kPa per degree Celsius
Δt	Time step	Day
x_{cell}	Residence time of water particle in a grid cell	Day
τ	Finite time during which the contaminant load enters the aquifer	days