Draft Report

Identification of flood risk on urban road network using Hydrodynamic Model

Case study of Mumbai floods

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Abbreviations

ASCII: American Standard Code for Information Interchange

AWS: Automatic Weather Station

BMC: Brihanmumbai Municipal Corporation

BRIMSTOWAD: Brihanmumbai Storm Water Disposal System

CPU: Central Processing Unit

CRZ: Coastal Regulation Zone

DEM: Digital Elevation Model

DFS: Data File System

DHI: Danish Hydrological Institute

FCC: False Colour Composite

FEMA: Federal Emergency Management Agency

FIG: Figure

GIS: Geographical Information System

GOM: Government of Maharashtra

IMD: Indian Meteorological Department

IPCC: Intergovernmental Panel on Climate Change

IST: India Standard Time

LANDSAT: Land Satellite

LULC: Land Use Land Cover

MSL: Mean Sea Level

MSS: Multi Spectral Scanner

NASA: National Aeronautics and Space Administration

SWD: Storm Water Drainage

1D: One Dimensional

2D: Two Dimensional

3D: Three Dimensional

Identification of flood risk on urban road network using Hydrodynamic Model: Case study of Mumbai

Introduction

Water and water related problems like water quality, water scarcity, drought and flood have always been a major concern all over the world. Global warming has a direct influence on precipitation and heavy rains and it is likely to increase the intensity and frequency of extreme rainfall events in future (Roy, 2009; Trenberth, 2011). The International Panel on Climate Change (IPCC) states that the warming on the earth surface is unequivocal by concluding from the observational and modelling studies that an increase in the frequency of heavy precipitation events is likely to have occurred over most land areas during the 20th century (IPCC, 2007). Several studies on Indian region has also reinforced a significant rise in the frequency and duration of monsoon breaks over India during recent decades (Ramesh Kumar et al., 2009 and; Turner and Hannachi, 2010), with increase in the frequency of extreme rainfall events in certain parts of the country (Goswami et al., 2006). Thus, higher intensities of rainfall are therefore the likely hydrological future for India. Along with this climate change via changes in sea level is a threat to the coastal cities. A global average sea level rise of 9–88 cm is expected over the next hundred years (UNFCCC, 2005). Sea level rise increases the risk of coastal and delta floods, particularly in cases of storm surges (Huong and Pathirana, 2013).

Accompanying the change in climate patterns is the rapid urbanisation and growth of cities in the twentieth century. Heavily urbanized megacities in the low-lying deltas of Asia have been identified as “hotspots”, especially vulnerable to climate risks (ADB, 2008; IPCC, 2007). The level of urbanization in India has increased from 27.81% in 2001 to 31.16% in 2011 (Census 2011). To accommodate accelerating urbanisation more wet lands, open spaces, tanks and wooded areas are converted to urban and suburban areas, thus, the amount of surface area available for water infiltration into the soils decreases. Home sites, parking lots, buildings, and roadways all decrease the surface area of soil on Earth's surface. The increase in artificial surfaces will increase the flooding frequency due to poor infiltration and reduction of flow resistance (Huong and Pathirana, 2013). In Urban drainage system water is redirected into sewage and storm water drains. These drainage systems are presently insufficient to cope with the increase volume of water created from high intensity rainfall and generates flood (Nair, 2009; Avinash, 2016).

Over the coming decades, the pressures of urbanisation along with climate change will aggravate this situation. There are evidences in recent years where heavy precipitation events have resulted in several damaging floods in India. A number of major cities and towns in India reported a series of devastating urban floods in the recent decade. The consecutive flash floods over three major metro cities in the same year, i.e., Mumbai in July 2005, Chennai in October 2005 and again in December 2005 and Bangalore in October 2005 caused heavy damages in economy, loss of life, disruption of transport etc (Guhathakurta and Sreejith, 2011.

The transport system receive the immediate impact of floods as the storm water drains which are unable to cope the storm water are encountered with blockage and as a result the runoff inundates the urban settlements in low laying areas and submerge the roads (Avinash, 2016). Flooding of roads has the potential to cause a range of major difficulties, from harm to people, damage to vehicles, damage to the road infrastructure and the resulting economic disruption (Hankin et al., 2012). There is abundant research on how the urban transportation sector may contribute to the climate change through emissions but less attention is given to the potential impacts of flooding events on the performance of urban transportation network as integrated systems (Suarez, P., 2005).

In the present study, the aim was to understand the process of flooding from extreme rainfall. The study domain for this study is MMR, where the hydrodynamic responses post event in terms of storm water depth has been studied. For this, a 2D hydrodynamic simulation model using DHI MIKE 21 HD model was developed, followed by creation of time varying flood risk map for selected precipitation events.

Model results can be used to identify areas or hotspots which would have higher risk of flooding during extreme precipitation events. This will be helpful for policy-making and planning such that identified areas can get maximum attention during any such extreme event. The results of this model can thus be used for the further urban planning and flood management.

Objectives

The objective of this study is to access the impacts of urban flooding on traffic congestions by using geo-spatial datasets and explore the possibility of using hydrodynamic modelling to identify the points of flood risk. The key objectives are:

- Creating Hydrologically conditioned depression less DEM for the study area to generate the bathymetry data in MIKE model for 2D overland hydrodynamic simulation
- Generate flood risk maps of Mumbai for estimation of the areas which are going to be flooded in the case of different rainfall intensities, duration and volume, with spatial information about the flood water depth.
- Identification of flood hotspots on urban road network

Literature Review

There is a wealth of information on the effect of urbanization on the hydrologic processes. Leopold (1968) stated that the percentage of impervious area (type of land use), characteristics of the channel and provision for storm sewerage are the principal factors that govern the flow regime in a catchment. After synthesizing many studies, Hollis (1975) concluded that small frequent floods are increased with shorter recurrence interval. Number of studies assessed the impact of land use change on runoff (Hollis 1975; Bultot et al 1990; Crooks and Davies 2001; Istomina et al 2005; Brath et al 2006; Rongrong and Guishan 2007; Mao and Cherkauer 2009; Sheng and Wilson 2009; Solin et al 2011). Several researchers acknowledge that urbanization in the flood plain areas would increase the peak discharge, decrease the time to peak and increase the volume of runoff (Liu et al 2004; Campana and Tucci 2001; Brilly et al 2006; Nirupama and Simonovic 2007; Saghafian et al 2008). Chen et al (2009) stressed on a better understanding and assessment of land use change impacts on watershed hydrologic processes for predicting flood potential and mitigation of hazard, and has become a crucial issue for planning, management and sustainable development of the watershed. Kibler et al (2007) measured the anthropogenic impact on the hydrology of watersheds in terms of the ratio: flood peak after development to flood peak before development over a range of return periods. The flood peak ratio depends on the impervious fraction and percent of basin sewered and these factors have been taken into account in an urban flood peak model. They concluded that the analysis of urbanization effects on flood frequency is a vexing problem because of lack of flood data in urban areas and also because of the dynamic nature of development process. The spatial and temporal changes of land use/land cover can be assessed using satellite imageries (Yu et al 2003; Geymen and Baz 2008; Kadiogullari and Baskent 2008; Solin et al 2011). Remote sensing (RS) techniques along with Geographic Information System (GIS) have been applied extensively in recent times and are recognized as powerful and effective tools for detecting land-use change, flood mapping and flood risk assessment (Sarma 1999; Islam and Sado 2000; Sanyal and Lu 2004; Dewan et al 2007).

The influence of land use changes on runoff was examined by Yu et al (2003) using a rainfall–runoff model and design hyetographs with various return periods in Ta-Chao basin, Taiwan. Their results indicate that peak discharge and runoff volume increase significantly from 1972 to 2000. Liu et al (2004) presented a distributed hydrologic modelling and GIS approach for the assessment of land use change on flood processes. WETSPA (Water and Energy Transfer between Soil, Plants and Atmosphere) and GIS techniques were used to predict flood hydrograph to evaluate storm runoff from different land use areas and to assess the impact of land use changes on flood behaviour. Three hypothetical scenarios namely urbanization, deforestation and afforestation were considered. They concluded deforestation has a fair negative impact and afforestation has a moderate positive impact on flooding.

Mumbai District Profile

Geography

Mumbai consists of two distinct regions: Mumbai City district and Mumbai Suburban district, which form two separate revenue districts of Maharashtra. The city district region is also commonly referred to as the Island City or South Mumbai. The total area of Mumbai is 603.4 km². Of this, the island city spans 67.79 km², while the suburban district spans 370 km² together accounting for 437.71 km² under the administration of Municipal Corporation of Greater Mumbai (MCGM).

Hydrology

Mumbai lies at the mouth of the Ulhas River on the western coast of India, in the coastal region known as the Konkan. It sits on Salsette Island (Sashti Island), which it partially shares with the Thane district. Mumbai is bounded by the Arabian Sea to the west. Many parts of the city lie just above sea level, with elevations ranging from 10 m to 15 m ; the city has an average elevation of 14 m. Northern Mumbai (Salsette) is hilly, and the highest point in the city is 450 m at Salsette in the Powai–Kanheri ranges. The Sanjay Gandhi National Park (Borivali National Park) is located partly in the Mumbai suburban district, and partly in the Thane district, and it extends over an area of 103.09 km².

Apart from the Bhatsa Dam, there are six major lakes that supply water to the city: Vihar, Lower Vaitarna, Upper Vaitarna, Tulsi, Tansa and Powai. Tulsi Lake and Vihar Lake are located in Borivili National Park, within the city's limits. The supply from Powai lake, also within the city limits, is used only for agricultural and industrial purposes. Three small rivers, the Dahisar River, Poinsar (or Poisar) and Ohiwara (or Oshiwara) originate within the park, while the polluted Mithi River originates from Tulsi Lake and gathers water overflowing from Vihar and Powai Lakes. The coastline of the city is indented with numerous creeks and bays, stretching from the Thane creek on the eastern to Madh Marve on the western front.The eastern coast of Salsette Island is covered with large mangrove swamps, rich in biodiversity, while the western coast is mostly sandy and rocky.

Geology

Soil cover in the city region is predominantly sandy due to its proximity to the sea. In the suburbs, the soil cover is largely alluvial and loamy. The underlying rock of the region is composed of black Deccan basalt flows, and their acidic and basic variants dating back to the late Cretaceous and early Eocene eras. Mumbai sits on a seismically active zone owing to the presence of 23 fault lines in the vicinity. The area is classified as a Seismic Zone III region which means an earthquake of up to magnitude 6.5 on the Richter scale may be expected.

Climate

Mumbai has a tropical climate, specifically a tropical wet and dry climate under the Köppen climate classification, with seven months of dryness and peak of rains in July. The cooler season from December to February is followed by the summer season from March to June. The period from June to about the end of September constitutes the south-west monsoon season, and October and November form the post-monsoon season. Between June and September, the south west monsoon rains lash the city. Pre-monsoon showers are received in May. Occasionally, north-east monsoon showers occur in October and November. The highest rainfall recorded in a single day was 944 mm (37 in) on 26 July 2005.

Mumbai Susceptibility for flooding

There are many reasons and some of the important arguments include both natural and manmade activities responsible for flooding in Mumbai. The geographical condition makes Mumbai susceptible for heavy rainfall. Impact of anthropogenic activities i.e. unsustainable use of resources, reclamation of low lying areas, climate change and global warming, antiquated drainage system and chocked sewers, uncontrolled and unplanned development of the city especially in Northern suburbs, destruction of mangrove and natural ecosystem because of the encroachment by the builders and irresponsible city dwellers, violation of Coastal Regulation Zone (CRZ) rule, loss of wetlands, lack of disaster management plan and no clear coordination between several agencies responsible for city development and planning.

Geographical condition

The main reason of flooding in Mumbai is its geography, both natural and manmade (Duryog Nivaran, 2005). Firstly, the city's location leaves it exposed to heavy rainfall during the summer; typically, 50% of the rainfall during the two wettest months, July and August, falls in just two or three events (R.K. Jenamani, 2006). This situation is aggravated by the manmade geography; as in Mumbai; large areas of the land are reclaimed from the Arabian Sea and are situated only just above sea level and below the high-tide level. This inhibits natural runoff of surface water. Complicated network of drains, rivers, creeks and ponds drains directly into the sea but at the time of high tides, sea water can enter the system preventing drainage and in extreme events, leading to Sea water natation. This occurred during the July 2005 event; a massive inundation of the drainage systems caused as almost 1000 mm of rainfall fell on the city in 24 h was combined with a failure of the system as sea water entered during high tide

Impact of global warming

Studies carried out over the past decade indicate that Mumbai is likely to be highly vulnerable to climate change with majority of its population living on the flood prone and reclaimed land. Estimates obtained in 2001 from the Goddard Institute for Space Studies suggest that in the Canadian Climate Centre's business-as-usual emissions (A2) scenario and sustainable path (B2) scenario, the average annual temperatures in the city would increase by 1.750C and 1.250C respectively. Mumbai is also predicted to have an average annual decrease in precipitation of 2% for the A2 scenario and an increase of 2% in the B2 scenario. Perhaps, the most damaging scenario for the city would be the predicted sea-level rise of 50cm by 2050.

Moreover, studies in global warming, have led to the conclusion that extreme rainfall events are likely to become more frequent in future. The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change has concluded that the "amplitude and frequency of extreme precipitation events is very likely to increase over many areas". In other words, the 1-in-50 year probability event of today is likely to become a 1-in-25 year event of the future. Global climate researchers have pointed out 'increase in monsoon strength as earth's atmosphere is warming up'. They are suggesting that any future warming may give more rains to India, and more rains with increased intensity of precipitation. Higher intensities of rainfall are therefore the likely hydrological future for India. Scientists are also warning about the rise in sea levels from increased snow melt process. Hence the planning of a coastal city like Mumbai – which has developed mostly on flat reclaimed lands, will have to be very carefully evaluated in terms of risks to the population from inadequate carrying capacities of the stream channels. (Chitale, 2006)

Inadequate Drainage Network

The present storm-water drainage system in Mumbai was put in place in the early 20th century and is capable of carrying only 25 mm of water per hour which was extremely inadequate on a day when 944 mm of rain fell in the city. The drainage system is also clogged at several places. Only 3 'outfalls' (ways out to the sea) are equipped with floodgates whereas the remaining 102 open directly into the sea. As a result, there is no way to stop the seawater from rushing into the drainage system during high tide. Also, many gradients are flat and drainage networks are poorly designed with lack of maintenance and supervision. There are no holding ponds/rain garden developed to control water during storms and high tides. Choking of drainage system with extreme rainfall causes the additive effect in flooding in Mumbai.

Sewage Network

At present, the collection and disposal of waste water and sewage in Mumbai is divided into seven zones, viz., Colaba, Worli, Bandra, Versova, Malad, Bhandup and Ghatkopar. From each of these, sewage and waste water is conveyed to the respective final discharge points for disposal through marine outfalls, some three kilometres into the sea. There are 53 pumping stations for pumping the sewage/waste water from lower level to higher level and there are 54,000 manholes for maintenance of 1,400 km long network of the sewerage system. The underground drainage pipes of the sewerage system in Mumbai are more than 100 years old and needs renovation. In congested parts, the sewerage lines and water pipelines run together and leakages contaminate drinking water. The unplanned and unauthorised growth of the city makes it difficult and, at times, impossible to replace old sewerage lines. The problem of sewer lines of small diameters getting choked due to solid waste and silt entering them is rampant. The result is that instead of getting drained, sewage overflows on to the surface. Mumbai has a two-tier sewerage system. One is the underground sewerage system that discharges about 3.5 km into the sea. The other is storm water drains that carry surface and flood water during monsoon and discharges directly into the sea right at the sea shore. However, what complicates the already overloaded sewerage system is the presence of a large percentage of the city's population that has no access to it in the first place.

While toilets in the buildings and establishments are connected to the underground sewerage system, this facility is not available to the slum dwellers. Nearly 65% of Mumbai's population of 13 million, i.e., about 8million people live in slums, of which 50% live in authorised slums with some toilet facility. The other 50%, i.e., about 4 million slum residents have no choice but to ease themselves in the open spaces, along roads, highways, railway tracks, parks, playgrounds, open plots and beaches. During monsoons, this excreta flows through open drains and nallas into the storm water drains and gets discharged right near the coast.

Solid Waste Management

Mumbai generates waste to the tune of approximately 7,025tonnes per day. The waste consists of 5,025 tonnes of mixed waste (bio-degradable and recyclable) and 2,000 tonnes of debris and silt. The Municipal Corporation of Greater Mumbai (MCGM) is formally responsible for the management of waste in the city. The prevailing approach has been one of collection and disposal that is, garbage is collected from communities by the municipal authorities and disposed of at the three main dumping sites that are currently servicing the city. Garbage collectors employed by various housing societies manually collect the waste generated at the household level and dump it in the garbage bin at specified street corners. There are around 5,800 community bins in the city. In case of South Mumbai, trucks collect garbage from the garbage bins and transport it to a transfer station which is located in Mahalakshmi. A separate transport is arranged for transferring the garbage from Mahalakshmi to the northern part of Mumbai where the dumping grounds are situated. From all other parts of the city, garbage is sent directly to the dumping grounds. Nearly 95% of the waste generated in the city is disposed off in this manner. This largely manual operation involves 35,000 personnel employed by the MCGM and is collected by a fleet of 800 vehicles, including vehicles hired from private contractors, that work in shifts each day. MCGM spends about Rs15-20lakh per day on collecting and transporting garbage and debris with municipal and private vehicles making about 2,000 trips every day.

Coastal influence

The entire storm water outflow system of Mumbai has been so far based purely on gravity. There are closed drains in the old island city (Colaba to Mahim) and open drains or nallas in suburbs. (Chitale, 2006). They both discharge by gravity either in the creek arms or in to the open sea along the east and west coasts of Mumbai. The low lying portions of the island city have a history of getting regularly flooded up to 5-6 times a year, generally for a few hours every time, when high intensity rainfall is coupled with high tide in the sea. There is water logging in the central Mumbai belt under such conditions. At many locations, land levels are below the high tide level e.g. Sat Rasta, Lower Parel, Grant Road, etc. The mean sea level of Mumbai is very close to the Indian Mean Sea level at 0.01 m. The average high tide level is 2.5 m, the annual highest peak tide level being 2.75 m. The average low tide level is (-) 2.0 m (i.e. two meters below the mean sea level). It is the low tide periods (about 10 to 12 hrs in a day below the mean sea level) that have been providing relief during the storm by draining out the accumulated surface waters. The level of a large coastal belt in Mumbai is close to 3.00 M e.g. Juhu aerodrome; and Khar. These are the vulnerable areas for congestions and submergence by tide and flood interacting. Ground levels in many low lying areas in Island city & suburbs are just 2.25 to 3 meters above MSL, while the flood levels in the creeks also have the same heights.

Changing land use land cover

Understanding of hydrological process is very important component for the comprehensive study of flooding which convulsed Mumbai. Hydrology is the study of occurrence, circulation and distribution of water into earth and earth's atmosphere. It deals with the precipitation, evaporation, base flow condensation, transpiration, infiltration, retention and surface runoff. Runoff is that part of rainfall which flows over the ground and into the stream channels and rivers. Runoff is dependent on the amount of rainfall, availability of impervious strata, vegetation cover, soil type and other topographic and physical properties. These components of natural system play a key role in influencing the storm water velocity and depth in urban areas. The developmental works involving physical, topographical changes alter the natural hydrological process. It is necessary to evaluate the effects of such changes on the hydrological performance of the urban areas. The flow of water is a dynamic process and is continuous in time and space. It is necessary to study how the precipitated water travels in the catchment to understand the process of inundation and flooding. The developmental structures in urban areas like roads, buildings, subways, paved catchment reduces infiltration and ground water recharge. The paved surface area does not only reduce the infiltration but they become preferential path for water flow with great velocity. Reduction in vegetative cover in the catchment has the same impact on runoff as it facilitates water retention, evapotranspiration and velocities check. So is the case with Mumbai, the impervious strata within a catchment area is a significant parameter to estimate the runoff. It decides that how much will be the quantum of change in runoff. When there are no detention basins to arrest this additional flow the flooding and inundation of low lying urban areas can be catastrophic.

Model Setup

Model Area

Mumbai also known as Bombay is the capital city of the Indian state Maharashtra, situated along the coast of Arabian Sea on Western coast of India. It is the most populous city in India with 12,478,447 city population (census 2011), and 4th in world. The seven islands that came to constitute Mumbai were home to communities of fishing colonies. For centuries, the islands were under the control of successive indigenous empires before being ceded to the Portuguese and subsequently to the British East India Company. The Model area comprises the entire metropolis region and lies in geographical coordinates between 72.73^0 longitudes to 18.84^0 latitudinal extents. Fig. 1 bellow showing the study area map with boundaries processed in ArcGIS 10.

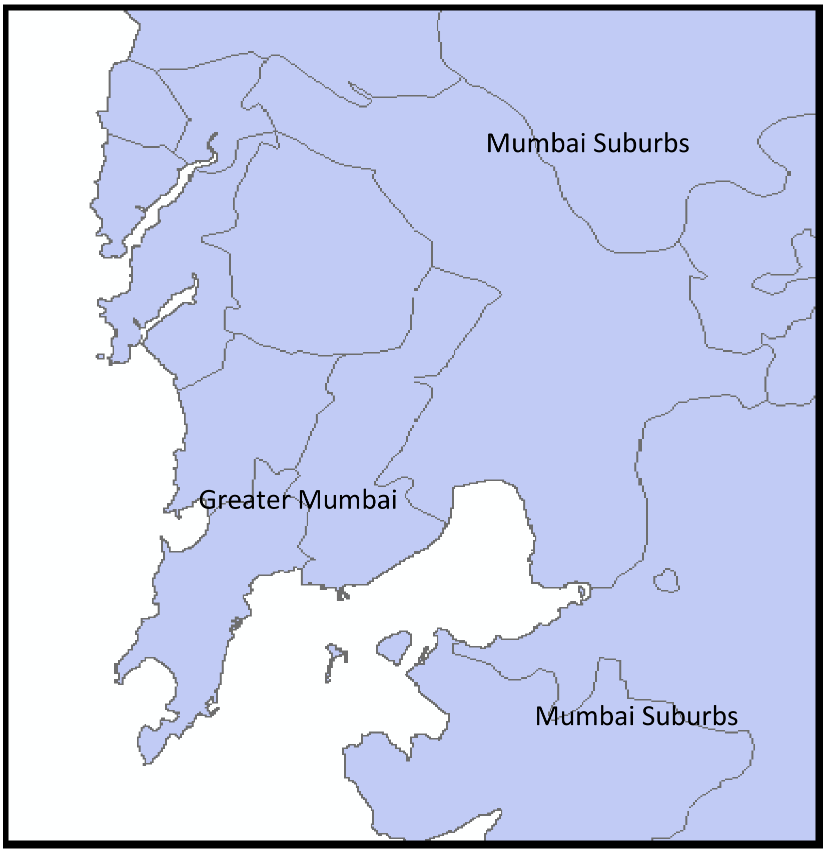


Figure 1 Study Area, Mumbai Metropolitan Region (MMR)

MIKE 21

The hydrodynamic model in the MIKE 21 Flow Model (MIKE 21 HD) is a finite-difference general numerical modelling system for the simulation of water levels and flows in estuaries, bays and coastal areas. It simulates unsteady two dimensional flows in one layer (vertically homogeneous) fluids and has been applied in a large number of studies. The model is based on the very basic mass balance equation and conservation of momentum equation. These two equations together, describe the flow and water level variations. These equations are in the form of Saint Venant equation used in MIKE 21. (DHI, 2011)

Mass Balance Equation

$$\frac{\partial \xi}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=\frac{\partial d}{\partial t}$$

Conservation of Momentum Equation in x-direction:

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)+gh\frac{\partial \xi}{\partial x}+\frac{gp\sqrt{p^2+q^2}}{C^2.h^2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx})+\frac{d}{dy}(h\tau_{xy}\right]-\Omega_q$$
$$-fVV_x+\frac{h}{\rho_w}\frac{\partial}{\partial x}p_a=0$$

Conservation of Momentum Equation in y-direction:

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+gh\frac{\partial \xi}{\partial y}+\frac{gq\sqrt{p^2+q^2}}{C^2.h^2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial y}(h\tau_{yy})+\frac{d}{dx}(h\tau_{xy}\right]+\Omega_p$$
$$-fVV_y+\frac{h}{\rho_w}\frac{\partial}{\partial y}p_a=0$$

The following symbols are used in these equations:

h(x,y, t) – water depth =ξ-d, m

d(x,y,t) – time varying water depth , m

ξ(x,y,t) –surface elevation, m

p,q (x,y,t)- flux densities in x- and y-directions (m 3 /s/m) = (uh,vh);

(u,v) = depth averaged velocities in x- and y-directions

C(x,y)- Chezy resistance (m ½ /s)

g- acceleration due to gravity (m/s 2)

f (V)- wind friction factor

V, Vx, Vy (x,y, t)- wind speed and components in x- and y-directions (m/s)

$\Omega(x,y)$- Coriolis parameter, latitude dependent (s^{-1})

Pa (x,y,t)- atmospheric pressure ($kg/m/s^2$)

Pw- density of water (kg/m^3)

x,y- space coordinates (m)

t- Time (s), τxx, τxy, τyy- components of effective shear stress

Methodology

Two different rainfall intensities, duration and frequencies are selected in this modelling approach; DHI MIKE21 was used to simulate the rainfall events. The rainfall Data for 25-26 July 2005 was obtained from IMD Mumbai for Santa cruse rain-gauge station of 1 hr frequency and other rainfall data was collected from BMC for Andheri rain gauge station at 15 minute frequency. ASTER GDEM procured from USGS web portal with 30 m spatial resolution was used for the surface elevation, Global Sea Bathymetry data was used for sea bathymetry. Other spatial information such as Road network, water bodies are obtained from OSM metro extract data set in the form of shapefiles. These shapefiles has been gone under quality test in Google earth to rectify the errors in the network datasets and then merged with the Landuse map for the creation of surface roughness in ArcView grid data. The topographic data (DEM) was first converted in ArcGIS to ASCII format to be used in MIKE 21 simulation to determine the water level. Figure below schematises the overall approach of the study. The detail description of data processing is provided in the section Pre-processing of data section in the report.

Modelling Approach

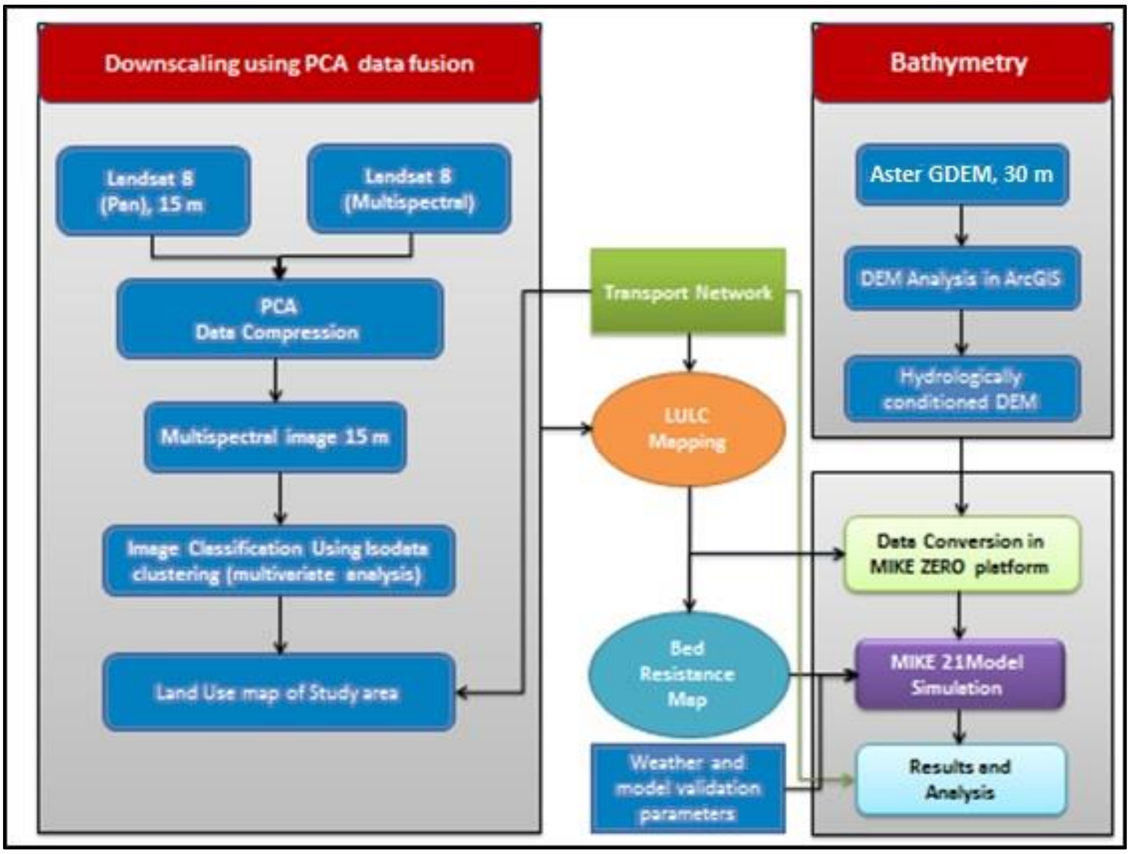


Figure 2 Schematic Diagram of Model using Spatial-Numerical Model

Data Collection and Pre-Processing of data

Rainfall Data

Rainfall is the main driving parameter of urban floods in Mumbai. Since, rainfall intensity, duration and frequency determine the extent and severity of flooding, it is important to analyse the rainfall for the selection of events in the modelling process.

The rainfall data of Mumbai city measured at Santacruz, Colaba and Dahanu weather stations for the event 26-27 July 2005 is provided by the IMD Mumbai. For the estimation of flooding we need fine time resolution rainfall data. Hourly data was available only for Santacruz station between 26th July 2005, 14:30 IST to 27th July 2005, 02:30 IST. 15 minute rainfall data for other than 26-27 July is collected from BMC AWS. These rainfall data is converted into time series data in .dfs0 format in MIKE ZERO toolbox and added in the model.

The rainfall data can be analysed and presented in many ways. Here, we have analysed the rainfall data of Mumbai provided by IMD.

Table I Rainfall Events Selected for Flood Modelling

Events	Total Rainfall (mm)	Total Duration	Return Period
*26-07-2005	944.42	24 Hrs	>200 years
30-06-2007	314.45	18 Hrs 30 min	>10 years

*Extreme Event of 2005, highest rainfall event ever recorded over Mumbai

Processing of Hydrologically Conditioned Depressionless DEM

Hydrologically conditioned DEM is a DEM whose flow direction defines expected flow of water over the terrain. The flow pattern and flow direction are important and it should be correcting before going for any kind of hydrological assessment using DEM. The Hydrologically conditioned Dem is a function of analysis being performed and the analysis would be different for different assessments. For flood analysis, surface storage can be avoided as they store water and get and will contribute to downstream catchments during the rainfall event eventually. (ESRI UC, 2014)

ASTER DEM with 30m spatial resolution is processed in ArcGIS to make it Hydro Conditioned. First all the tiles (30) of ASTER have been joined together using Mosaic tool in ArcGIS. The resulting layer file then gets filled to form a depression less DEM. The resulting DEM file was converted from Raster to Point vector data using raster to vector tool in ArcGIS followed by removal of specific point removal. The grid points which has unrealistic elevation they could be a natural depressions or manmade trenches. These depressions form sink in the model and have to be removed from the DEM as they results in changes in flow path of the flood water (Anon, 2010). These sinks have to be removed as during simulation these grid points will show unrealistic and high water depth. All no data values and unrealistic elevation points in land has been deleted. Interpolation tool is used for assigning values to those points. The processed Point data file then gets converted to DEM raster. The resulting raster data is used for defining flow pattern and flow direction. The process of making a hydro conditioned DEM is an iterative process and the correction technique run several times to make the Hydro DEM which can be used in the model. The Resulting Hydro DEM (figure 4) was used to create bathymetry data for MIKE 21 model.

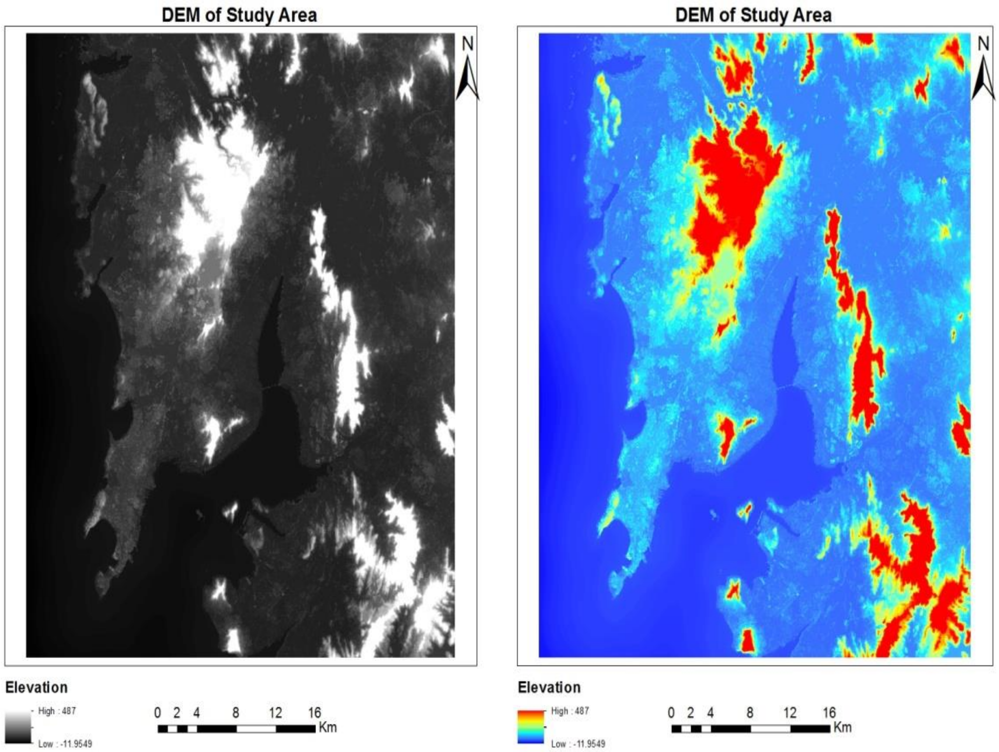


Figure 3 DEM of the study Area in ArcGIS 10

Bathymetry

The bathymetry file was created in MIKE21 using the Mike Zero toolbox. The tool Grd2MIKE was used to convert the ASCII file to dfs2 file which can be used in MIKE21. For the boundary in MIKE 21 either elevation or the flux can be assigned at the boundary position (DHI, 2011). In this model elevation has been given at the land boundary and tide level is given at water boundary. When importing GIS surface data for a MIKE21 bathymetry, it is recommended to ensure that the *'True Land'* value is set to a sufficiently large value as these nodes never become active computational nodes within the model domain (DHI, 2011). The grid spacing of 30 m was used in this model Bathymetry file. In the model it is important to have same geographical datum and projection system for entire study domain.

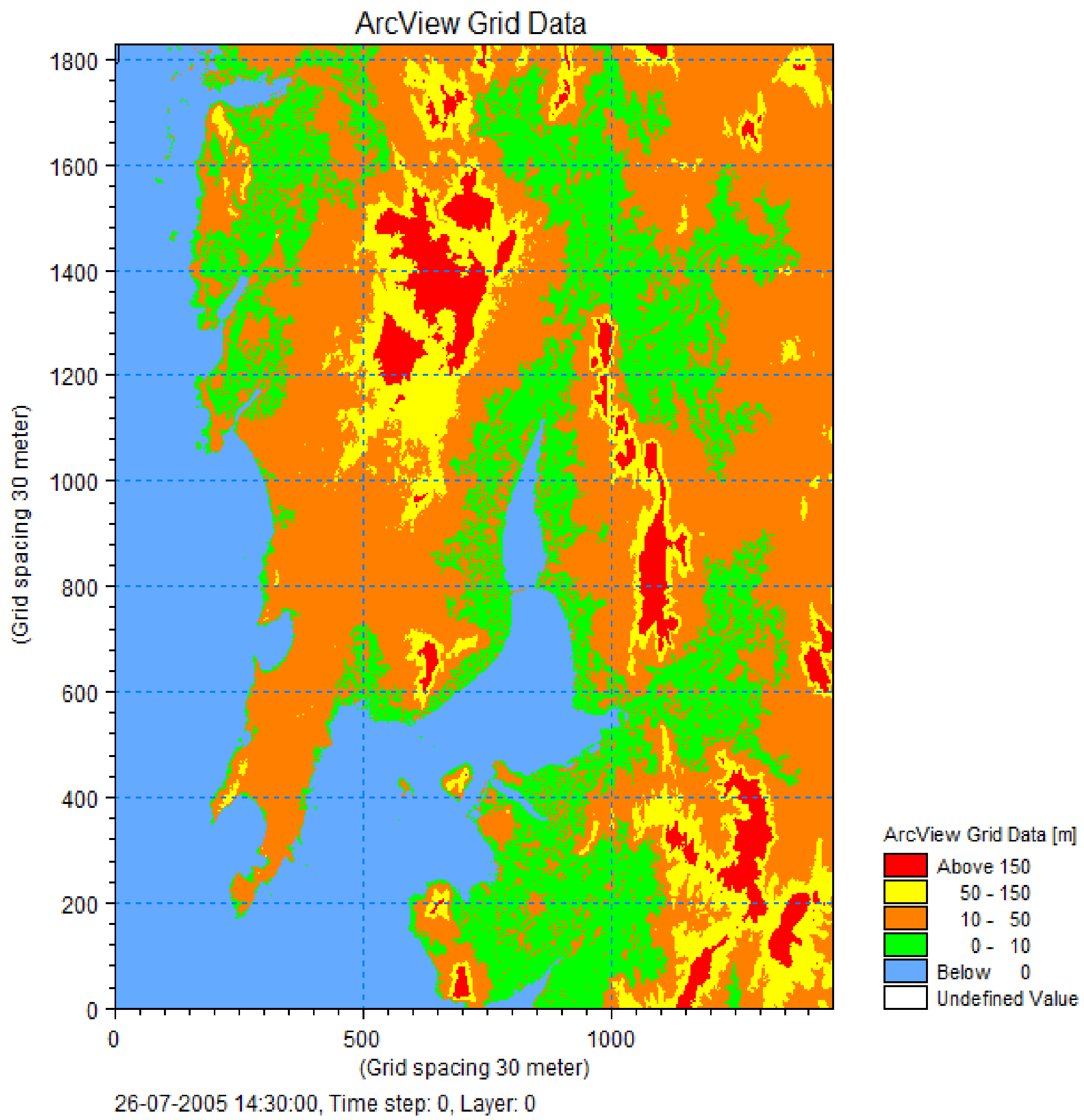


Figure 4 Bathymetry File in ArcView Grid data processed in MIKE Zero toolbox

Processing of Surface Roughness Data

The bed roughness values can be specified as Chezy or Manning numbers in the model. Either a constant value can be used for the whole area or different values for the different Land use can be considered for better simulation. In this study Grid file of the manning number has been created for better simulation.

The satellite imagery of Landsat 8 having 30 m spatial resolution was merged with 15 m panchromatic band to develop 15m spatial resolution multispectral image by data fusion through PCA in ArcGIS. The 15 m multispectral image then classifiesd using isodata clustering technique of unsupervised data classification through multivariate analysis. 50

classes were made with the aid of Dendogram. Reclassification into seven classes namely, water bodies, forest, built up, Mangroves, fallow land and lastly roads consisting of primary, secondary, tertiary and link roads obtened from OSM metro extract was prcessed in ArcGIS. The water bodies and road network shapefiles being in vector format were converted to raster format using polygon to raster tool and merged with the classified image in ArcGIS. These seven classes were then allotted the manning's coefficient. Roughness coefficients represent the roughness of the surface in channels and flood plains.

The results of Manning's formula, an indirect computation of stream flow, have applications in flood-plain management, in flood insurance studies, and in the design of bridges and highways across flood plains.

Manning's Equation

$$V = \frac{R^{2/3} S^{1/2}}{n}$$

Where,

V is Average velocity (m/s)

R is Hydraulic radius (m)

S is Energy slope (m/m)

n is Manning's roughness coefficient

The land use land cover classification consisting of seven classes were converted to ASCII format. The tool Grd2MIKE was used to convert the ASCII file to dfs2 file which can be used in MIKE21. LULC data file processed in ArcGIS is used to create Gridded data for the bed roughness. Different manning number values are assigned for different land cover. The recommended manning number values for different land cover is given bellow in table.

MIKE 21 HD SIMULATION

The hydrodynamic model in the MIKE 21 Flow Model (MIKE 21 HD) is a general numerical modelling system for the simulation of water levels and flows in estuaries, bays and coastal areas. The model has been used successfully in overland flow modelling for flood plain applications. It simulates unsteady two dimensional flows in one layer (vertically homogeneous) fluids and has been applied in a large number of studies. The model is based on the very basic mass balance equation and conservation of momentum equation. These two equations together, describe the flow and water level variations. These equations are in the form of Saint Venant equation used in MIKE 21. (DHI, 2011).

In MIKE 21 flow model simulation two type of model parameterization is required. First, the basic parameters which include selection of models, Bathymetry data, Simulation Period, Boundary conditions, defining Source and Sink in the model, Mass Budget and flood and dry depth as per the application. The other is hydrodynamic parameters like The MIKE 21 hydrodynamic (HD) module is a mathematical modelling system for calculation of the hydrodynamic behavior of water in response to a variety of forcing functions, e.g. specified wind conditions and prescribed water levels at open model boundaries. (DHI, 2011). The following HD related parameters one has to define to validate and simulate the model; Initial Surface Elevation, Boundary as per the bathymetry, Source and Sink wherever applicable with the discharge value, eddy viscosity, resistance using a constant value or in gridded form, wave radiation and wind conditions. After having all defined parameters HD simulation has been run and resulting flood level maps were generated for selected two rainfall events in every15 minute interval. Also, a maximum flood level map was also generated in the process and the results were analysed for both the events. The complete series of maps are placed in the Annexure section.

Table II Manning Number Value, mcIvor et al. 2012

Surface type	**Manning's n**	**Manning’s Number M = (1/n), [m^(1/3)/s]**
Forests/Tree	0.1	10
Water Bodies	0.04	25
Built up	0.083	12
Mangrroves	0.143	7
Fallow land	0.03	33.3
Roads	0.016	62.5

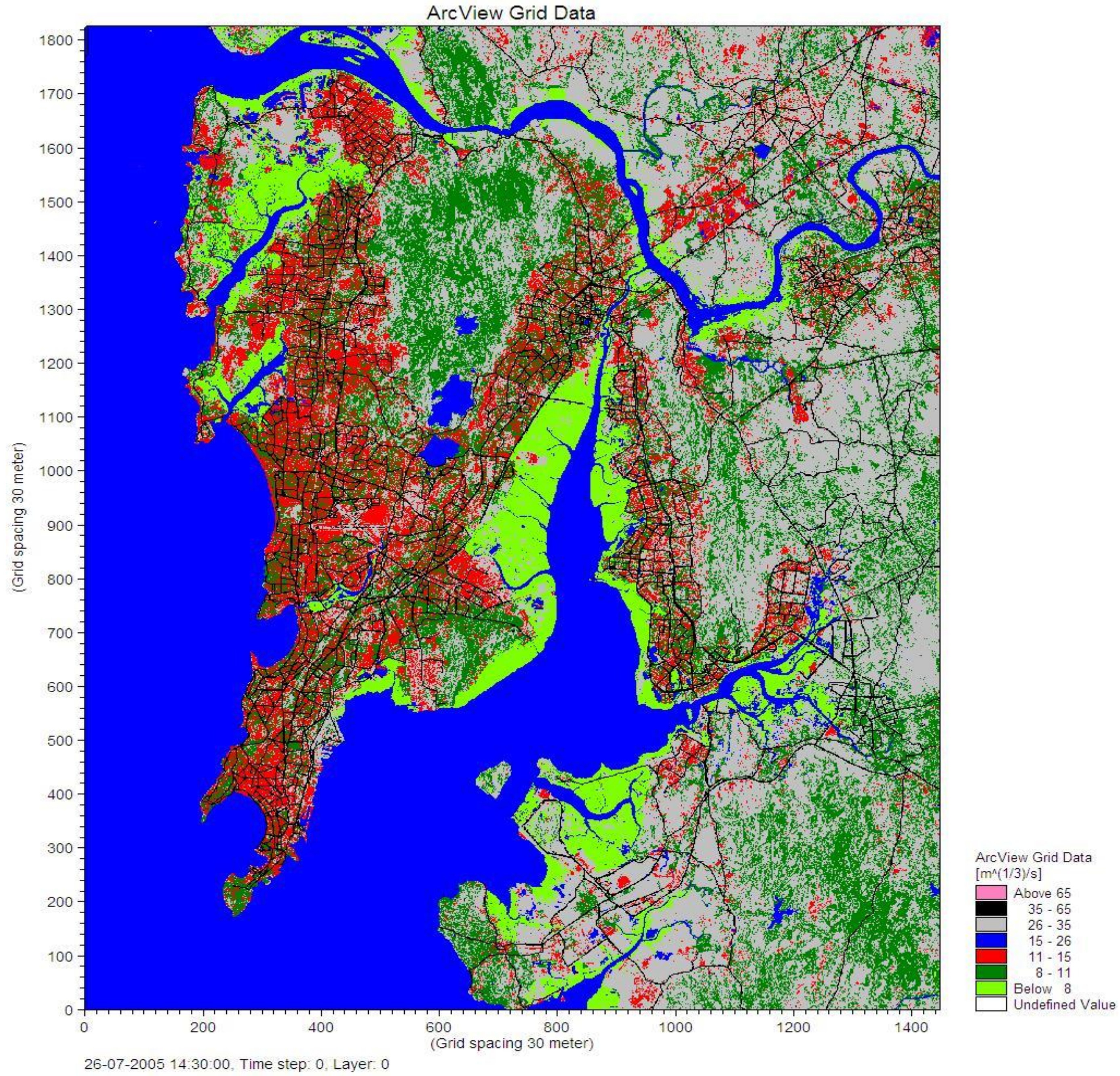


Figure 5 Bed Resistance Map (Manning's number)

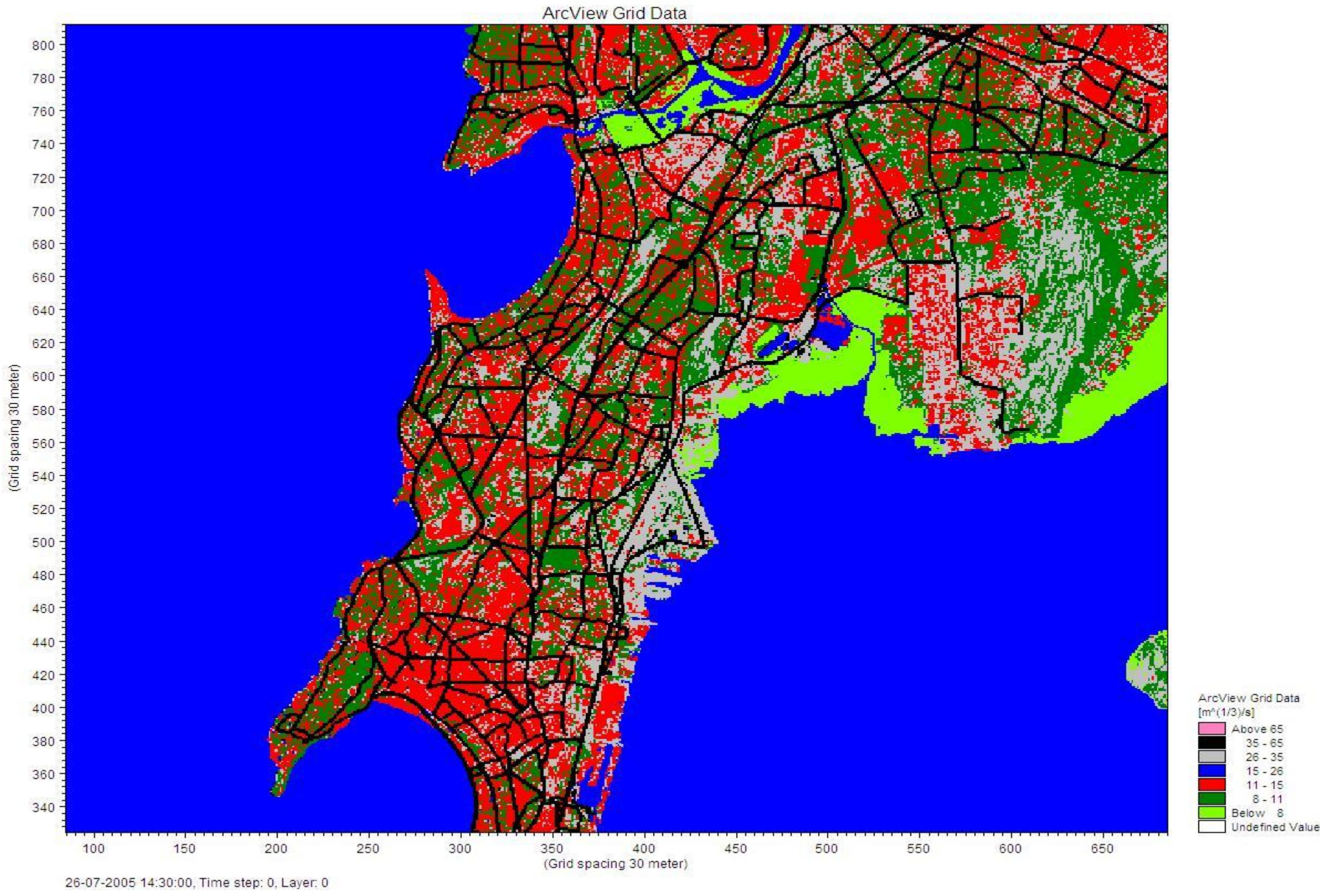


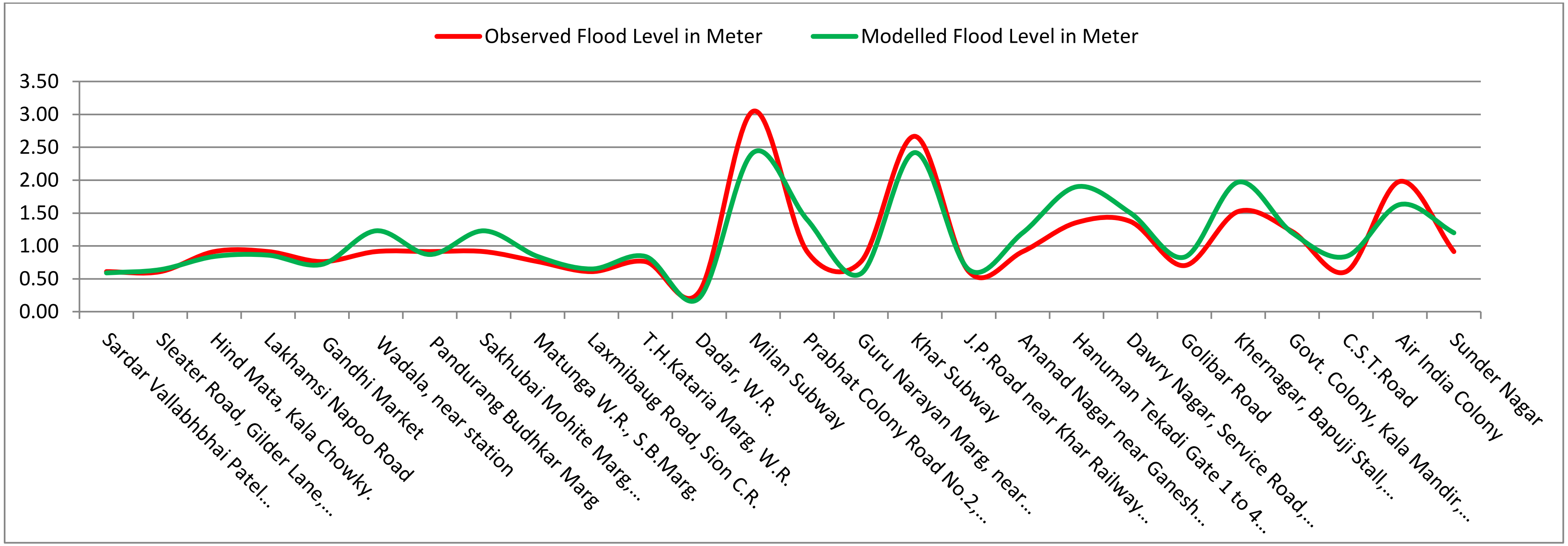
Figure 6 Enlarged Bed Resistance Map (Manning's number)

Wind Data

Wind data is obtained from the Weather Research and Forecasting (WRF) Model, published in 2010 for Mumbai rainfall. The wind condition is considered as a constant value in time and space. From the WRF model the value of wind speed was 15 m/s in 254^0 directions for 2005 events. For other events wind data is collected from the BMC AWS at 15 minute time series format. Evaporation from the surface is considered 5 mm/day for this model. The evaporation data was obtained from the monthly evaporation map prepared for the entire India by IMD. Drainage capacity of the city is taken as 25 mm/hour (Chitale, 2006). Tide data which is an important hydrodynamic parameter for this study is sited from the online data source for Arabian Sea which is recorded on daily basis near Mumbai station.

Model Simulation

Simulation of the model is based on Accuracy analysis. Observed flooded points in Mumbai are taken from the Greater Mumbai Disaster management action plan report and Fact finding committee report Vol 2. 27 flood points were taken for the validation from the different part of the Mumbai which includes slums, roads, junction, subways, railway stations and proper settlements. The figure bellow shows the correlation between modelled vs observed values, with significant accuracy.



Results and analysis

The model is simulated and the results were obtained for every 15 minute interval. The maximum flood level map at the end of the simulation has been analyzed for both the events selected for simulation. Flood map of Greater Mumbai and suburbs has been created and spatial information of flood level is calculated for the entire area of interest. Flood on road networks has been anlysed as per the administrative boundary of various zones of Mumbai.

Resulting Flood maps below shows the spatial information of flood level and extent of flooding both on overland and on road networks. The results indicate that the extent of flooding is wide spread and in some places the water level is alarmingly high. Areas nearby the drainage lines are most affected followed by the road cross sections and low lying areas. The low lying areas are worst flood affected areas both in terms of spatial extent and flood level height.

Maps showing the maximum flood extent over land as well as on road networks in Greater Mumbai and suburbs. Further, the zone wise maps has also been created to provide more details of flood level and its extent.

Rainfall Event of 26 July, 2005

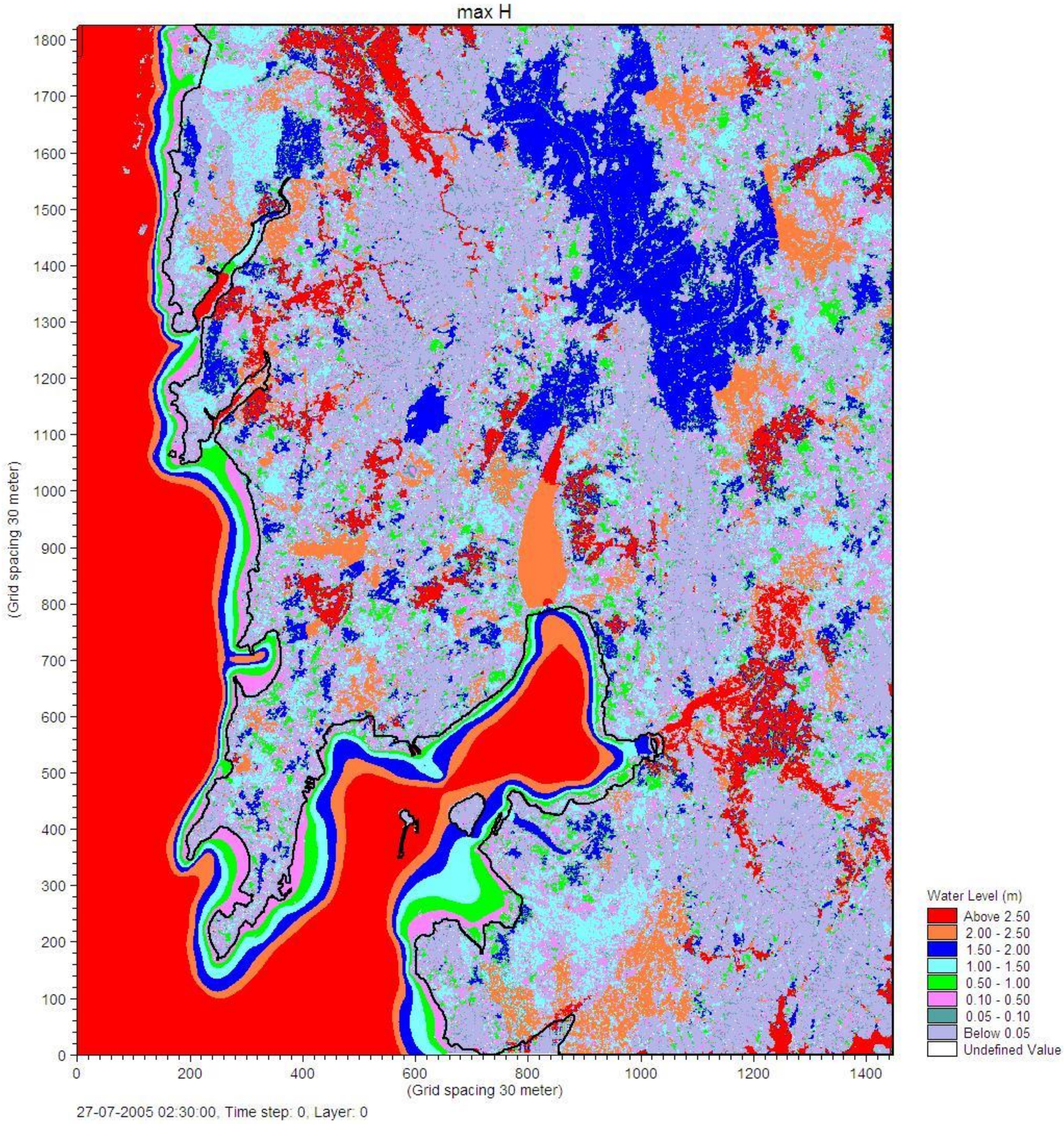


Figure 7 Highest flood level map during 26th July 2005

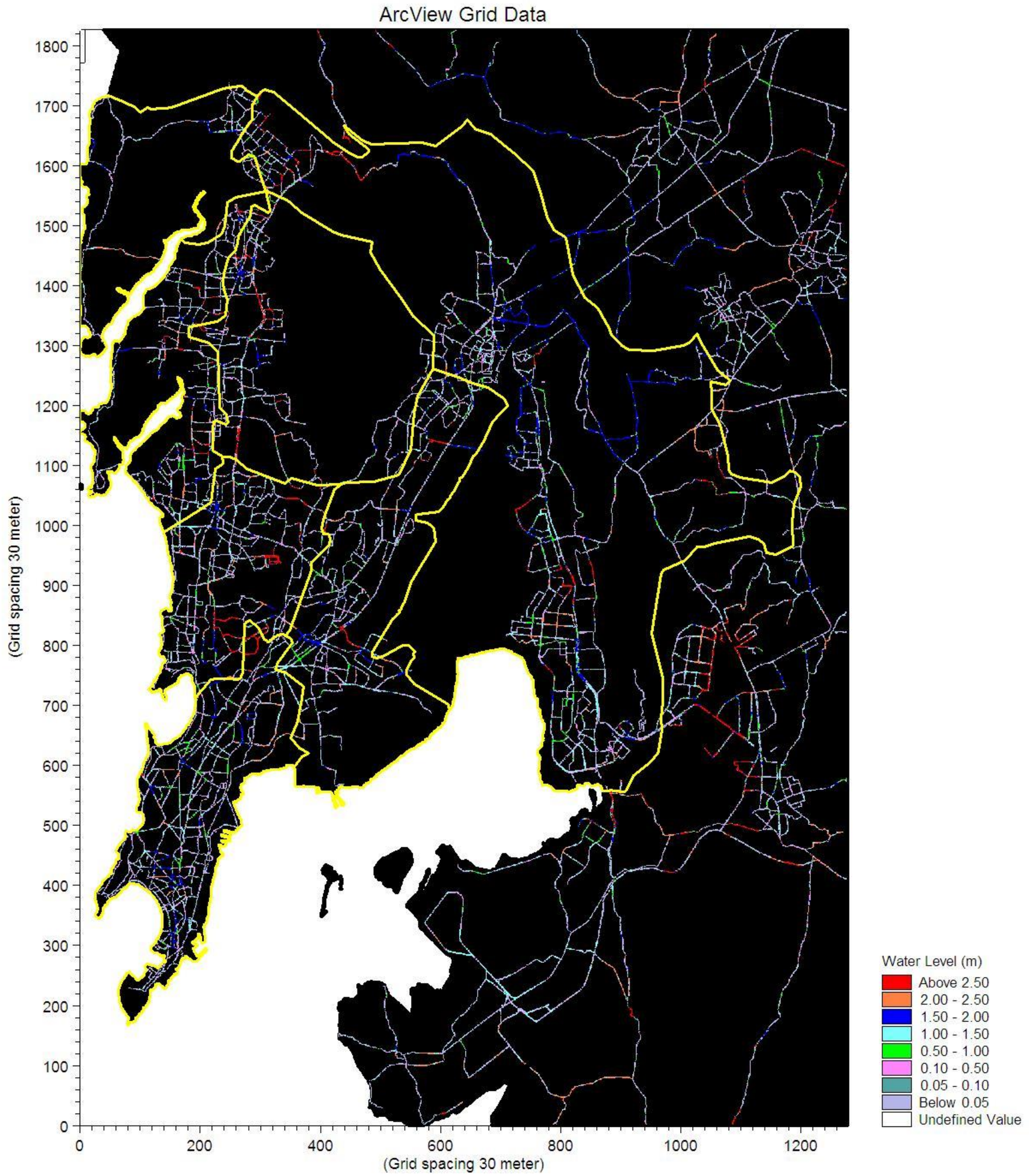


Figure 8 Highest Flood level over road network, 26th July 2005

Zone 1

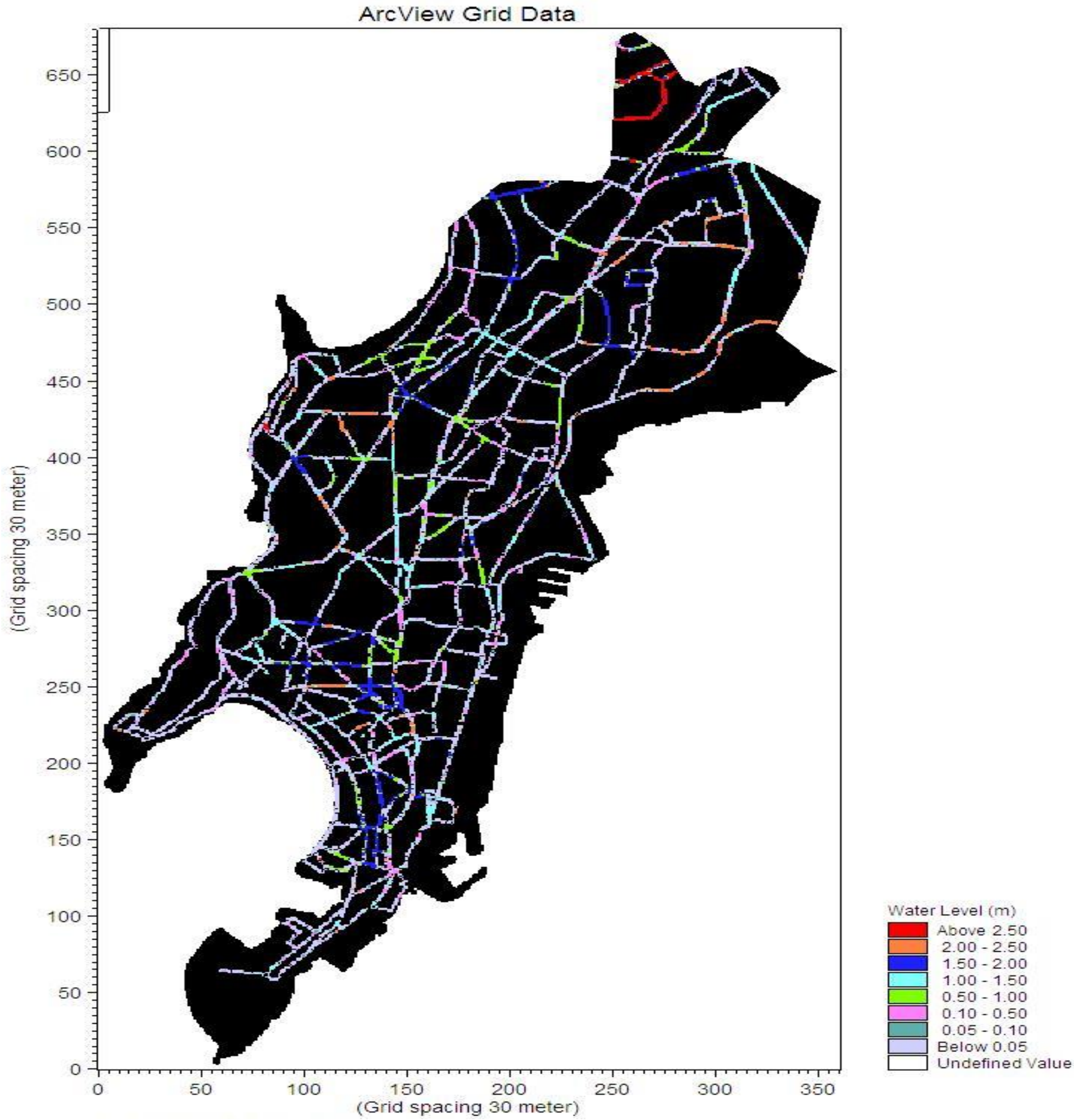
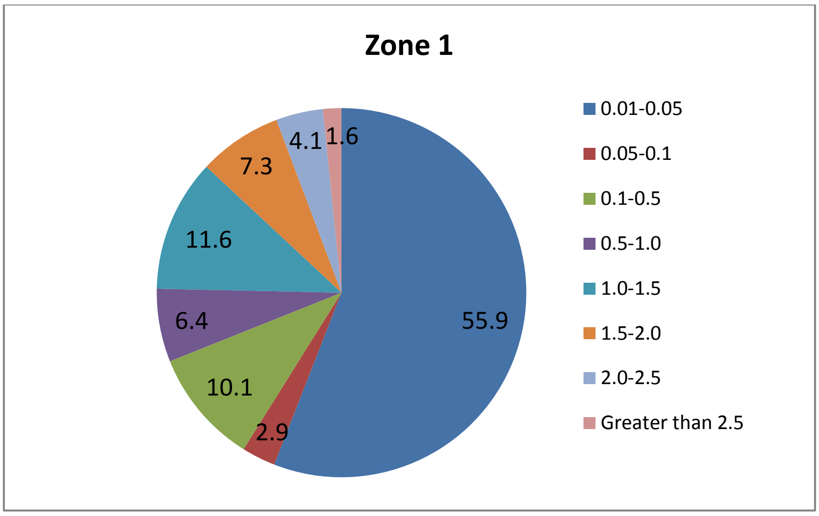


Figure 9 Highest flood level over road network in Zone 1

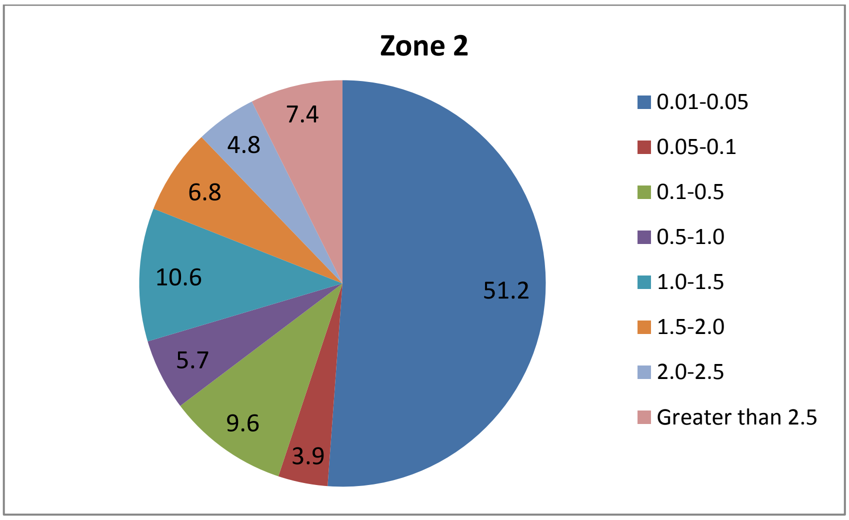
In Mumbai 93% of roads were flooded during the event of 26th July 2005.The Percentage of flooded roads for various zones of Mumbai is illustrated below:



Zone 1 of Mumbai recorded 55.9 % of road length to be flooded in the range 0.01-0.05m water level which can be considered unde no flood areas, followed by 2.9% and 10.1% of flooded road length in the range 0.05-0.1 and 0.1-0.5 respectively. 6.4% of flooded road length are in the range of 0.5-1m water level. 11.6 % road length were flooded in the range of 1.0-1.5m water level. The water level ranging from 1.5m and above constitutes about 13.1% of flooded road length.

Zone 2

Zone 2 of Mumbai recorded 51.2 % of road length to be flooded in the range 0.01-0.05m water level which can be considered unde no flood areas, followed by 3.9 % and 9.6% of flooded road length in the range 0.05-0.1 and 0.1-0.5 respectively. 5.7% of flooded road length are in the range of 0.5-1m water level. The maximum flooded road length of 10.6% was recorded in the range of 1.0-1.5m water level. The water level greater than 1.5 m has flooded road length of 19%.



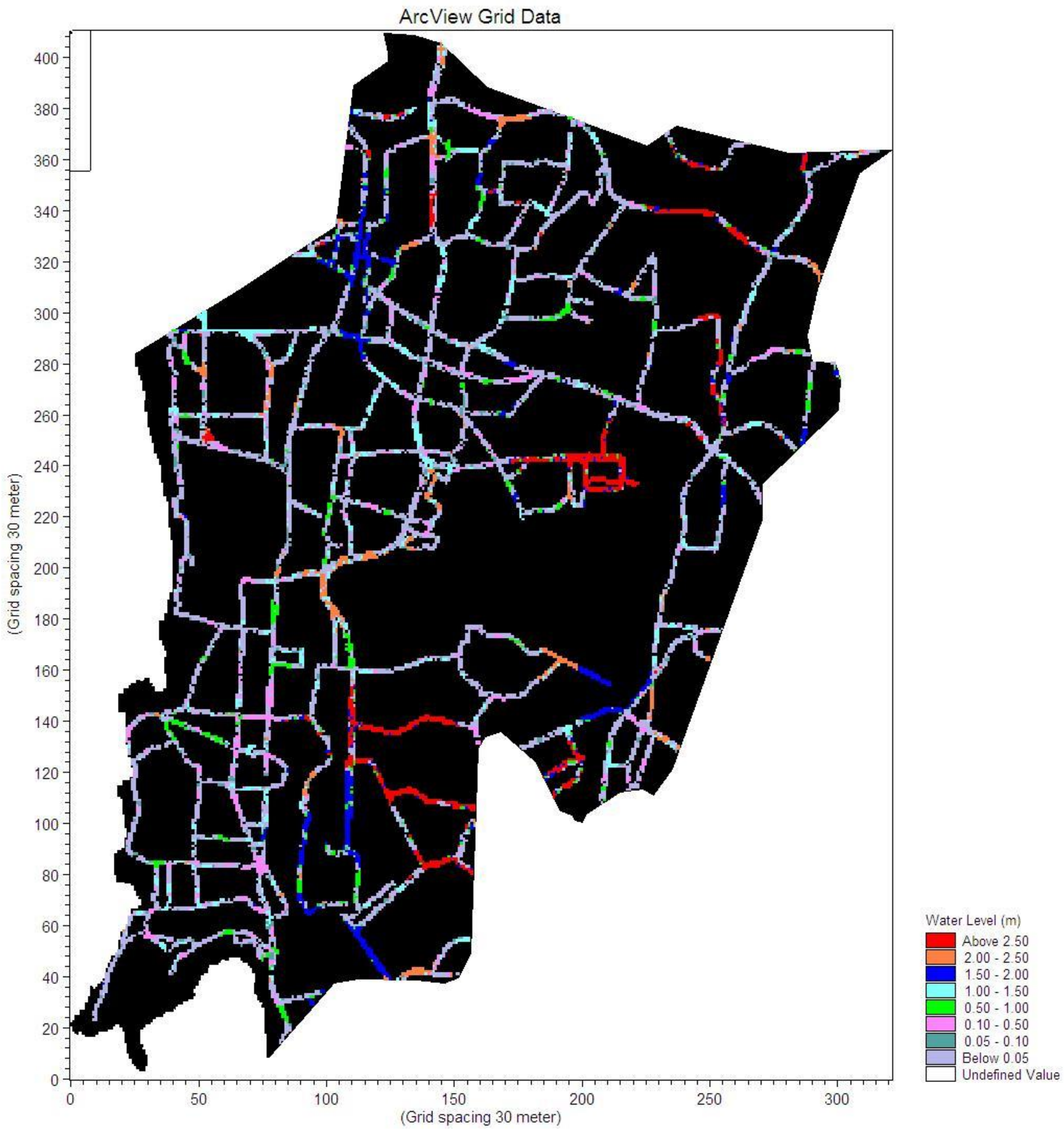
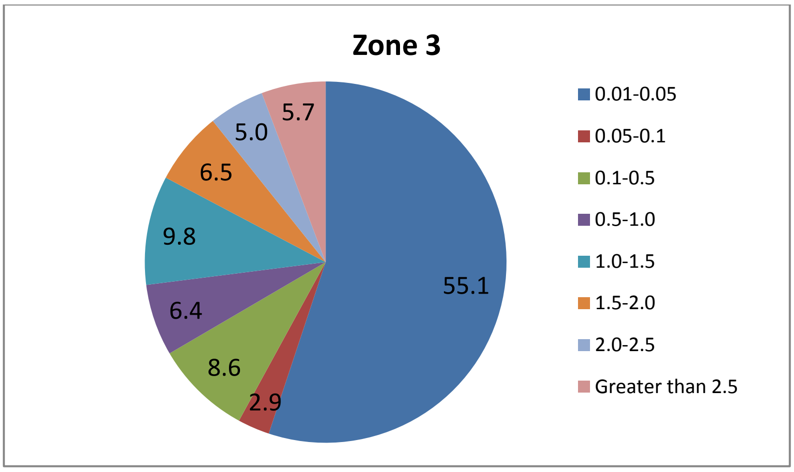


Figure 10 Highest flood level over road network in Zone 2

Zone 3

Zone 3 of Mumbai recorded 55.1 % of road length to be flooded in the range 0.01-0.05m water level which can be considered under no flood areas, followed by 2.9 % and 8.6% of flooded road length in the range 0.05-0.1 and 0.1-0.5 respectively. 6.4% of flooded road length are in the range of 0.5-1m water level. The maximum flooded road length of 9.8% was recorded in the range 1.0-1.5m water level. The water level ranging from 1.5m and above constitutes about 17.3% of flooded road length.



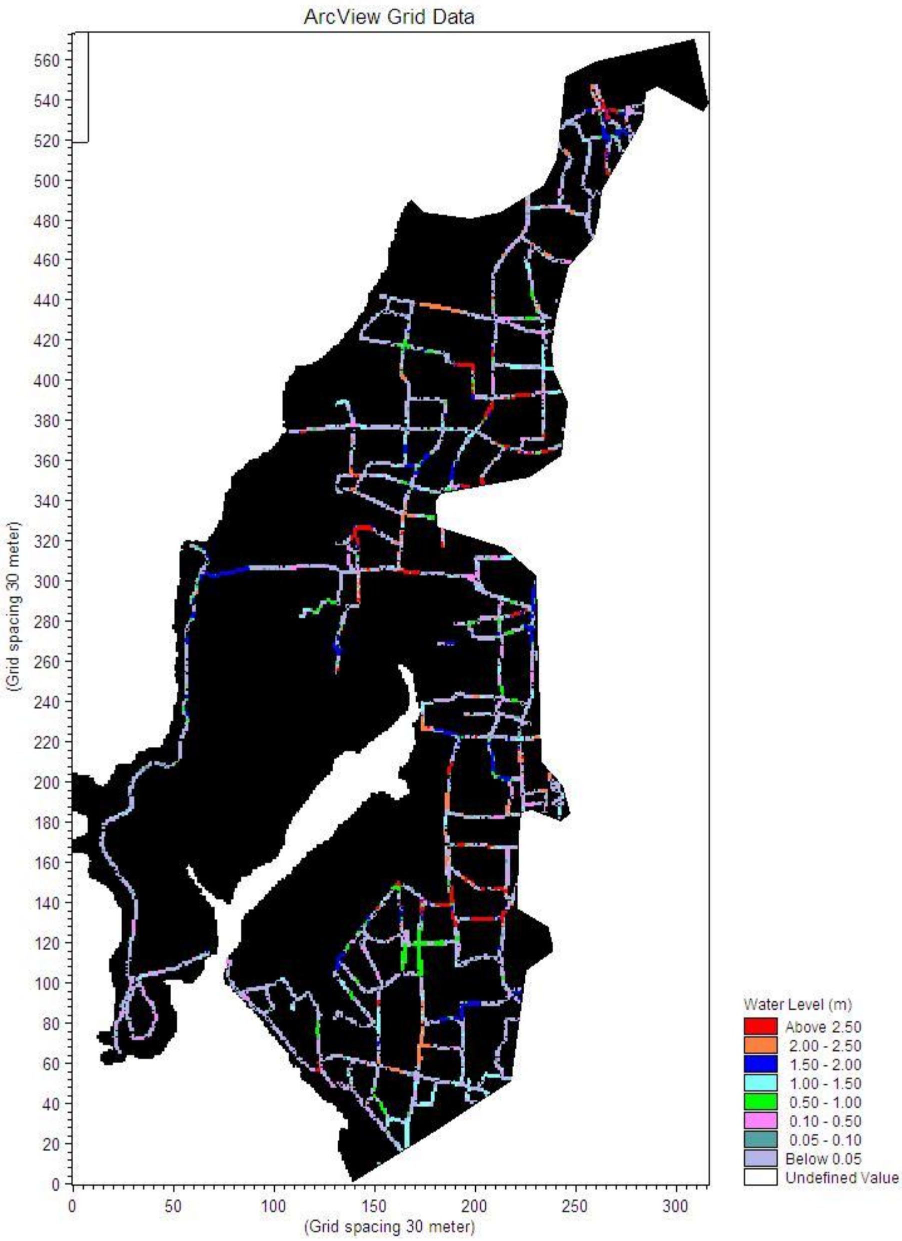


Figure 11 Highest flood level over road network in Zone 3

Zone 4

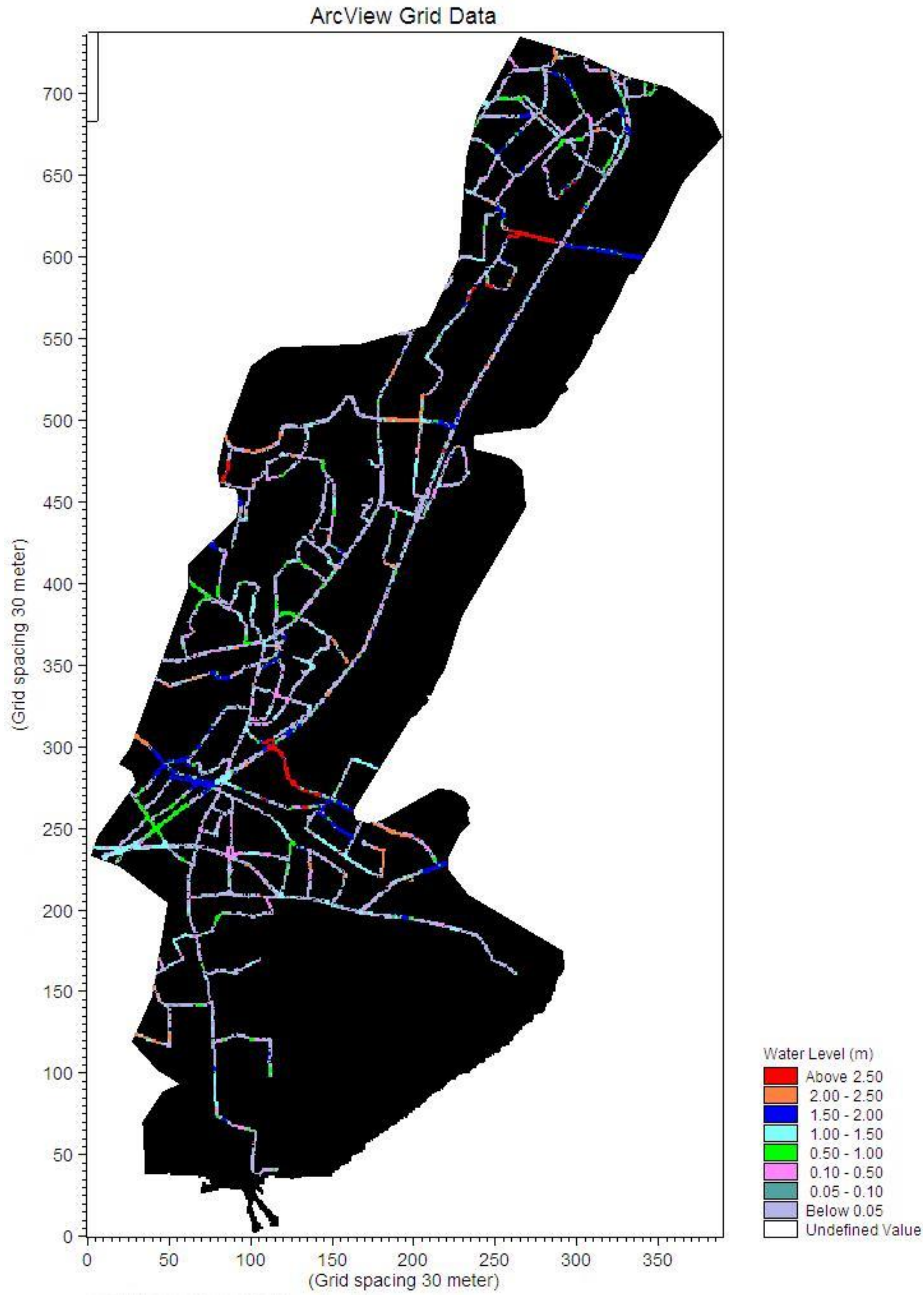
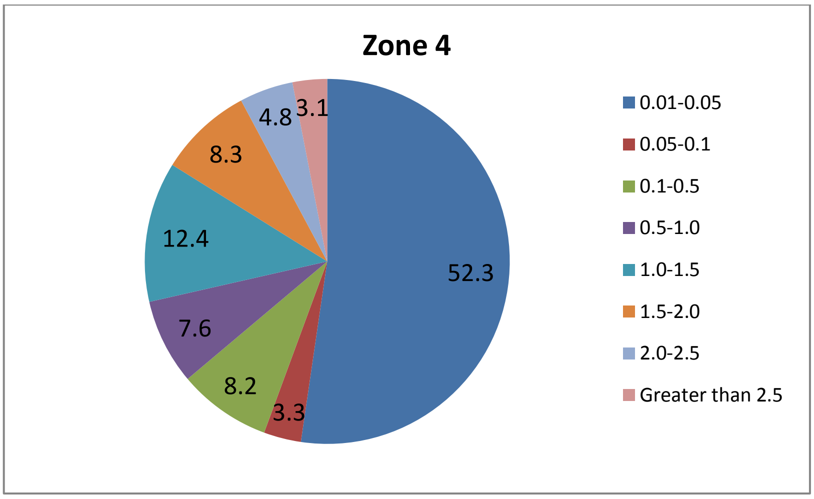


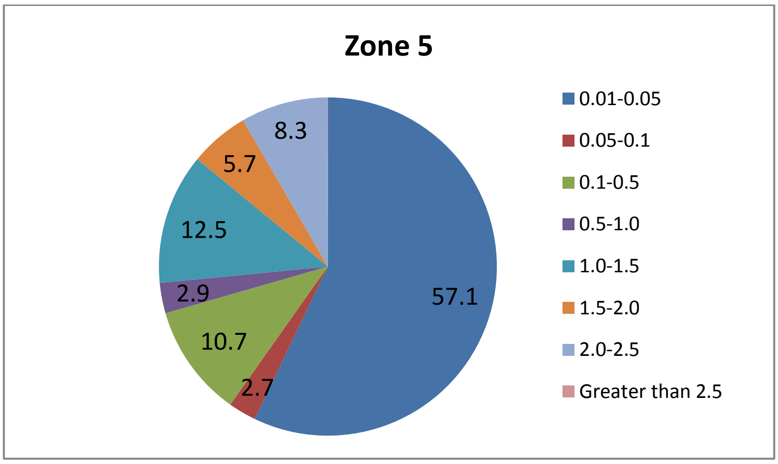
Figure 12 Highest flood level over road network in Zone 4

Zone 4 of Mumbai recorded 52.3 % of road length to be flooded in the range 0.01-0.05m water level which can be considered under no flood areas, followed by 3.3 % and 8.2% of flooded road length in the range 0.05-0.1 and 0.1-0.5 respectively. 7.6% of flooded road length are in the range of 0.5-1m water level. The maximum flooded road length of 12.4%

was recorded in the range 1.0-1.5m water level. The water level ranging from 1.5m and above constitutes about 16.1% of flooded road length.



Zone 5



Zone 5 of Mumbai recorded 57.1 % of road length to be flooded in the range 0.01-0.05m water level followed by 2.7 % and 10.7% of flooded road length in the range 0.05-0.1 and 0.1-0.5 respectively. 2.9% of flooded road length are in the range of 0.5-1m water level. The maximum flooded road length of 12.5% was recorded in the range 1.0-1.5m water level. The water level greater than 1.5m constitutes about 14.1% of flooded road length.

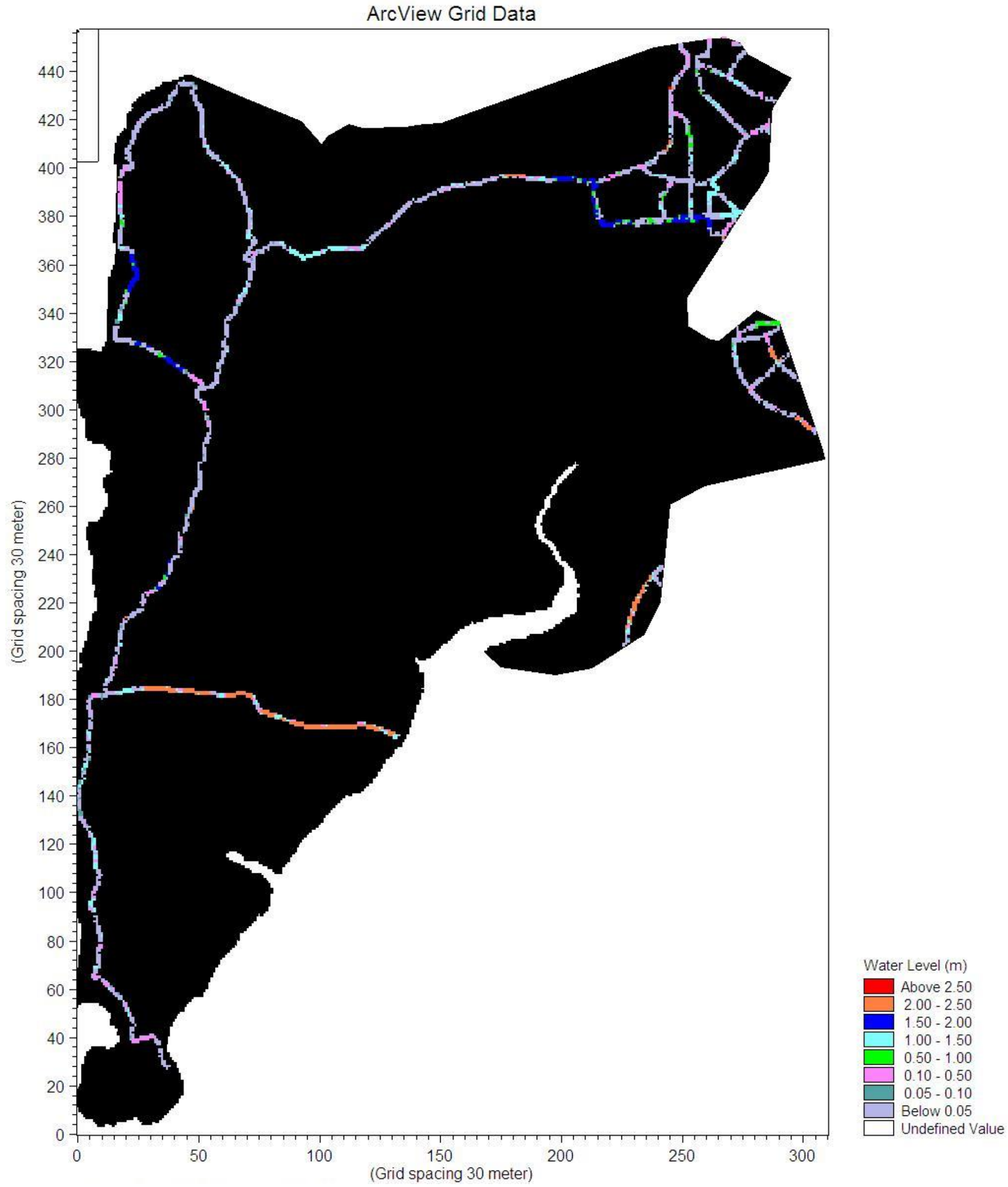
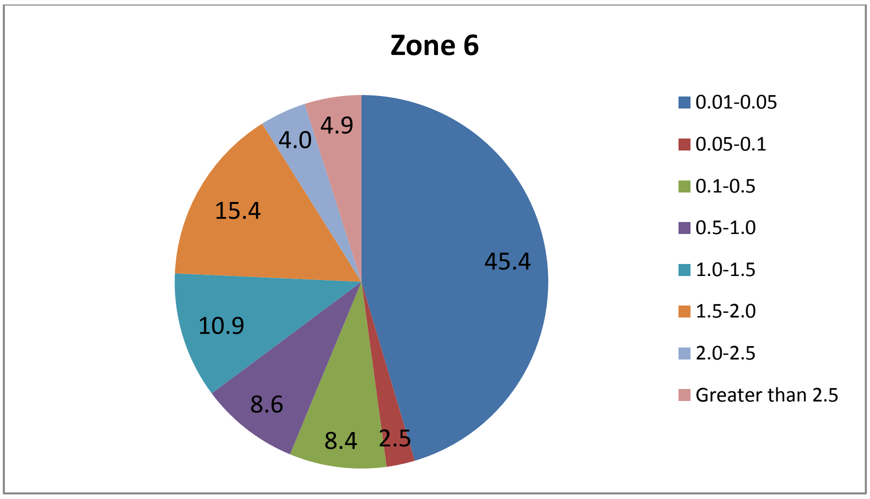


Figure 13 Highest flood level over road network in Zone 5

Zone 6

Zone 6 of Mumbai recorded 45.4 % of road length to be flooded in the range 0.01-0.05m water level which can be considered under no flood areas, followed by 2.5% and 8.4% of flooded road length in the range 0.05-0.1 and 0.1-0.5 respectively. 8.6% of flooded road length are in the range of 0.5-1m water level. The maximum flooded road length of 15.4% was recorded in the range 1.5-2.0m water level and was preceded by 10.9% of flooded road length in the range 1.0-1.5m of water level. The water level ranging from 1.5m and above constitutes about 24.3% of flooded road length.



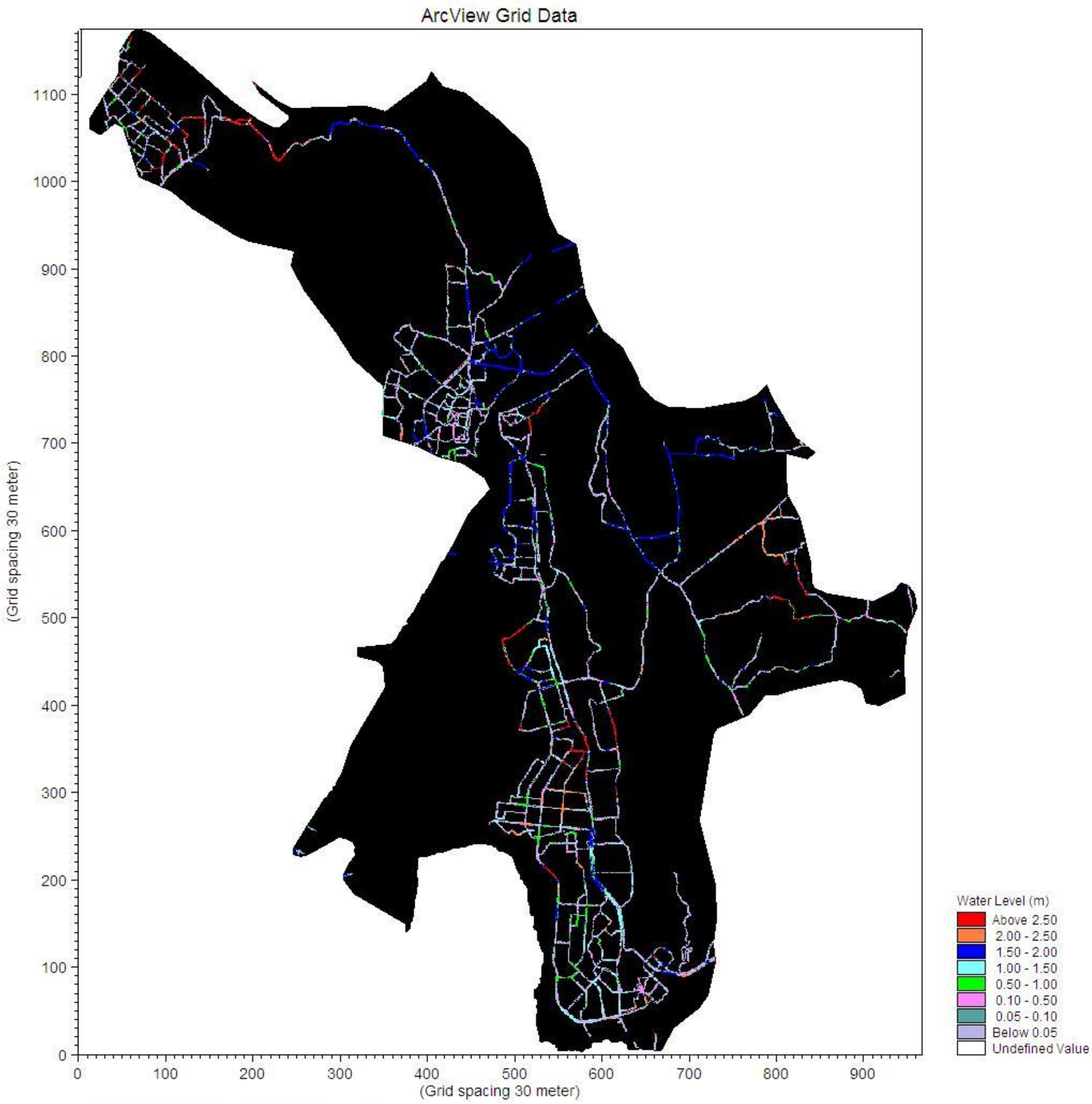


Figure 14 Highest flood level over road network in Zone 6

Rainfall Event of 30 June 2007

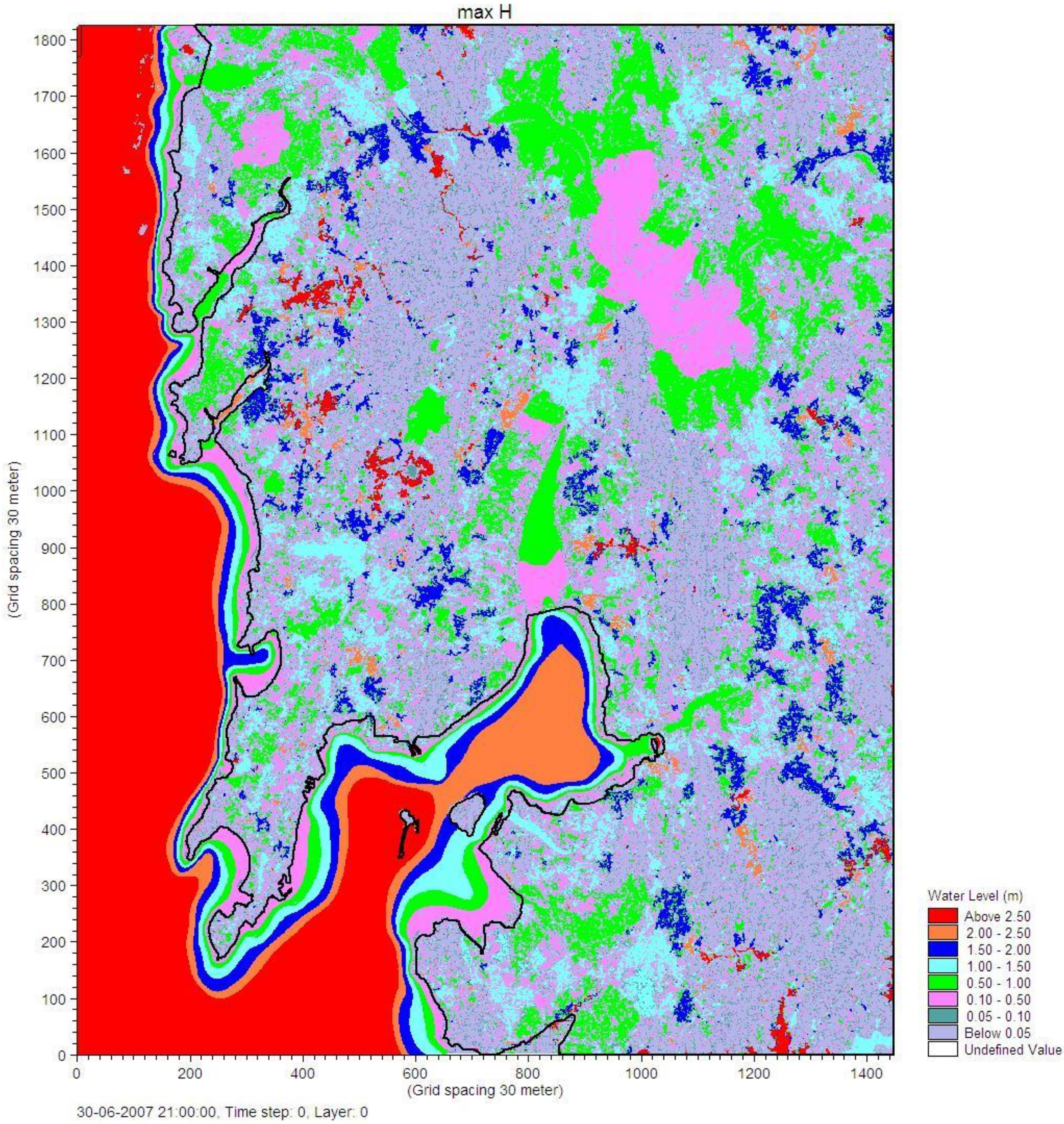


Figure 15 Highest flood level map during 30th June, 2007

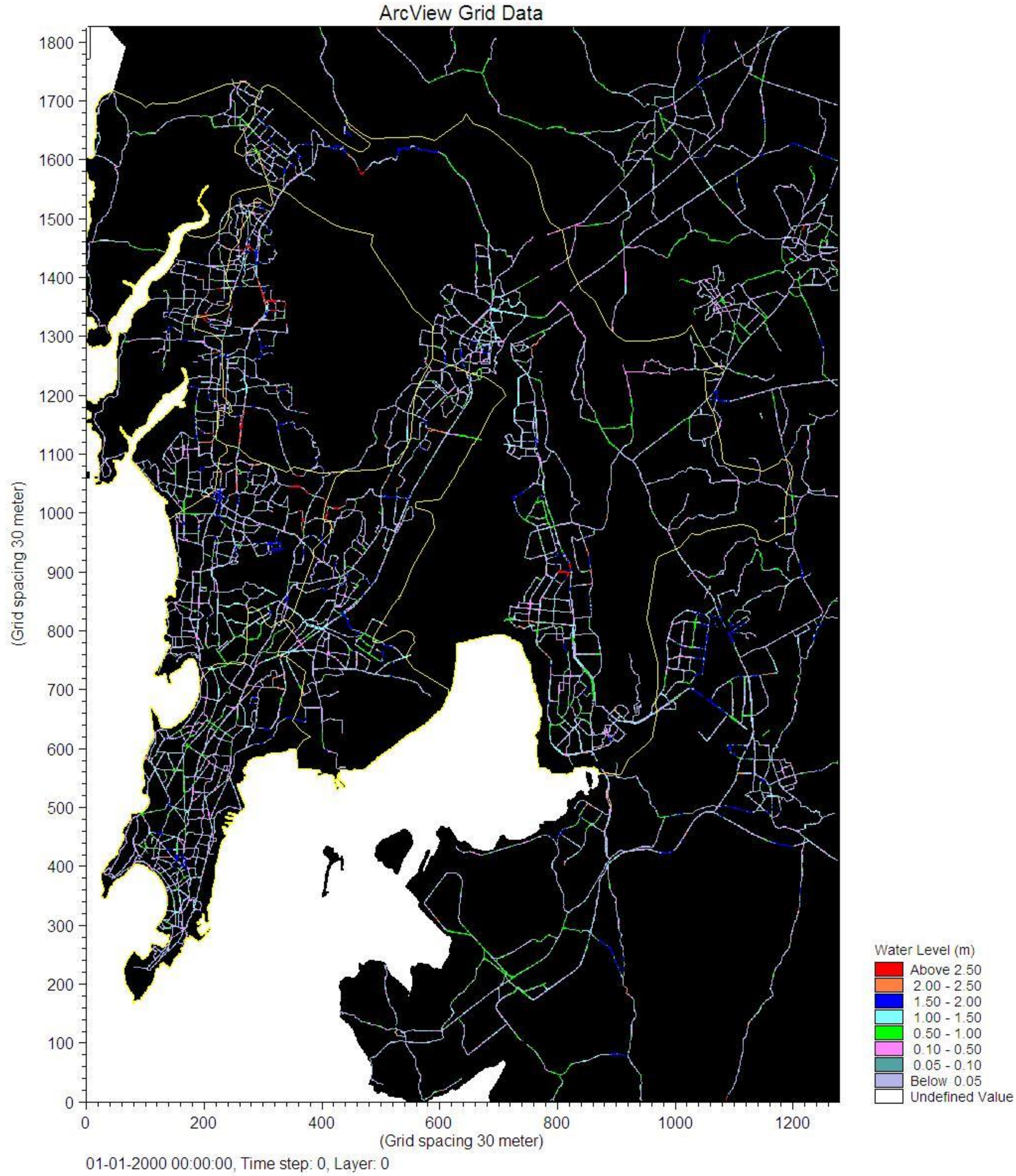


Figure 16 Highest Flood level over road network, 30th June 2007

In Mumbai 99.9% of road length were flooded during the event of 30th June, 2007.The Percentage of flooded roads for various zones of Mumbai is illustrated below:

Zone 1

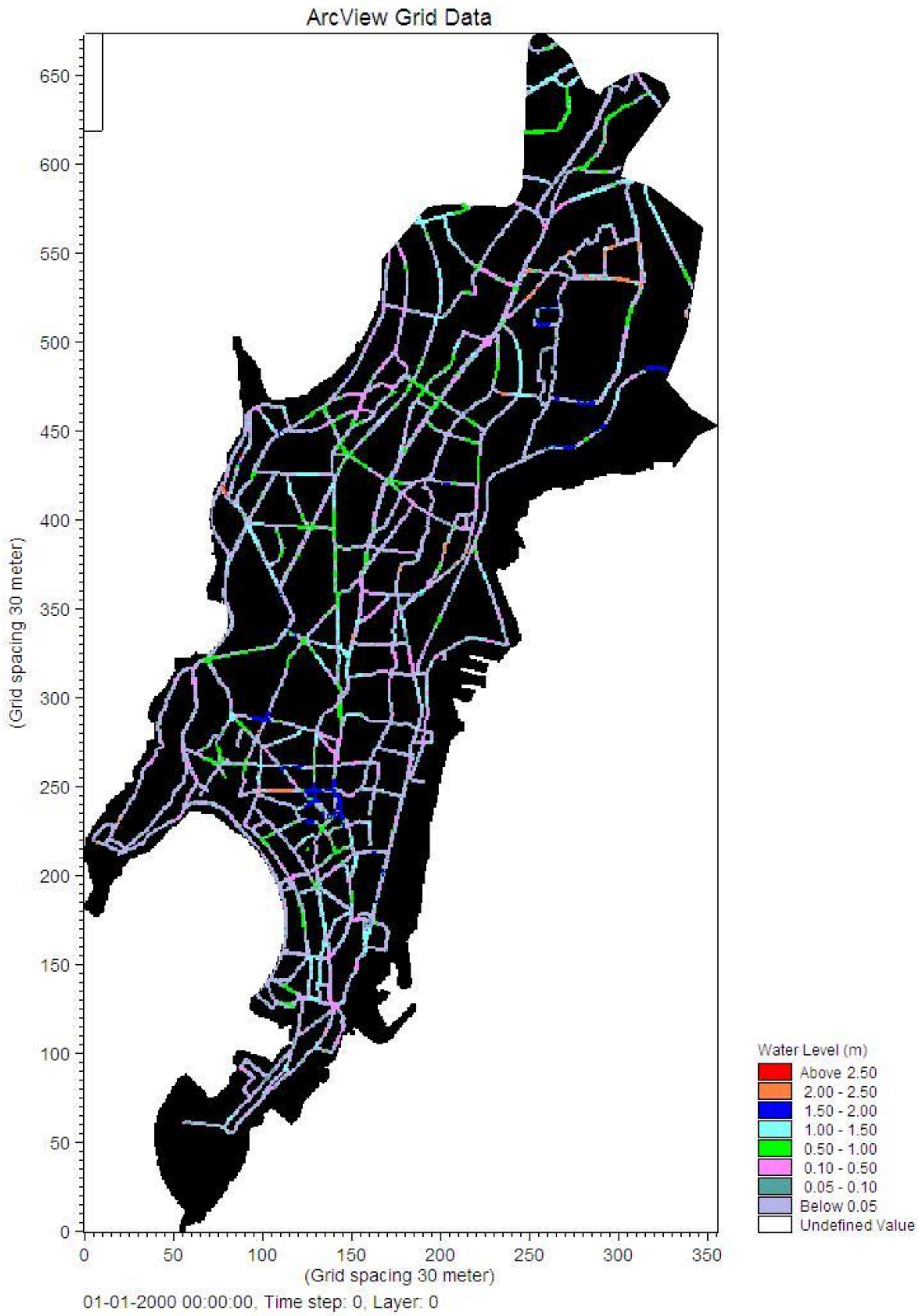
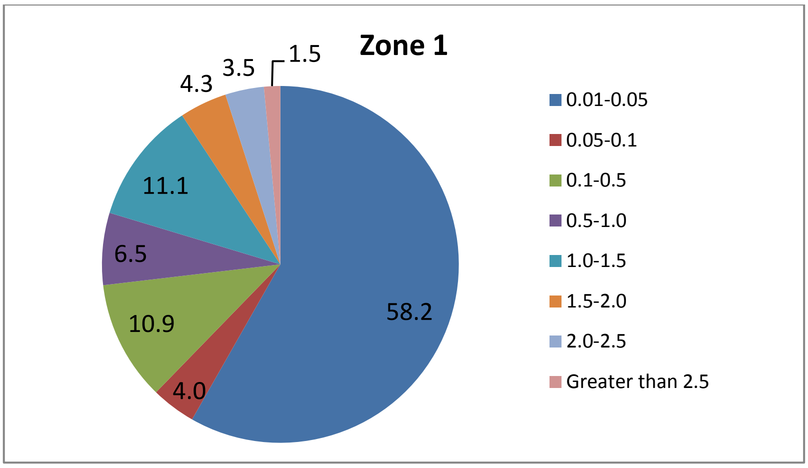
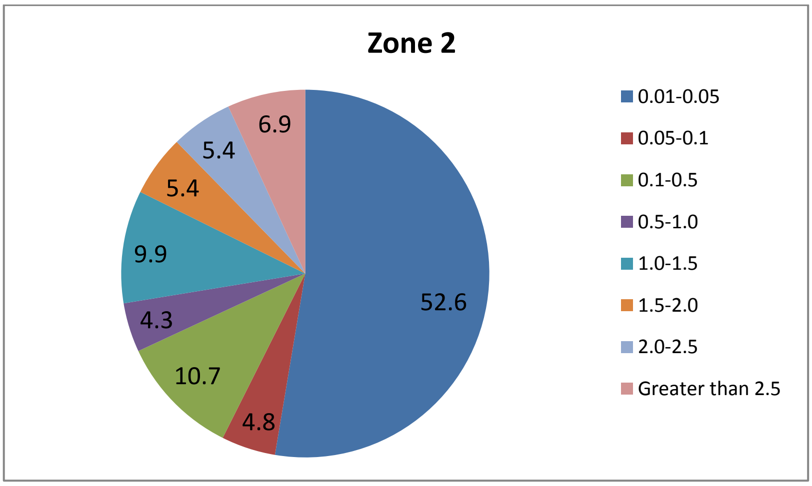


Figure 17 Highest flood level over road network in Zone 1



Zone 1 of Mumbai recorded 58.2 % of road length to be flooded in the range 0.01-0.05m water level followed by 4% and 10.9% of flooded road length in the range 0.05-0.1 and 0.1-0.5 respectively. 6.5% of flooded road length are in the range of 0.5-1m water level. The flooded road length of 11.1% was recorded in the range 1.0-1.5m water level. The water level ranging from 1.5m and above constitutes about 9.3% of flooded road length.

Zone 2



Zone 2 of Mumbai recorded 52.6 % of road length to be flooded in the range 0.01-0.05m water level which can be considered under no flood areas, followed by 4.8% and 10.7% of flooded road length in the range 0.05-0.1 and 0.1-0.5 respectively. 4.3% of flooded road length are in the range of 0.5-1m water level. The flooded road length of 9.9% was recorded in the range 1.0-1.5m water level. The water level ranging from 1.5m and above constitutes about 17.7% of flooded road length.

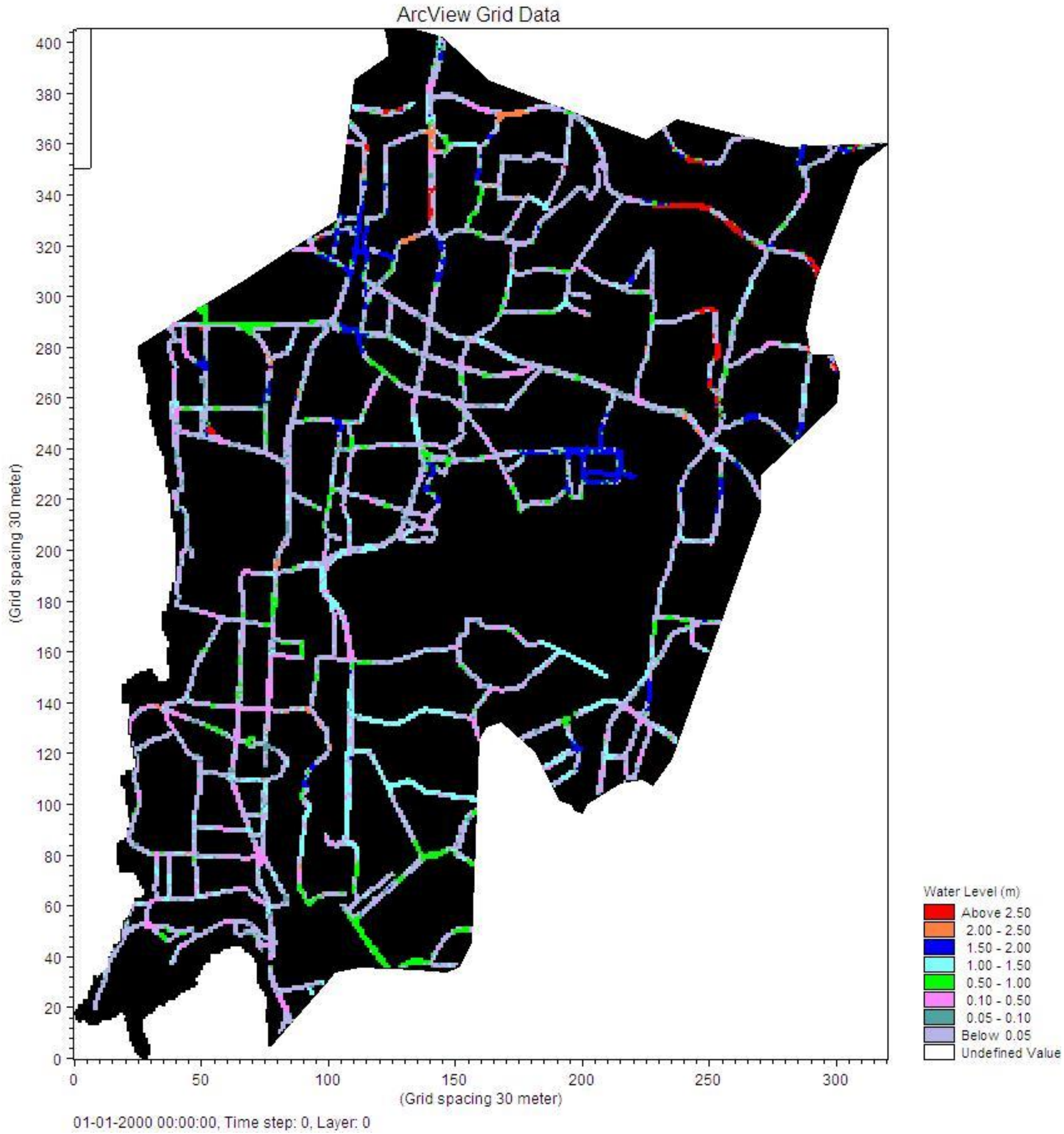


Figure 18 Highest flood level over road network in Zone 2

Zone 3

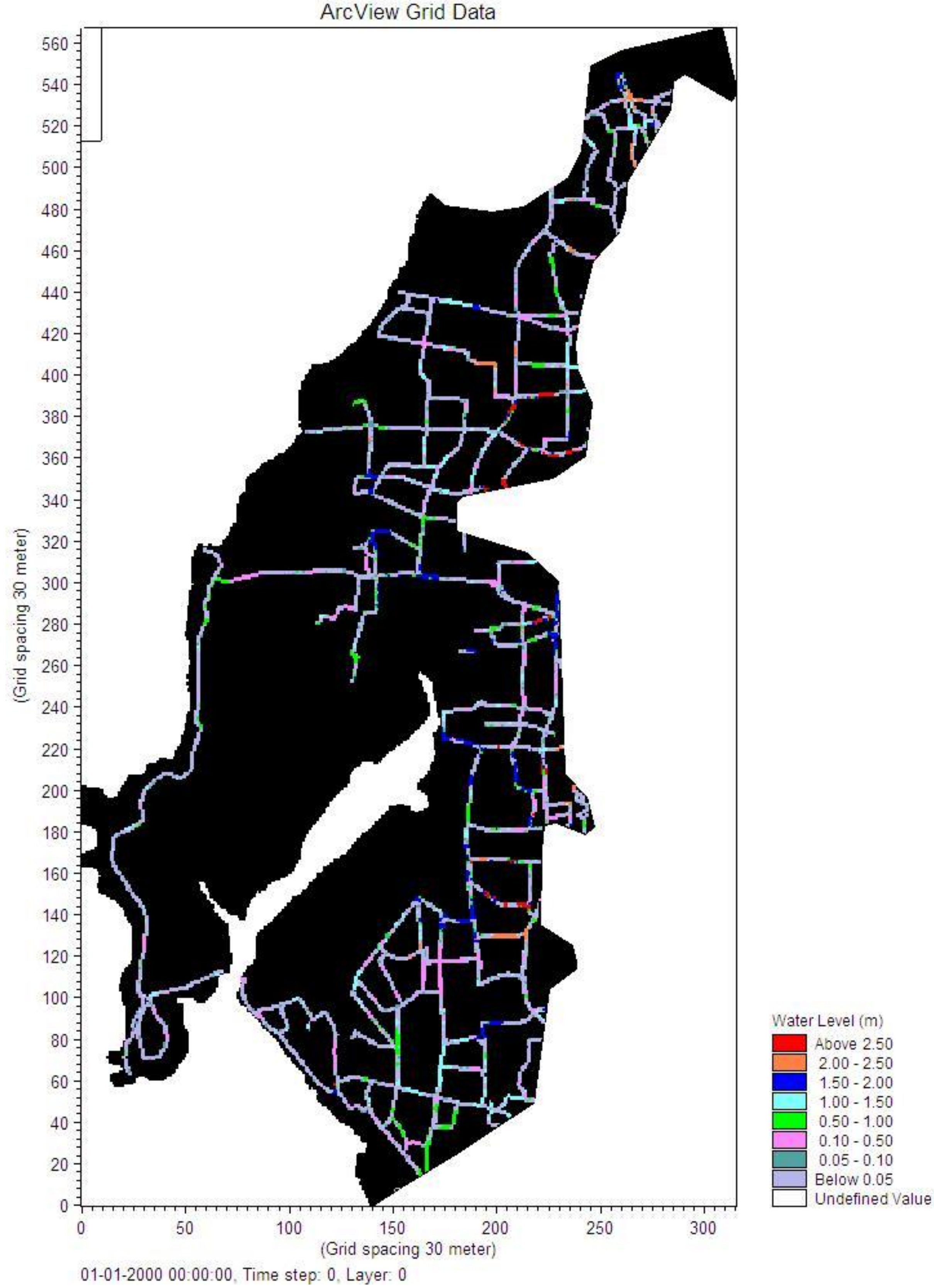
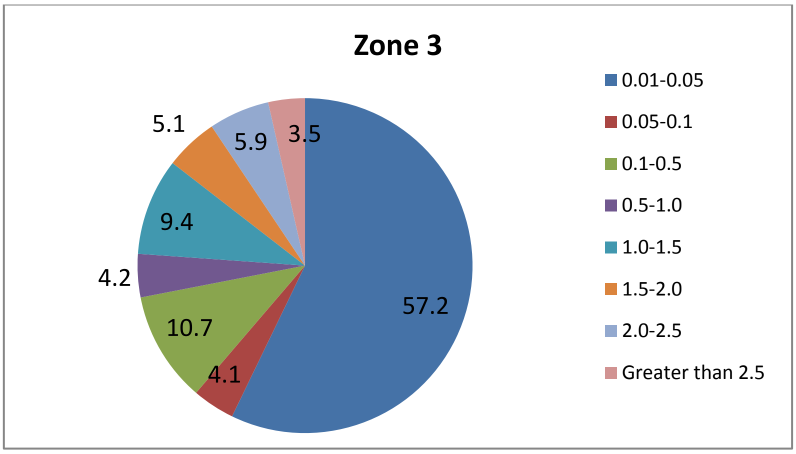
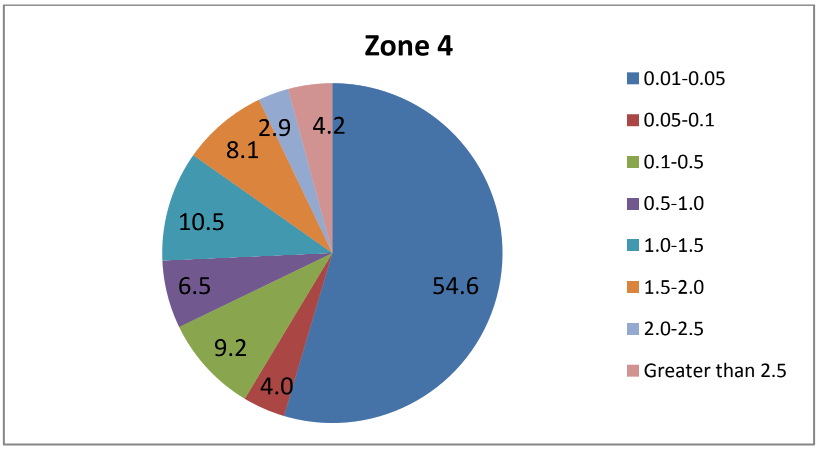


Figure 19 Highest flood level over road network in Zone 3



Zone 3 of Mumbai recorded 57.2 % of road length to be flooded in the range 0.01-0.05m water level which can be considered under no flood areas, followed by 4.1% and 10.7% of flooded road length in the range 0.05-0.1 and 0.1-0.5 respectively. 4.2% of flooded road length are in the range of 0.5-1m water level. The flooded road length of 9.4% was recorded in the range 1.0-1.5m water level. The water level ranging from 1.5m and above constitutes about 14.5% of flooded road length.

Zone 4



Zone 4 of Mumbai recorded 54.6 % of road length to be flooded in the range 0.01-0.05m water level which can be considered under no flood areas, followed by 4% and 9.2% of flooded road length in the range 0.05-0.1 and 0.1-0.5 respectively. 6.5% of flooded road length are in the range of 0.5-1m water level. The maximum flooded road length of 10.5% was recorded in the range 1.0-1.5m water level. The water level ranging from 1.5m and above constitutes about 15.2% of flooded road length.

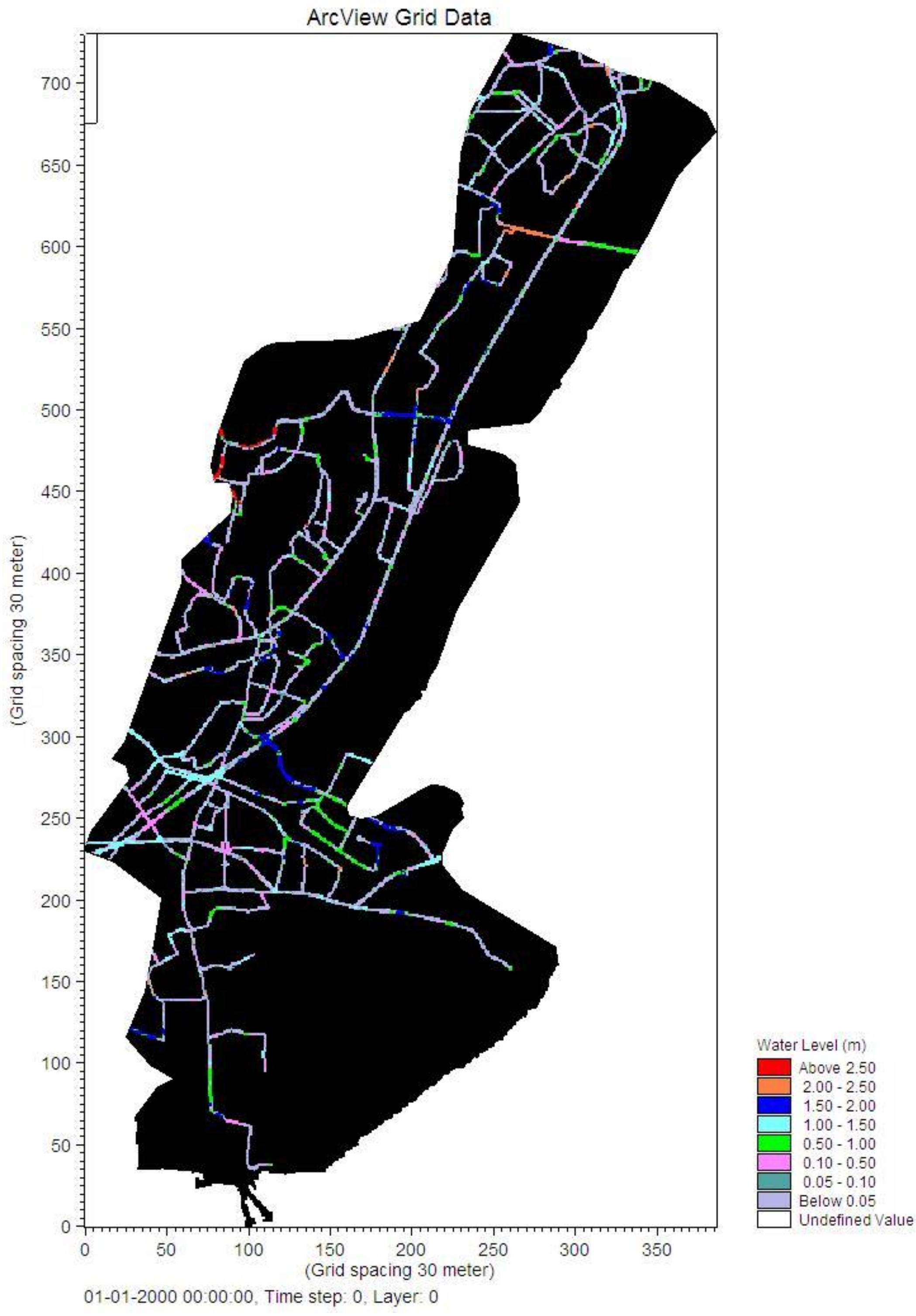


Figure 20 Highest flood level over road network in Zone 4

Zone 5

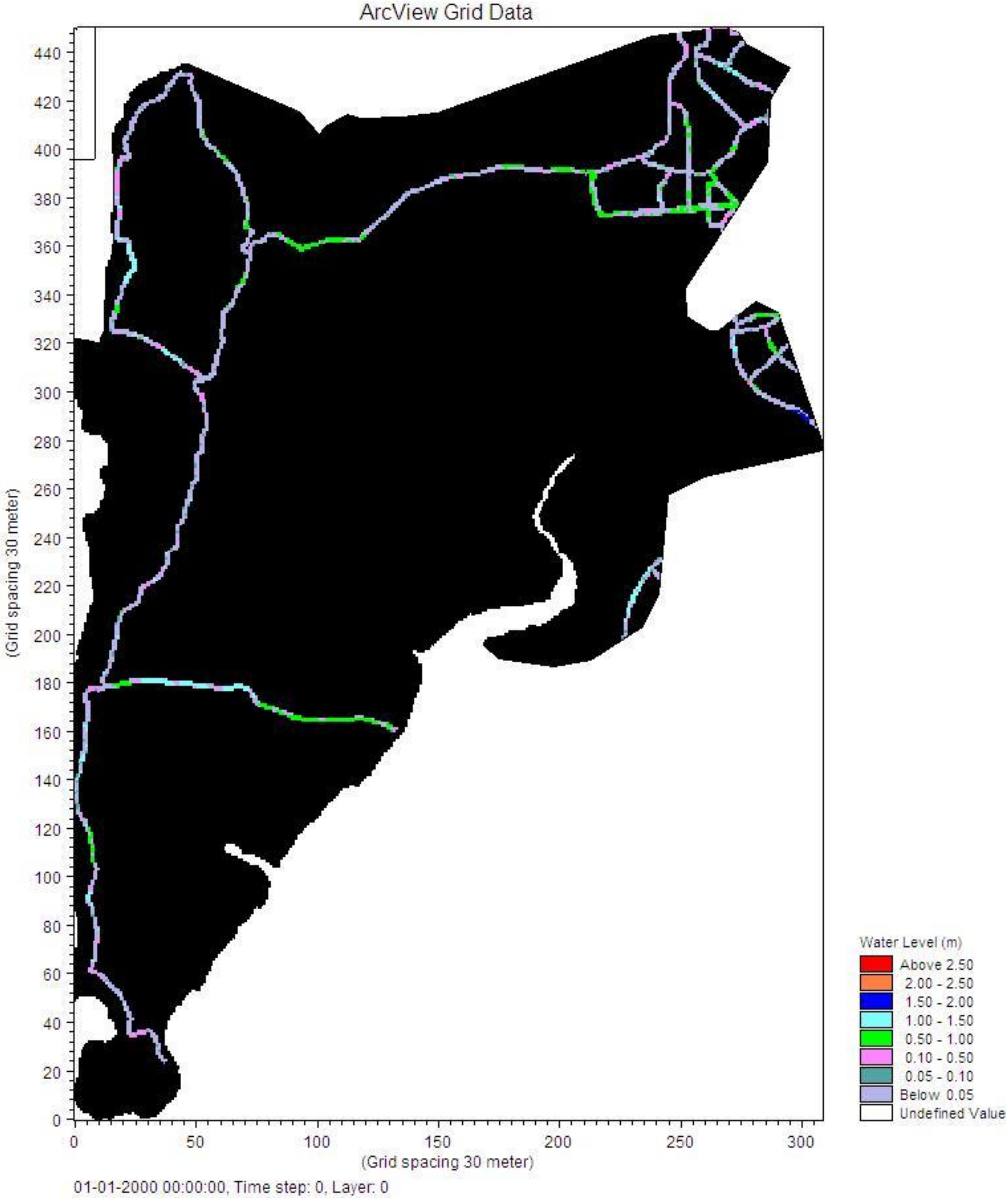
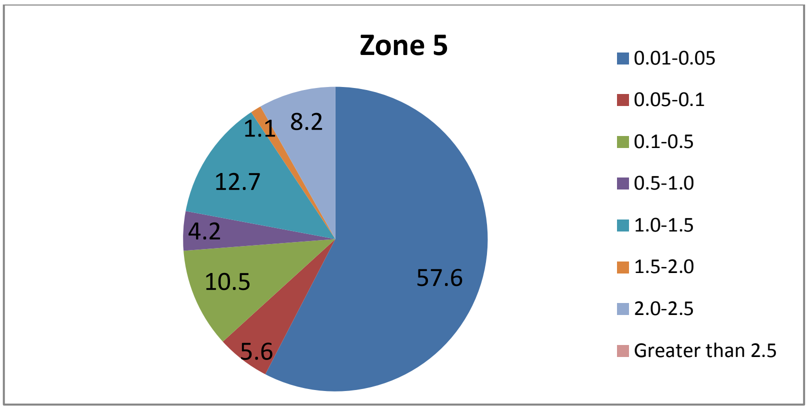
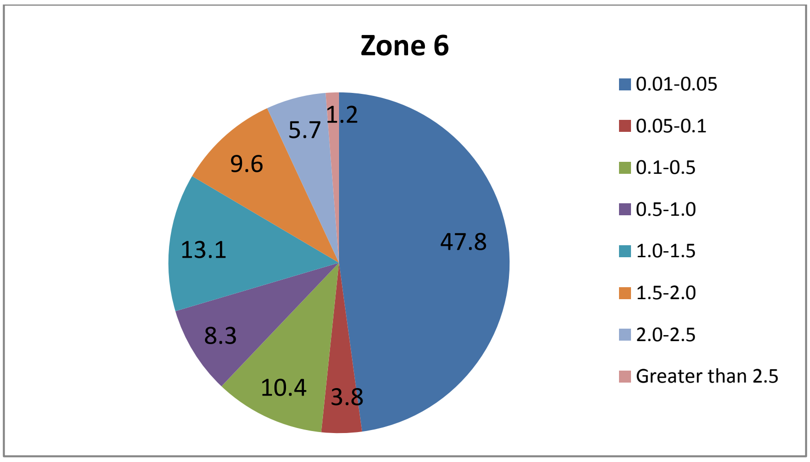


Figure 21 Highest flood level over road network in Zone 5



Zone 5 of Mumbai recorded 57.6 % of road length to be flooded in the range 0.01-0.05m water level followed by 5.6% and 10.5% of flooded road length in the range 0.05-0.1 and 0.1-0.5 respectively. 4.2% of flooded road length are in the range of 0.5-1m water level. The flooded road length of 12.7% was recorded in the range 1.0-1.5m water level. The water level ranging from 1.5m and above constitutes about 9.3% of flooded road length.

Zone 6



Zone 6 of Mumbai recorded 47.8 % of road length to be flooded in the range 0.01-0.05m water level which can be considered under no flood areas, followed by 3.8% and 10.4% of flooded road length in the range 0.05-0.1 and 0.1-0.5 respectively. 8.3% of flooded road length are in the range of 0.5-1m water level. The maximum flooded road length of 13.1% was recorded in the range 1.0-1.5m water level. The water level ranging from 1.5m and above constitutes about 16.5% of flooded road length.

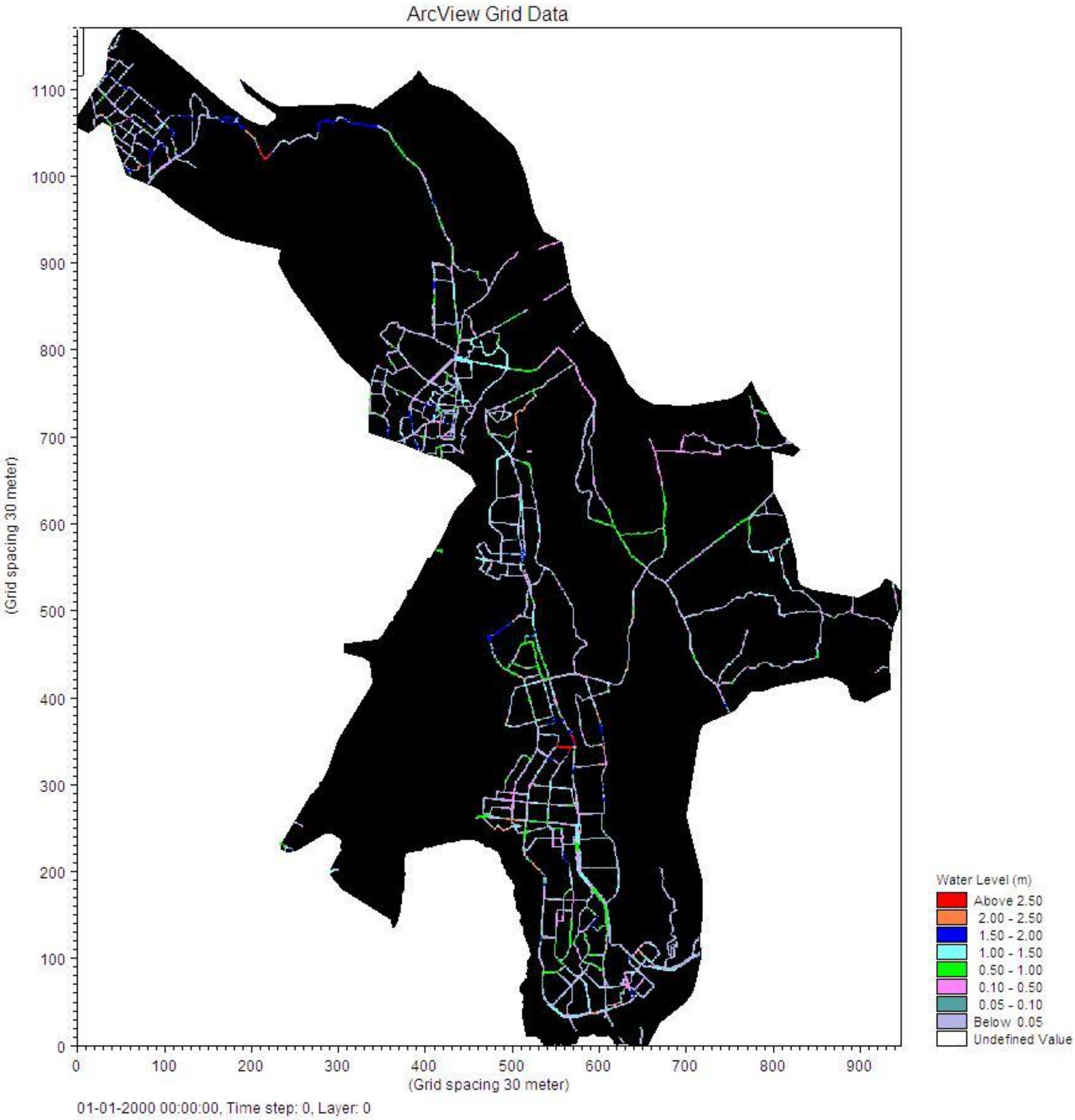


Figure 22 Highest flood level over road network in Zone 6

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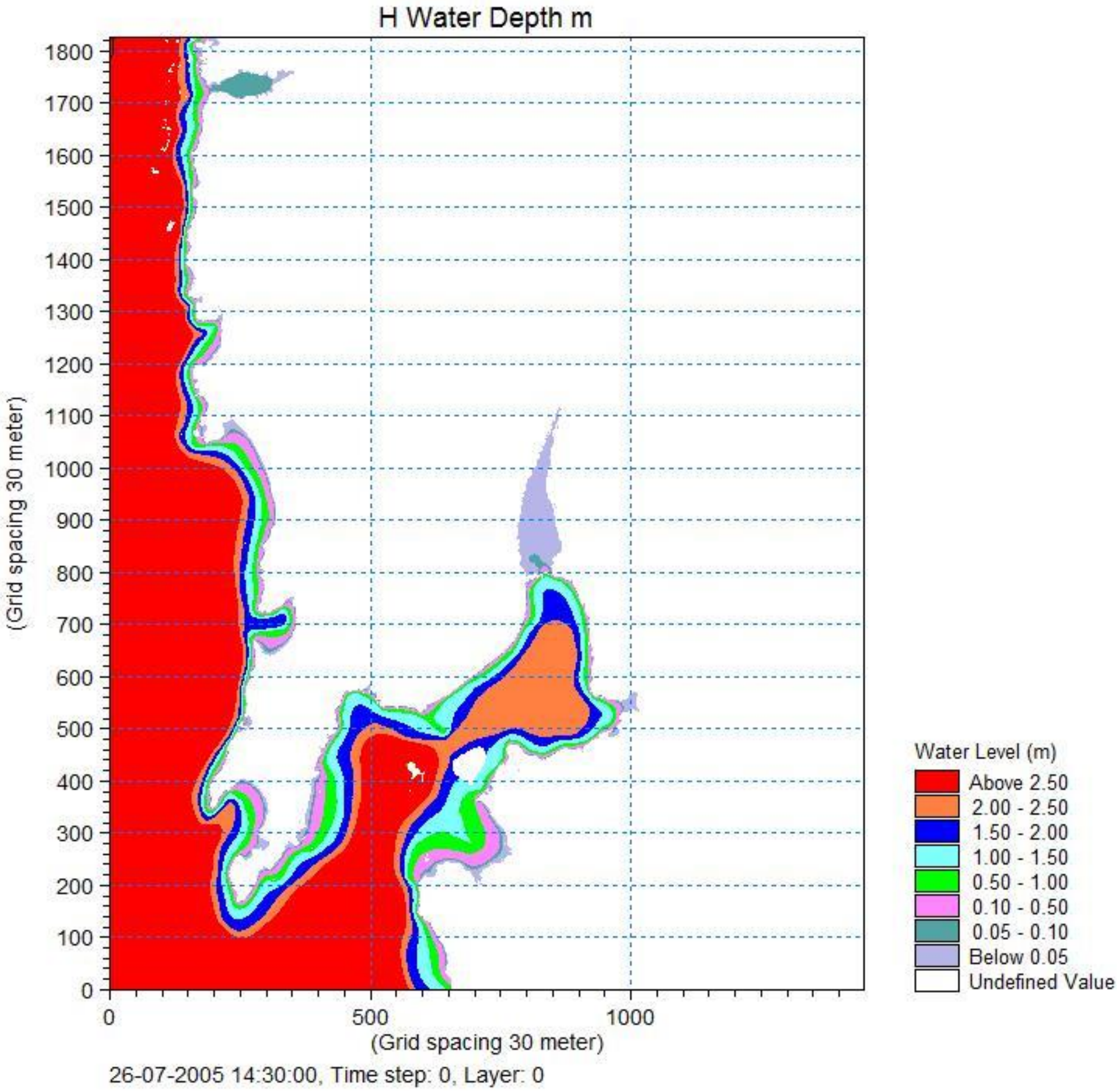
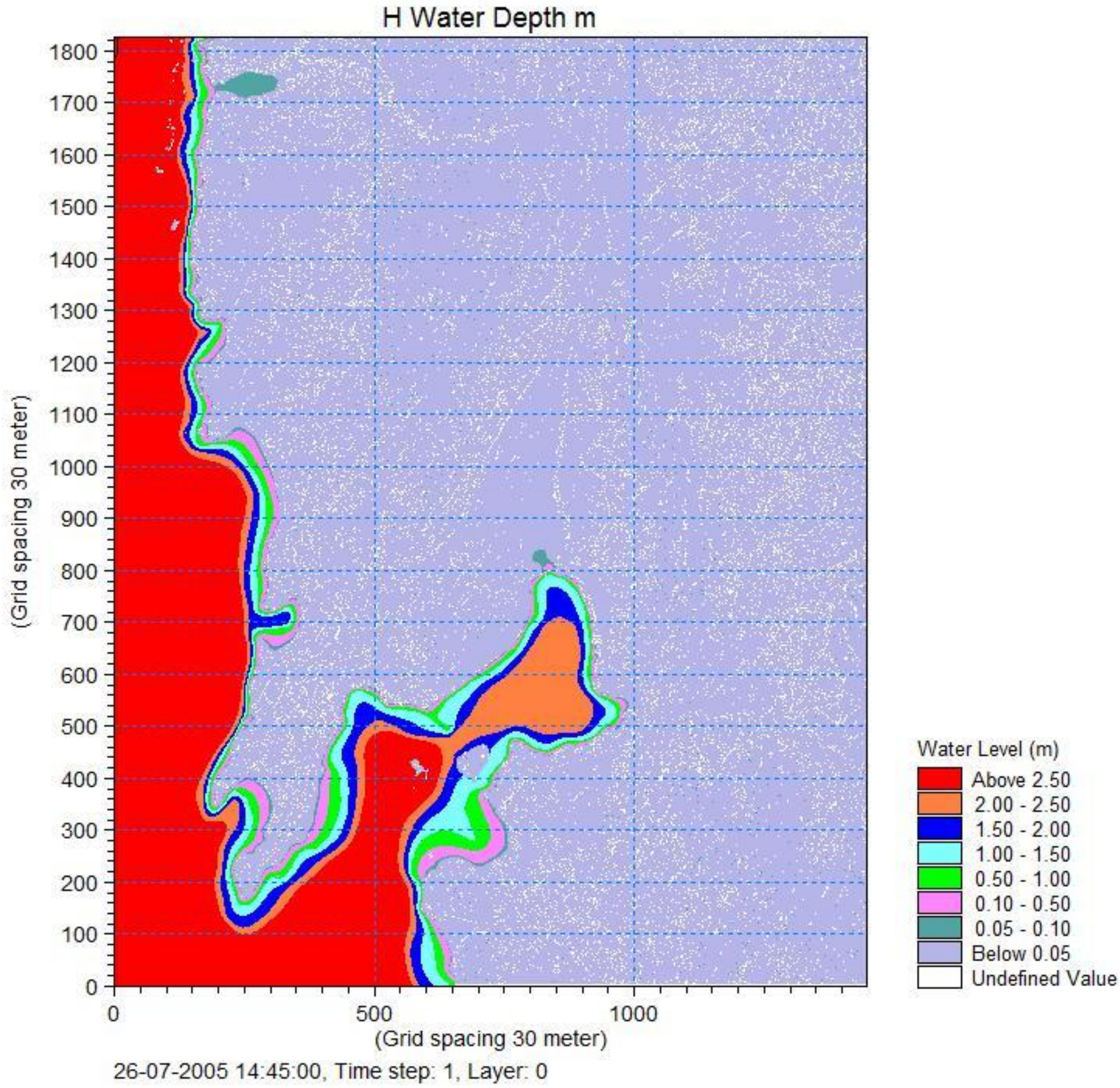
Annexure I

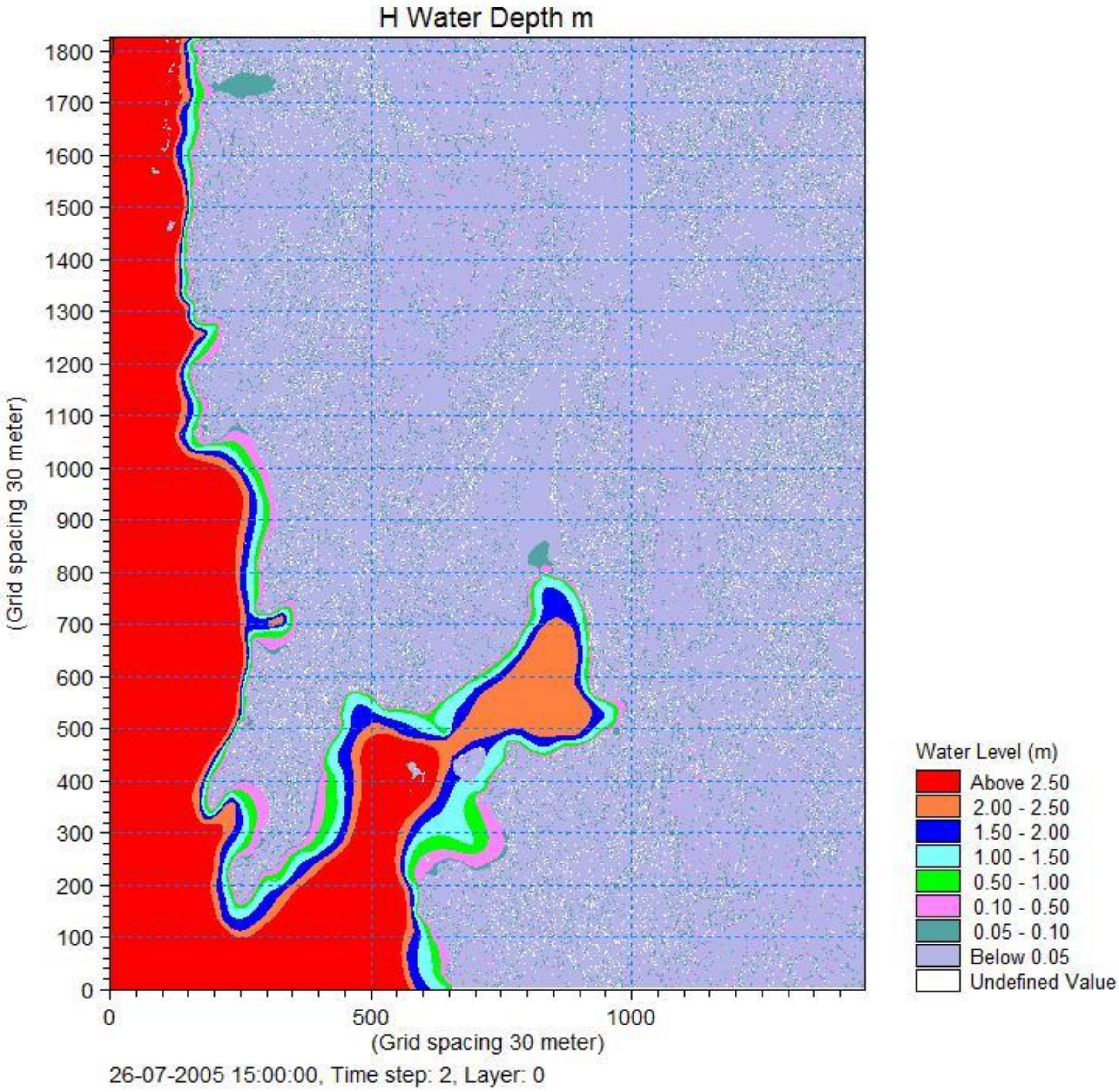
Flooded Road map overlay on Google Earth (26th July 2005)

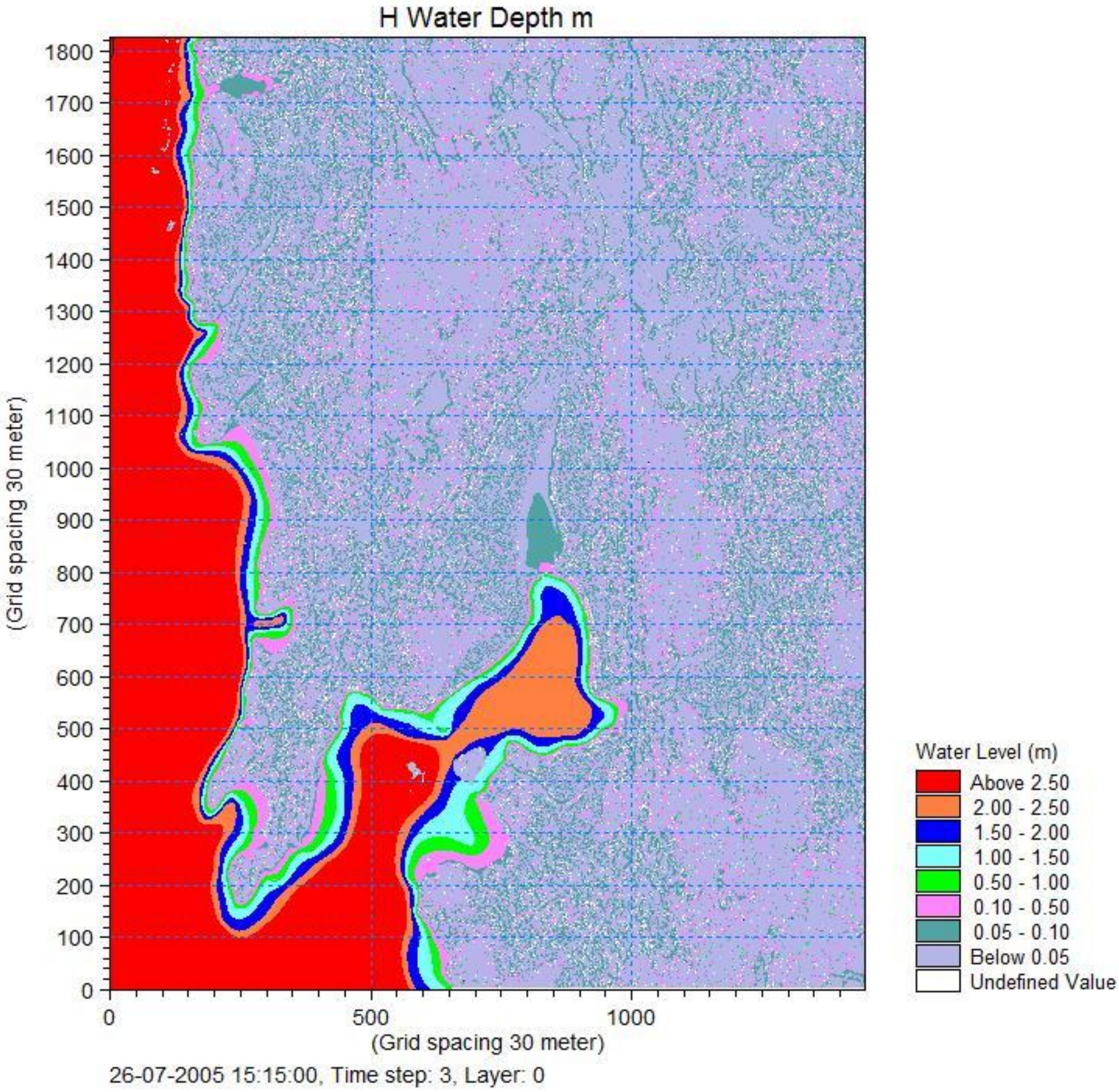
Annexure II

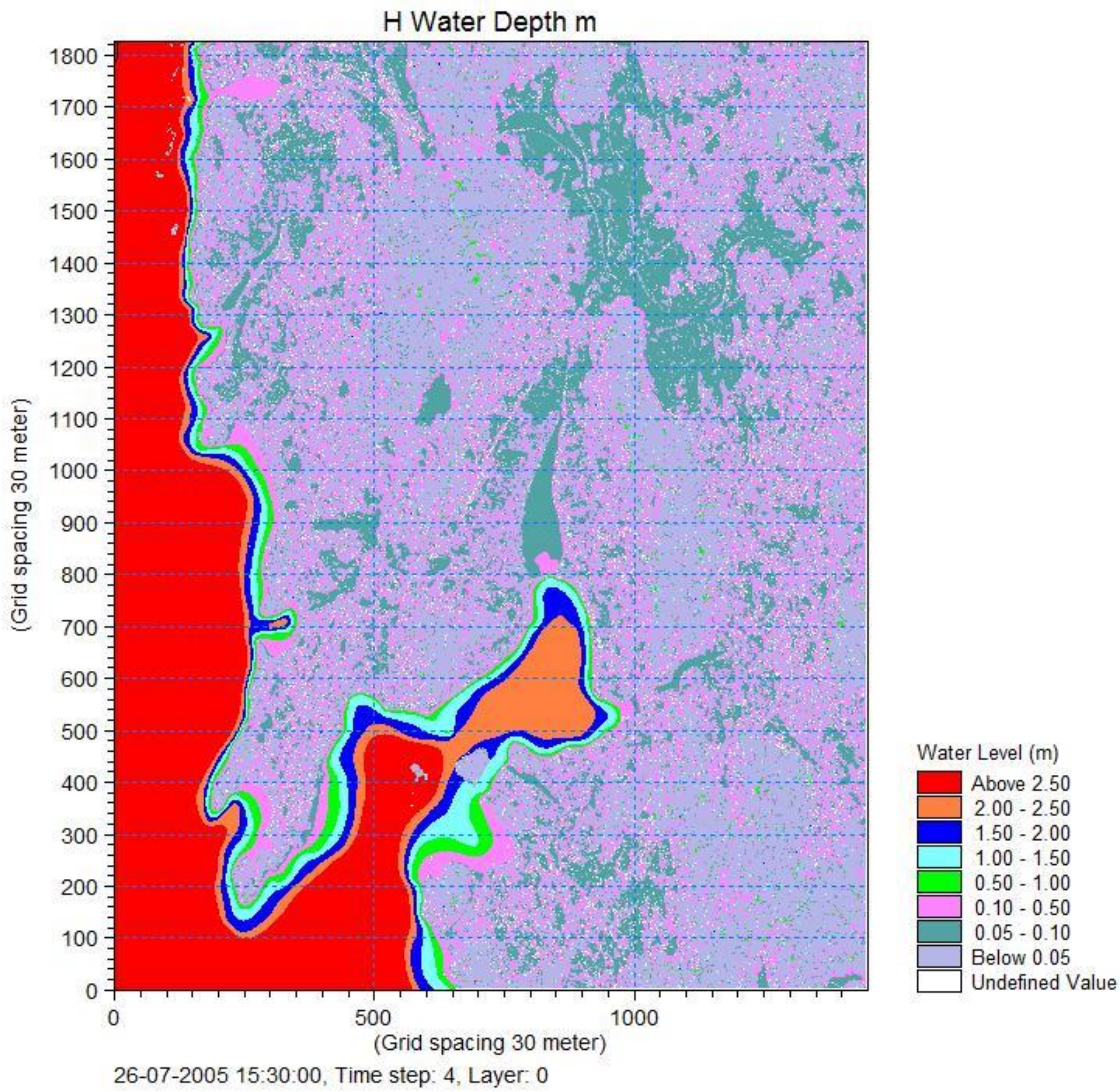
Flood Map Series (26th July 2005)

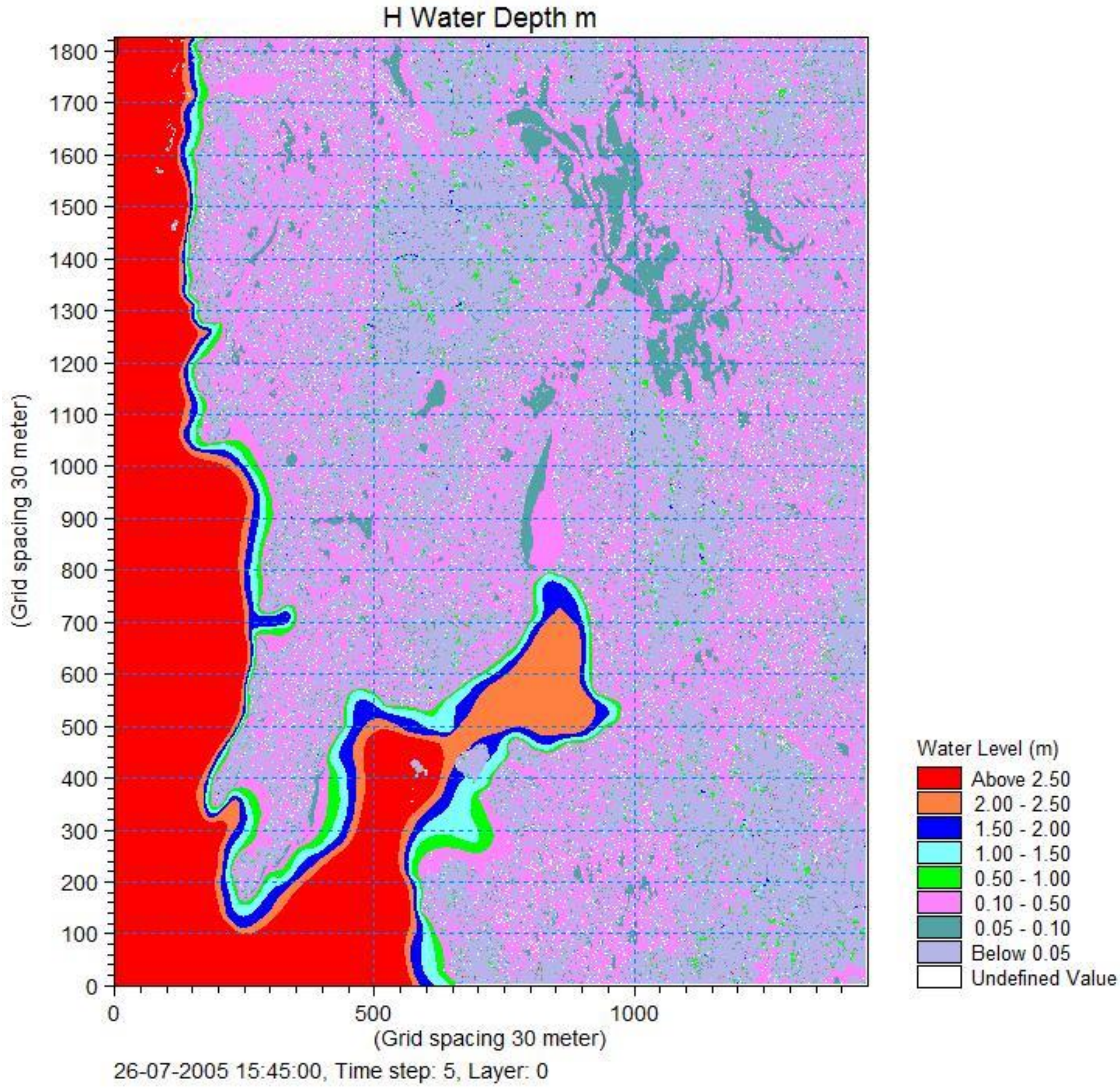


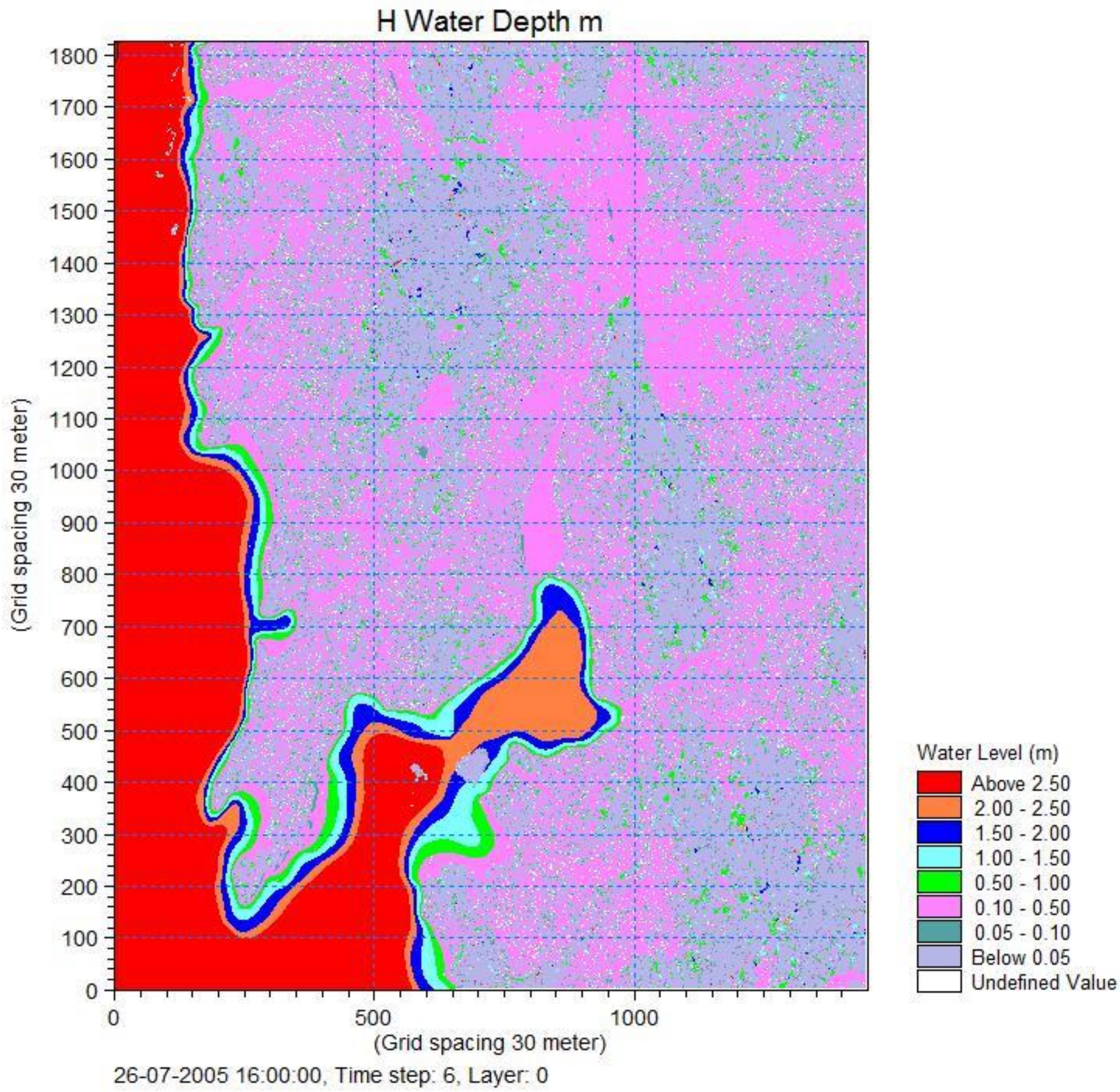

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 14:45:00, Time step: 1, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

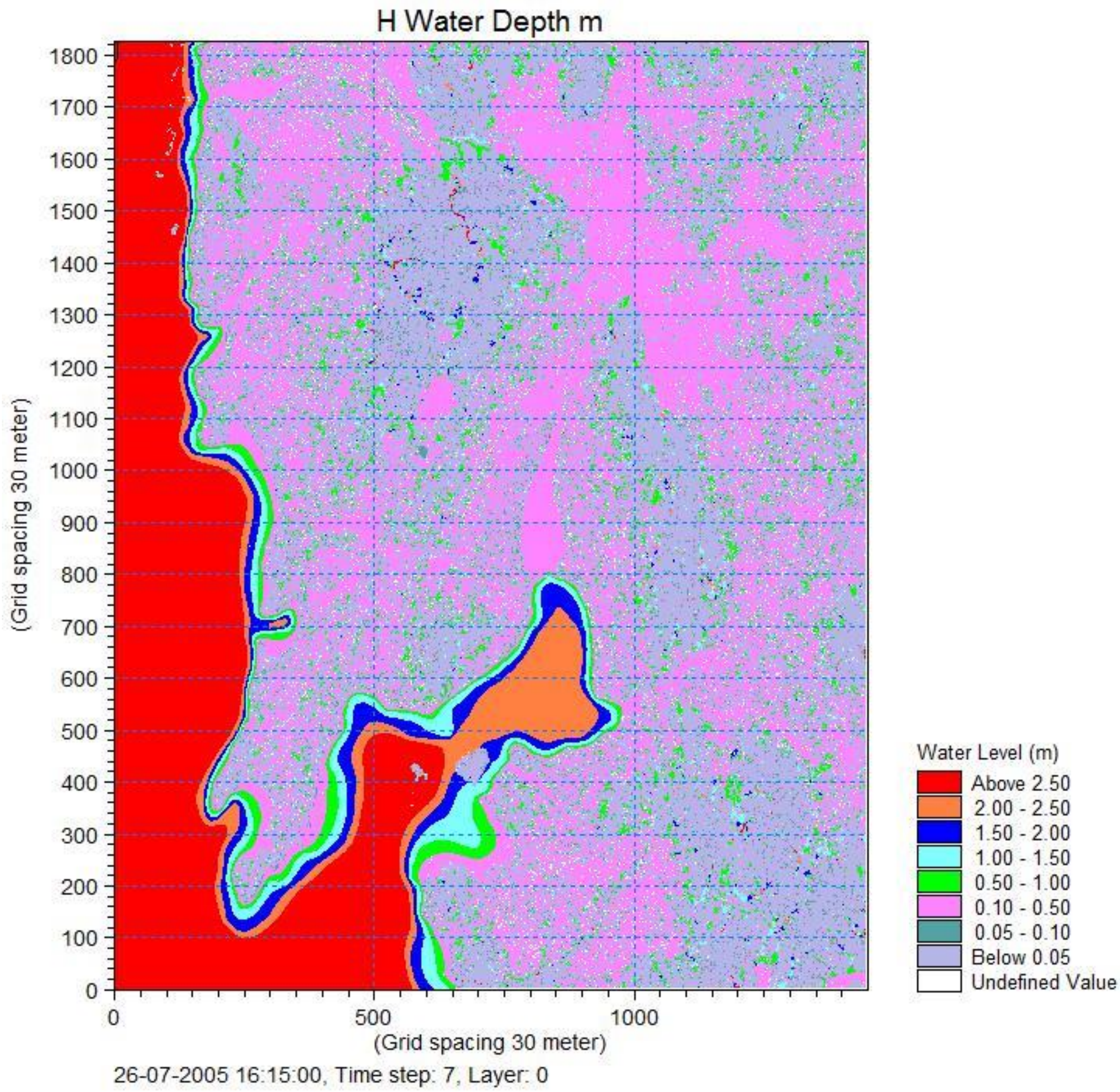

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 15:00:00, Time step: 2, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

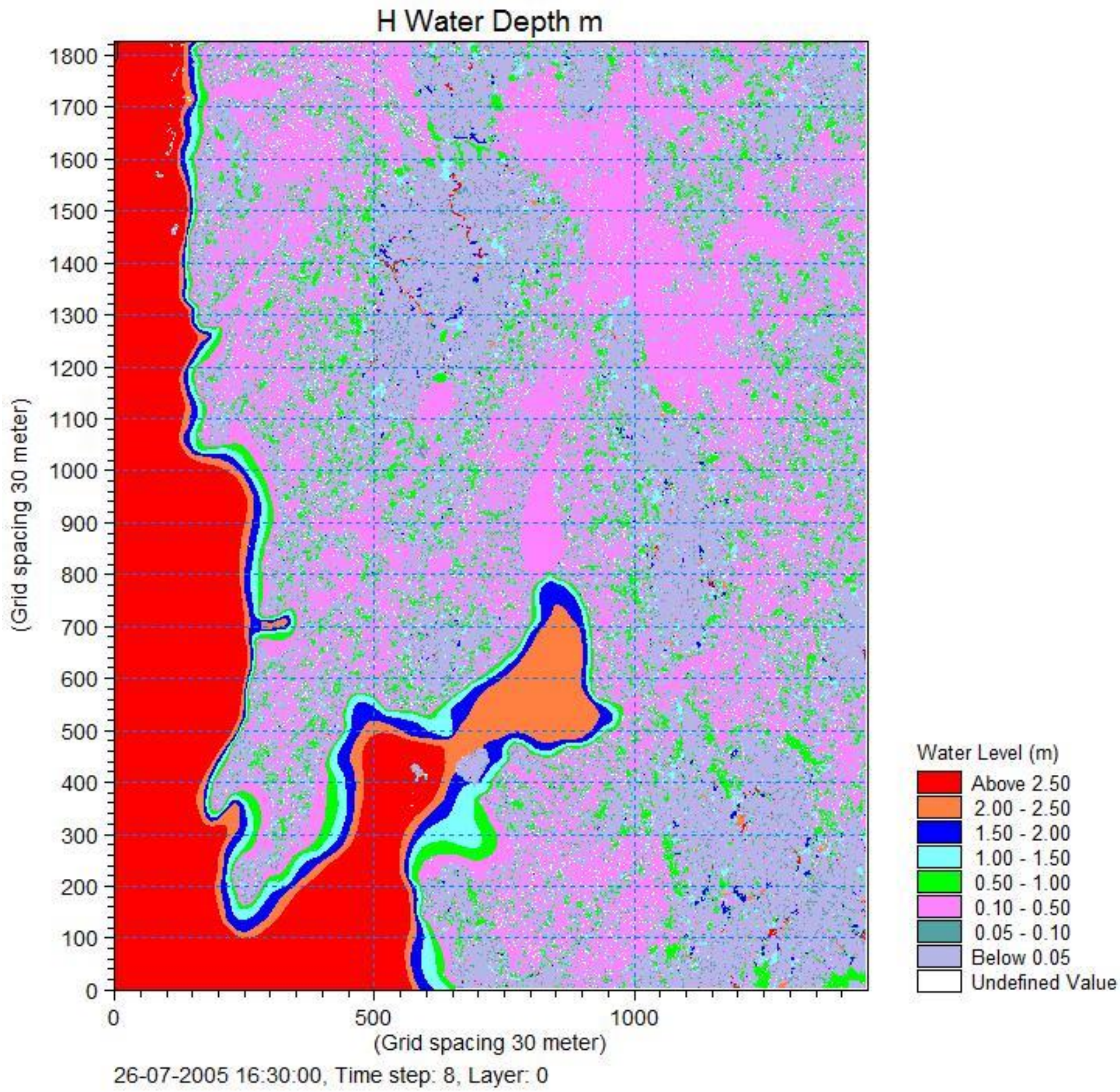

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 15:15:00, Time step: 3, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

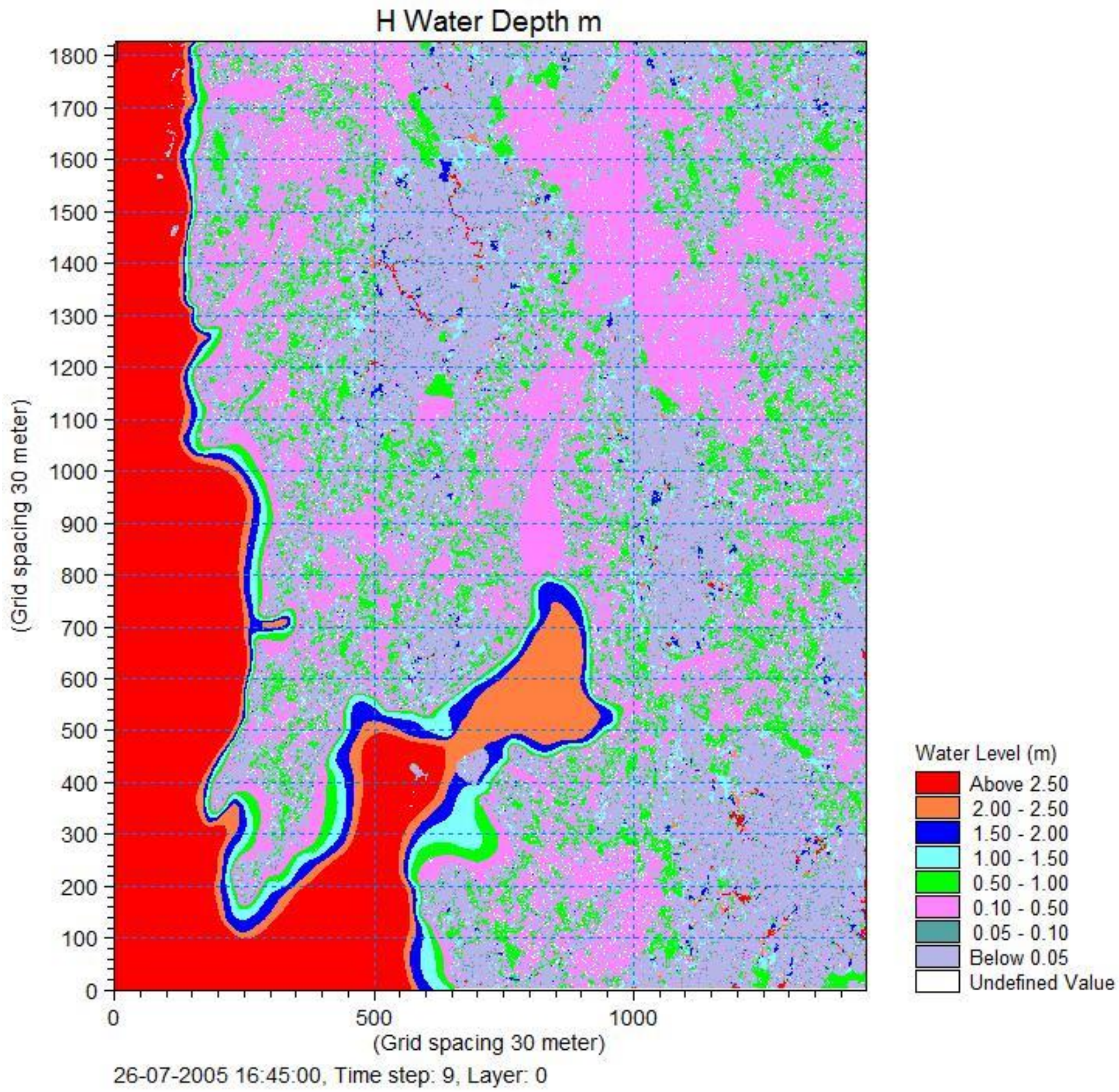

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 15:30:00, Time step: 4, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

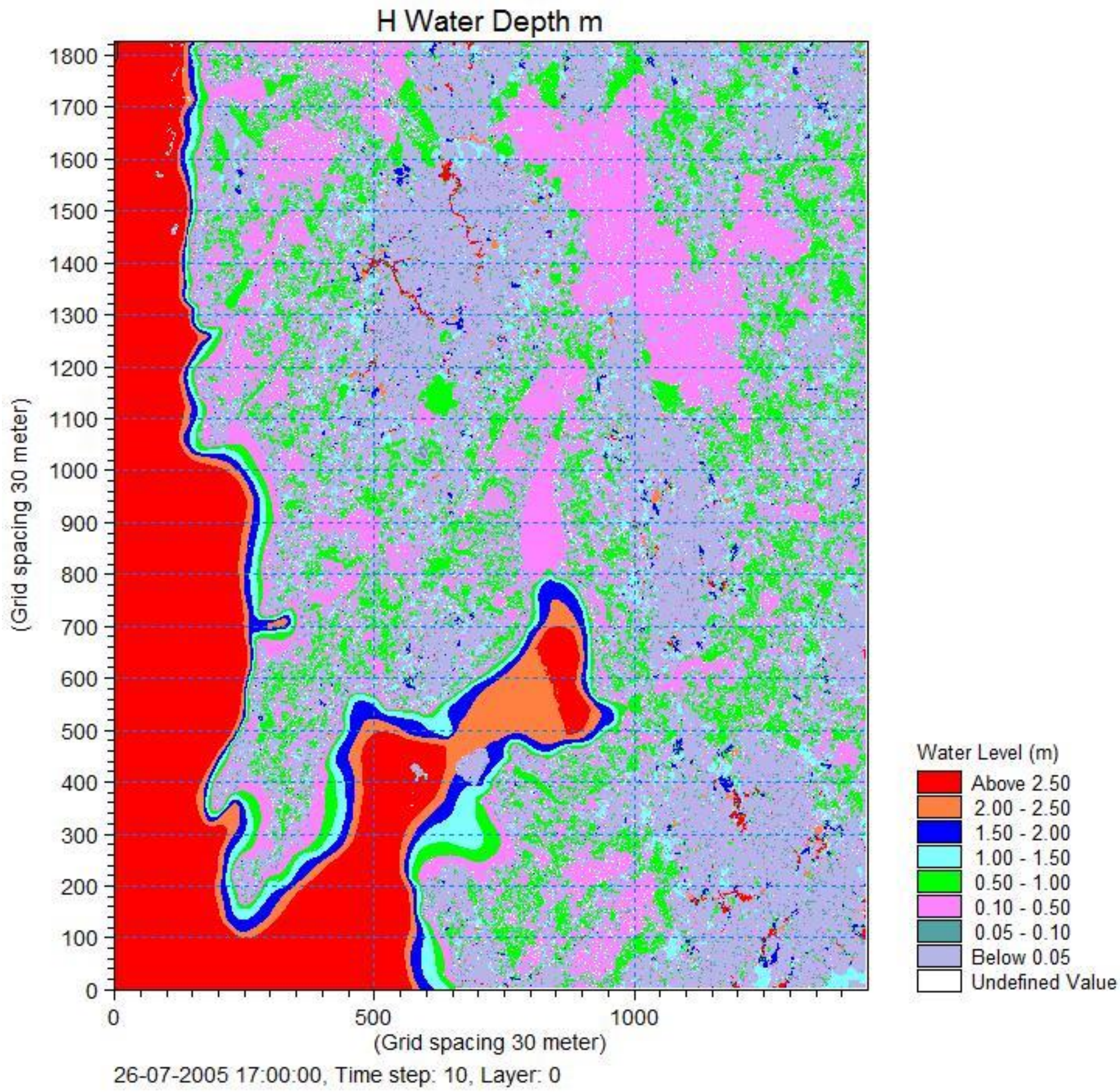

H Water Depth m
(Grid spacing 30 meter)
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
26-07-2005 15:45:00, Time step: 5, Layer: 0

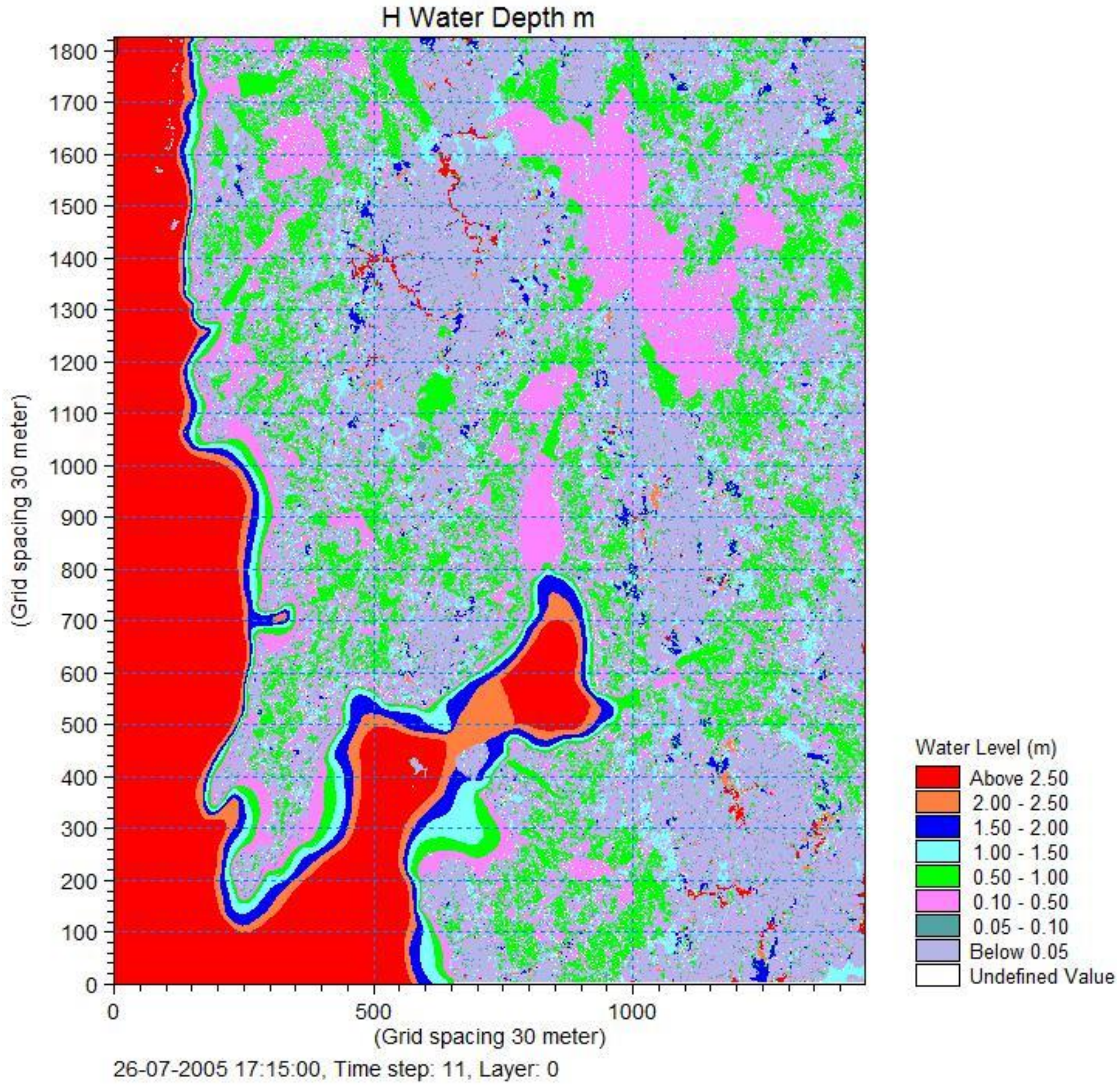

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 16:00:00, Time step: 6, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

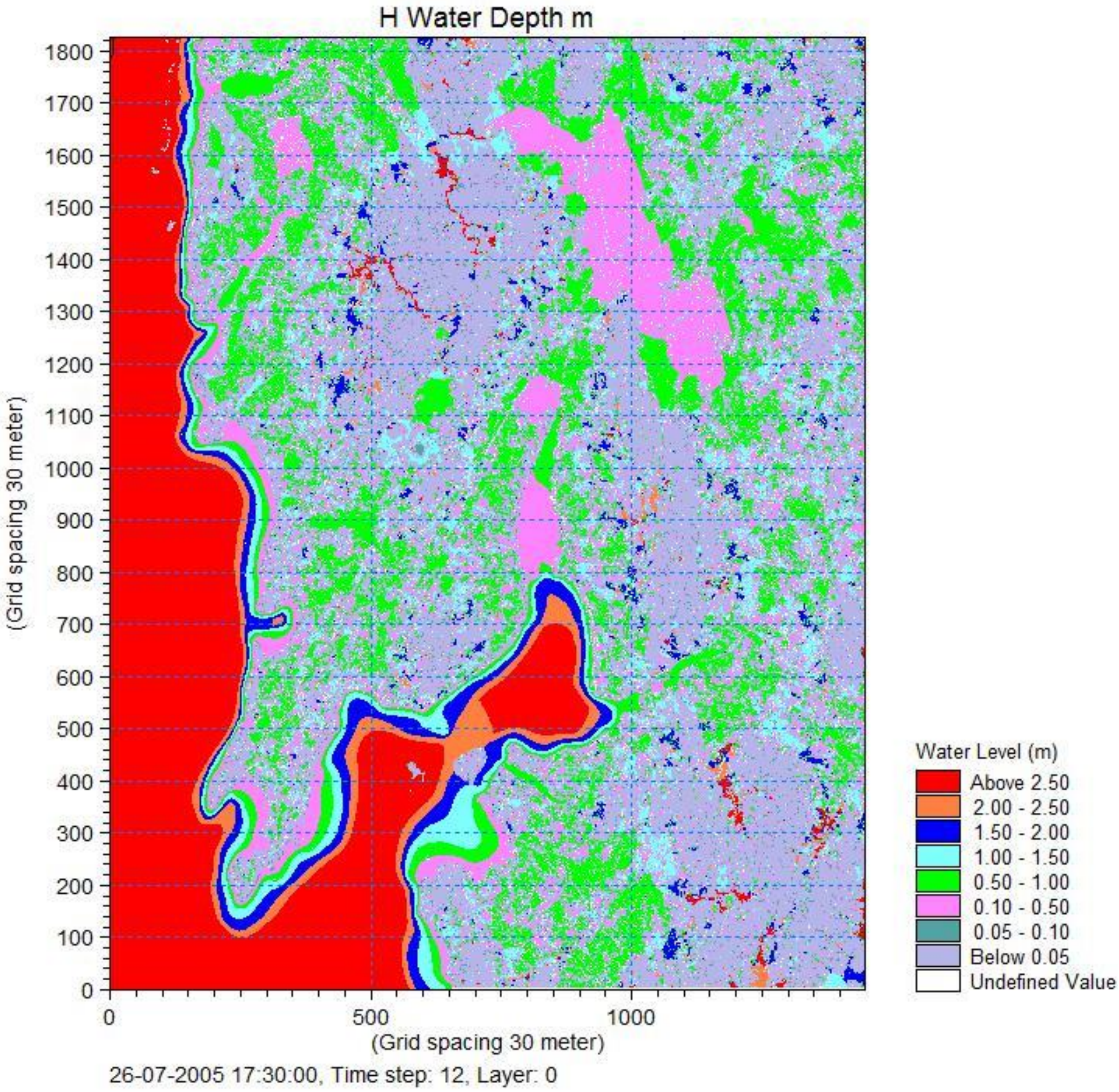

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 16:15:00, Time step: 7, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value


H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 16:30:00, Time step: 8, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

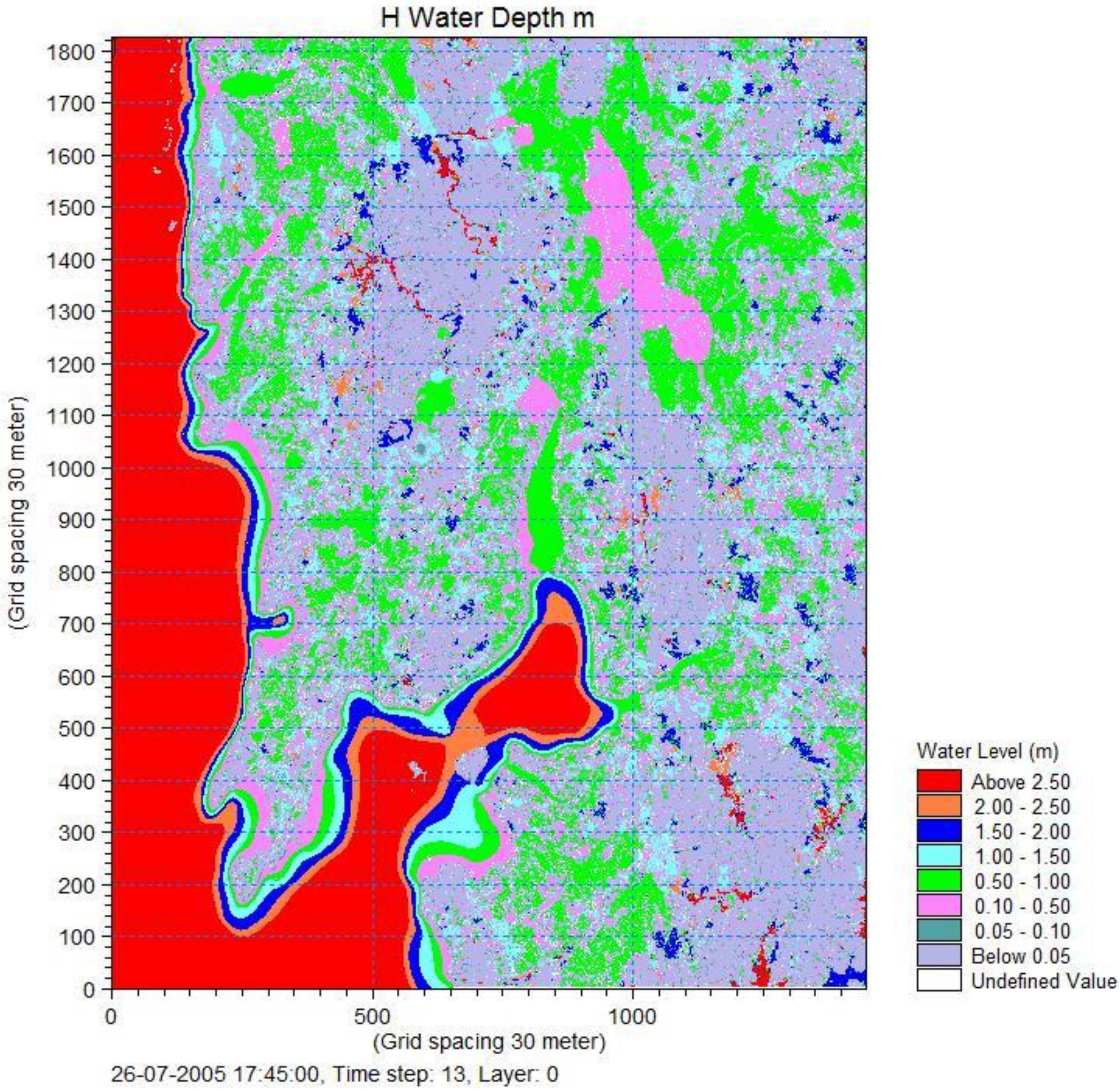

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
26-07-2005 16:45:00, Time step: 9, Layer: 0

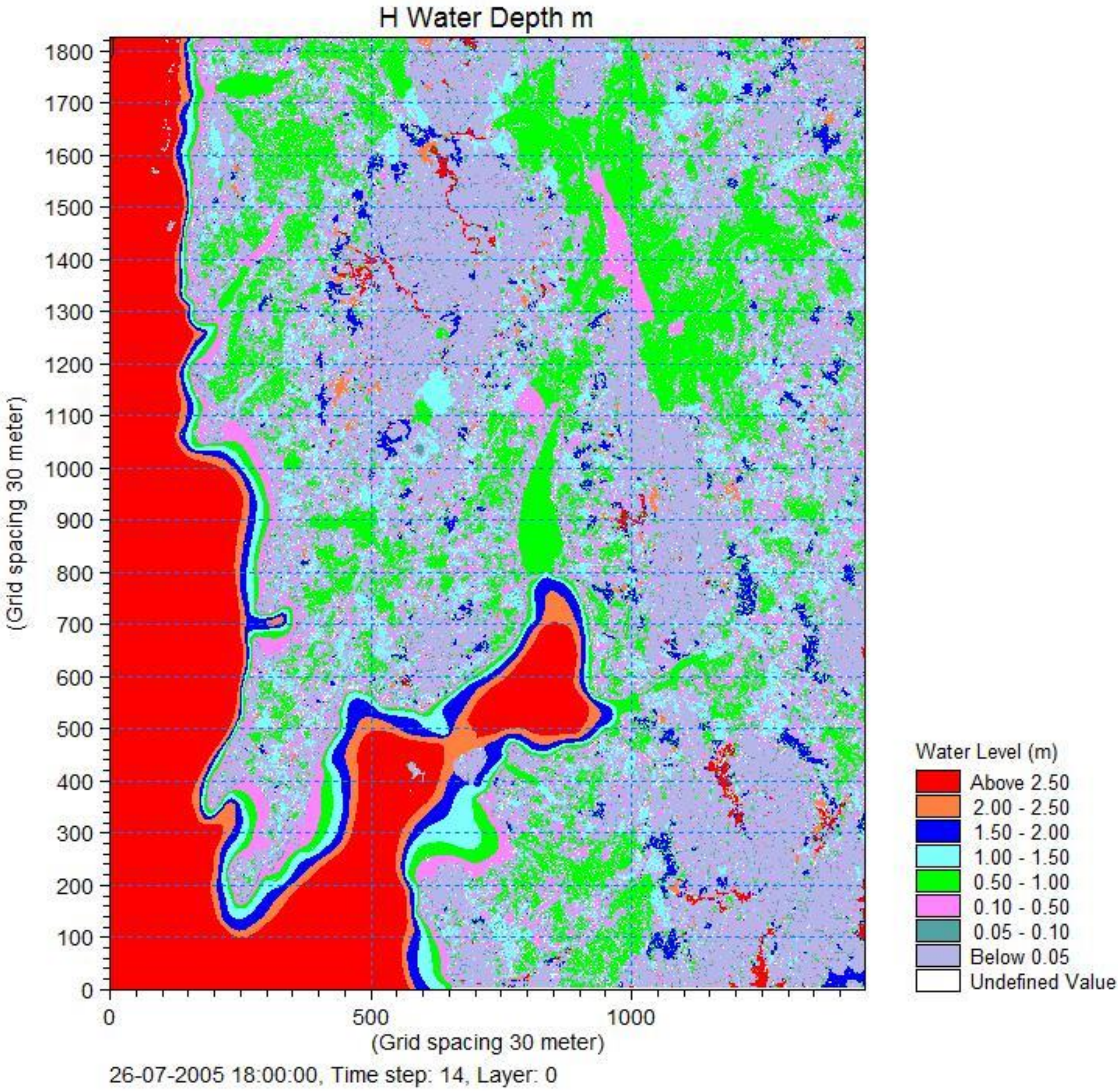

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
26-07-2005 17:00:00, Time step: 10, Layer: 0

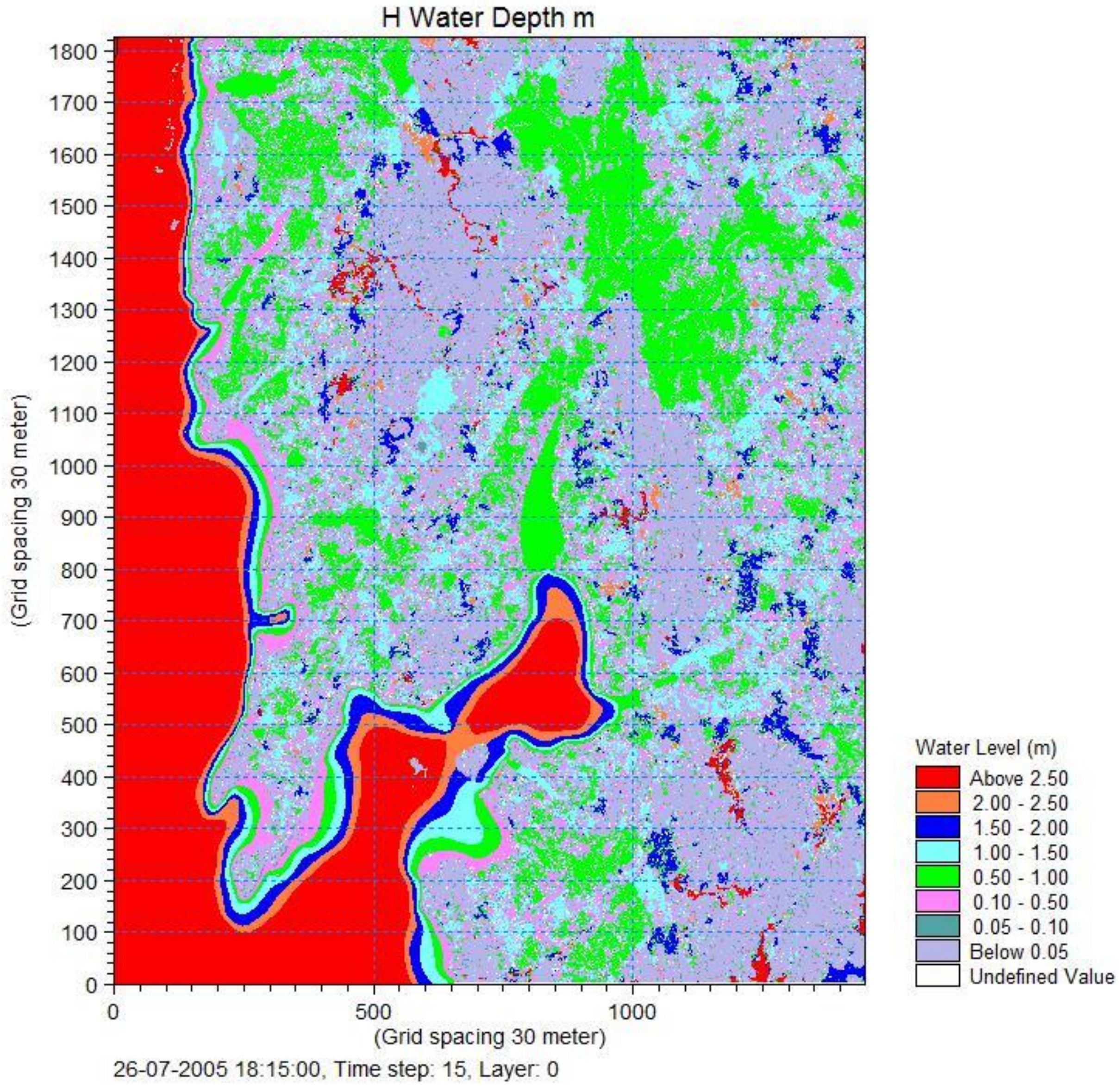

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 17:15:00, Time step: 11, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

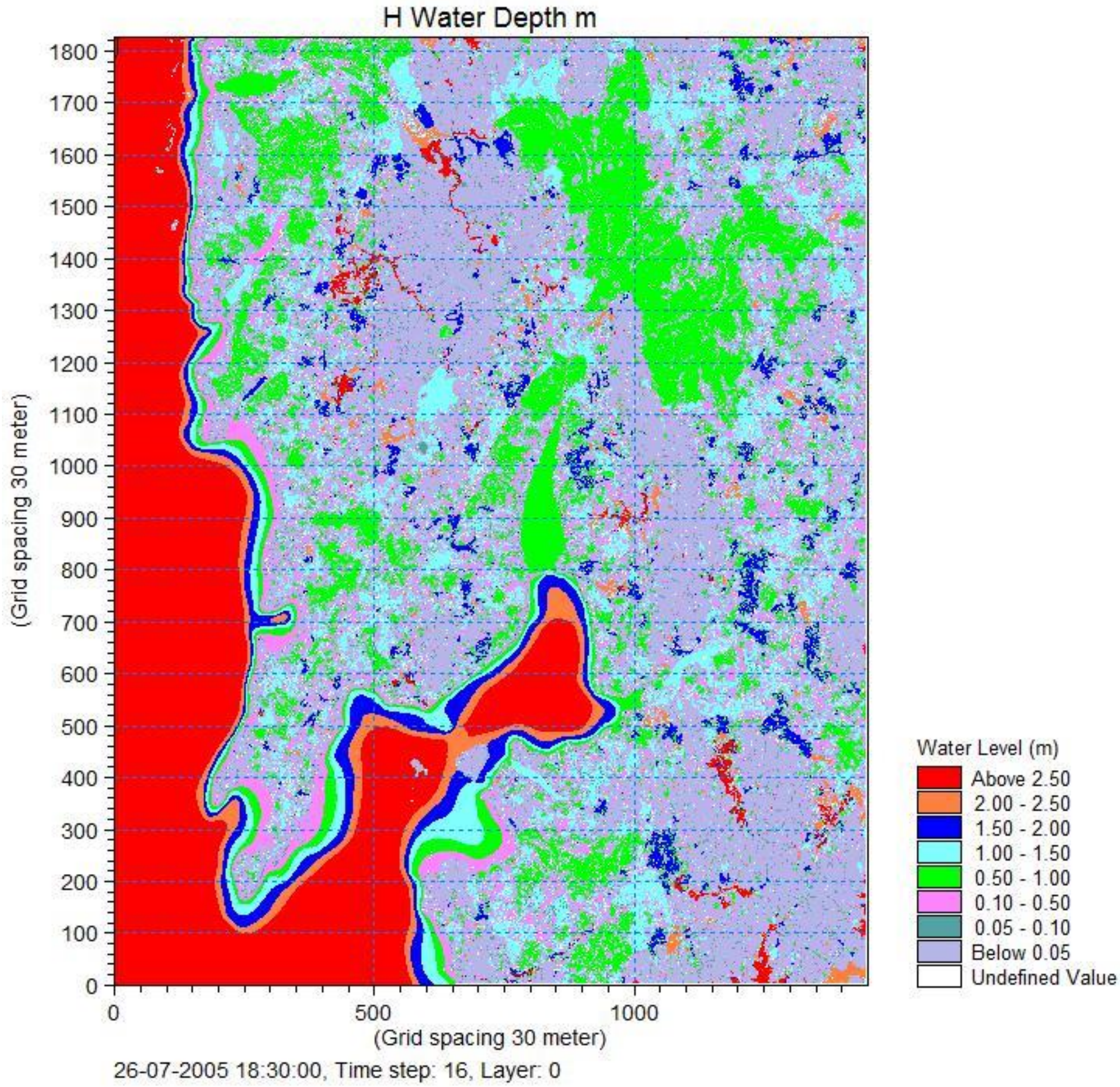


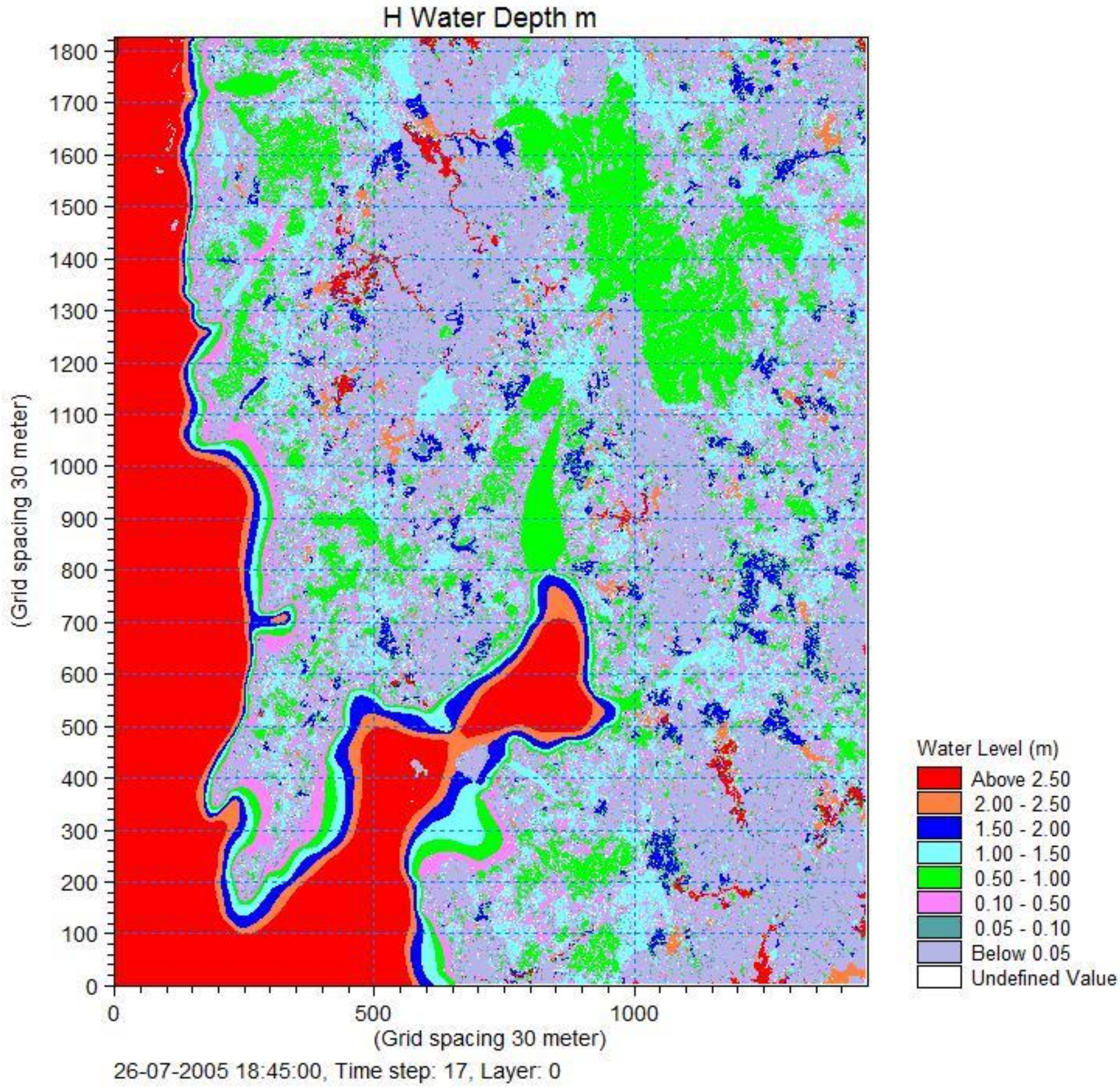
H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 17:30:00, Time step: 12, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

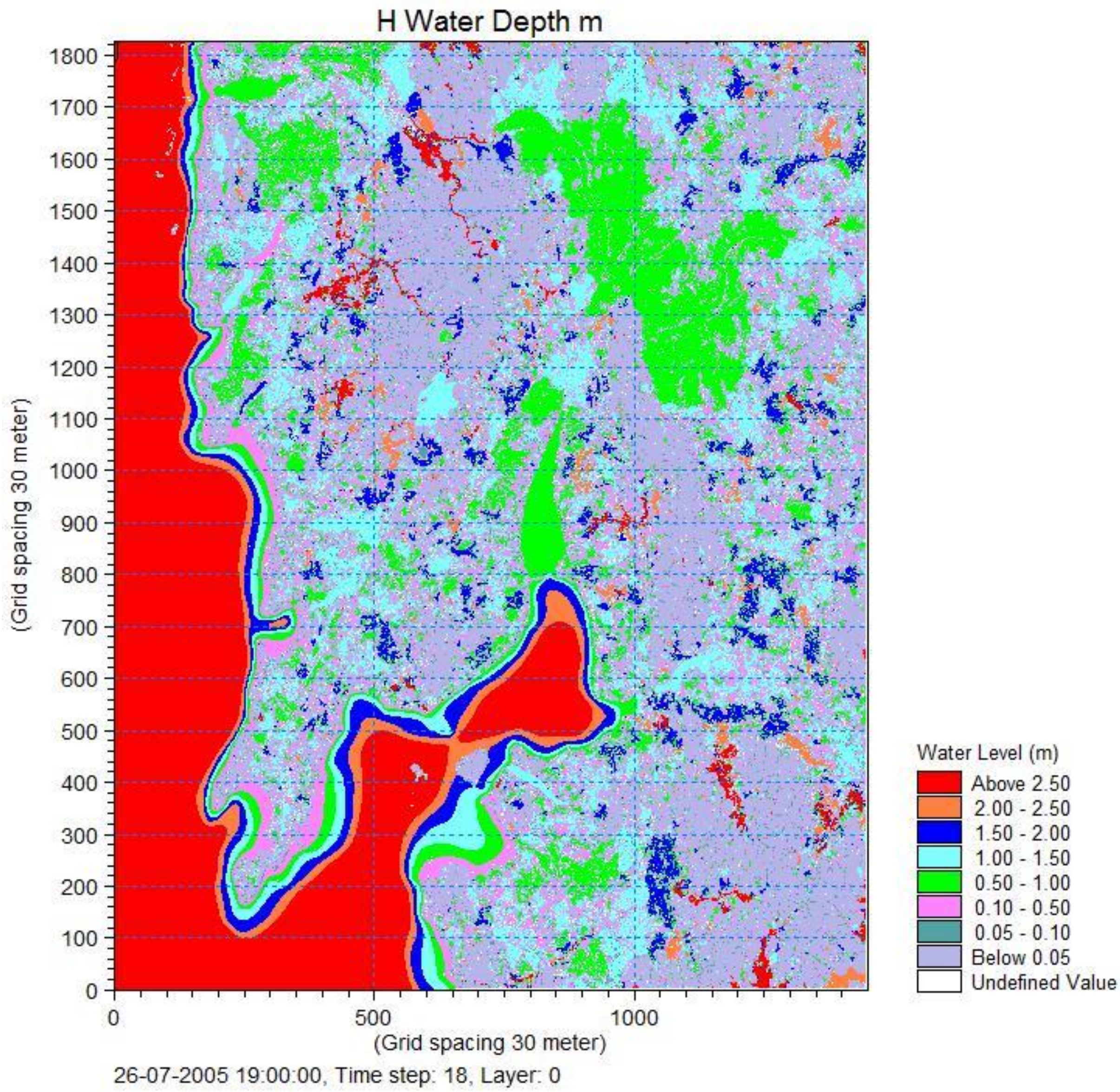

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 17:45:00, Time step: 13, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

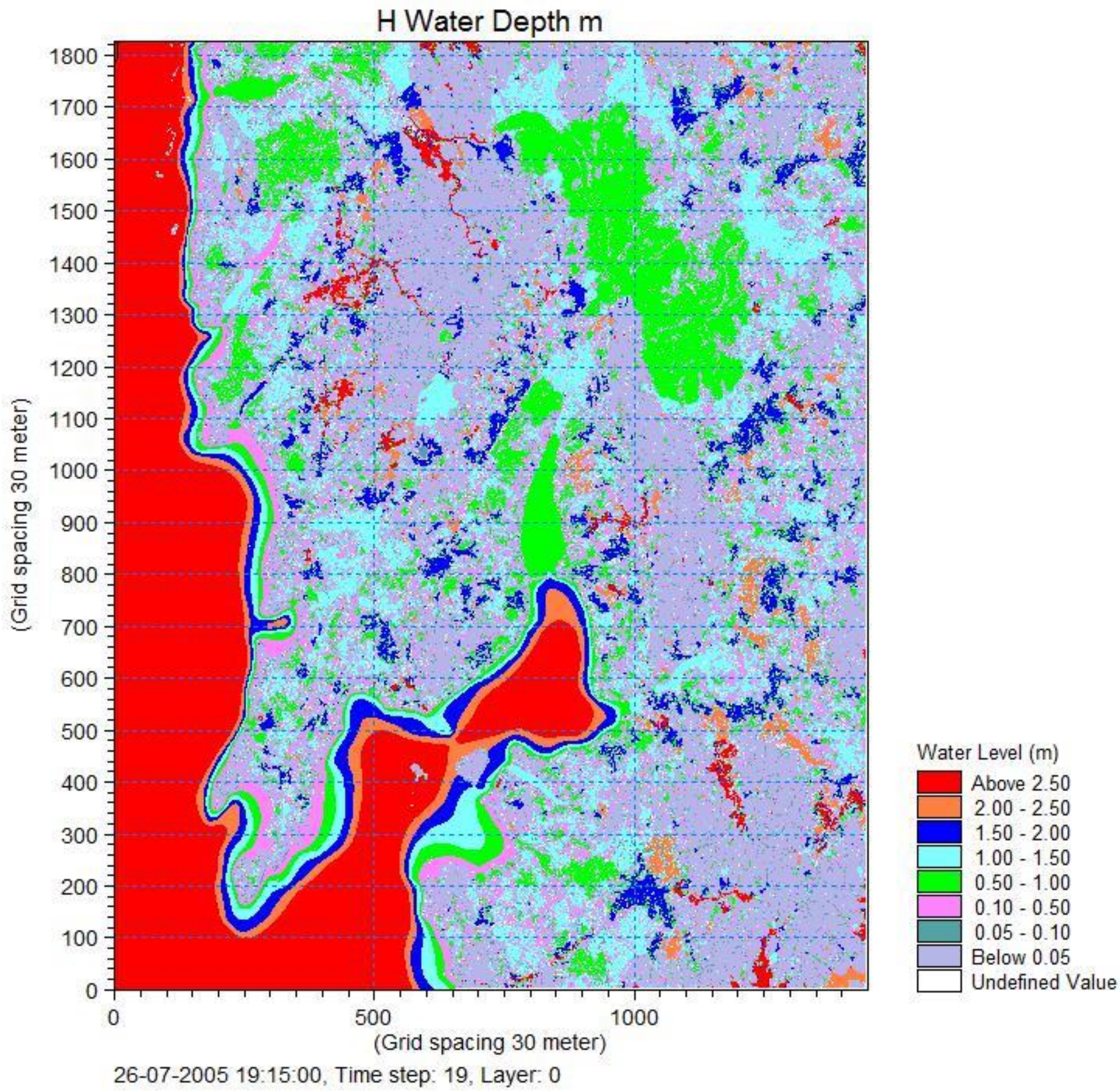

H Water Depth m
(Grid spacing 30 meter)
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
500
1000
(Grid spacing 30 meter)
26-07-2005 18:00:00, Time step: 14, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

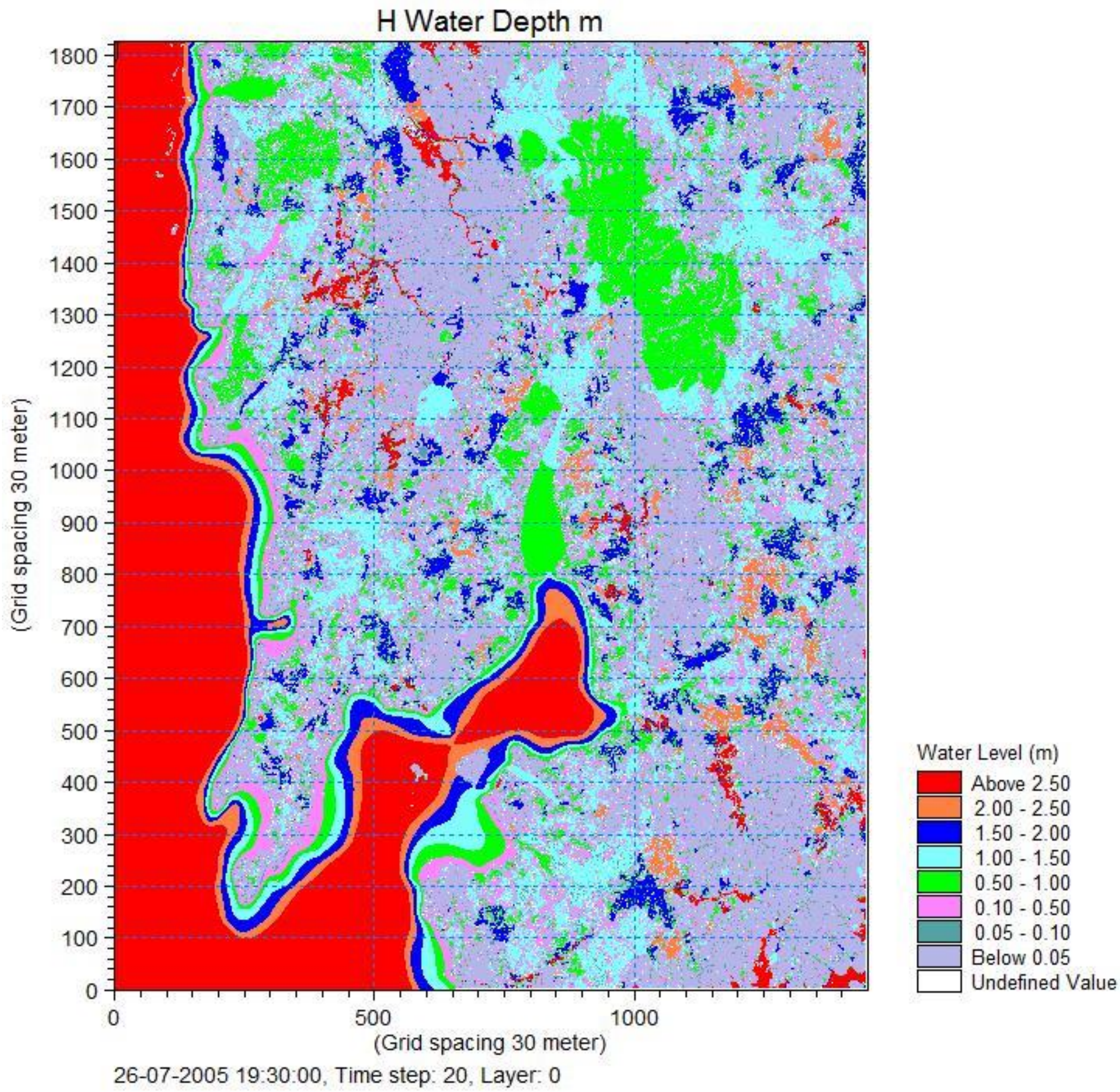

H Water Depth m
(Grid spacing 30 meter)
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
500
1000
(Grid spacing 30 meter)
26-07-2005 18:15:00, Time step: 15, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value


H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 18:30:00, Time step: 16, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

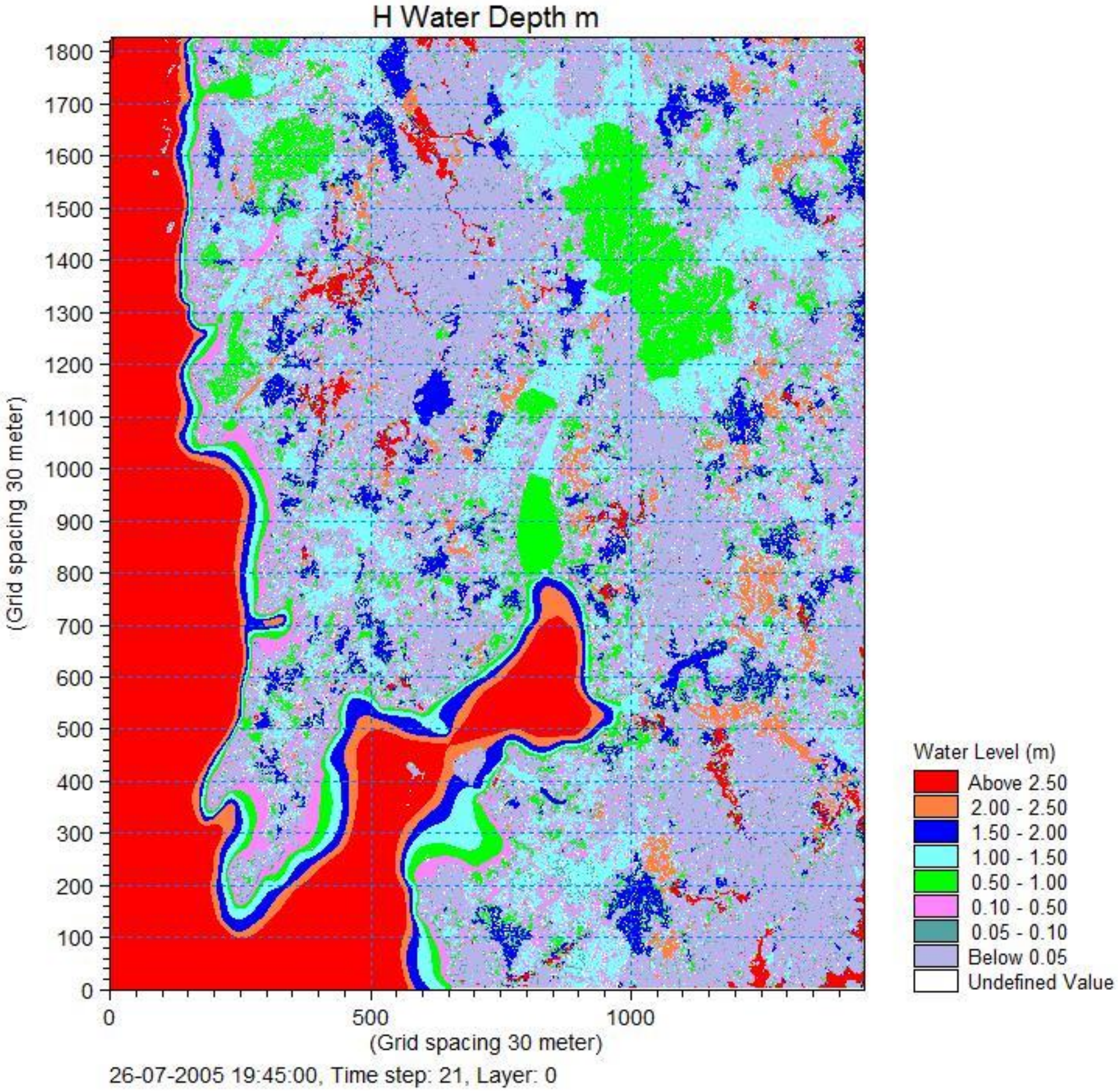

H Water Depth m
(Grid spacing 30 meter)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
0
500
1000
(Grid spacing 30 meter)
26-07-2005 18:45:00, Time step: 17, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

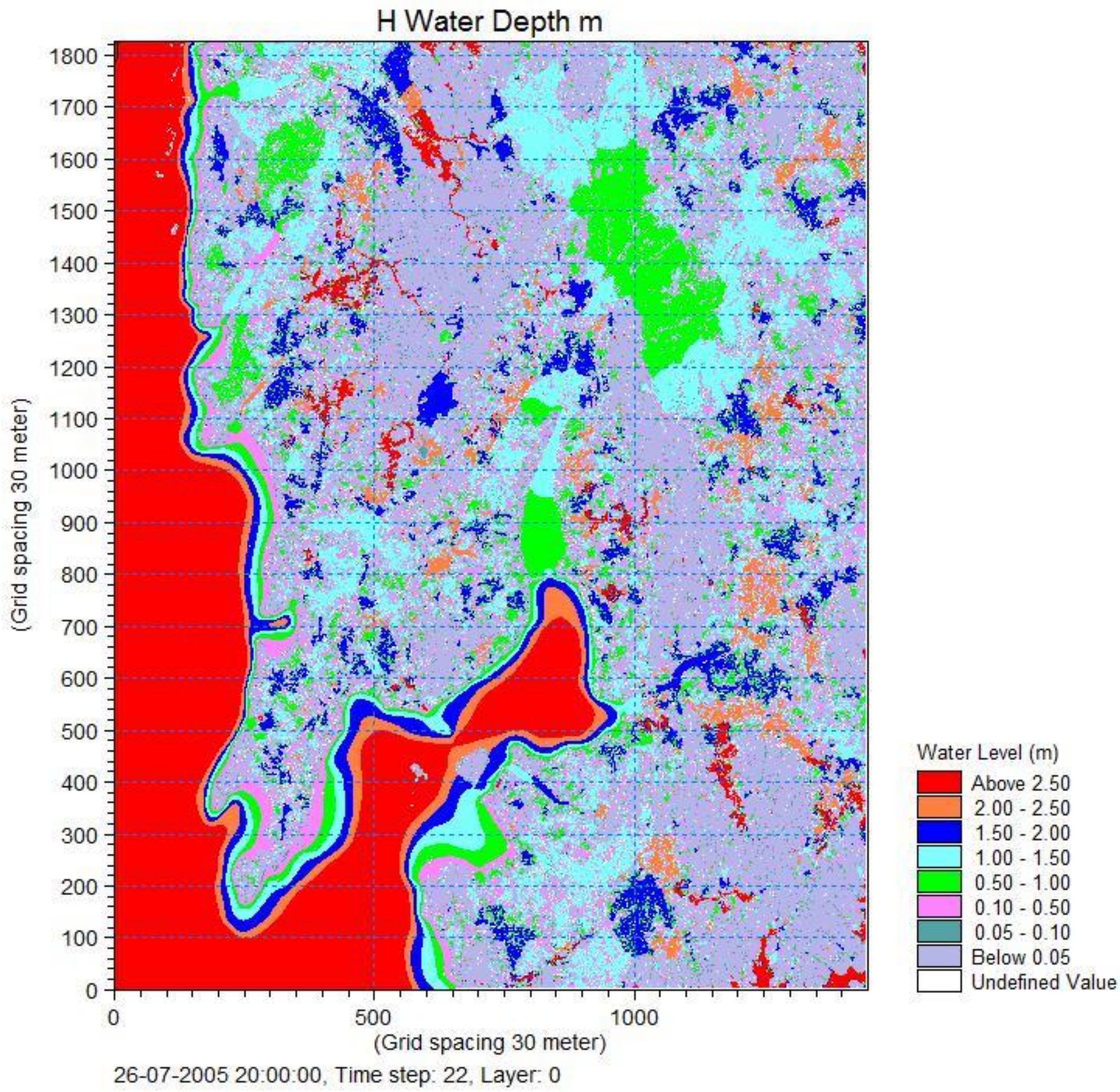

H Water Depth m
(Grid spacing 30 meter)
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
26-07-2005 19:00:00, Time step: 18, Layer: 0

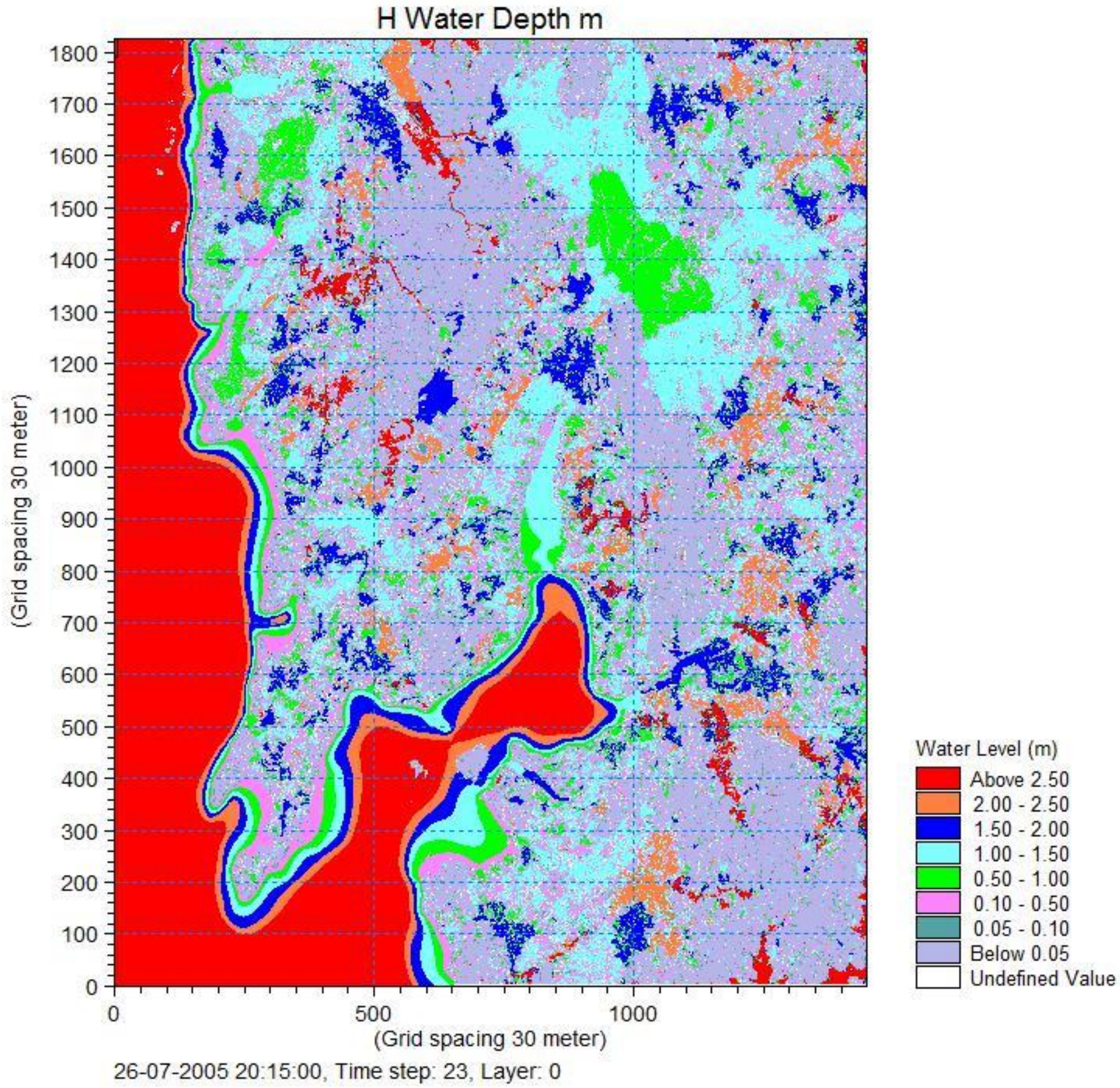

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 19:15:00, Time step: 19, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

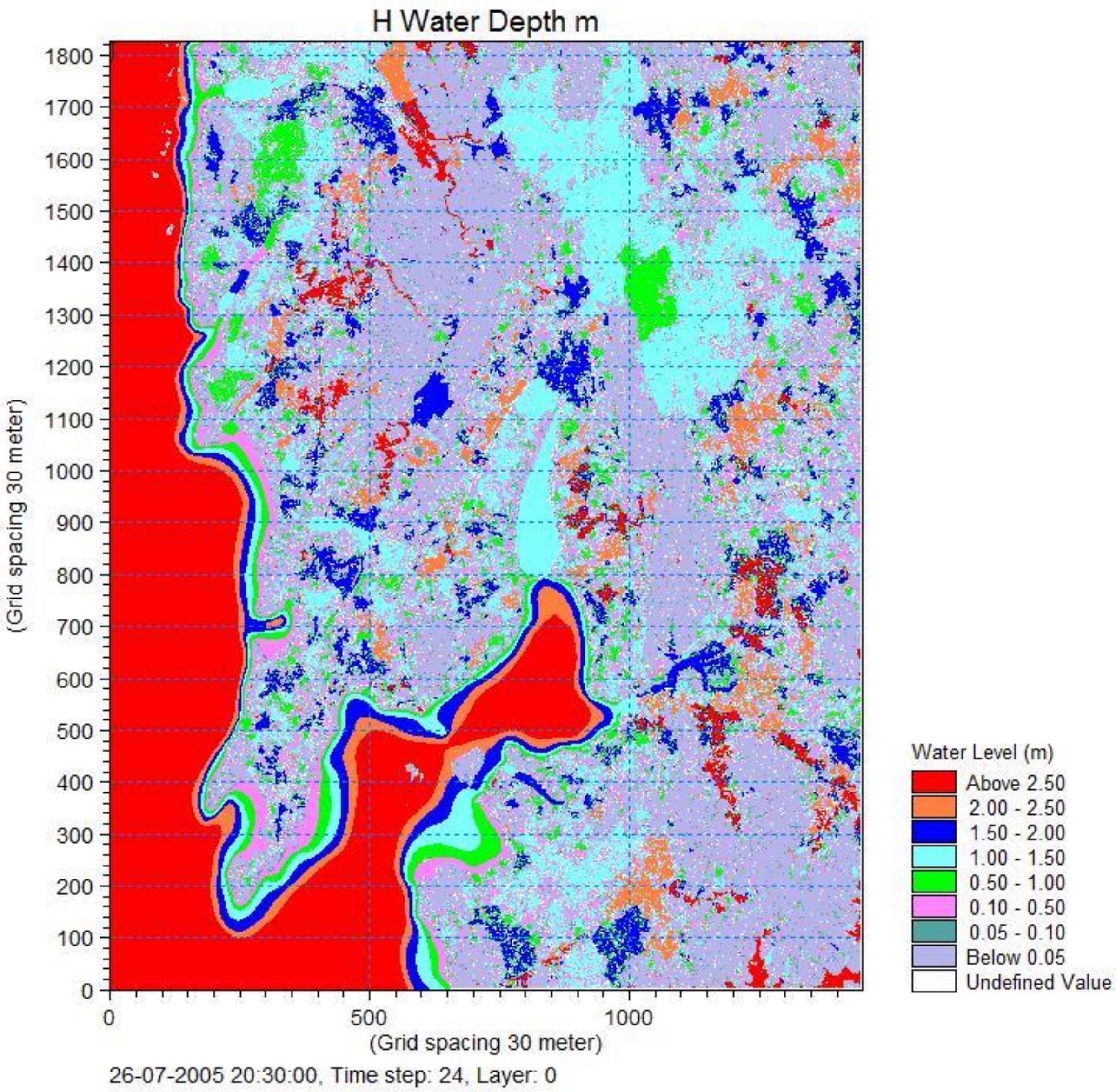


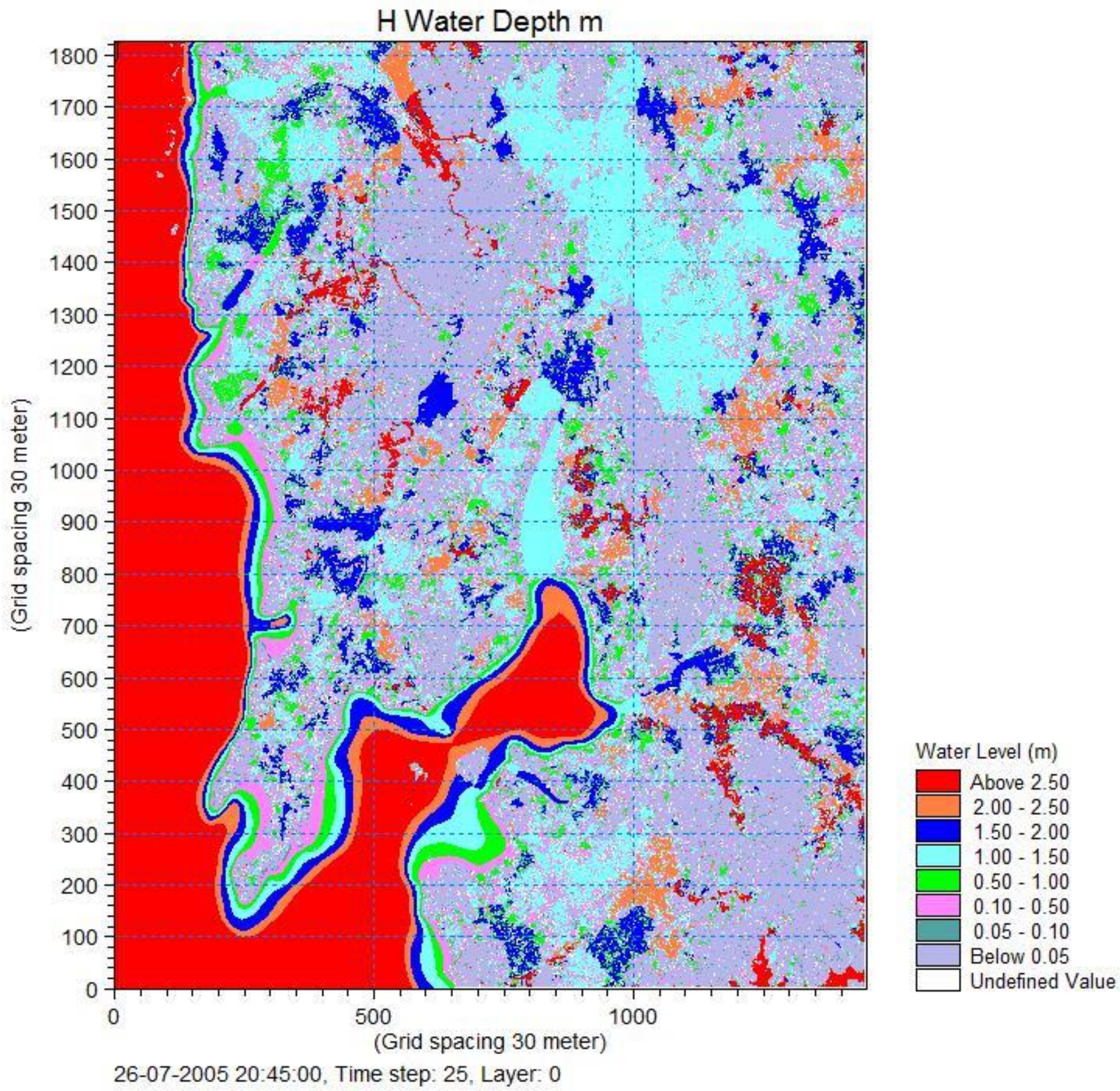
H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 19:30:00, Time step: 20, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

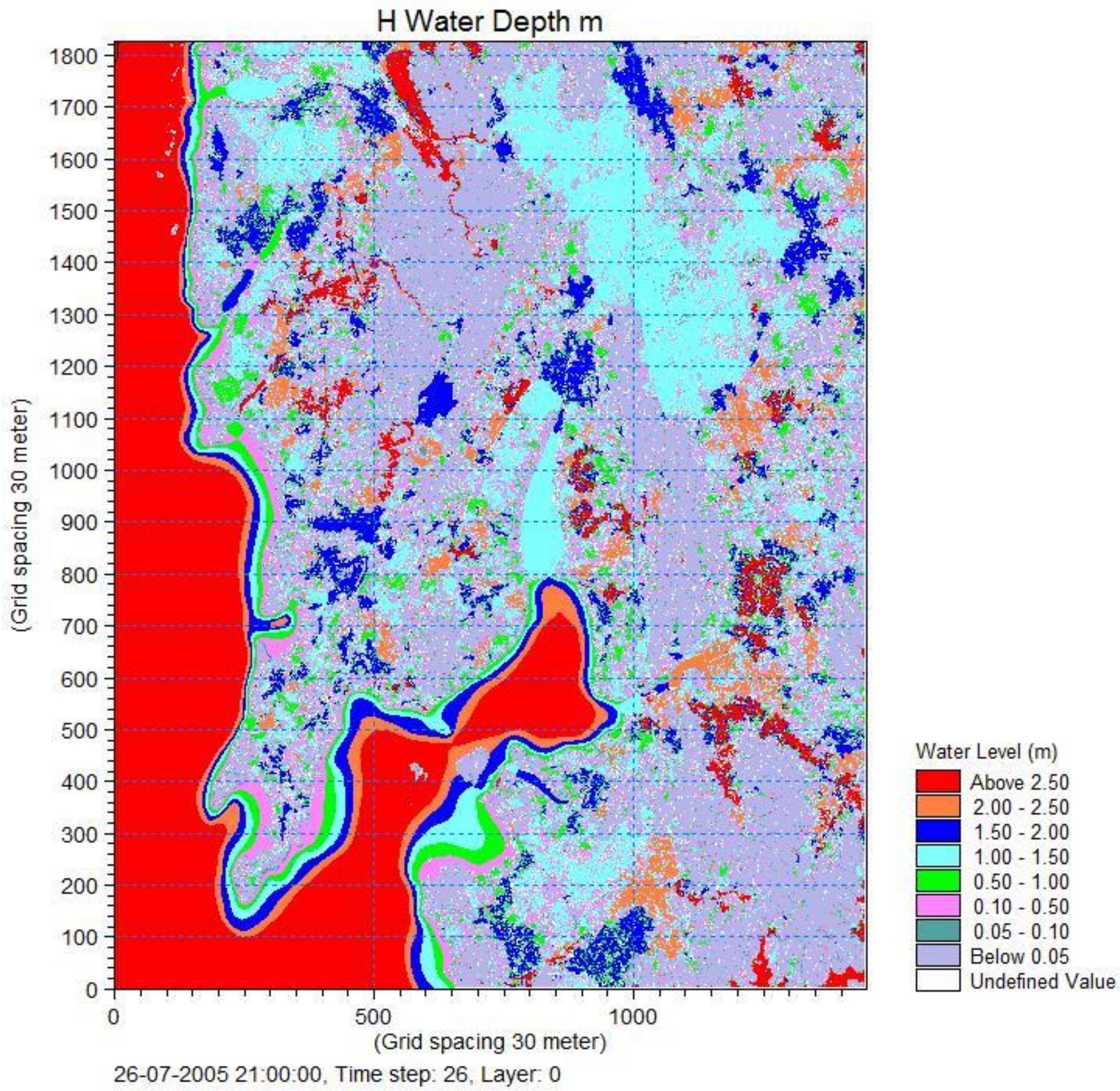

H Water Depth m
(Grid spacing 30 meter)
(Grid spacing 30 meter)
26-07-2005 19:45:00, Time step: 21, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

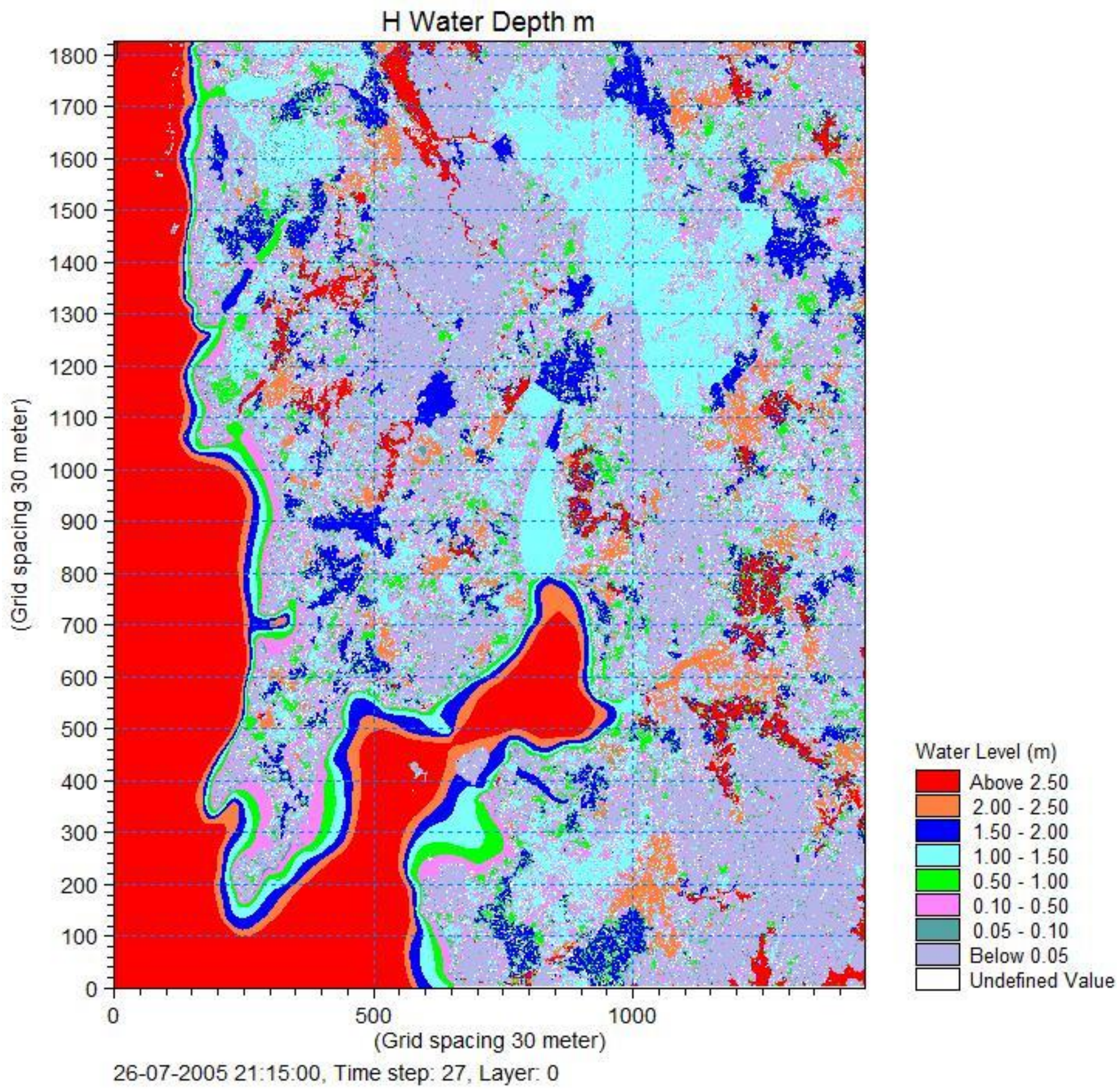

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 20:00:00, Time step: 22, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

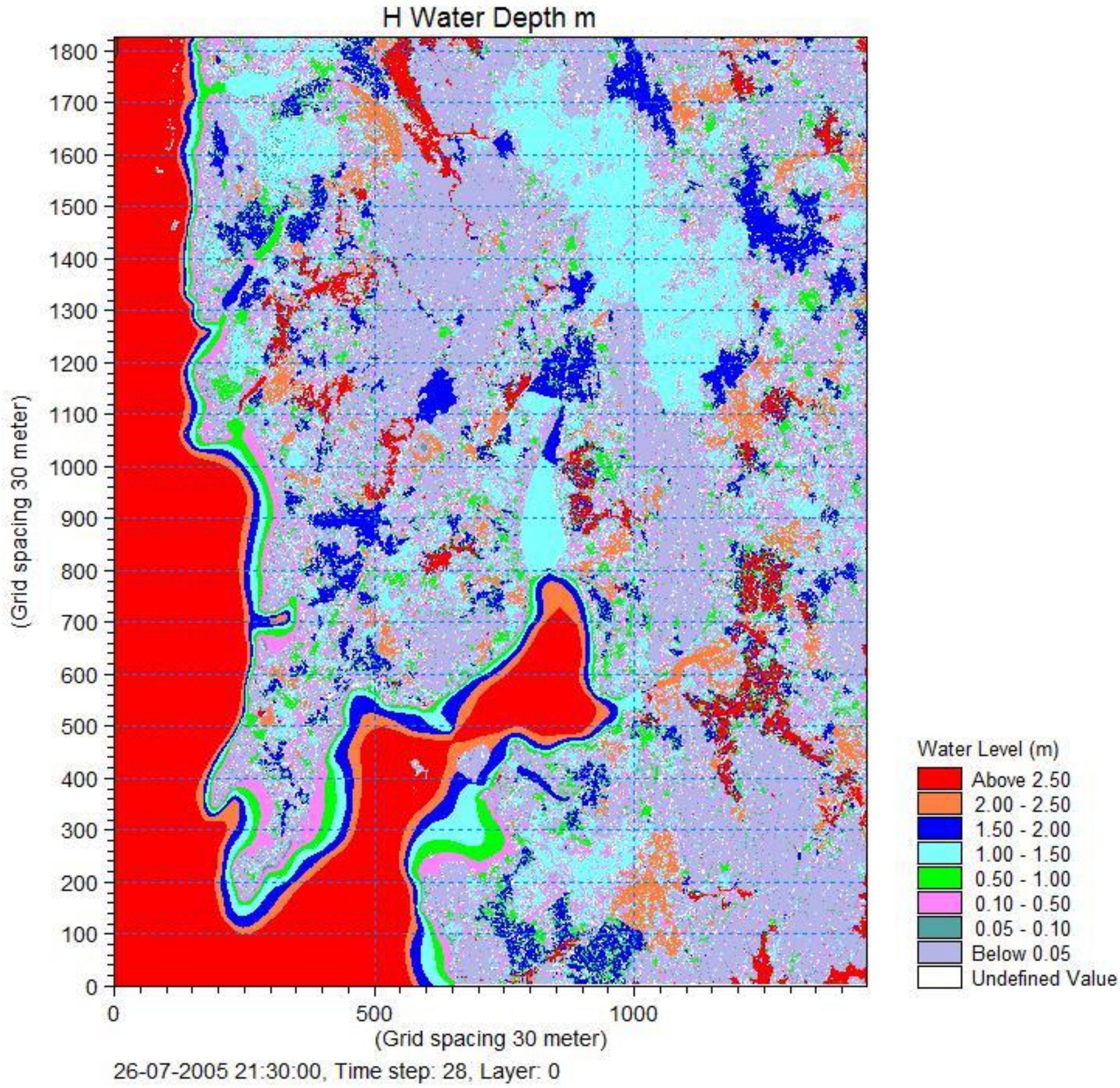

H Water Depth m
(Grid spacing 30 meter)
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
500
1000
(Grid spacing 30 meter)
26-07-2005 20:15:00, Time step: 23, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

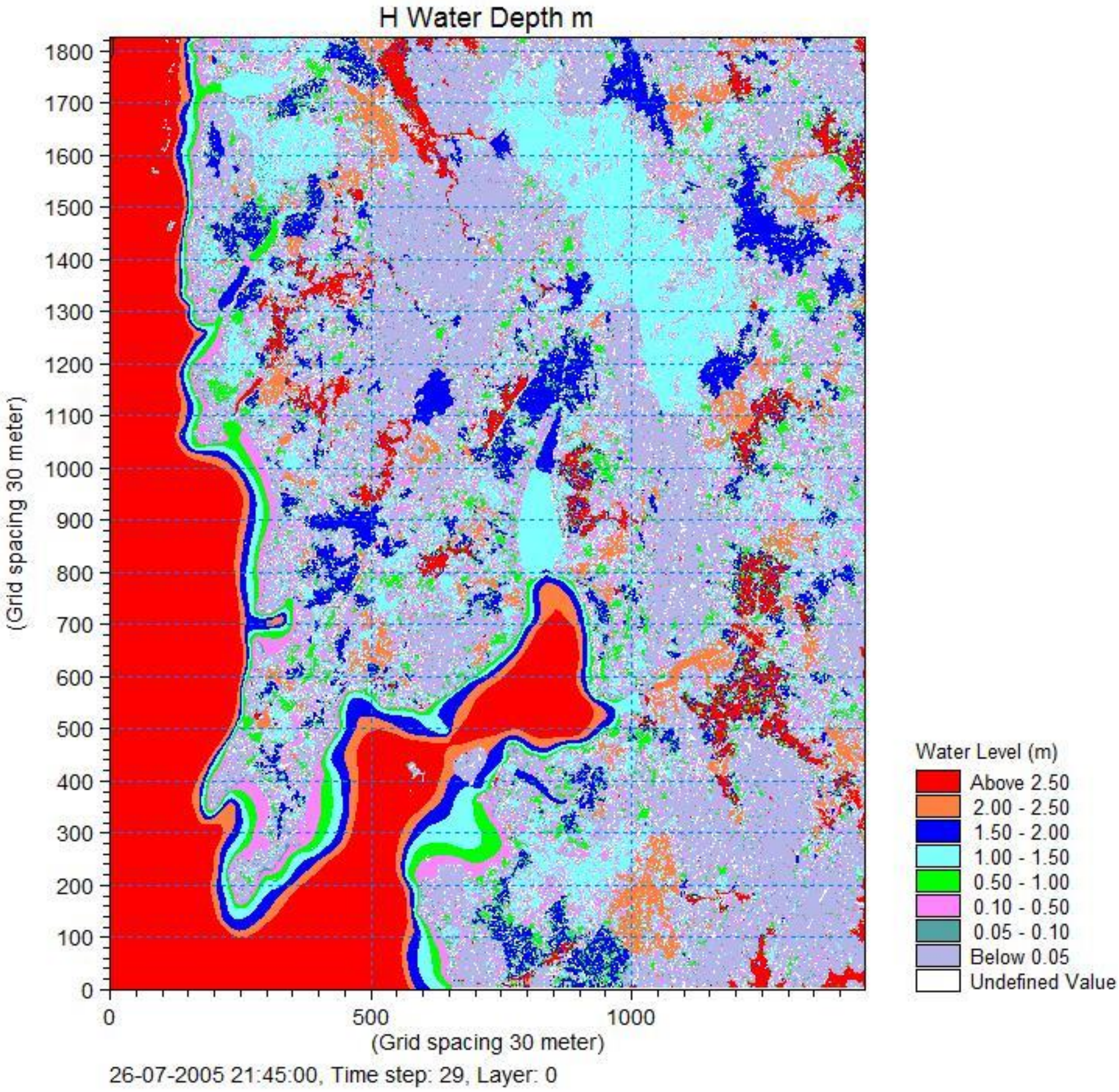

H Water Depth m
(Grid spacing 30 meter)
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
500
1000
(Grid spacing 30 meter)
26-07-2005 20:30:00, Time step: 24, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

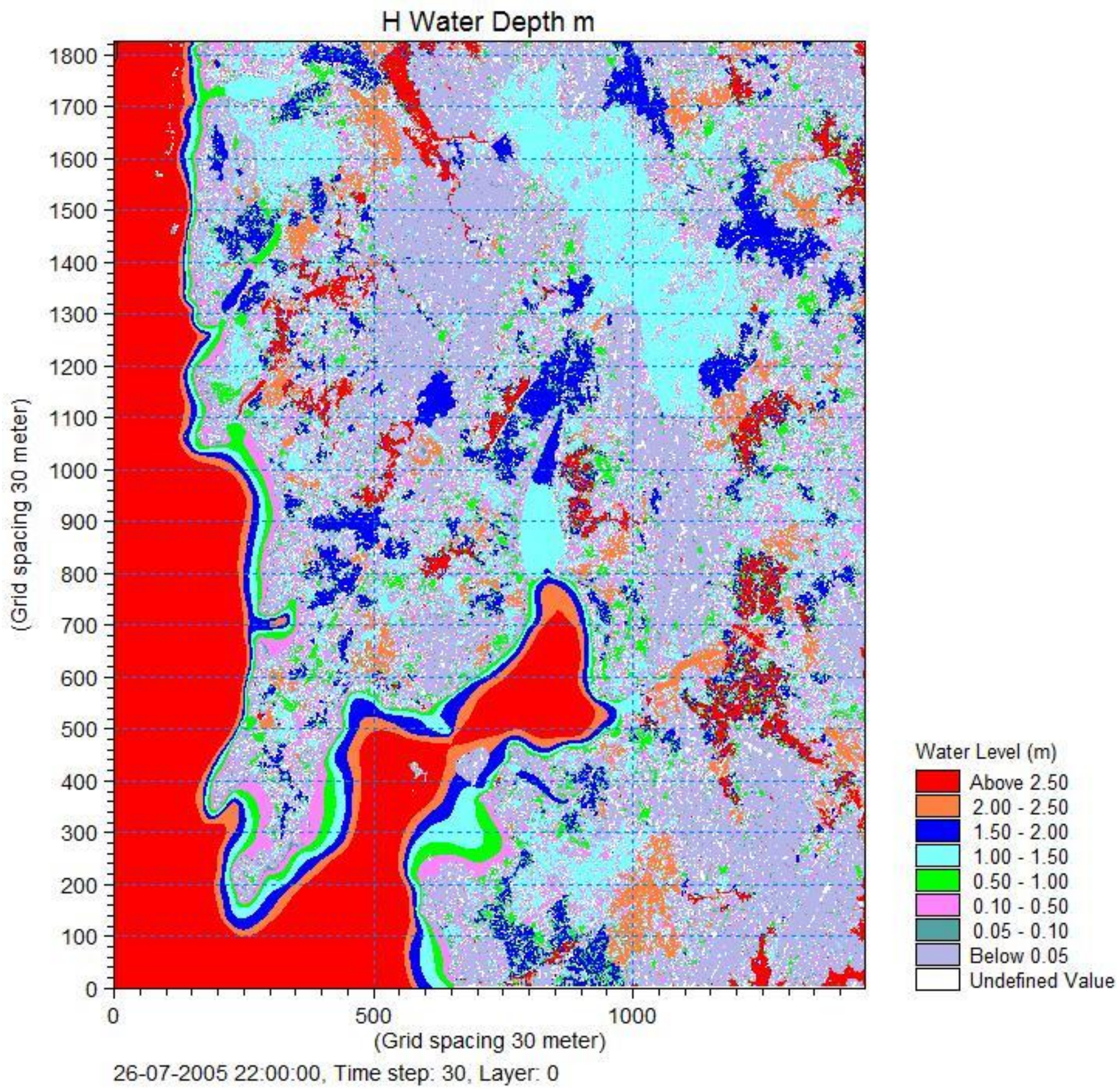

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 20:45:00, Time step: 25, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

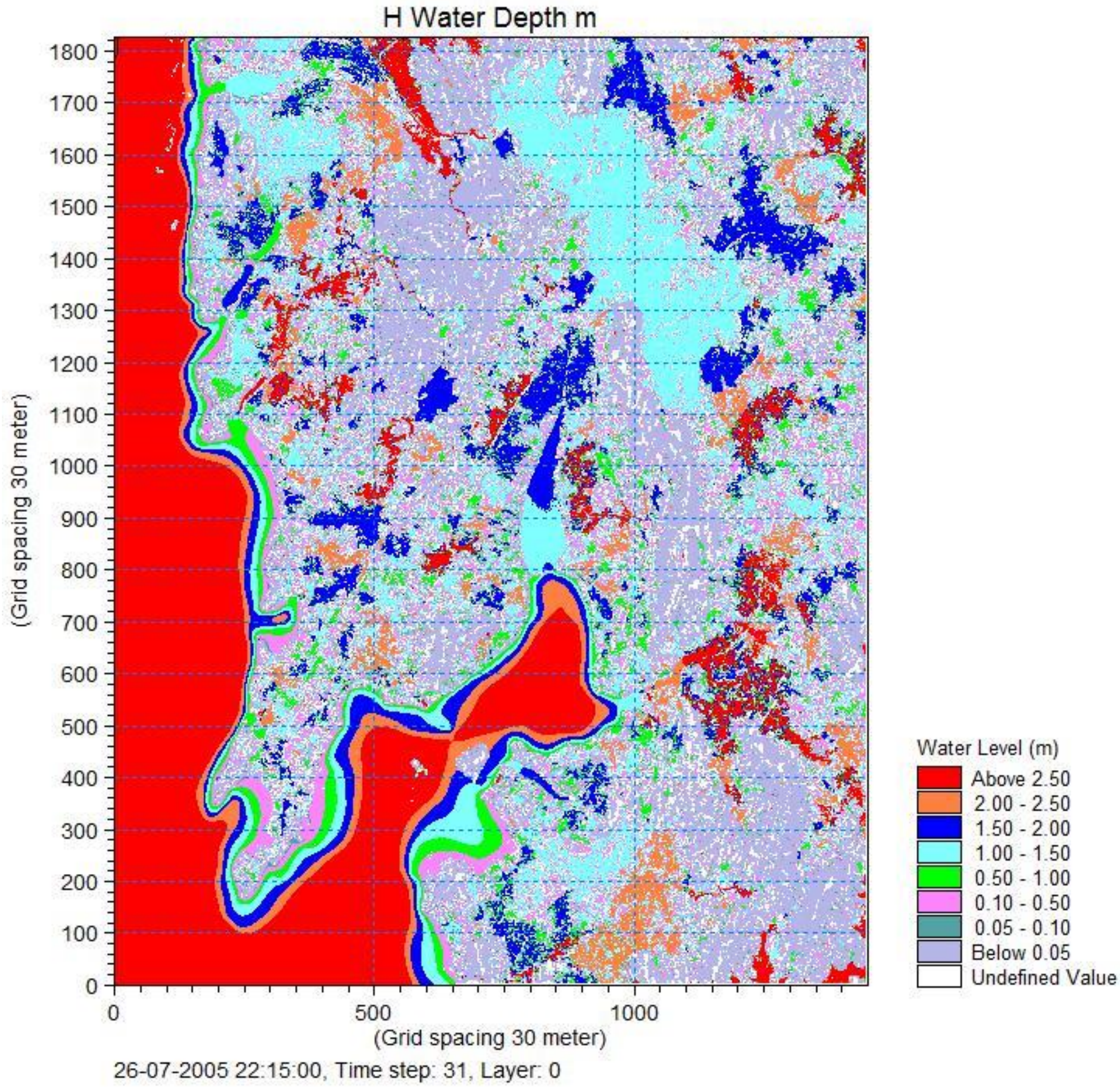

H Water Depth m
(Grid spacing 30 meter)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
0
500
1000
(Grid spacing 30 meter)
26-07-2005 21:00:00, Time step: 26, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

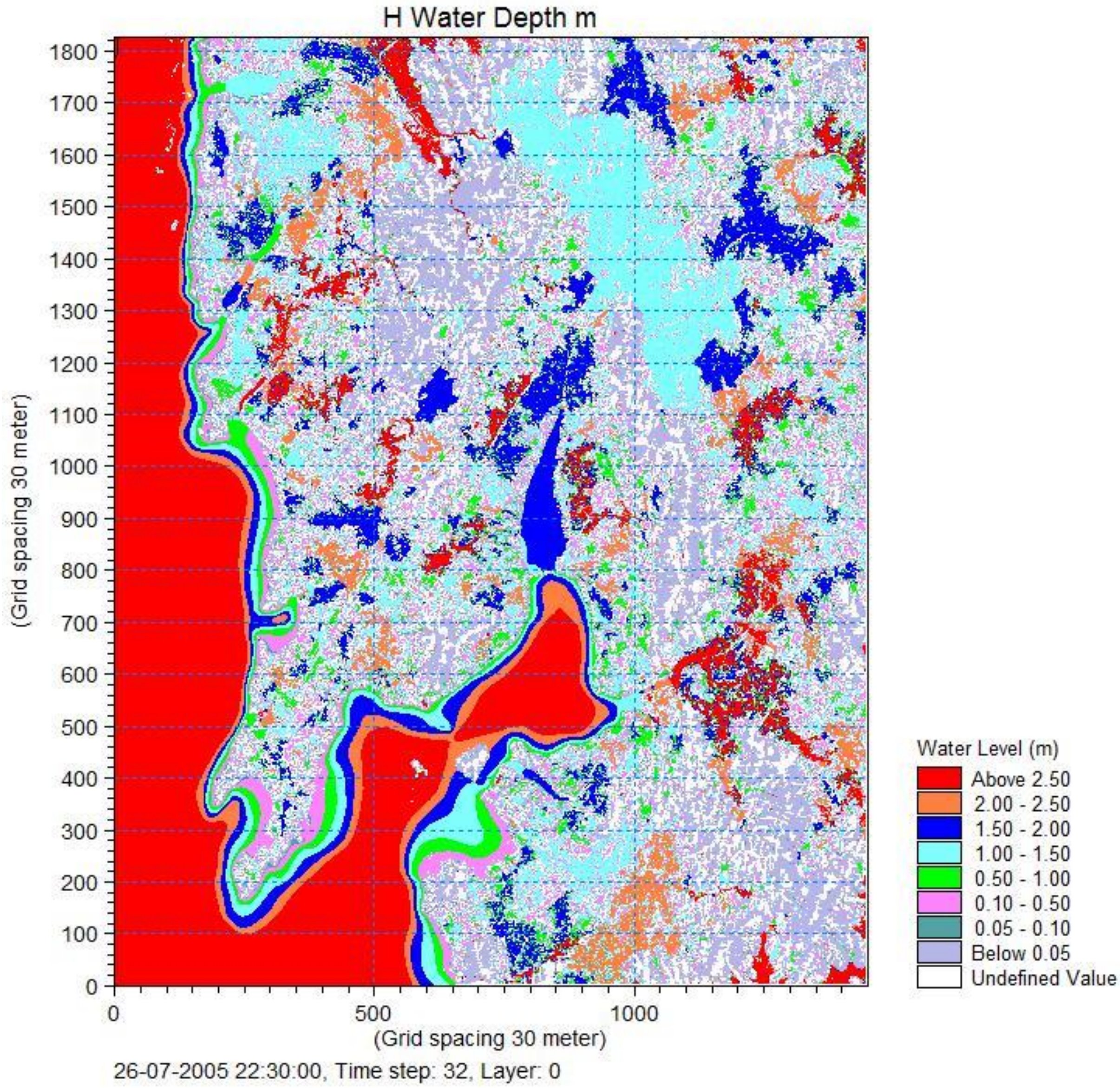

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
26-07-2005 21:15:00, Time step: 27, Layer: 0

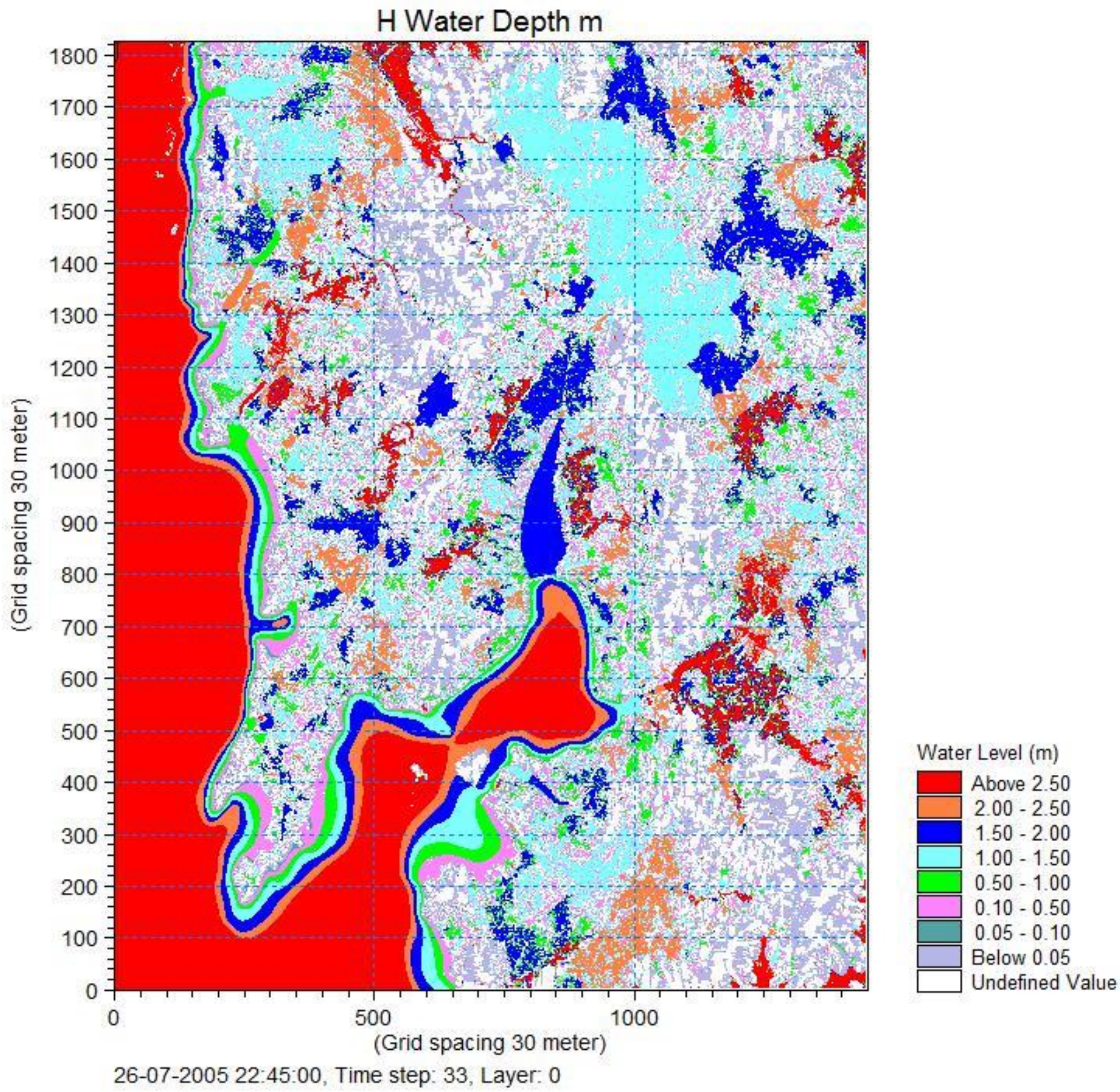

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
26-07-2005 21:30:00, Time step: 28, Layer: 0

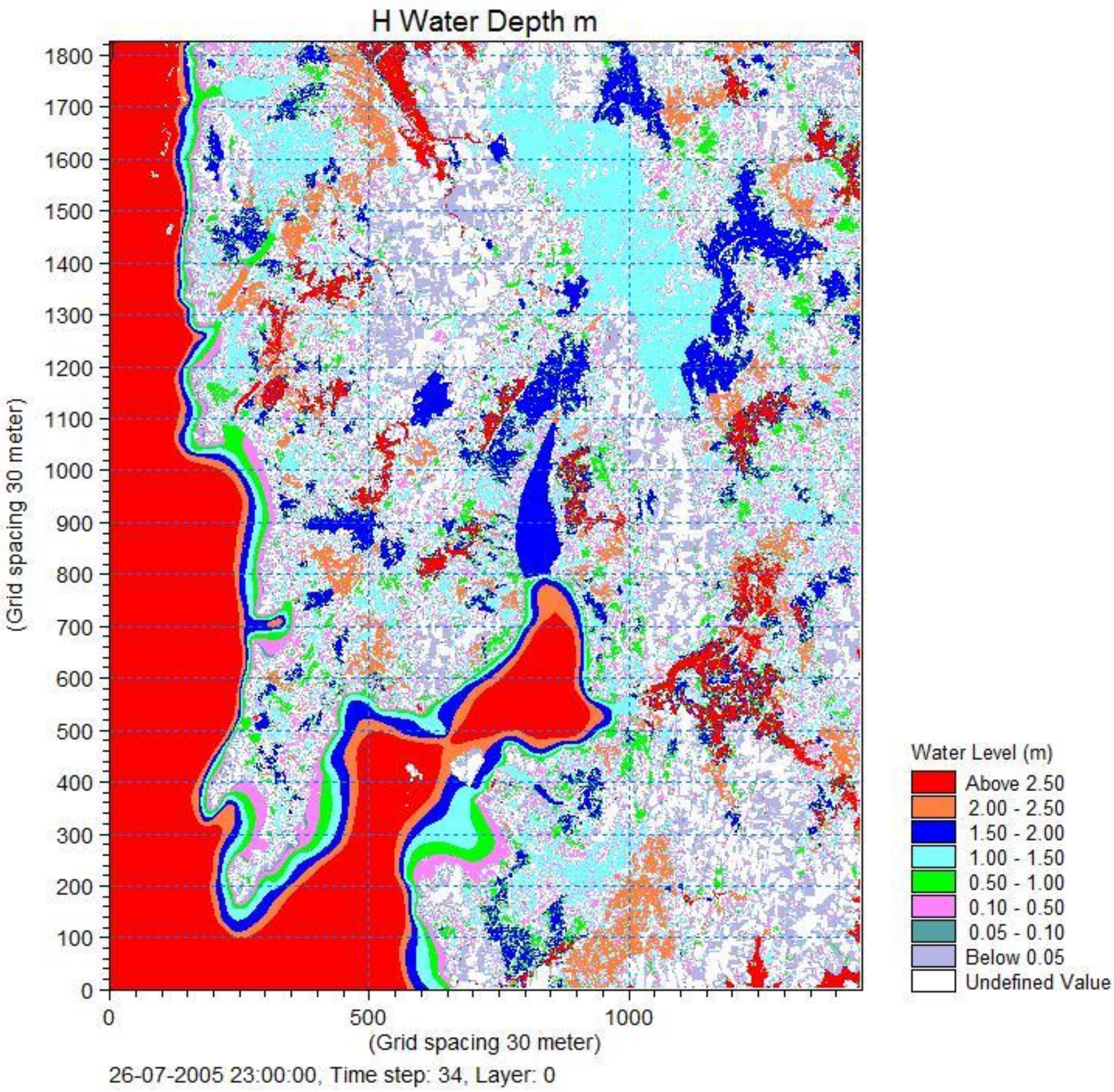

H Water Depth m
(Grid spacing 30 meter)
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
26-07-2005 21:45:00, Time step: 29, Layer: 0

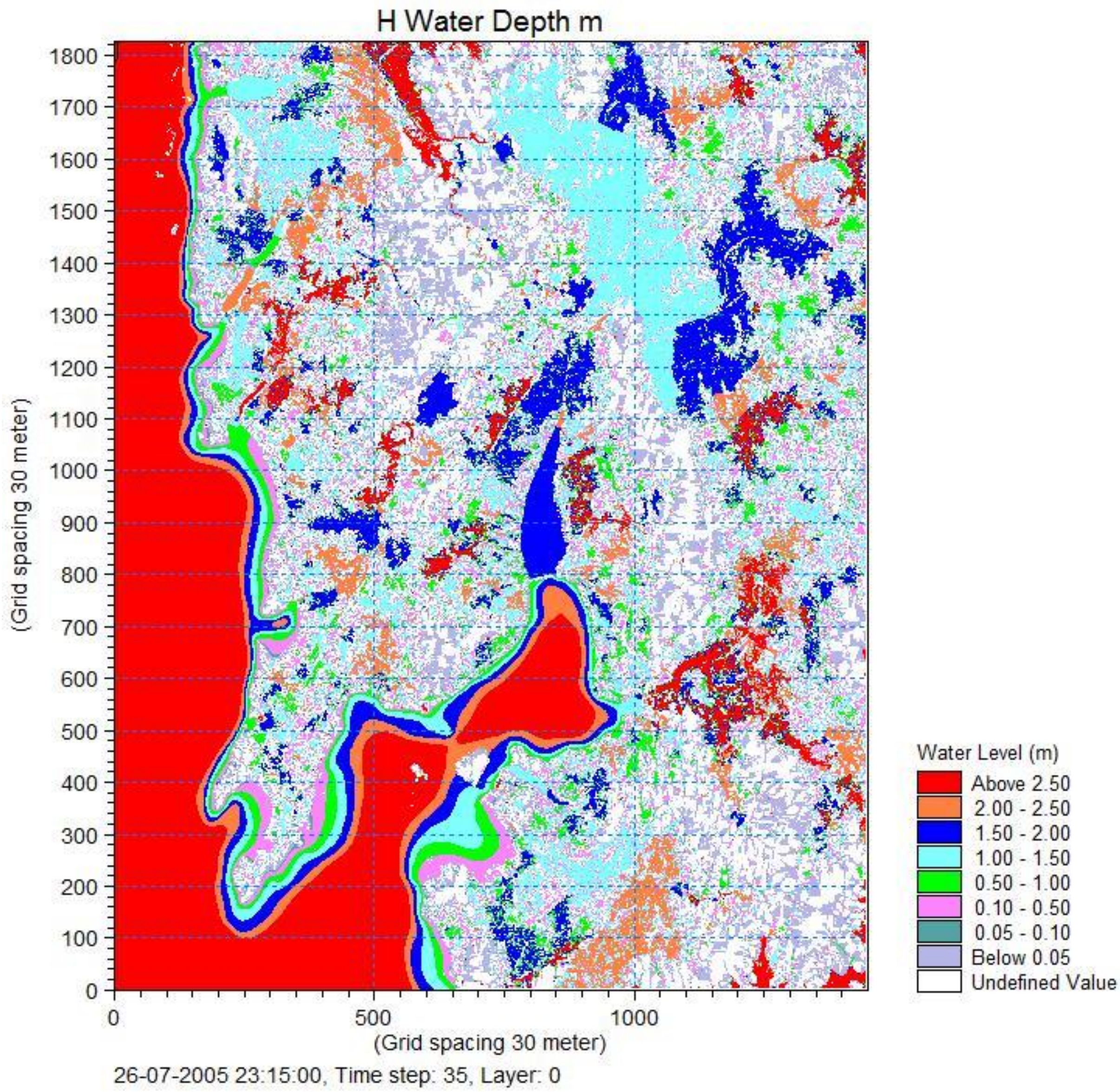

H Water Depth m
(Grid spacing 30 meter)
(Grid spacing 30 meter)
26-07-2005 22:00:00, Time step: 30, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

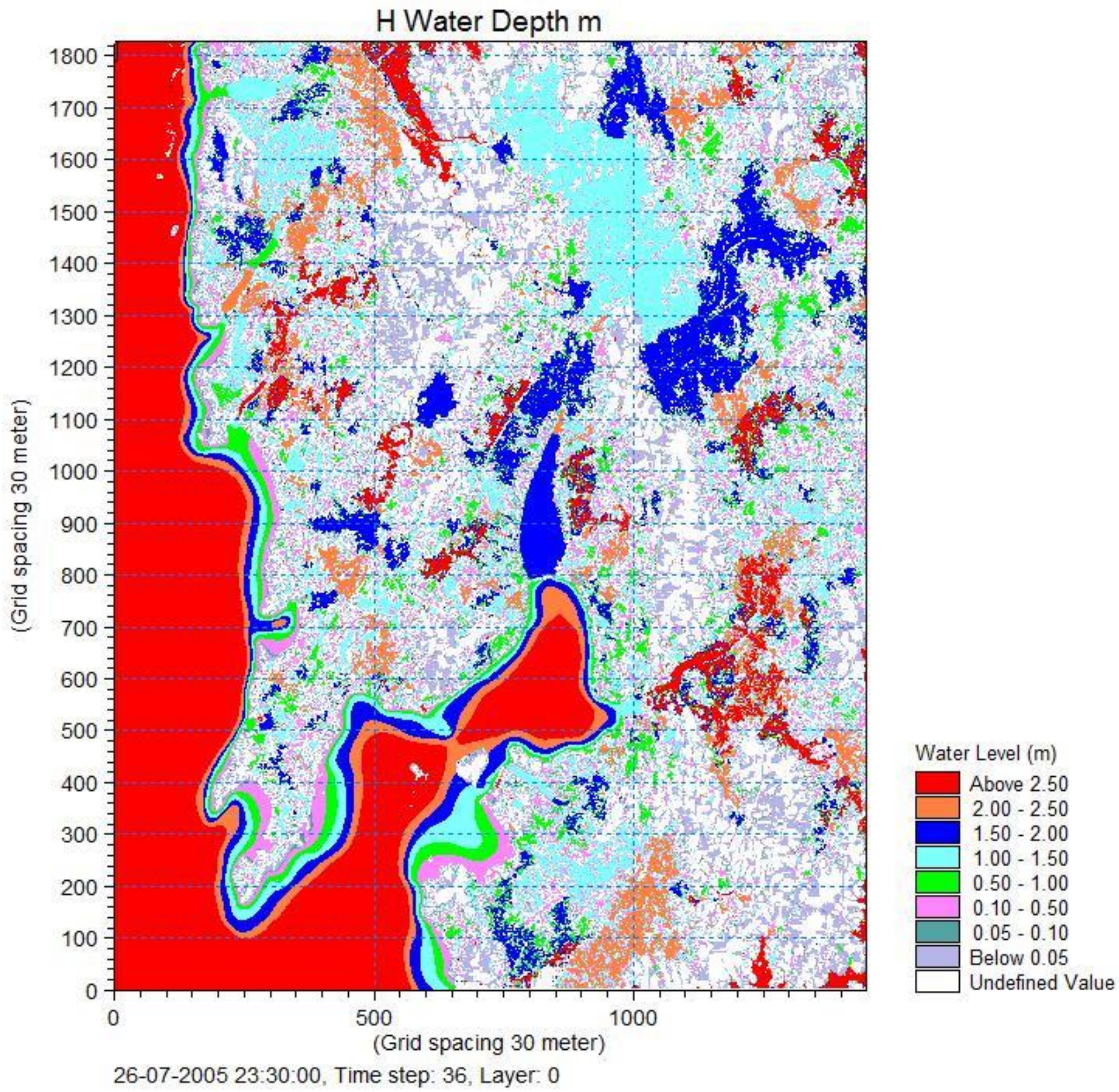

H Water Depth m
(Grid spacing 30 meter)
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
26-07-2005 22:15:00, Time step: 31, Layer: 0

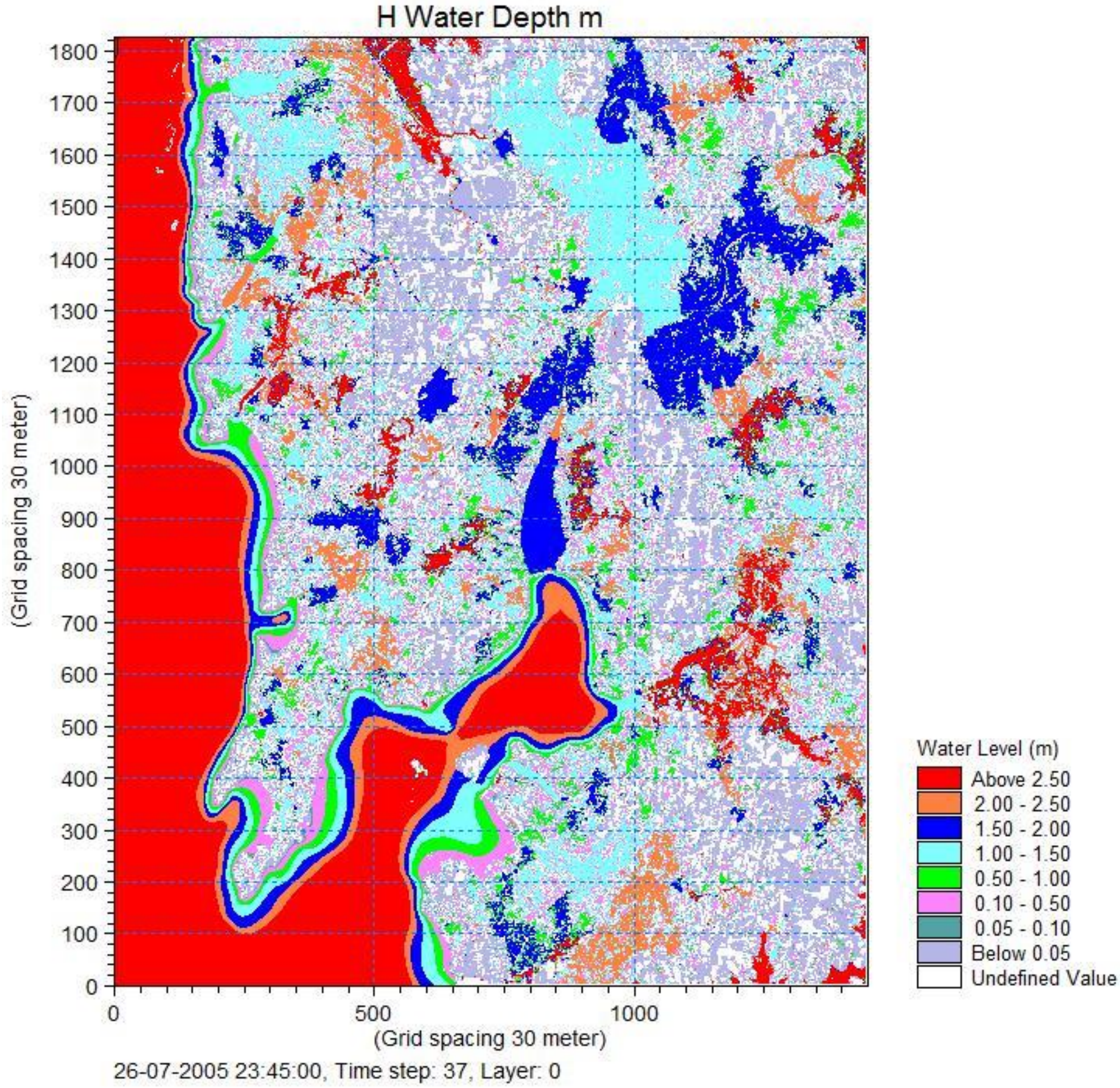

H Water Depth m
(Grid spacing 30 meter)
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
500
1000
(Grid spacing 30 meter)
26-07-2005 22:30:00, Time step: 32, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

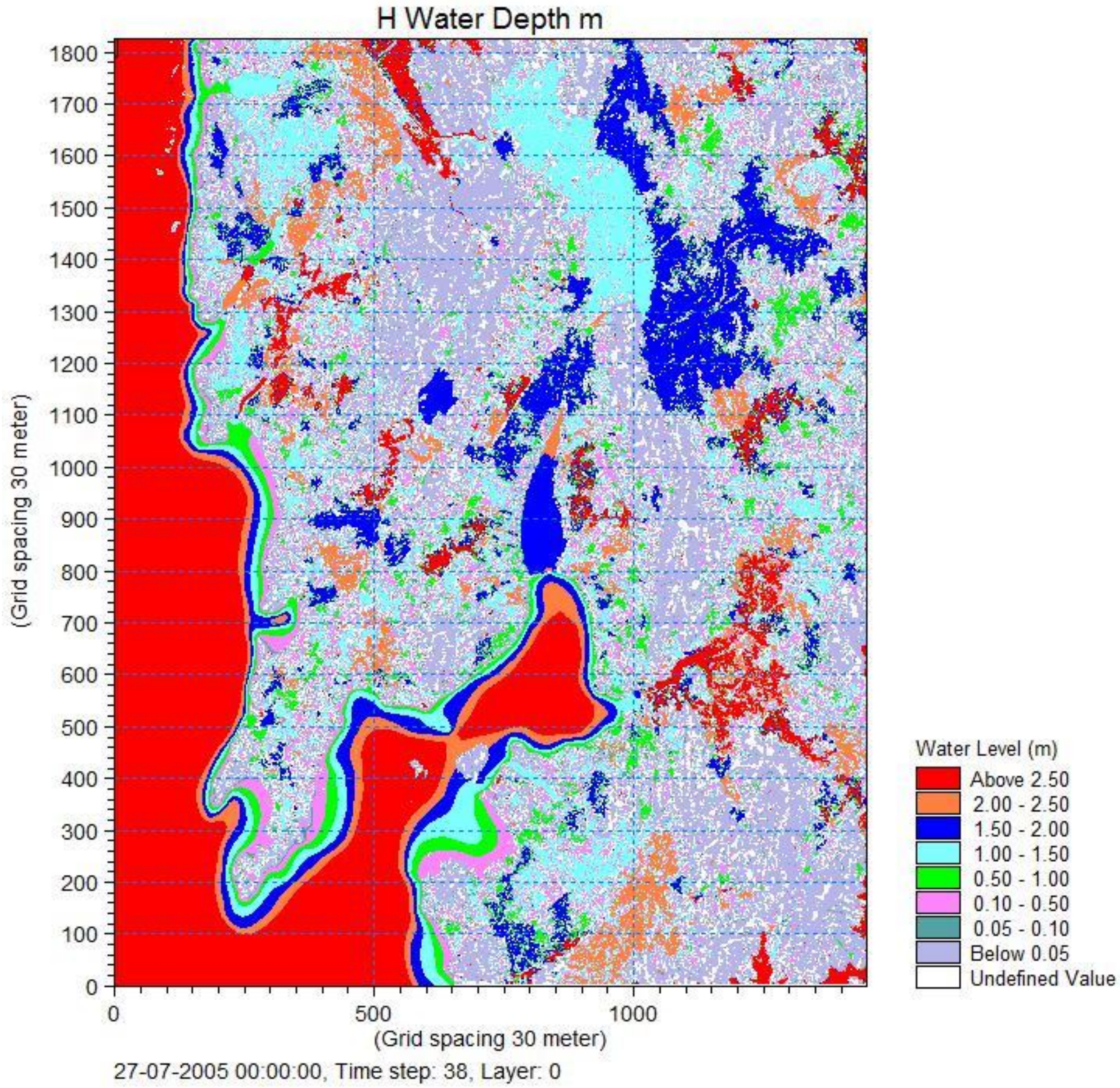

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 22:45:00, Time step: 33, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

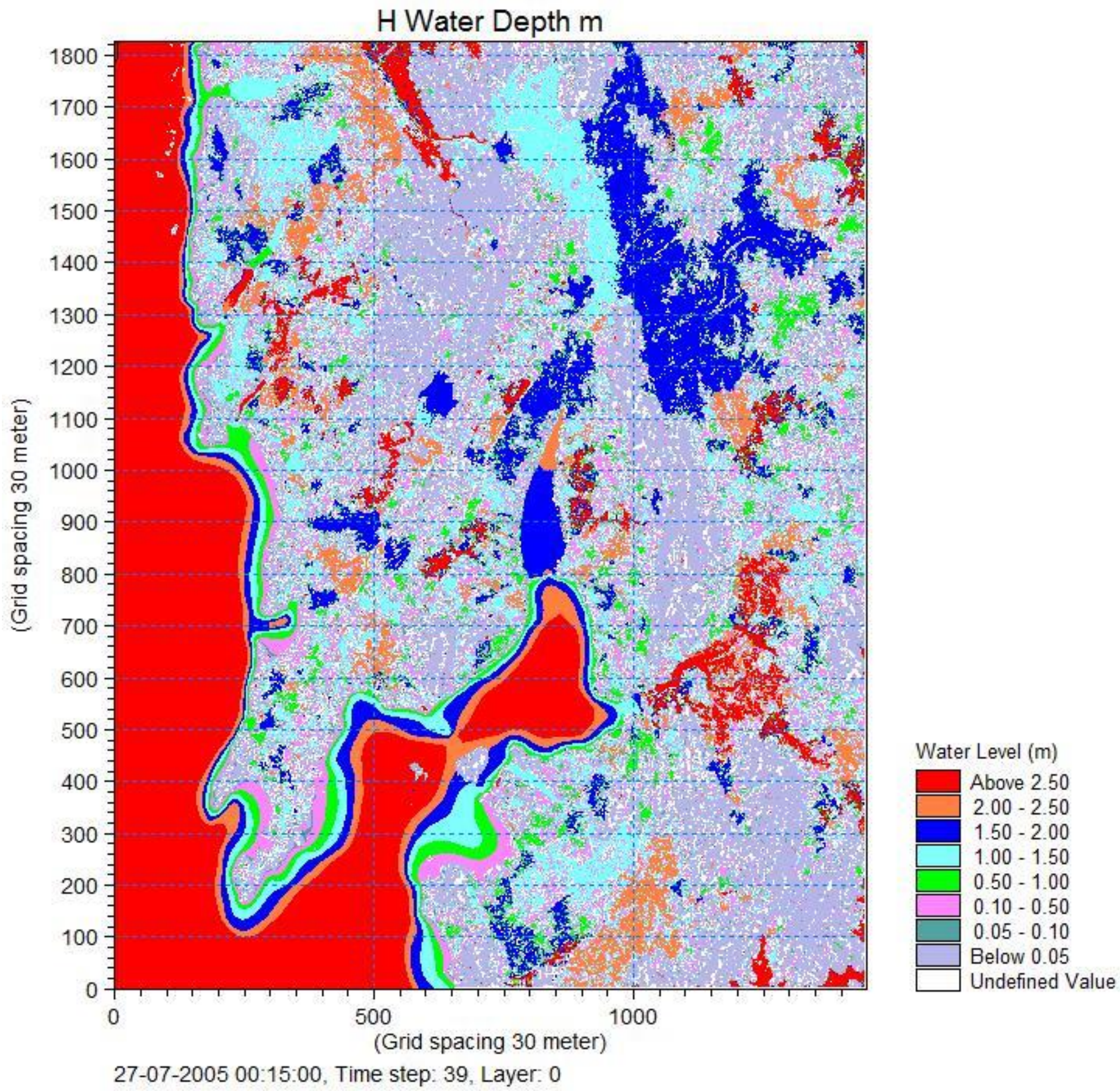

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
26-07-2005 23:00:00, Time step: 34, Layer: 0

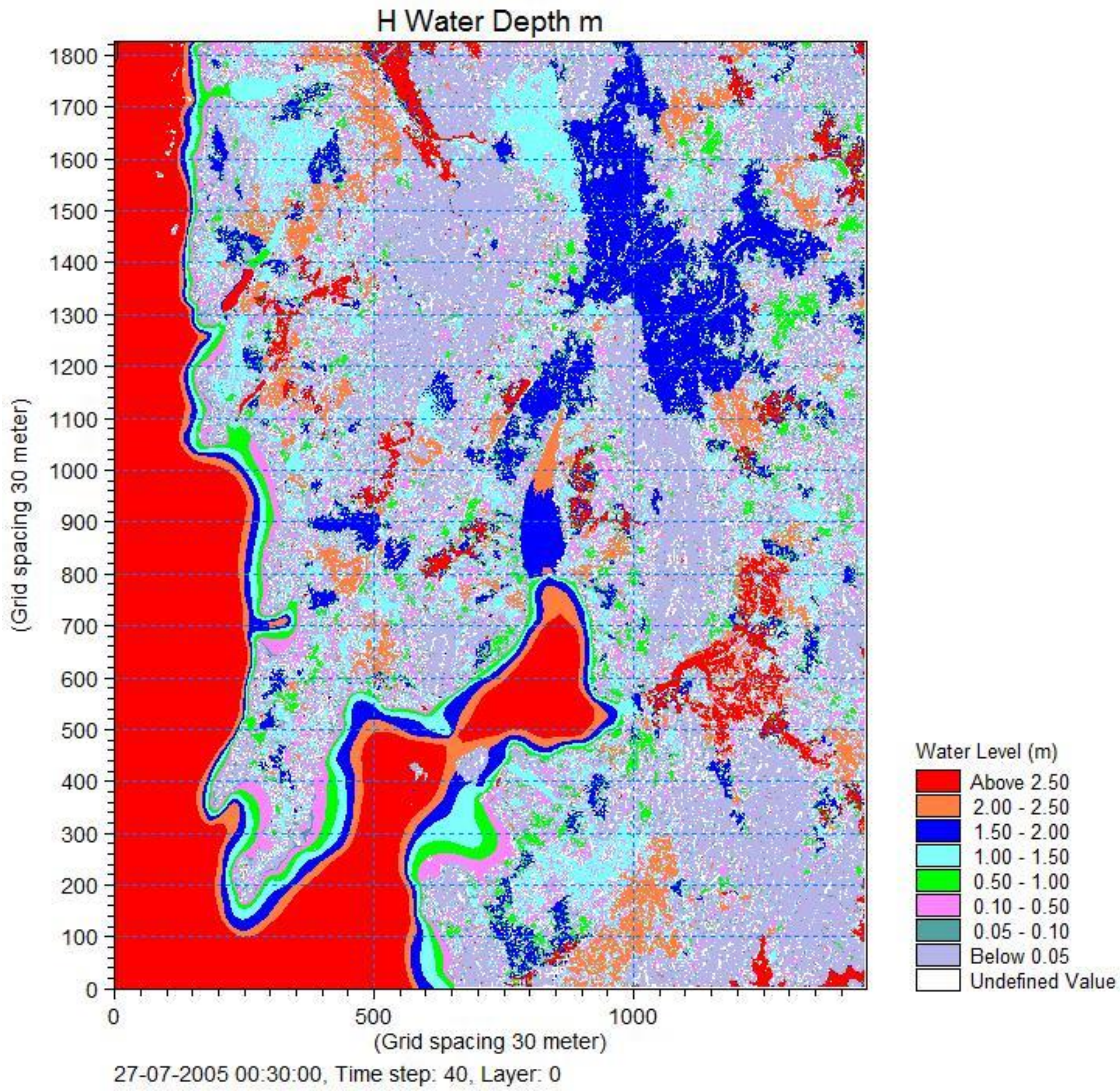

H Water Depth m
(Grid spacing 30 meter)
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
500
1000
(Grid spacing 30 meter)
26-07-2005 23:15:00, Time step: 35, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

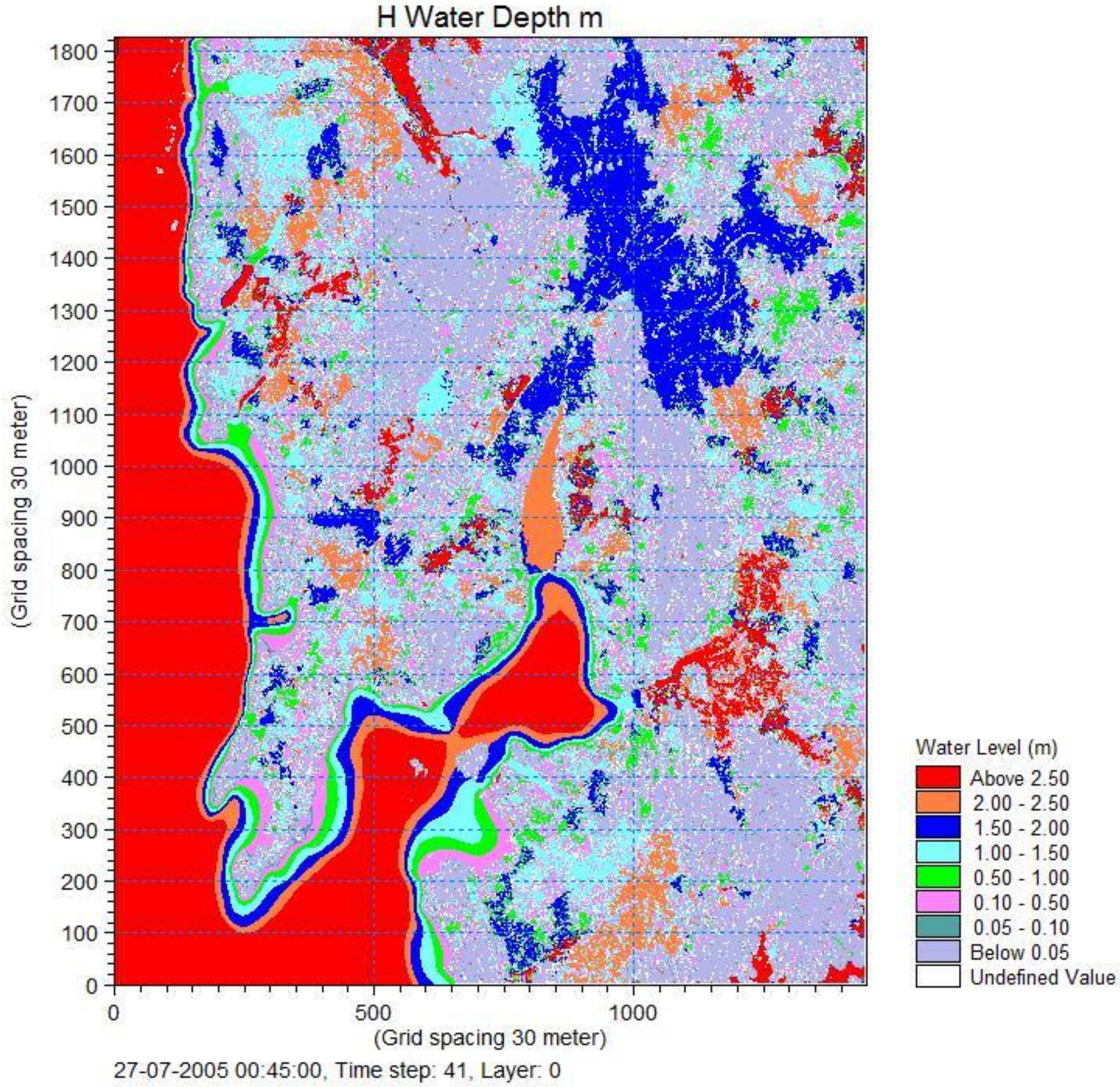

H Water Depth m
(Grid spacing 30 meter)
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
26-07-2005 23:30:00, Time step: 36, Layer: 0

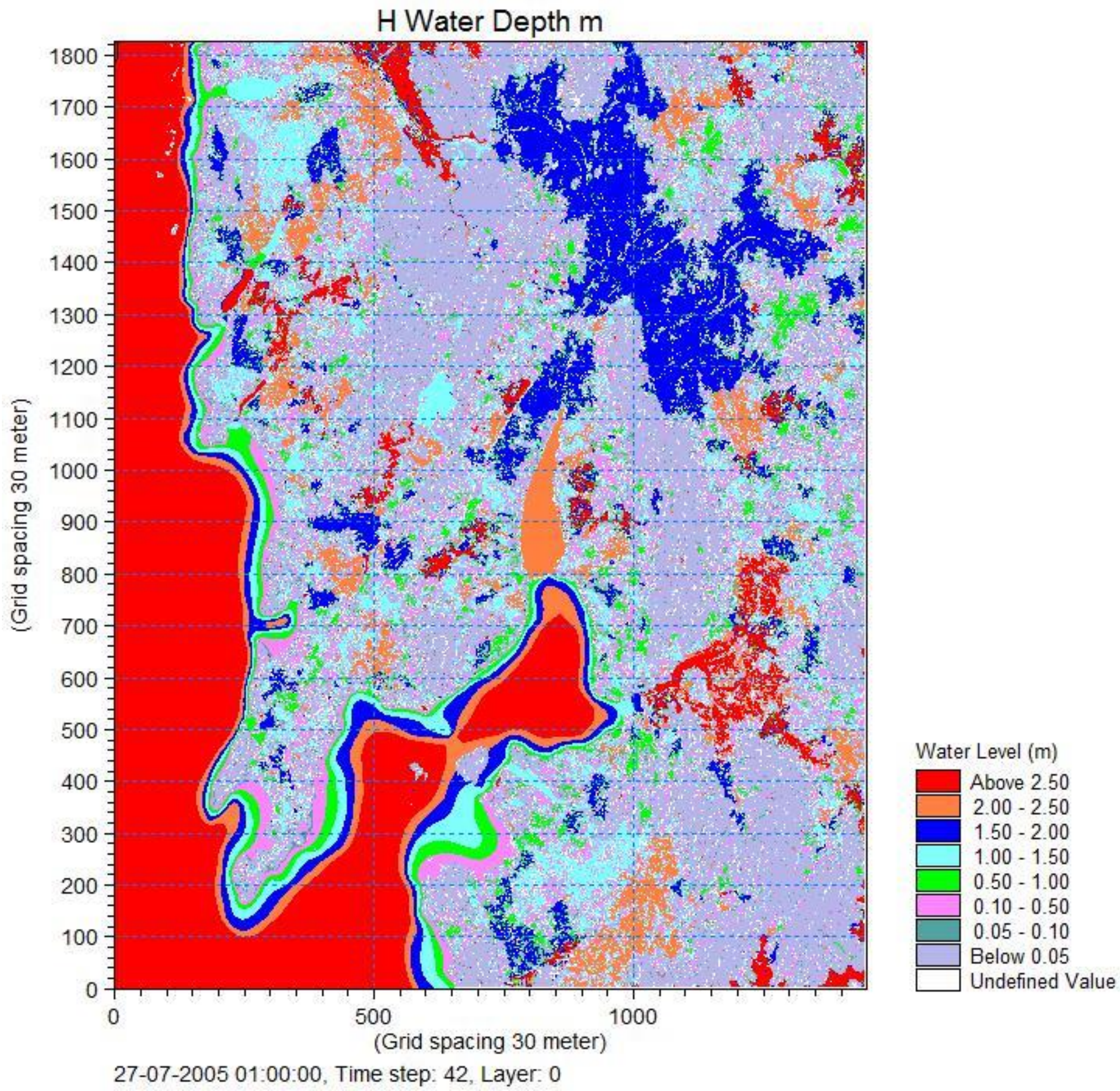

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
26-07-2005 23:45:00, Time step: 37, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

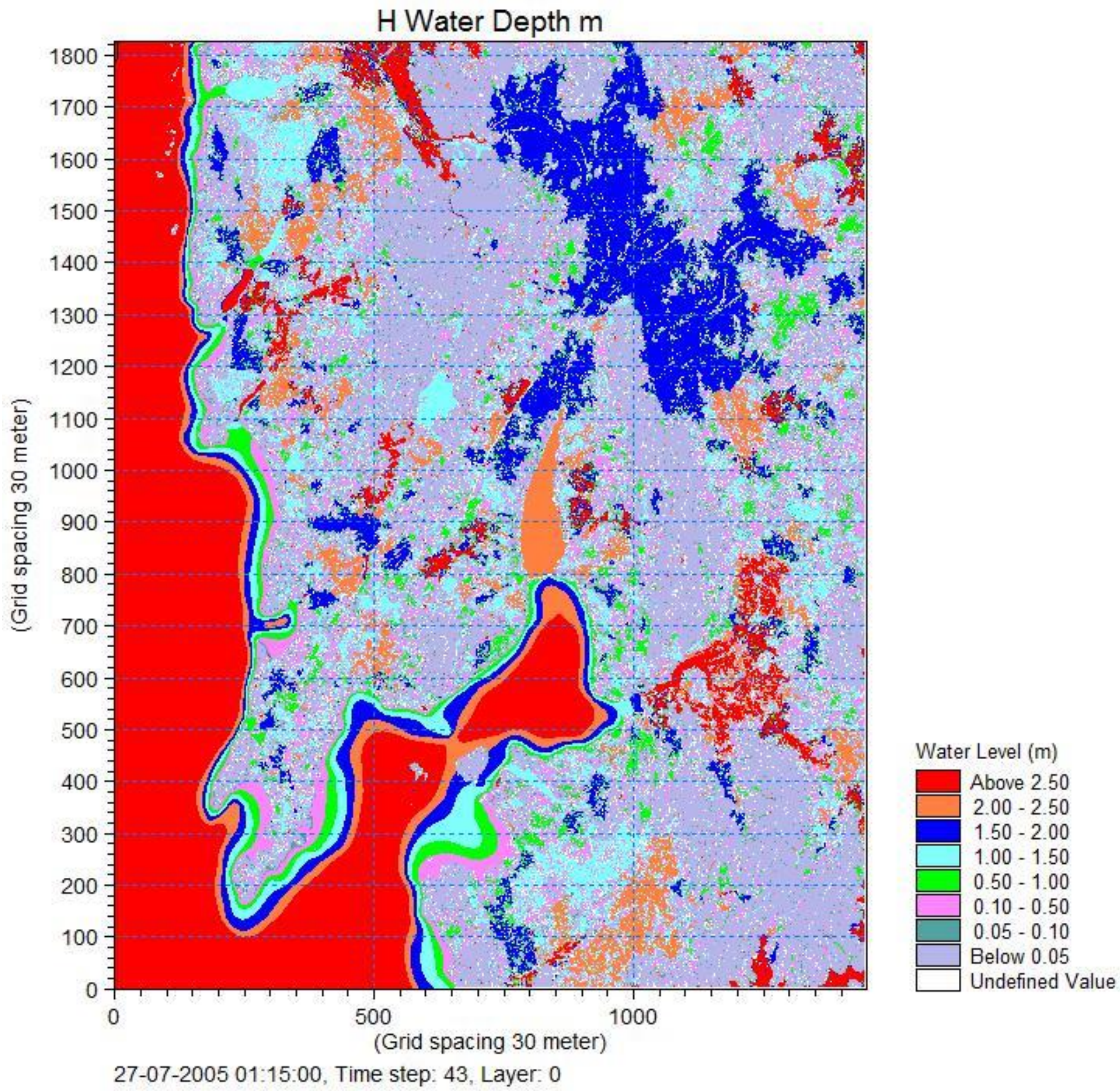

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
27-07-2005 00:00:00, Time step: 38, Layer: 0

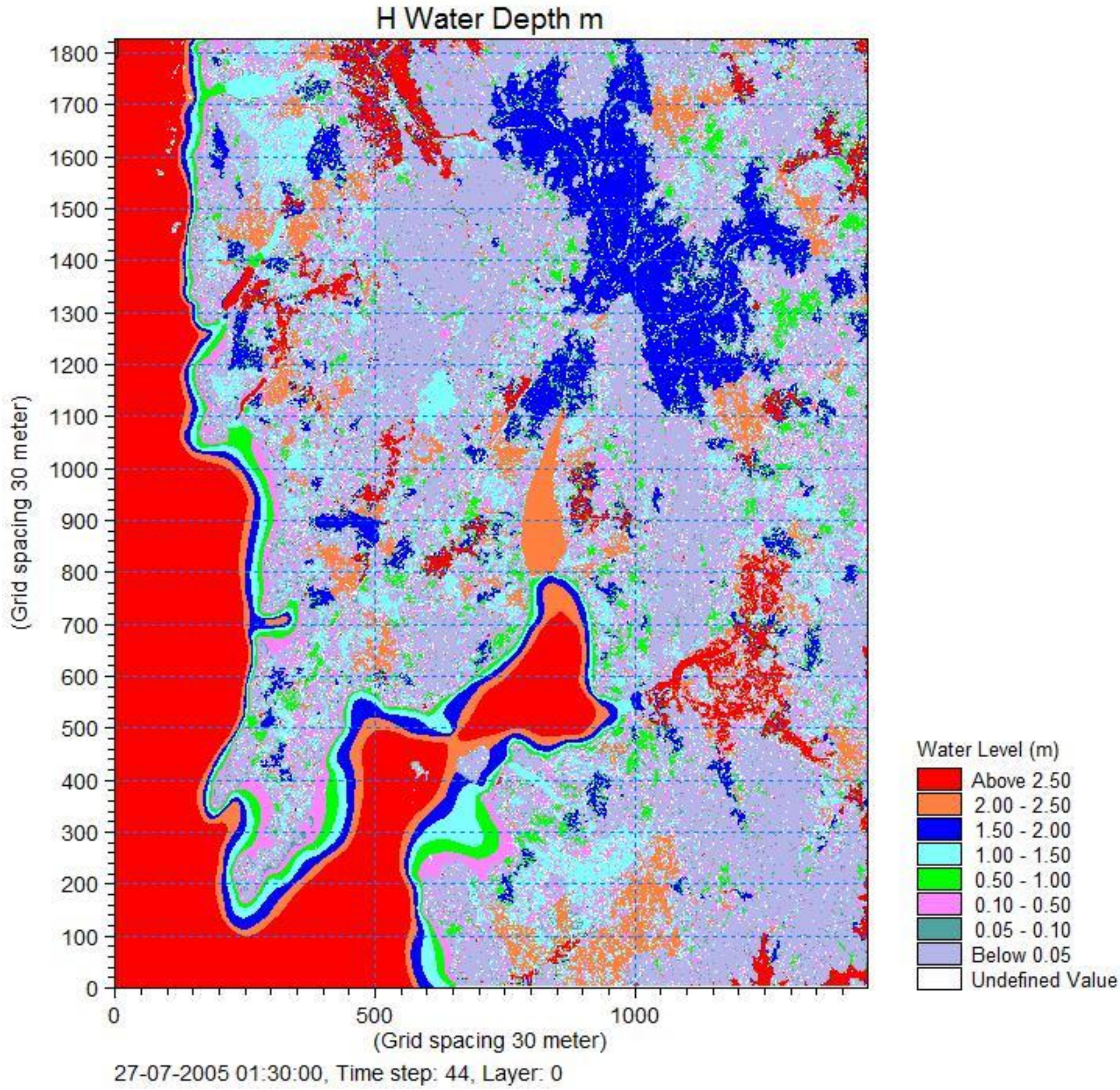

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
27-07-2005 00:15:00, Time step: 39, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

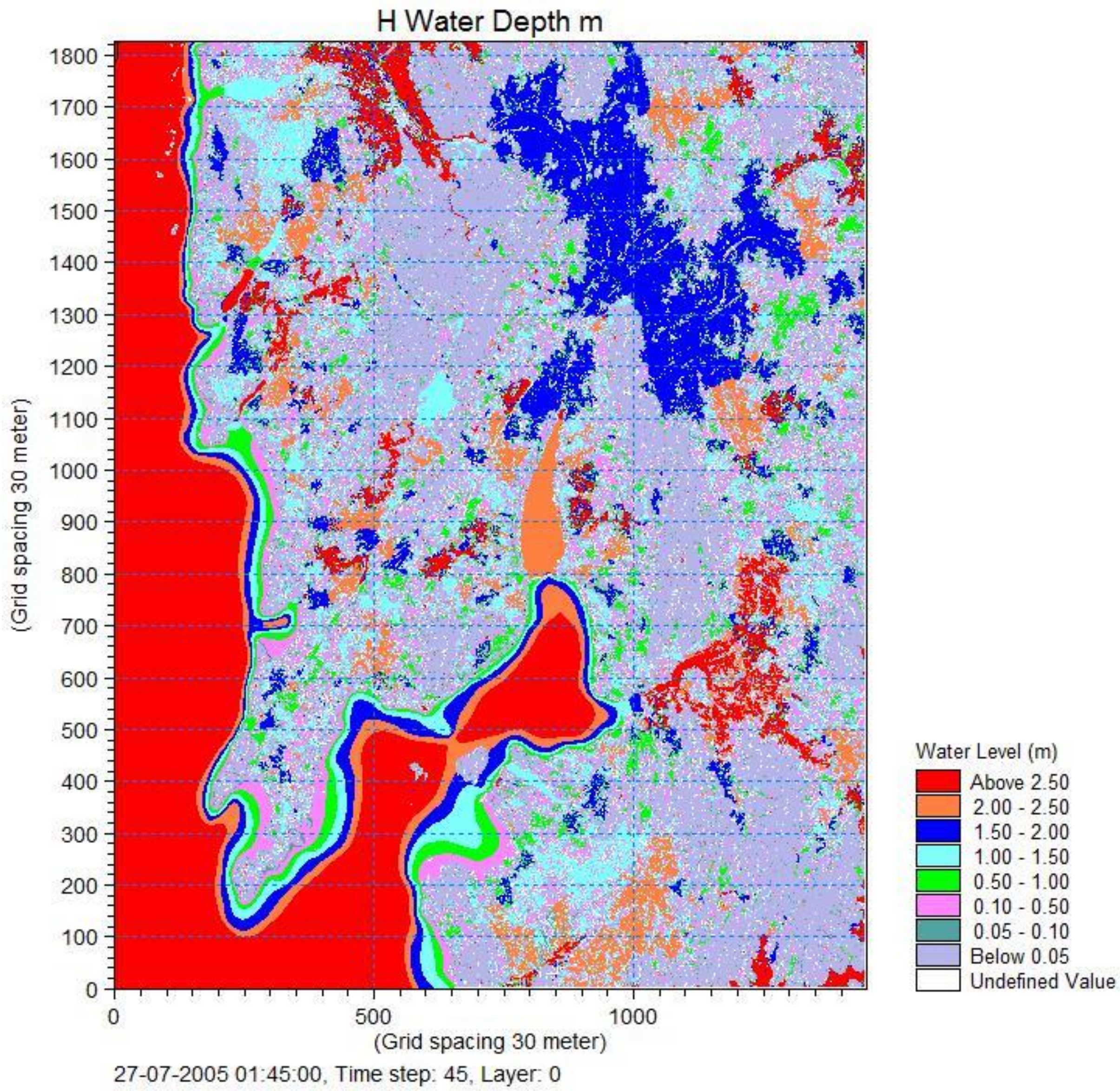

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
27-07-2005 00:30:00, Time step: 40, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

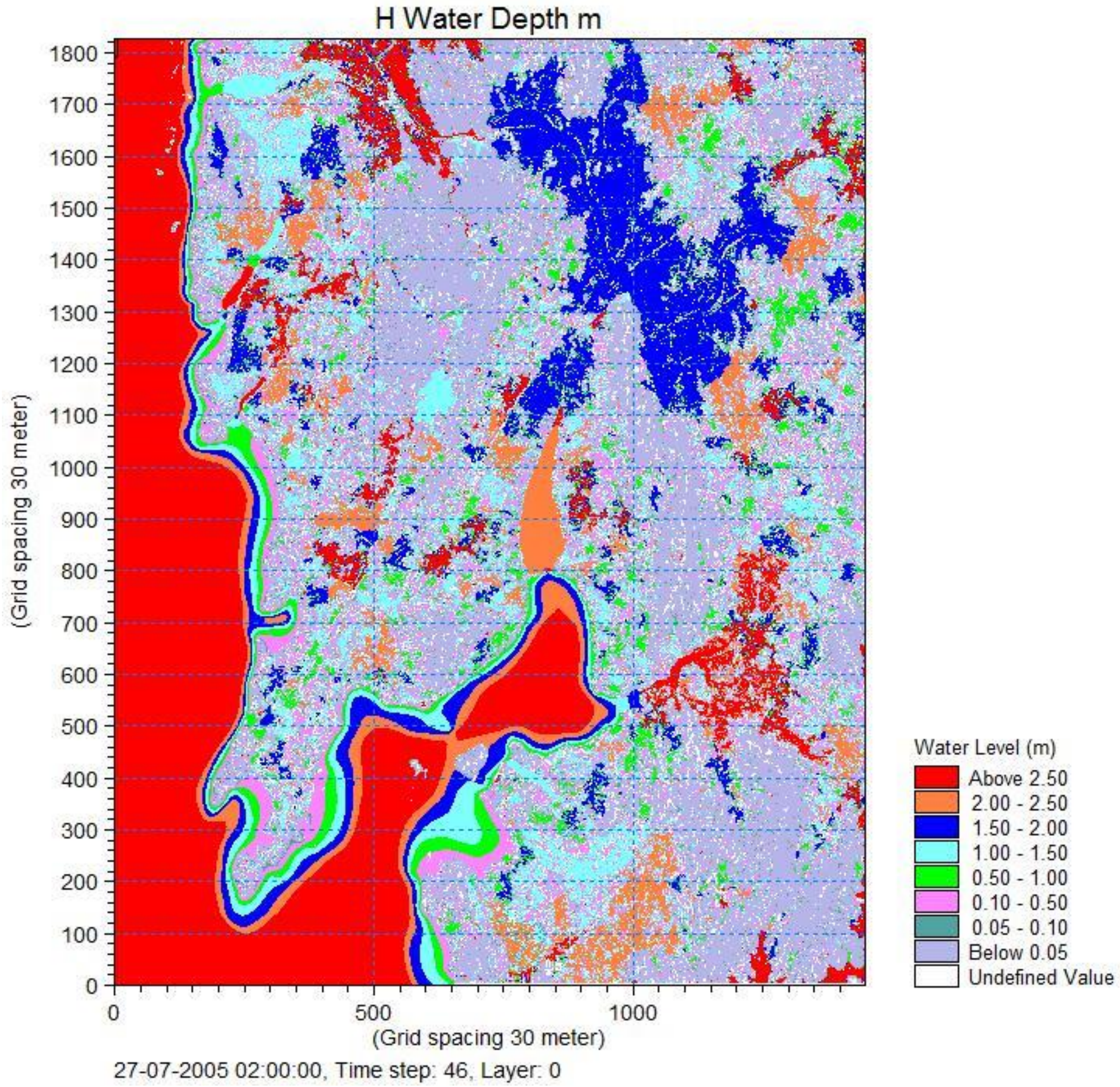

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
27-07-2005 00:45:00, Time step: 41, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

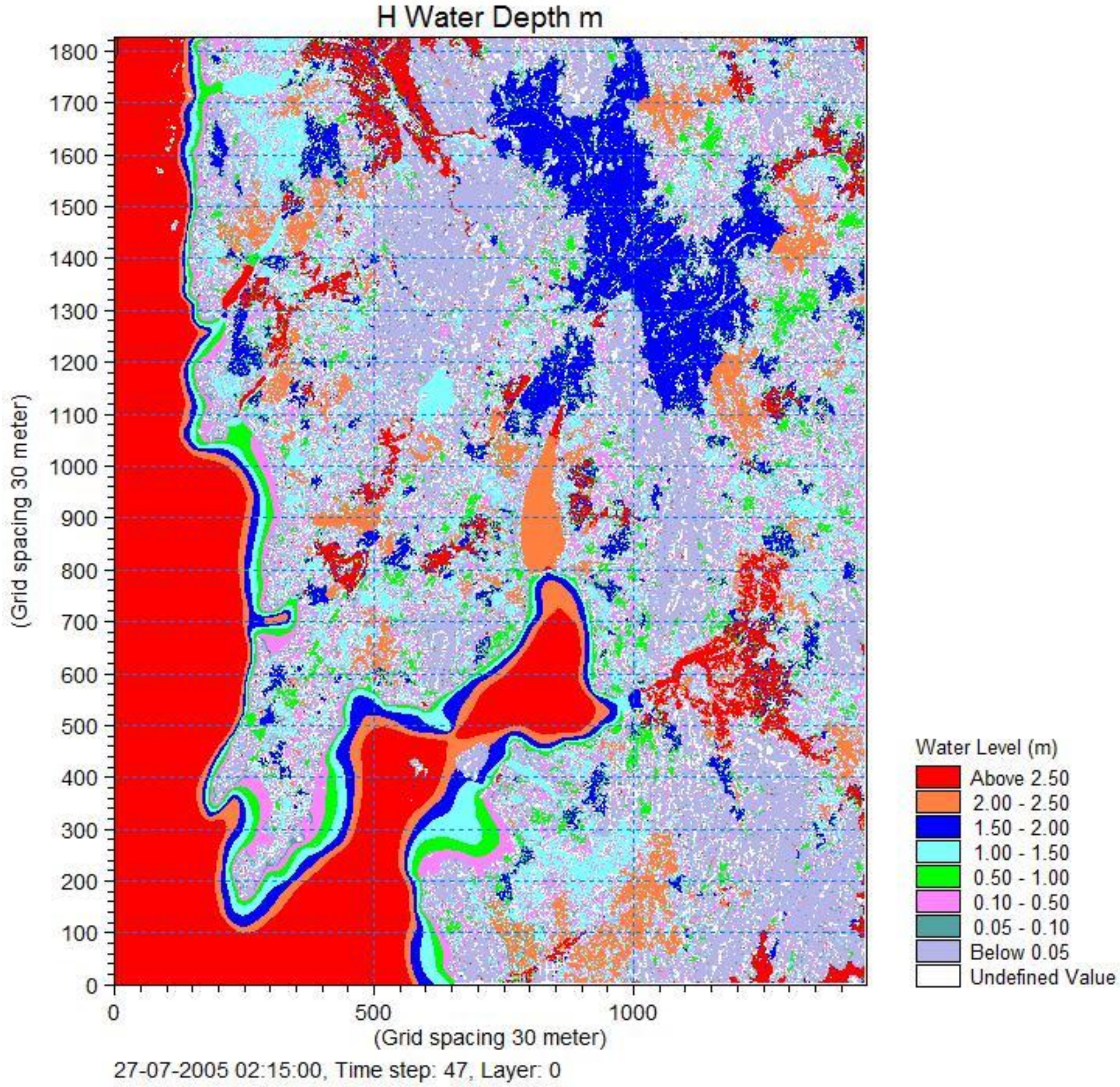

H Water Depth m
(Grid spacing 30 meter)
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
500
1000
(Grid spacing 30 meter)
27-07-2005 01:00:00, Time step: 42, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value

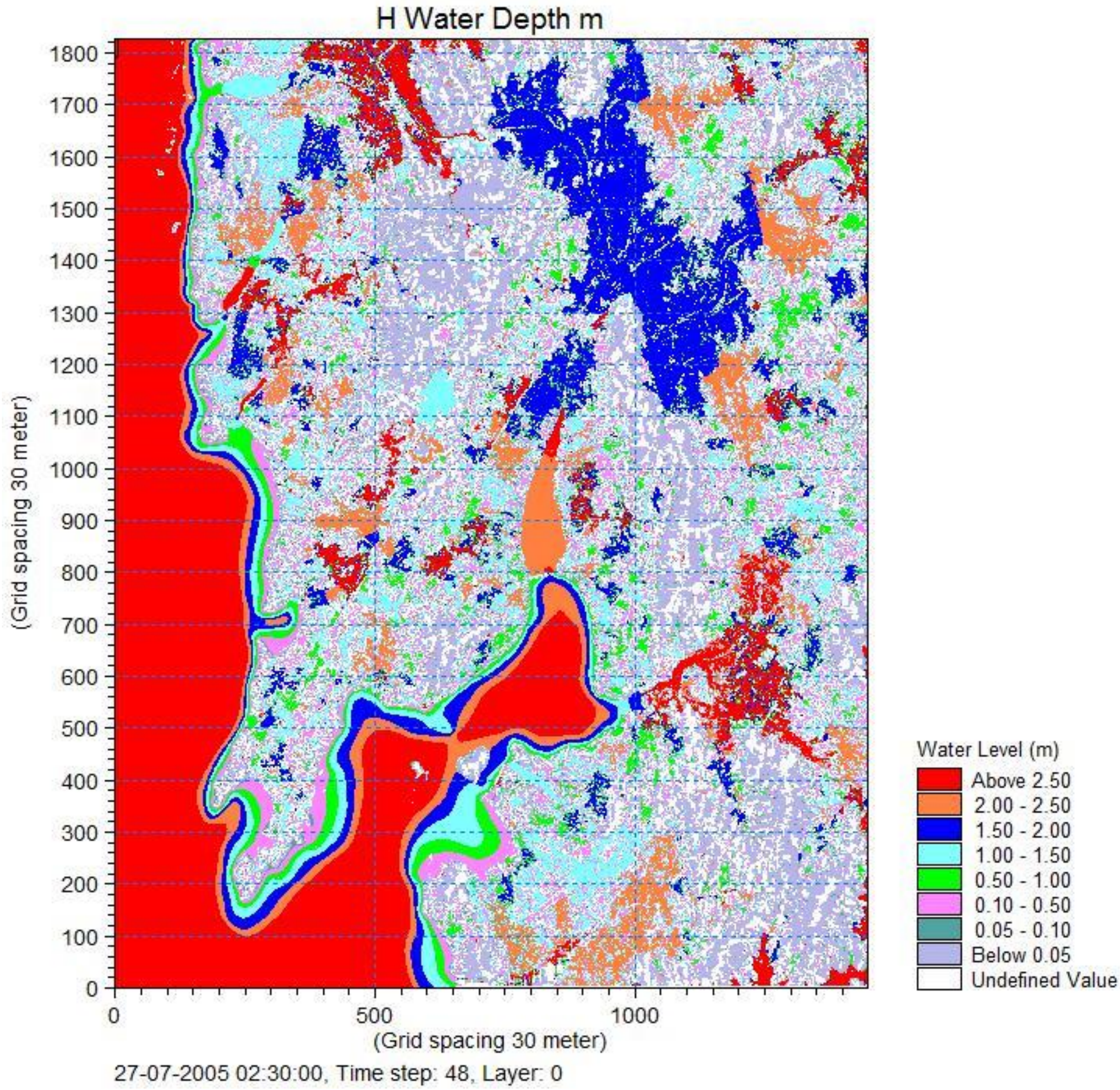

H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
27-07-2005 01:15:00, Time step: 43, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value


H Water Depth m
(Grid spacing 30 meter)
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
500
1000
(Grid spacing 30 meter)
27-07-2005 01:30:00, Time step: 44, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value


H Water Depth m
(Grid spacing 30 meter)
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
27-07-2005 01:45:00, Time step: 45, Layer: 0


H Water Depth m
(Grid spacing 30 meter)
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
27-07-2005 02:00:00, Time step: 46, Layer: 0


H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value
27-07-2005 02:15:00, Time step: 47, Layer: 0


H Water Depth m
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
(Grid spacing 30 meter)
0
500
1000
(Grid spacing 30 meter)
27-07-2005 02:30:00, Time step: 48, Layer: 0
Water Level (m)
Above 2.50
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.10 - 0.50
0.05 - 0.10
Below 0.05
Undefined Value