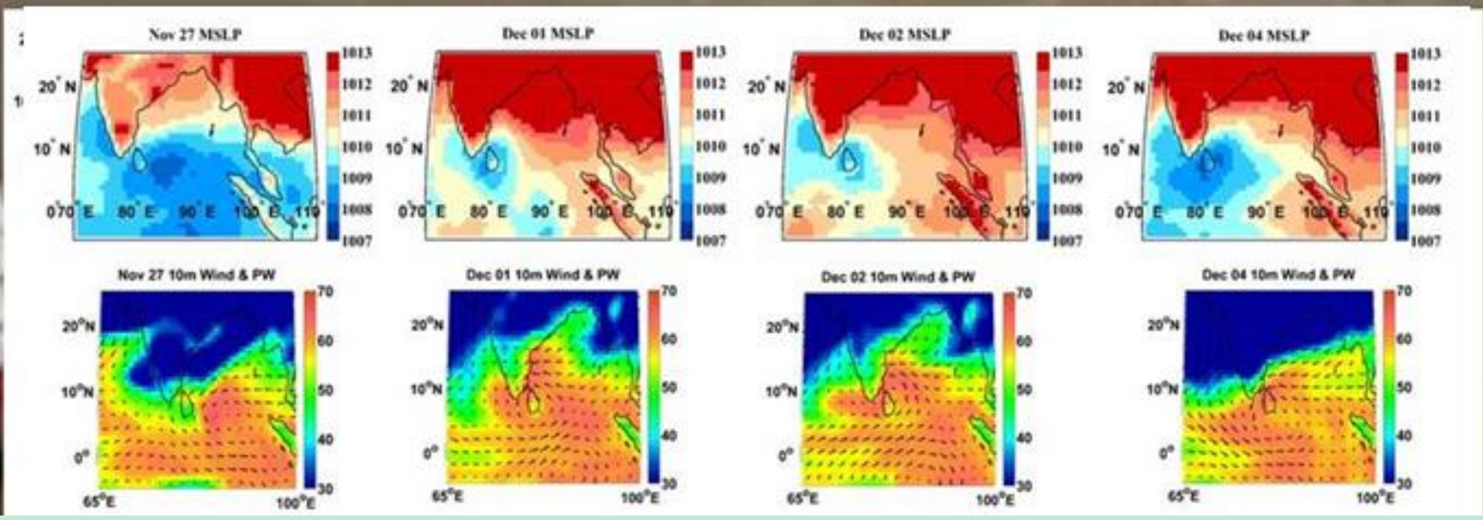
Chennai Floods 2015

A Rapid Assessment

Balaji Narasimhan, IIT Madras
S. Murty Bhallamudi, IIT Madras
Arpita Mondal, IIT Bombay
Subimal Ghosh, IIT Bombay
Pradeep Mujumdar, IISc Bangalore



Interdisciplinary Centre for Water Research
Indian Institute of Science, Bangalore
May 2016

Author Details

Corresponding Author:

Prof. P. P. Mujumdar
Chairman, Interdisciplinary Centre for Water Research (ICWaR)
Indian Institute of Science, Bangalore 560 012
E-mail: chairman@icwar.iisc.ernet.in

Contributing Authors:

Dr. Balaji Narasimhan
Associate Professor
Department of Civil Engineering
Indian Institute of Technology, Madras
Chennai 600 036
E-mail: nbalaji@iitm.ac.in

Prof. S. Murty Bhallamudi
Department of Civil Engineering and
Indo-German Center for Sustainability
Indian Institute of Technology, Madras
Chennai 600 036
E-mail: bsm@iitm.ac.in

Dr. Arpita Mondal
Assistant Professor
Department of Civil Engineering and Interdisciplinary Program in Climate Studies
Indian Institute of Technology, Bombay
Mumbai 400 076
E-mail: marpita@civil.iitb.ac.in

Dr. Subimal Ghosh
Associate Professor
Department of Civil Engineering and Interdisciplinary Program in Climate Studies
Indian Institute of Technology, Bombay
Mumbai 400 076
E-mail: subimal@iitb.ac.in

Contents

Preface

On the sidelines of a workshop at IIT Bombay in early January 2016, a small group of Indian hydrologists met with Dr. Bhowmik, Principal Scientist Emeritus, Illinois State Water Survey, PRI of the University of Illinois at Urbana Champaign (UIUC), USA for an intense and animated discussion on the devastating floods that had recently hit the Chennai City, during November-December 2015. Dr. Bhowmik was the leader of a multidisciplinary team that had carried out a rapid assessment of the 1993 Mississippi floods in Illinois. During the discussions, he shared his experiences on how his team went about collecting scattered information on the floods of 1993 and documented it in a rapid assessment report (Bhowmik et al., 1994). A similar exercise was necessary on the Chennai Floods of 2015 to ensure that the vast amount of information and data put up on public domain during and immediately after the event was not lost.

This informal and an almost chance discussion formed the genesis of the rapid assessment of Chennai Floods, presented in this report. The authors of this report came together voluntarily to collate the information and data available through various channels – media, internet, government and other sources – and to present it as coherently as possible. They also decided to strengthen the report by adding some quickly conducted preliminary analyses of the data. Given the large number of issues related to the floods, this was quite challenging.

The team of authors consists of S. Murty Bhallamudi and Balaji Narasimhan (both from IIT Madras), Subimal Ghosh and Arpita Mondal (both from IIT Bombay), and Pradeep Mujumdar (IISc, Bangalore).The exercise was coordinated by the Interdisciplinary Centre for Water Research (ICWaR), IISc Bangalore.

The information presented in this report would be useful to anyone interested in studying urban floods in the country and to policy makers. However, given the short time in which the report is prepared, the information presented on any individual issue discussed in the report is not comprehensive. A more thorough follow-up study is necessary to get clarity on several aspects of the event. The size of the report is kept purposefully small, to keep the discussions focussed, but this necessitated excluding many details which perhaps would be of interest to an informed reader. Most material collected during the assessment is available as supplementary material on the web link, www.icwar.iisc.ernet.in.

The authors thank Ms. Lubna and Ms. Srivani for their excellent help in collection of material, preparation of figures and tables, proofreading and copyediting the report. Ms. Anjana Devanand performed the WRF model runs, the results of which are used in this report. The authors also benefited by discussions with Prof. Dev Niyogi of Purdue University, USA and Dr. Ashok Karamuri, University of Hyderabad.

1. Introduction

The devastating floods that hit Chennai city and other parts of Tamil Nadu during November-December 2015 have claimed more than 400 lives and caused enormous economic damages. This has posed a challenge to the scientific community in developing a comprehensive understanding of the event. Answers to a number of pressing questions related to the conditions prevailing during and immediately preceding the flooding period are necessary towards developing such an understanding. These include, among others: (a) what were the atmospheric conditions that caused the high intensity rainfall, (b) how was the rainfall distributed spatially and temporally, (c) how much flow occurred in the three rivers passing through the city– the Kosasthalaiyar River, the Cooum River and the Adyar River - and the Buckingham canal, (d) how were the two reservoirs upstream of the city, viz., the Chembarambakkam reservoir and the Poondi reservoir, operated, (e) how much overland flow was generated in the city due to rainfall over the city alone, (f) how did the storm water drainage system respond, (g) which areas in the city were inundated and for how long, (h) how did the waters recede after the rains ceased, (i) what were the health implications of the event, (j) did the land use change in the city over the years exacerbate the flooding, and, most importantly, (k) what actions need to be taken so that for similar rainfall patterns repeating in future, the city would not face such a devastating deluge? To seek even partial answers to these questions, it is vital that all available information and data are compiled and presented in a coherent manner. Such a compilation of information immediately after the event is of immense importance, since the information is likely to be lost soon.

The objective of this report is to provide such a compilation of data and information along with an informed rapid assessment of the event based on first-cut, untested results of preliminary analyses. In preparing the report, a large body of information available through newspapers, news magazines, TV reports, government documents, web pages and other freely available sources was sifted through. A field visit was undertaken by the team on March 16, 2016 to get a first-hand impression on the flooded areas in the city. Extensive discussions were also carried out through e-mails and web meetings.

The report is prepared with a view to provide a rapid assessment of the event, useful for more rigorous scientific studies that should be taken up in the country to address the increasing urban flooding problems. The long-, medium- and short term issues affecting urban floods, discussed in this report with specific reference to the Chennai floods of 2015 are schematically shown in

Figure 1. Recommendations arising out of this rapid assessment are summarised in the report to help policy makers, researchers and other stakeholders.

Figure 1: Spatial and Temporal Range of Issues Addressed in the Report

This report is organised as follows: Observed rainfall during the event and historical rainfall analysis are presented in Section 2. This is followed by Section 3 which presents a preliminary analysis of the atmospheric conditions that caused the high intensity rainfall. The macro and micro drainage network in Chennai city is discussed in Section 4. Section 5 provides details of the releases from upstream reservoirs during the flooding period. The observed maximum tidal levels in the ocean are presented in Section 6. This is followed by an assessment of the magnitude of flooding, and loss of life and property in Section 7. The subsequent two sections, Sections 8 and 9, discuss briefly the responses and recovery and the post-flood health impacts. Discussion on the field visit is provided in Section 10. Recommendations from this rapid assessment are provided in Section 11. Section 12 presents concluding remarks.

2. Observed Rainfall

The city of Chennai and its suburb areas recorded multiple torrential rainfall events during November-December 2015 that inundated the coastal districts of Chennai, Kancheepuram and Tiruvallur, and affected more than 4 million people with economic damages that cost around US$3 billion (The National, 2015). There was very heavy rainfall on November 8, 9, 12, 13, 15, 23, and December 1. During the 24 hours ending 8:30 a.m. on December 2, 2015, "extremely heavy rainfall" was reported in Chennai: 49 cm at Tambaram in Kancheepuram district, 47 cm at Chembarambakkam in Tiruvallur district, 42 cm at Marakkanam in Tiruvallur district, 39 cm each in Chengalpattu (Kancheepuram district) and Ponneri (Tiruvallur district), and 38 cm each in Sriperumbudur and Cheyyur (both in Kancheepuram district), 35 cm at Chennai airport, and 34 cm in Mamallapuram, Poonamallee, Red Hills and Chennai city. Taramani, the information technology hub of Chennai, north Chennai, Cholavaram and Thamaraipakkam (both in Tiruvallur district), and Madurantakam received between 28 cm and 30 cm (Frontline, 2015a).

According to the United States' National Aeronautics and Space Administration's (NASA's) Integrated Multi-Satellite Retrievals for Global Precipitation Measurement or GPM (IMERG), from November 29 to December 2 over 400 mm of rainfall fell over areas south of Chennai (Figure 2).

The hourly rainfall intensities for two IMD stations Nungambakkam and Chembarambakkam for Dec.1 & 2, 2015 are shown in Figures 3 and 4. The Nungambakkam rainfall intensity is plotted on the Intensity – Duration – Frequency plot derived for Chennai based on 30 years of hourly rainfall data (Figure 5). From the IDF plot it is clear that the 24 hour rainfall that was recorded in Nungambakkam (within the city) on December 1, 2015 was more like a 25-year storm whereas the rainfall that occurred in Chembarambakkam (outskirts of Chennai city, not shown in the IDF plot) could be higher than a 100-year storm. Although the maximum 1-hr storm seems to be a storm of less than 5-yr recurrence interval, it is the sustained rainfall over a long duration that caused the heavy deluge. Further, the upper catchment region, represented by rainfall data from Chembarambakkam (Figure 3), received much higher rainfall than the City itself (represented by rainfall data from Nungambakkam) and hence brought in a huge influx of flood waters into the city.

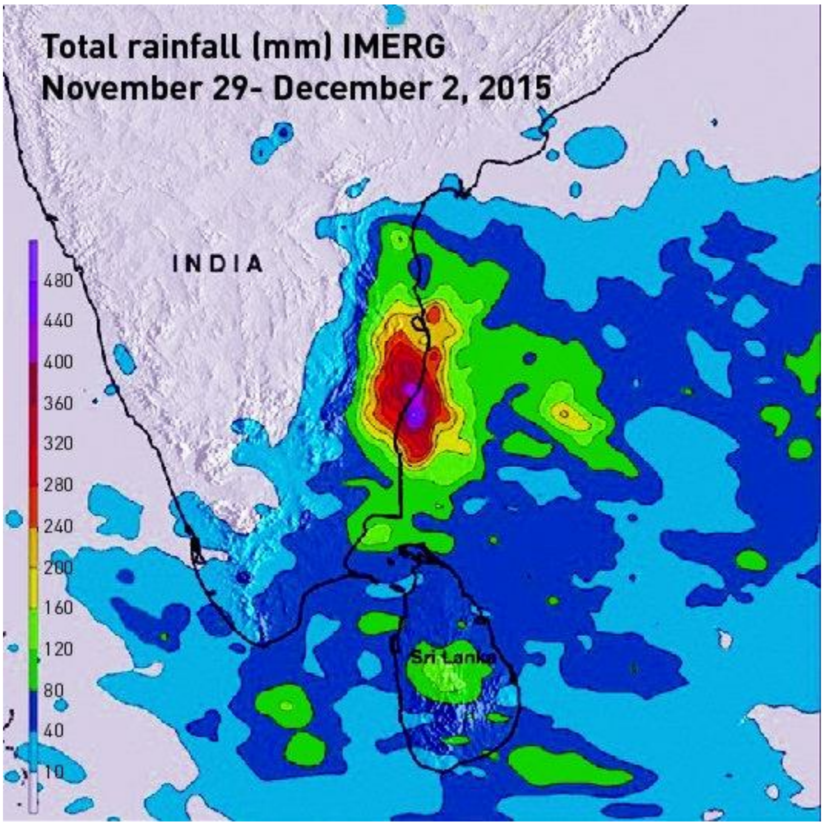


Figure 2: Accumulated rainfall between November 29 and December 2 over Chennai and neighbourhood measured by NASA's GPM satellites (Frontline, 2015b)

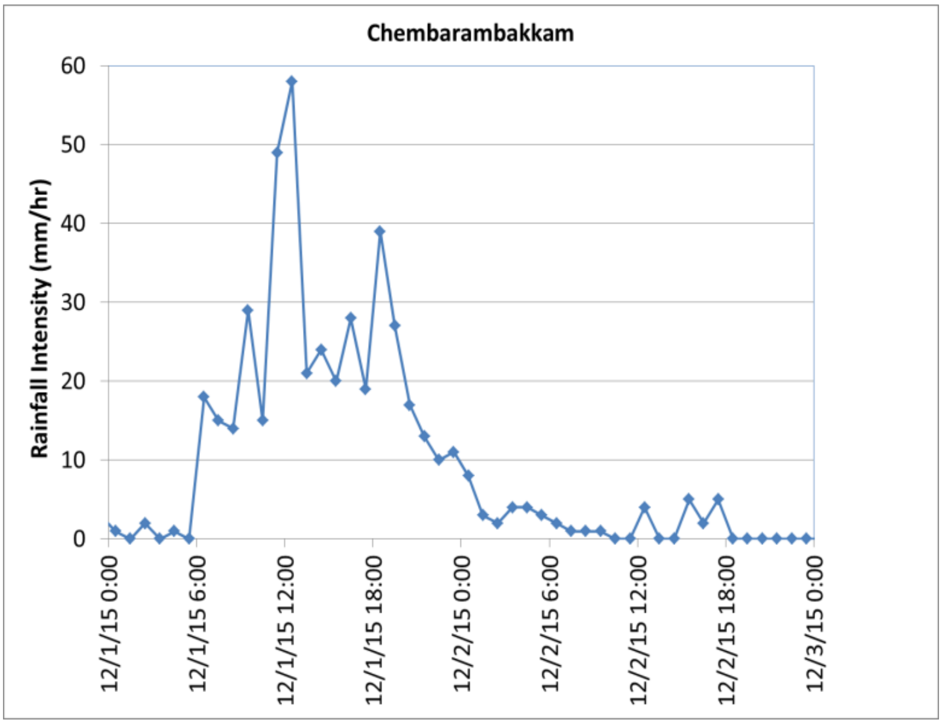


Figure 3: Rainfall Intensity at Chembarambakkam rain gage station

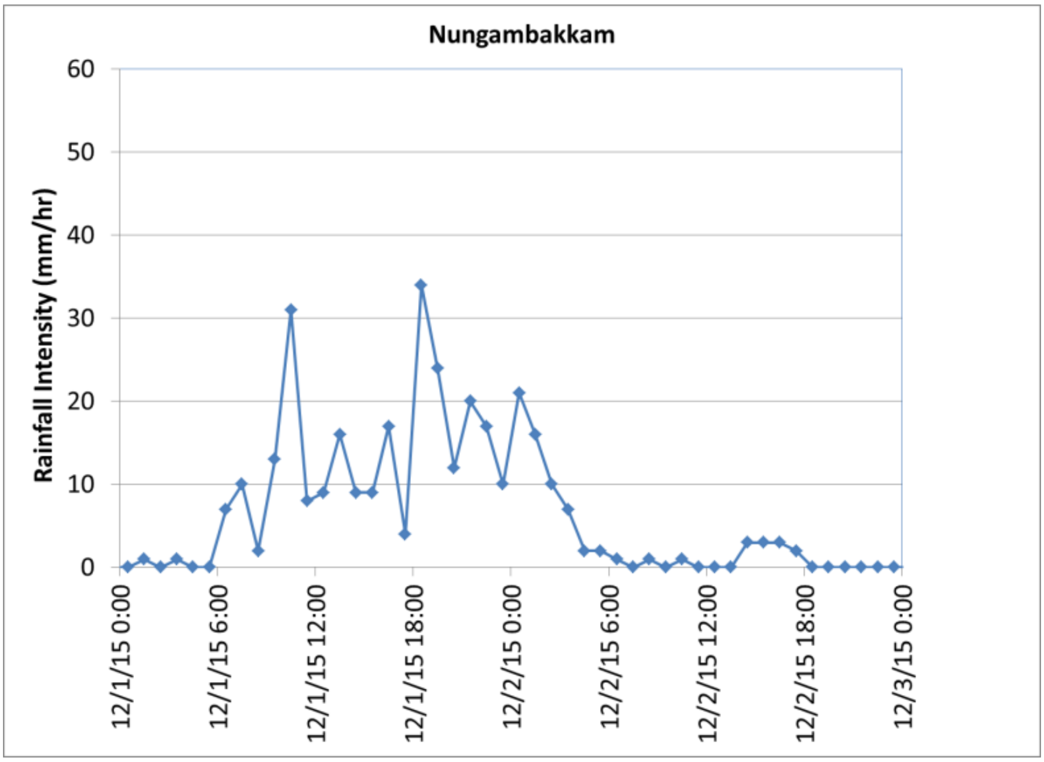


Figure 4: Rainfall Intensity at Nungambakkam rain gage station

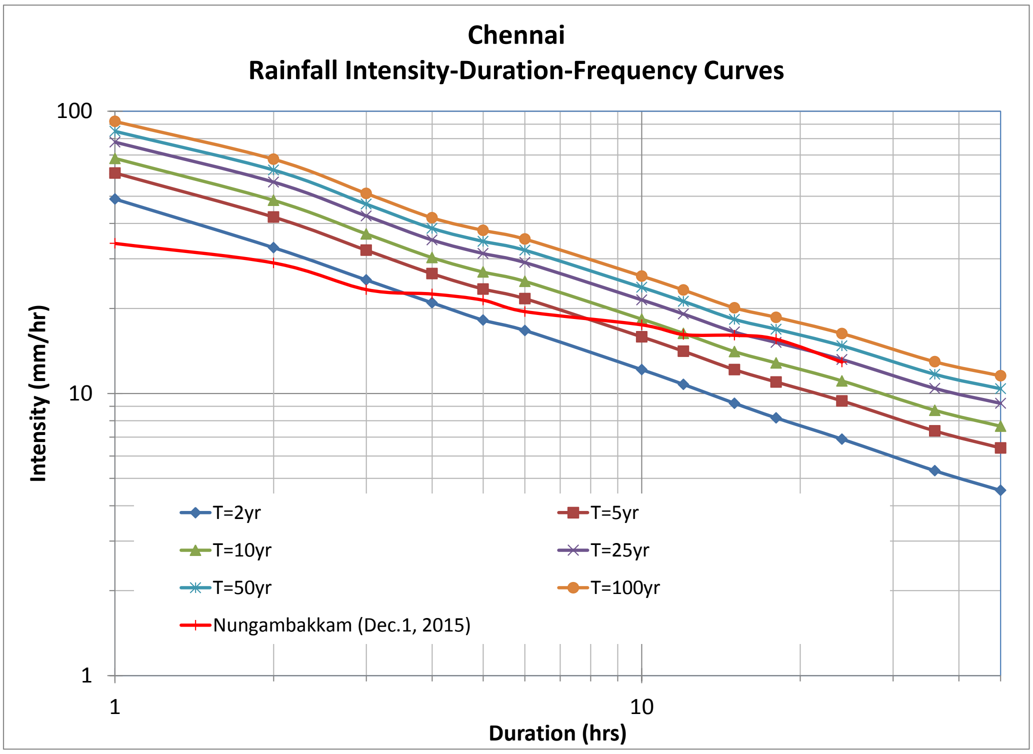


Figure 5: Rainfall Intensity-Duration-Frequency curves for various return periods along with the Dec. 1, 2015 event at Nungambakkam

A frequency analysis was also conducted for the maximum 24-hour rainfall at Minambakkam station, and at the India Meteorological Department's (IMD's) 1^0lat. x 1^0lon. grid point centred at 13.5N 80.5E over the Chennai city, using the statistical extreme value theory which relies on asymptotic models that categorically account for heavy tails (Coles, 2001). The analysis was done using two rainfall datasets 1) Global Historical Climatology Network (GHCNDX) for the Minambakkam station and 2) IMD's fine-resolution gridded daily rainfall data. Generalized Extreme Value (GEV) distribution was fitted individually to the annual maximum 24-hour rainfall series for the month of November. The return periods were computed both with and without considering this particular event in the observed record. As presented in Table 1, the 2015 extreme rainfall event in Chennai was found to be rare with a return period close to 100 years in the observed record excluding this event. This initial analysis can be further improved by investigating larger datasets (both in terms of temporal and spatial extent) and by taking into account other dependencies and variability.

Table 1: Return periods of the Chennai Dec.01, 2015 extreme rainfall event.

Event/Station Data	Historical Return period of the event under consideration (Assuming GEV distribution)	
	Considering the event	Without considering the event
Minambakkam (GHCNDX)	68 years	93 years
IMD 1^0 x 1^0 grid point 13.5N 80.5E	86 years	115 years

3. Atmospheric Circulation

3.1. Atmospheric Conditions during the Extreme Rainfall Event

The extreme high intensity rainfall event that occurred over Chennai was an outcome of a depression generated over a warm Bay of Bengal (BoB) which brought huge moisture from BoB and resulted in heavy precipitation over the South-East coast of India. The spatial distribution of Mean Sea Level Pressure (MSLP) till November, 27, 2015 shows a wide spread low pressure over the South of BoB, which became concentrated over Sri Lanka and brought huge moisture over Chennai region on Dec.1 (Figure 6). The high precipitable water (PW) over the same region made the conditions favourable for heavy precipitation over Chennai, which continued till December 2, 2015. The low MSLP remained concentrated over the same region during Dec.4, 2015, but low precipitable water over Chennai did not favour further extremes. The MSLP, PW and wind data are obtained from European Reanalysis Interim (ERA-Interim). Observed precipitation plotted in the bottom-most panel in Figure 6 is obtained from satellite measurements as part of NASA's Global Precipitation Measurement (GPM).

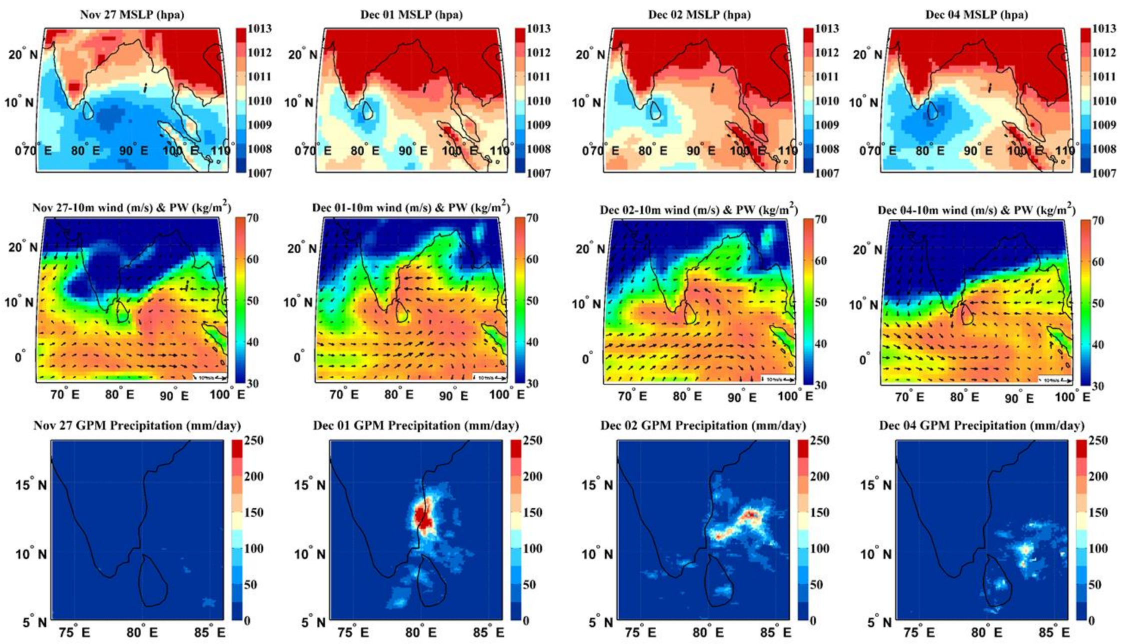


Figure 6: Distribution of Mean Sea Level Pressure (Panel 1), Precipitable Water (PW with color map) and Surface Wind (with arrows) (Panel 2) and satellite-observed Precipitation (Panel 3) during the Extreme Event over Southern India and Bay of Bengal.

3.2. Drivers of the Extreme Rainfall Event

Understanding the characteristics of extreme climate events and their drivers is one of the most challenging tasks in atmospheric science because of rarity in their occurrence and lack of sufficient data. Such an understanding is needed for making better forecasts. The recent extreme rainfall event over Chennai is also not an exception. Understanding the drivers of this extreme event needs the information of large scale atmospheric and oceanic conditions before, during and after the extreme event. While the impacts of global climate change versus local issues like urbanization on this extreme event will remain an important science question, which needs significant attention. However, addressing such a question is not possible without the insight on the mechanism and processes associated with the event. The important large scale characteristics of 2015 are very strong El-Nino phenomenon and very warm BoB (Figure 7), which have probably caused this extreme event.

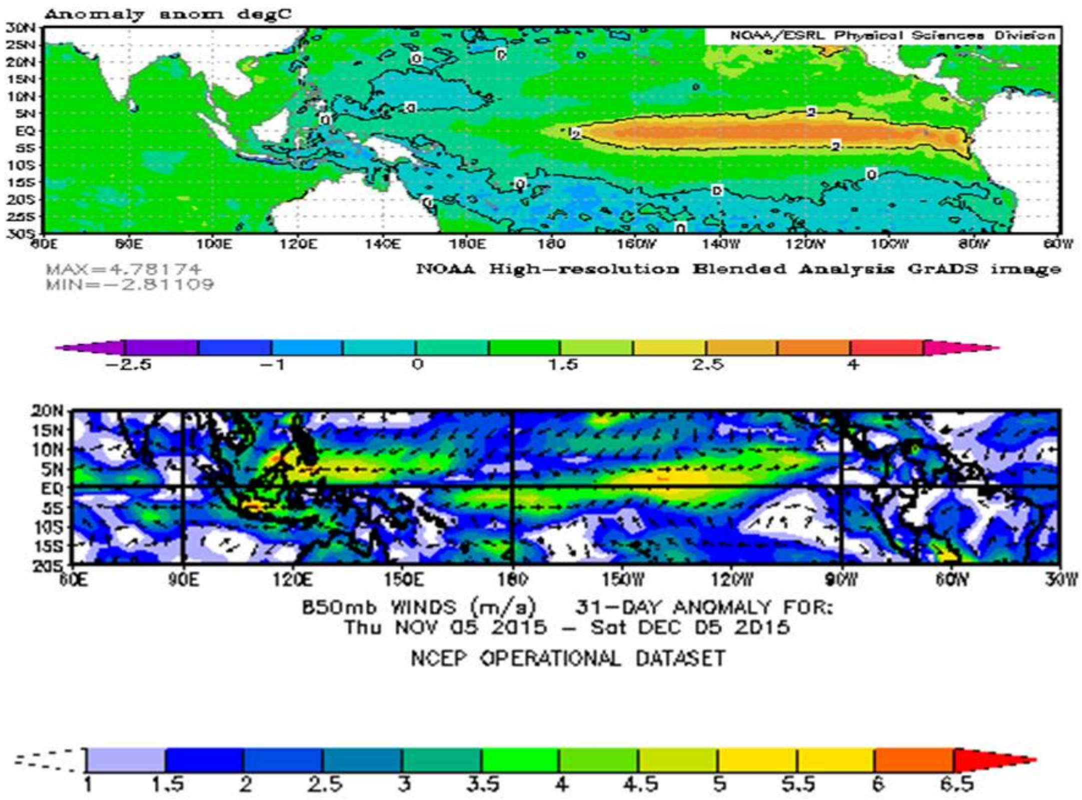


Figure 7: Distribution of SST (During Oct- Dec 2015) anomalies and wind speed at 850 mb (05 Nov- 05 Dec) based on NCEP/NCAR Reanalysis as plotted with the tool from *http://www.esrl.noaa.gov/*

Strong El-Nino of 2015 and the Possible Connection

The El-Nino of 2015 was one of the strongest reported, which started developing in 2014. El-Ninos are reported to have impacts on North East Monsoon (Zubair and Ropelewski, 2006) by modestly intensifying it. A possible hypothesis would be that a stronger El-Nino led to a strong easterly during Nov-Dec 2015 (Figure 7) which probably brought moisture to the East coast of India over Chennai with a much intensified rainfall. However, the scientific question remains if the easterlies (possibly) generated by El-Nino are the only reason or some other factors/ drivers have caused heavy precipitation over Chennai. This hypothesis needs climate model based verification.

Warming of Bay of Bengal

The other possible reason could be warming of BoB. Literature suggests that such warming may lead to increase in depressions during the post summer monsoon season (Balaguru et al., 2014). The Sea Surface Temperature (SST) over BoB has statistically significant increasing trend (Figure 8). Here, we performed an experiment with a regional climate model – the Weather Research and Forecasting (WRF) model, using the detrended and observed SST of BoB for the period of the extreme rainfall event. We found that the detrended SST values resulted in a decreased precipitation over Chennai on Dec 01, 2015; however an excess precipitation was simulated on 2nd December (Figure 9). This probably indicates that the space time distribution of precipitation has been perturbed by the changes in SST. However, it should be noted that the WRF runs were only for a few days and the BoB was warmer for a longer period of time which would have probably prepared the stage for extremes. This was not considered in this experiment. Hence, there is a need to have hypothesis-based model-driven testing to understand the individual contributions of El-Nino and warm BoB on the space time distributions of depressions leading to the extreme rainfall event.

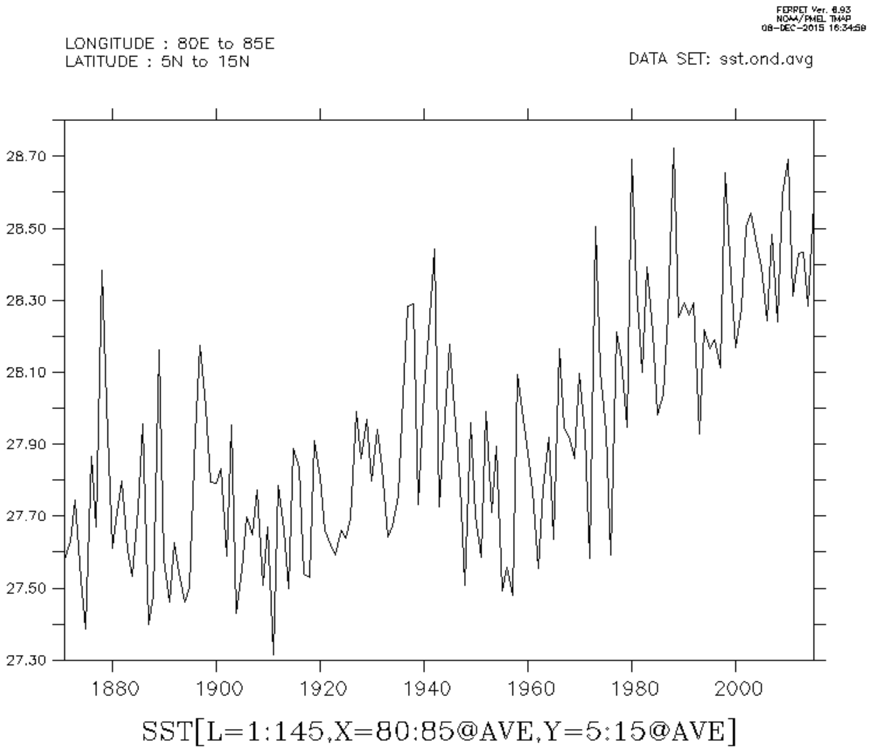


Figure 8: Observed Sea Surface Temperatures over the Bay of Bengal (In ^{0}C)

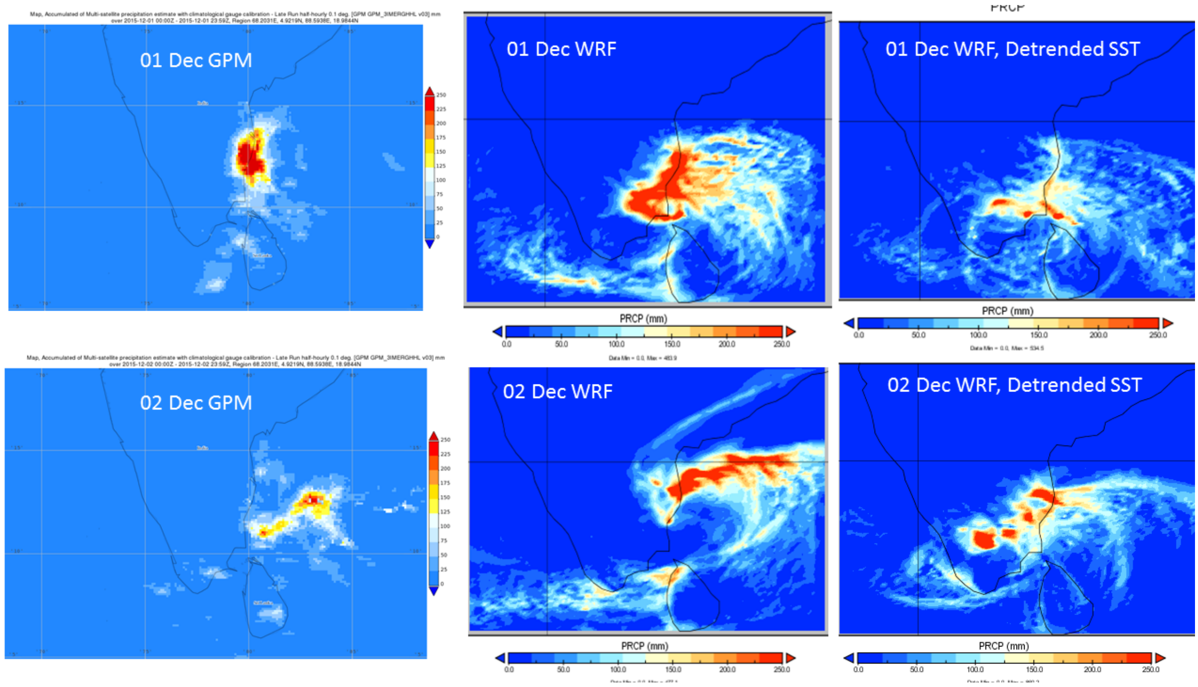


Figure 9: Observed Precipitation (GPM) and WRF Simulations with Actual and Detrended SST for BoB.

Impact of Global Warming and Urbanization

Scientific theories and model studies (Emanuel, 1987; Knutson and Tuleya, 2004) suggest an increase in tropical cyclones during recent decades, though these are not really very evident from the recorded number (counts) of cyclones. However, the potential destructiveness of cyclones, defined as the total dissipation of power, integrated over the lifetime of the cyclone has increased, is increasing and will increase in a warming environment (Emanuel, 2005) and this is primarily associated with the warming of SST (Knutson et al., 2010). It is true that the warming of BoB is attributed to the global warming, which is hypothesized to be a potential cause of the extreme event over Chennai; however to confirm this, it needs an event based attribution (King et al., 2016) study.

Urbanization is another factor which is reported to intensify the extreme precipitation, either through generation of convection due to urban heat island (UHI) or through the uneven urban terrain resulting in wake diffusion and turbulence (Shastri et al., 2015). Extremes in Southern and Central Region of India are observed to be affected by urbanization during summer monsoon season (Shastri et al., 2015); though the specific impacts during winter monsoon and cyclones have not yet been explored. Chennai is reported to have significant urban heat island (Swamy and Nagendra, 2016) and there is a possibility of such UHI-extremes link. However, it should be noted that the local temperature variations do not have the capacity to organize such a huge extreme events with high moisture flux, but can increase the intensity of a severe extreme event.

In order to minimize the impacts of severe extreme events, there is a need for good forecasting system. The extreme event over Chennai was forecasted well in advance by the National Centre for Medium range Weather Forecasts (NCMRWF). As an example, we present (Figure 10) the extended range forecasts by Indian Institute of Tropical Meteorology (IITM), Pune as released on 27th November, 2015, which clearly shows the possibility of a very heavy rainfall.

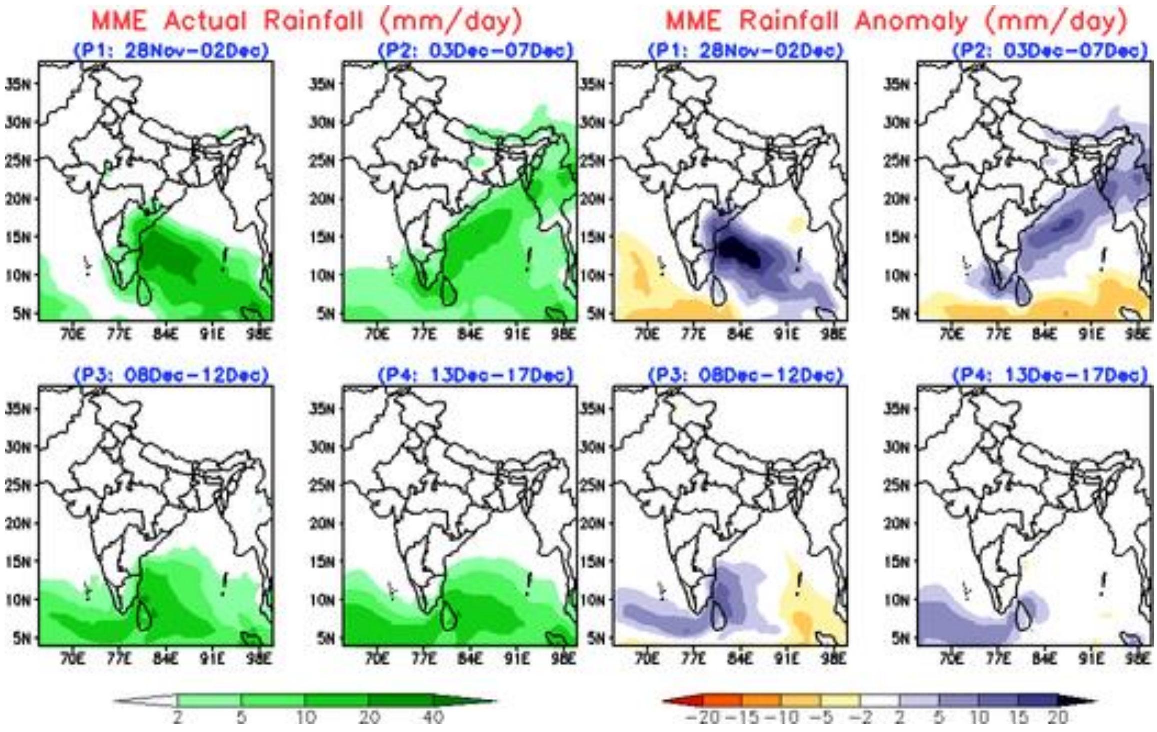


Figure 10: Extended range forecasts as released by Indian Institute of Tropical Meteorology, Pune on 27th November 2015 (Source: IITM, Pune).

Lack of effective usage of extreme weather forecasts is possibly a result of poor collaboration between meteorologic and hydrologic communities as well as low trust among practitioners on such forecasts. These forecasts are usually associated with very high false alarm (in Chennai we find that it is around ~70-80% with NCEP Global Forecast System (GFS) forecasts if 95 percentile is considered as a threshold for extremes, analysis not shown here), and such high rate is associated with the inherent space time variability of rainfall, which is nearly impossible to simulate. A possible solution to this problem would be probabilistic forecasts taking into account large scale forcings from GFS. Regional modelling with proper representation of urban canopy may also improve the forecast of urban rainfall extremes.

4. Drainage Network

4.1. Macro Drainage Network

The total area of CMA (Chennai Metropolitan Area) is 1189 km^2 and three rivers namely: (i) Kosasthalaiyar, (ii) Cooum and (iii) Adyar flow through the CMA (Figures 11a, 11b).

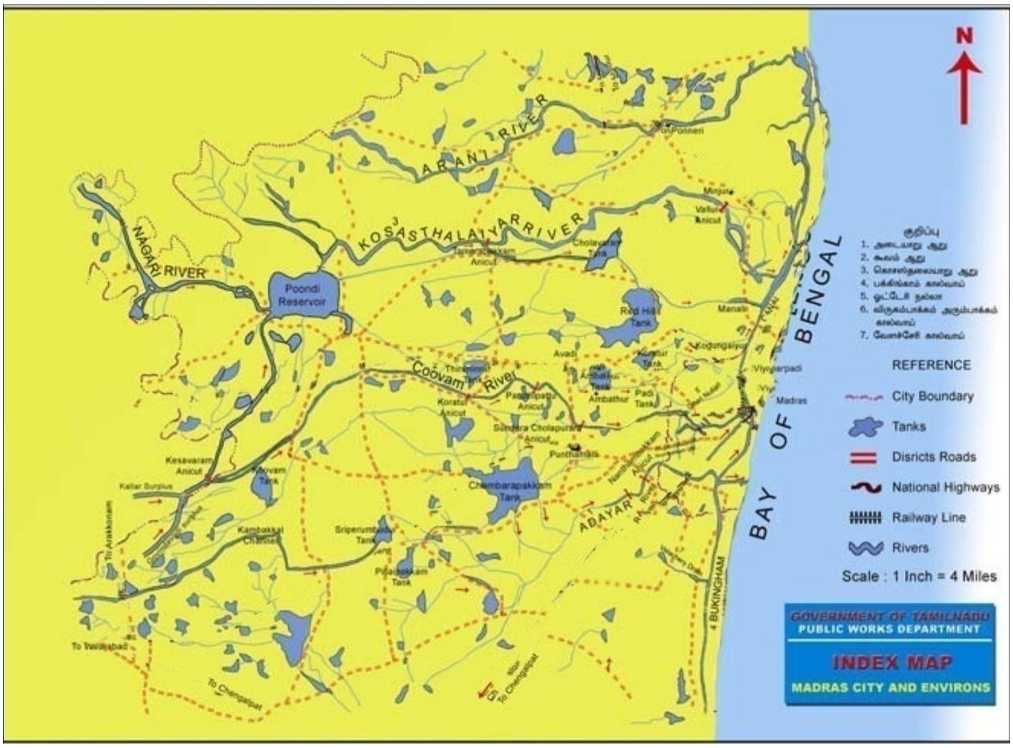


Figure 11(a): Rivers flowing through CMA and major reservoirs

[Source: Adopted from www.cmdachennai.gov.in/SMPS/SMPS.html]

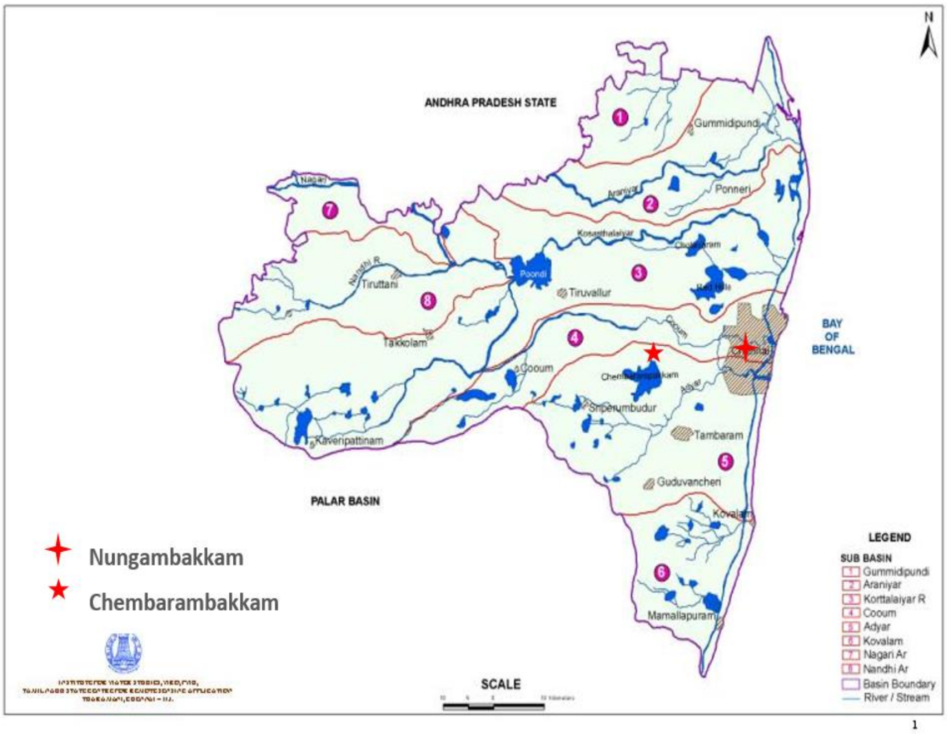


Figure 11(b): Watershed boundaries of different rivers in Chennai river basin
[Source: Adopted from www.wrd.tn.gov.in/maps.htm]

Kosasthalaiyar River originates near Kaveripakkam in North Arcot district and flows in general eastward direction. It bifurcates into Cooum River and Kosasthalaiyar main branch at Keshavaram anicut. The main branch of Kosasthalaiyar River then flows northwards and enters into Poondi Reservoir. Nagari River, originating in Chittoor district, is a northern tributary, and joins the Kosasthalaiyar River at Poondi reservoir. On the downstream side of Poondi reservoir, Kosasthalaiyar River flows through Thiruvallur district and CMA, and finally joins the sea at Ennore.

Cooum River bifurcates from the main Kosasthalaiyar River at the Keshavaram anicut and flows eastwards through Kanchipuram district into CMA and finally joins the sea near Napier Bridge. Surplus from about 75 tanks in the catchment reaches the Cooum River.

Adyar River originates from two tank groups namely: Pillapakkam and Kavanur, in Kanchipuram District and flows through the CMA before it joins the sea at Adyar Mouth. Surplus from about 450 tanks in the catchment, besides surplus from Chembarambakkam tank, reaches the Adyar River.

Besides the above three rivers, the macro drainage system of CMA consists of several canals (Figure 12; Table 2).

It is to be noted here that the Buckingham canal has been constructed more than 200 years ago, as a navigation channel. It originates close to Kakinada in Andhra Pradesh and runs along the east coast for a total length of 418 km. Its entry point into CMA is near Athipattu village and the exit point is near Semmencheri village. While the three rivers run west to east, Buckingham canal runs north to south and connects all these three rivers. While Otteri Nullah, Kodungaiyur drain and Captain Cotton Canal drain into the Buckingham canal, Veerangalodai and Velacheri drain discharge into Pallikaranai marsh. Virugambakkam drain discharges into Cooum River. Mambalam drain discharges into Adyar River. These macro drainage canals are mostly maintained by the Public Works Department (PWD) of Chennai city.

Table 2. Details of macro drainage of Chennai Metropolitan Area.

Macro Drainage	**Drainage Area (km^2)**	**Total Length (km)**	**Length within CMA (km)**	**Width (m)**	**Bankfull Discharge (m^3/s)**	**Flood Discharges in 2005 (m^3/s)**
Adyar	720	42	24	10 to 200	2038	1700 (~3000 during 2015 floods)
Cooum	502	72	24	40 to 120	991	708
Kosasthalaiyar	3741	136	16	150 to 200	3540	2548
Buckingham Canal		418	48		42.5	99 to 280
Otteri Nullah	38.4		38.4	4 to 20	17	51
Virugambakkam - Arumbakkam drain			6.9		17	48
Kodungaiyur drain			6.9			
Captain Cotton canal			4			
Velacheri drain	3.88		2.14	5.6	18.5	21
Veerangal Odai			2.78		18.5	18.5
Mambalam Drain			9.4			

(Sources: www.cmdachennai.gov.in/SMPS/SMPS.html; Narasimhan, B. 2016; http://www.cmdachennai.gov.in/volume3.html; IWS, 2007)

There are three major tanks in the CMA (Figures 11a, 11b), which cater to the drinking water needs of the Chennai City. These are: (i) Sholavaram Tank (25Mm^3), (ii) Red Hills Tank (93Mm^3) and (iii) Chembarambakkam Tank (103 Mm^3). Poondi Reservoir (91 Mm^3) located outside CMA is also a major source of drinking water supply to Chennai city. Sholavaram Tank receives water from Poondi Reservoir and supplies the water to the Red Hills tank. Surplus water from the Red Hills tank is released into Kosasthalaiyar River during floods. Chembarambakkam Tank is also a drinking water reservoir. It has its own catchment, and it also receives water from the Poondi reservoir. Excess water from this reservoir is released into the Adyar River. Besides these three major tanks, several water bodies exist in CMA area, although their number has come down significantly in the last three decades due to urbanization and encroachment of lake beds.

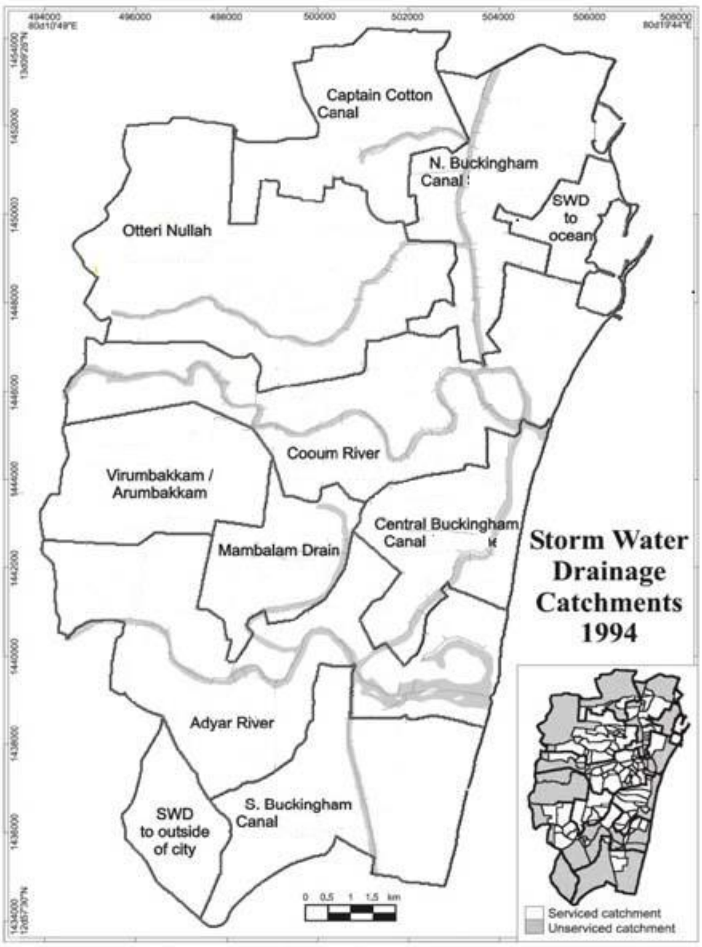


Figure 12: Macro drainage network in Chennai City

(Source: Adopted from www.cmdachennai.gov.in/SMPS/SMPS.html)

Thus it can be seen that the macro drainage of the CMA during floods is carried out by a complex web of three rivers and several major drains. The three drinking water reservoirs double up as flood control reservoirs in case of emergencies, and the multitude of water bodies perform the detention function to reduce the peak discharges.

4.2. Micro Drainage Network

The macro drainage is served by a network of 31 minor drainage canals (16 in old city and 15 in the expanded areas) maintained by the Greater Chennai City Corporation for storm water drainage within the CMA. In addition to this, a network of storm drains to the length of about 1660 km discharges stormwater into the rivers and major / minor drains [COC, 2016]. Eighty-four percent of these micro-drains carry sewage(www.cmdachennai.gov.in/SMPS/SMPS.html) while the rest carry storm water. Efforts are underway through the Jawaharlal Nehru National Urban Renewal Mission (JNNURM) and aid from World Bank and Asian Development Bank to further expand the network of storm drain to areas currently lacking proper storm drainage connectivity to natural waterways (TNUIFSL, 2015).

4.3. Problems with Drainage System

Chennai has experienced major floods during the last three decades in the years 1976, 1985, 1996, 1998 and 2005 and then the big one in 2015. The drainage system has been found wanting because of several reasons. These include: (i) reduction in the vent way caused by the construction of bridges, (ii) sand bar formation at the mouths of rivers, (iii) clogging of the drains due to indiscriminate dumping of solid waste and construction debris, (iv) inadequate design capacity, (v) lack of connectivity of storm sewers with macro drainage, and (vi) encroachments. While successive governments have focused on dredging of rivers and desilting of major drains, maintenance of minor drains is neglected due to scarcity of funds as well as public apathy. In this context it is important to bring out the effect of bad solid waste management on the condition of drainage channels, both major and minor.

Although a road network to the length of 6000 km (387 km of bus route and 5623 km of interior roads) is maintained by the Greater Chennai Corporation, only about 1660 km of storm drains exist (about 205 km of these drains have a width of 0.6m or more). Storm Water Drains are usually provided only for roads with 12 m width or more. Earlier, storm water drains were designed for a rainfall intensity of 31.39 mm/hr (storm duration of 1hr with 2-yr return period). However, this was subsequently revised in 2014 to 68 mm/hr based on recommendations from

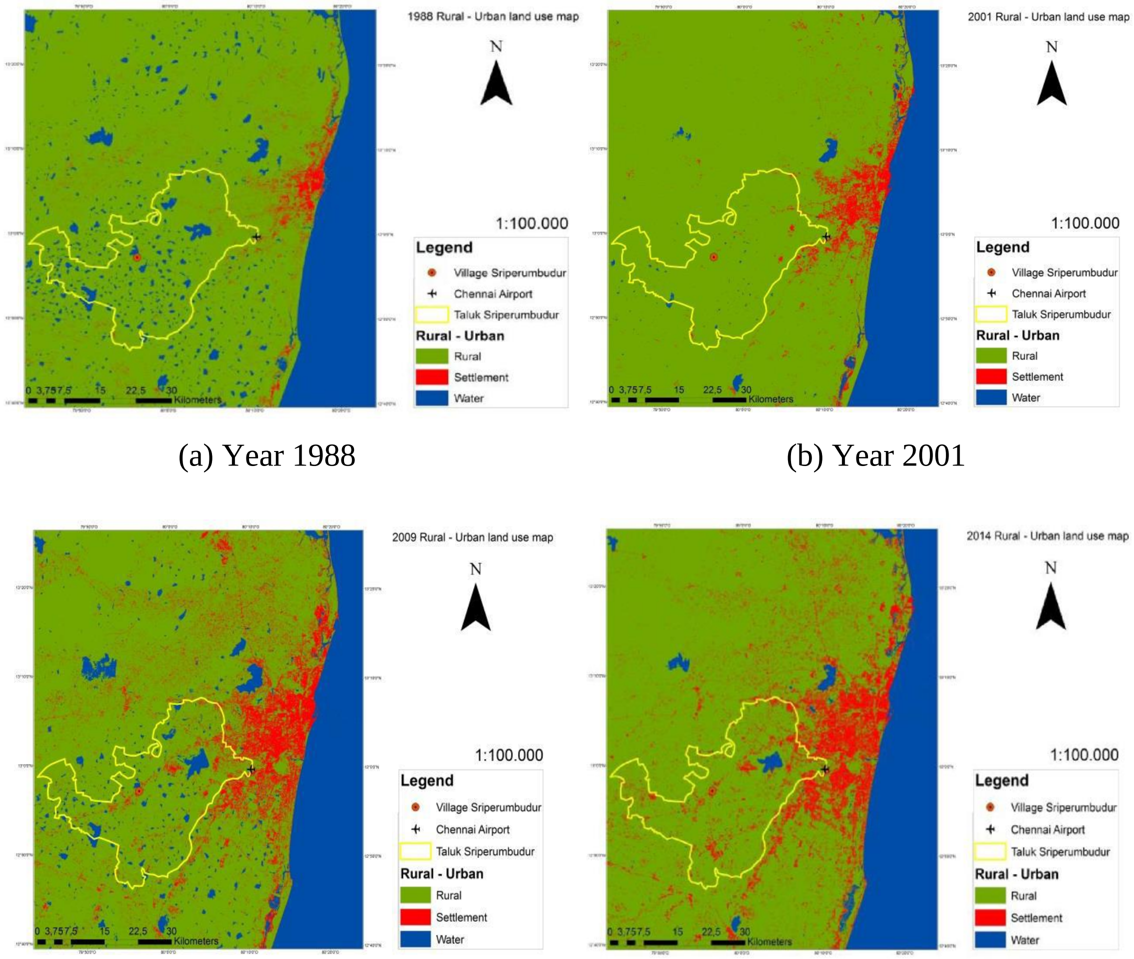
World Bank (TNUIFSL, 2014), though it is not immediately clear as to which return period this intensity corresponds.

Chennai city has been urbanizing very rapidly over the last few decades. Population in Chennai city has increased from a mere 500,000 in the year 1901 to more than 45 lakhs in the year 2011 [Source: Census of India, 2011]. The progression of urbanization and consequent land use change in and around Chennai in recent years is shown in Figure 13 (Murawski, 2015). It is estimated that the area covered by the high density urban areas increased from 81.32 km^2 in 1988 to 330.30 km^2 in 2014. The area covered by low density urban areas increased from 53.79 km^2 in 1988 to 303.14 km^2 in 2014 (Murawski, 2015). A major consequence of this urbanization is the reduction in the infiltration component of the hydrologic cycle, which would increase the peak run-off discharge. Another consequence of urbanization is the disappearance of many minor and medium water bodies. These water bodies served as detention basins and resulted in decrease in the peak discharge. Urbanization has reduced the detention effect.

Inappropriate urbanization may also lead to the encroachment of the waterways, which reduces their vent way. A glaring example of this is the construction of Mass Rapid Transit System (MRTS) along and in some locations in the Buckingham canal, as shown in Figure 14. The new runway of the Chennai airport has been built on the Adyar River. Similarly, culverts provided on many of the new roads have inadequate capacity to pass the flow from one side to the other (Figure 15).

Another effect of urbanization which is usually overlooked is the “compound wall effect”. Compound walls are built around almost all institutions, commercial and industrial organizations and large residential complexes, in order to prevent encroachment. These compound walls alter the local overland flow paths and sometimes even block the local channels because of inadequate provision of culverts. This in turn changes the local flooding pattern, protecting some areas while flooding the others. During major rainfall events many of these compound walls collapse because they are not usually designed to take water pressure from one side. In several cases, the compound wall and roads have affected the natural flow and the lack of adequate cross drainage has led to much of localized flooding and water logging. In some cases, people who are affected by flood, damaged these walls and roads in order to drain flood waters from their locality, as shown in Figure 16.

Aggradation of roads due to constant resurfacing without adequate milling is also one of the major reasons for localized flooding and water logging during the recent floods. Localized flooding and water logging is quite common and widely prevalent across the CMA every year, even during normal showers, due to aggradation of roads and lack of adequate cross drainage infrastructure. As per Indian Road Congress codes (IRC: 120-2015), the roads have to be milled before resurfacing. Although this is mandated by the corporation, this norm is usually flouted by the contractors and not strictly enforced.



(a) Year 1988 (b) Year 2001

(c) Year 2009 (d) Year 2014

Figure 13: Land use change in Chennai and its suburbs (Murawski, 2015)

Figure 14:MRTS station on Buckingham Canal *Figure 15: Culvert with inadequate Capacity*

Figure 16: Panels in compound wall taken off to let water flow

5. Reservoir Releases

Chembarambakkam tank receives water from its own catchment as well as some surplus water from Poondi through the Krishna water link canal. Before discharging at Chembarambakkam, Krishna water link canal crosses/joins Cooum at Aranvoil anicut and gathers some water from Cooum as well before taking off to Chembarambakkam. Chembarambakkam tank can hold water up to a maximum level of 7.315 metre, with a full capacity of 3645 million cubic feet (103.214 million cubic metre) (The News Minute, 2015). When the Chembarambakkam tank is full, excess water is released into the Adyar River.

The daily reservoir storage data obtained from Chennai Metropolitan Water Supply & Sewerage Board (http://www.chennaimetrowater.tn.nic.in/) during the period 10 November 2015 to 30

December 2015 for Chembarambakkam and Poondi reservoirs are shown in Figures 17 and 18. On Nov. 17, 2015, 18,000 cusecs (509.7 cumecs) was released from the reservoir in Chembarambakkam, causing massive flooding in areas such as Mudichur, West Tambaram, and Manapakkam among others. On Dec. 1, 2015, the Chembarambakkam reservoir was at 93% capacity with storage of 3396 million cubic feet due to a rainfall of 47.5 cm. This led to the release of 29,000 cusecs (821.2 cumecs) over 12 hours into the Adyar River (The Hindu 2015a). The outflow from Poondi reservoir (which empties into the Cooum River) was at 8,552 cusecs (242.2 cumecs) on Dec. 1, 2015. On Dec. 2, the outflow was at 30,200 cusecs (855.2 cumecs) – more than that of Chembarambakkam. On Dec. 3, Poondi discharged 36,484 cusecs (1033.1 cumecs), while the release from Chembarambakkam on the same day came down to 11,000 cusecs (311.5 cumecs) (The Wire, 2015).

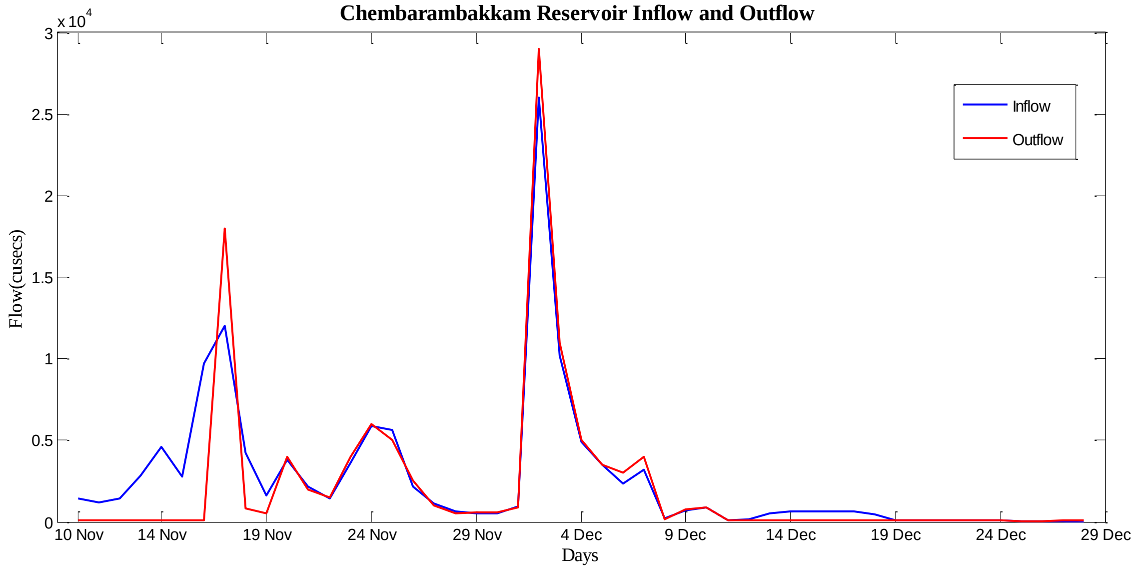


Figure 17: Daily Inflow and Outflow of Chembarambakkam tank for the Months of November and December, 2015 (Source: Chennai Metropolitan Water Supply & Sewerage Board)

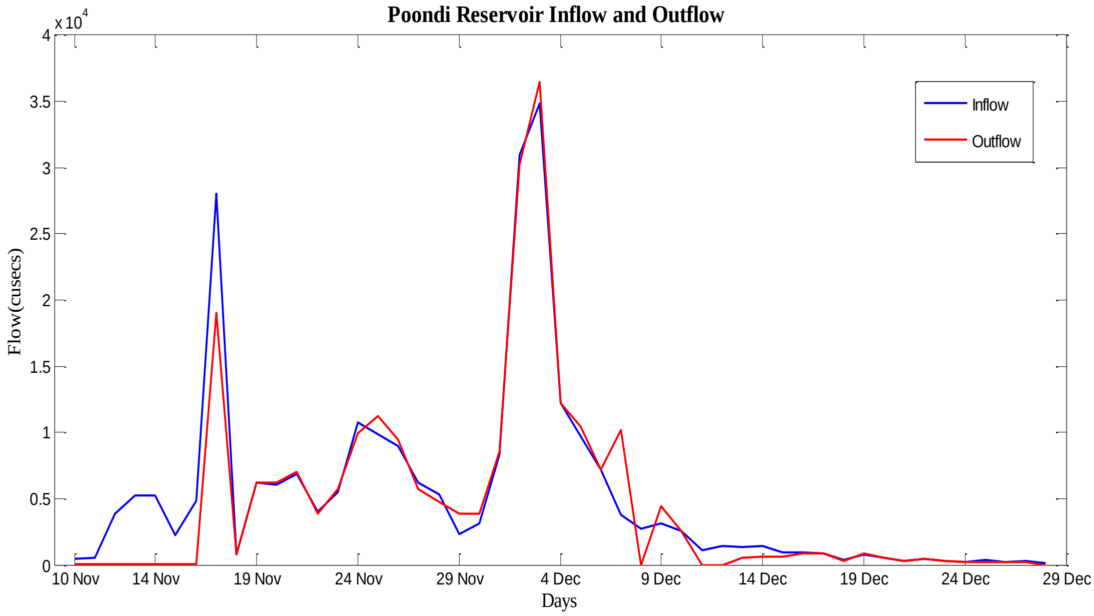


Figure 18: The Daily Inflow and Outflow (cumecs) of Poondi Reservoir for the Months of November and December, 2015 (Source: Chennai Metropolitan Water Supply & Sewerage Board)

Preliminary model simulations (Figure 19) using the hydrologic model HEC-HMS for the Adyar river basin showed that when compared to the reservoir release of about 800 m^3/s, the flood flow from the parallel catchment (uncontrolled by the reservoir and flowing from Manimangalam, Perungalathur, and Tambaram) alone may have contributed as much as 3000 m^3/s. Together, the flood at its peak when it entered the city has been estimated to be about 3,800 m^3/s (1,34,195 cusecs), whereas the flood carrying capacity of the Adyar river is only about 2,038 m^3/s (72,000 cusecs).

There are strong opinions from various parts that the authorities should have released the water from the Chembarambakkam reservoir gradually well ahead of the heavy rainfall since Chennai had been warned by IMD in mid-October of 2015 (NDTV, 2015). The situation would have been better if the authorities had released controlled quantities of water from Chembarambakkam and other reservoirs throughout November 2015. However, these are conservation reservoirs and not flood control reservoirs. Therefore, they are regulated differently. Being conservation reservoirs, without a reliable weather forecast (forecasts with ~70-80% false alarms) and a reservoir inflow forecast, decisions on timely release of flood waters are rather difficult. Further, all water bodies were completely full from the above-normal November rainfall and the catchment was completely saturated, resulting in heavy runoff

(Figure 19). Hence, the reservoir release alone cannot be blamed for the huge deluge in Chennai. Nonetheless, it is high time to have a comprehensive flood forecast system in place for assisting the authorities in making informed decisions about operating the reservoirs for managing floods in addition to making sure that the storage for drinking water supply is not compromised.

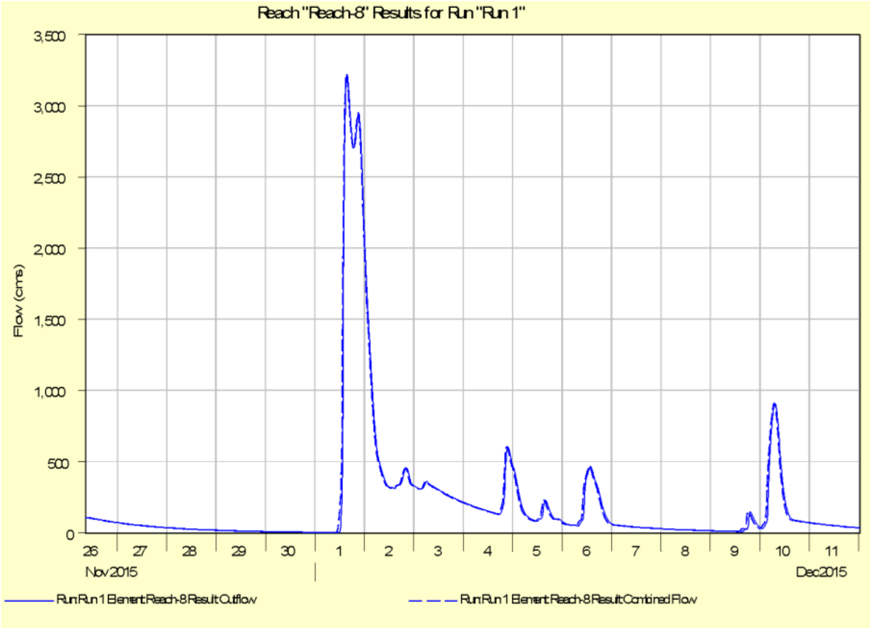


Figure 19: Flood runoff predictions using HEC-HMS for the catchment uncontrolled by Chembarambakkam tank

6. Tidal Levels in the Ocean

It is quite obvious that draining of flood waters through the three rivers in Chennai would depend upon the tidal levels in the Bay of Bengal. Flooding would be exacerbated and recession would be delayed if an intense rainfall event coincides with the occurrence of high tidal levels. However, this issue has not been focused in the mainstream discussions on Chennai floods. Data on tidal levels for the months of November and December are obtained from an organisation which guides fishing activities. This data is presented in Figure 20. From this figure, the tidal influence on the flooding event appears to have been minimal as the heavy rainfall and flooding is not found to coincide with the high tidal level.

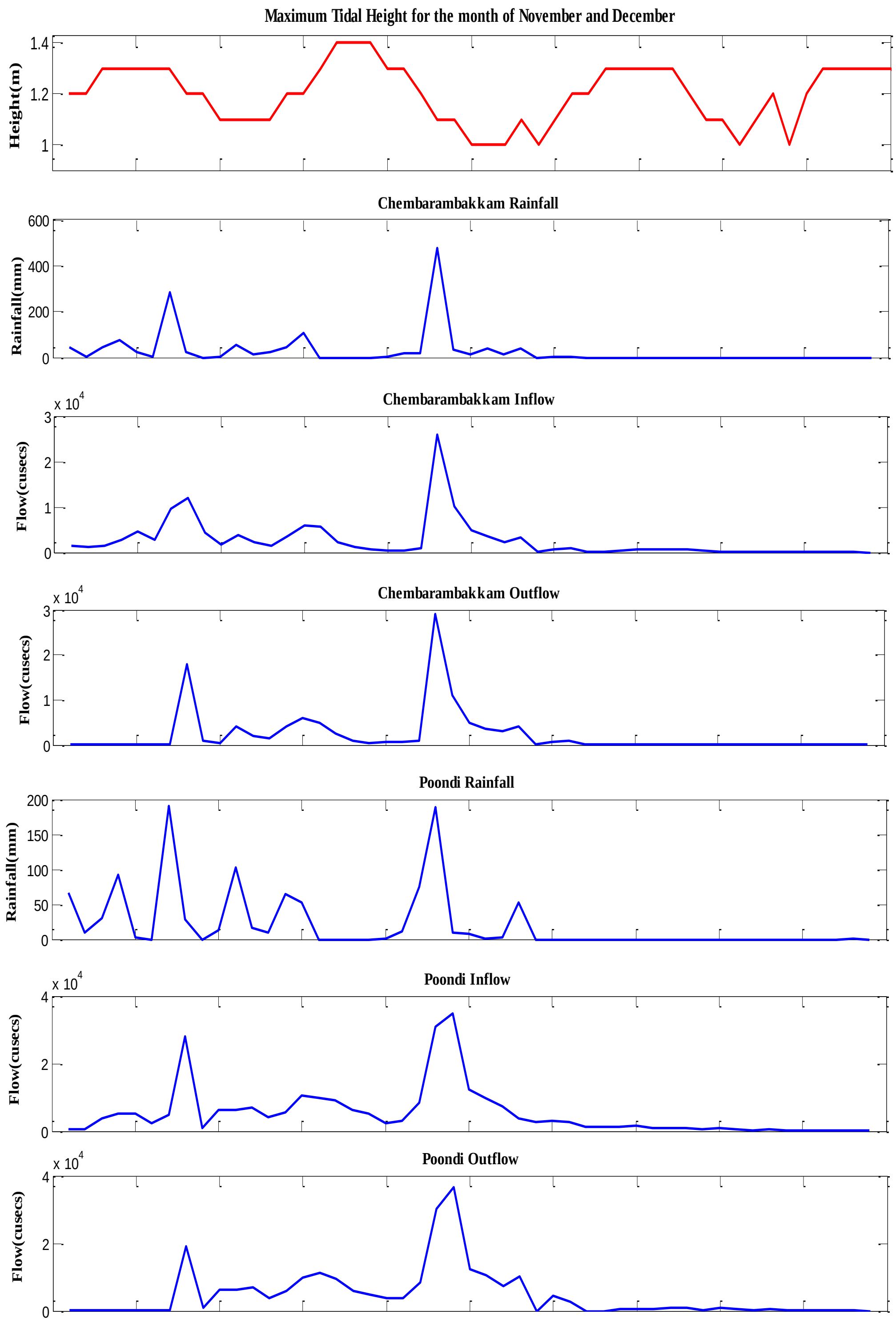


Figure 20: Maximum Tidal levels, Rainfall and Flows during November-December 2015 (Source: http://www.tides4fishing.com/as/india/chennai and Chennai Metropolitan Water Supply & Sewerage Board). 1 cusec = 0.028 cubic meters/sec.

7. Magnitude of Floods – Loss of life and property

It is not an overstatement to say that the December 2015 floods in Chennai have been mammoth although there have been varying reports on the number of casualties, areal extent of flooding and the magnitude of economic loss. Figure 21 shows the areas in the main part of Chennai which were affected by the floods on December 3, 2015

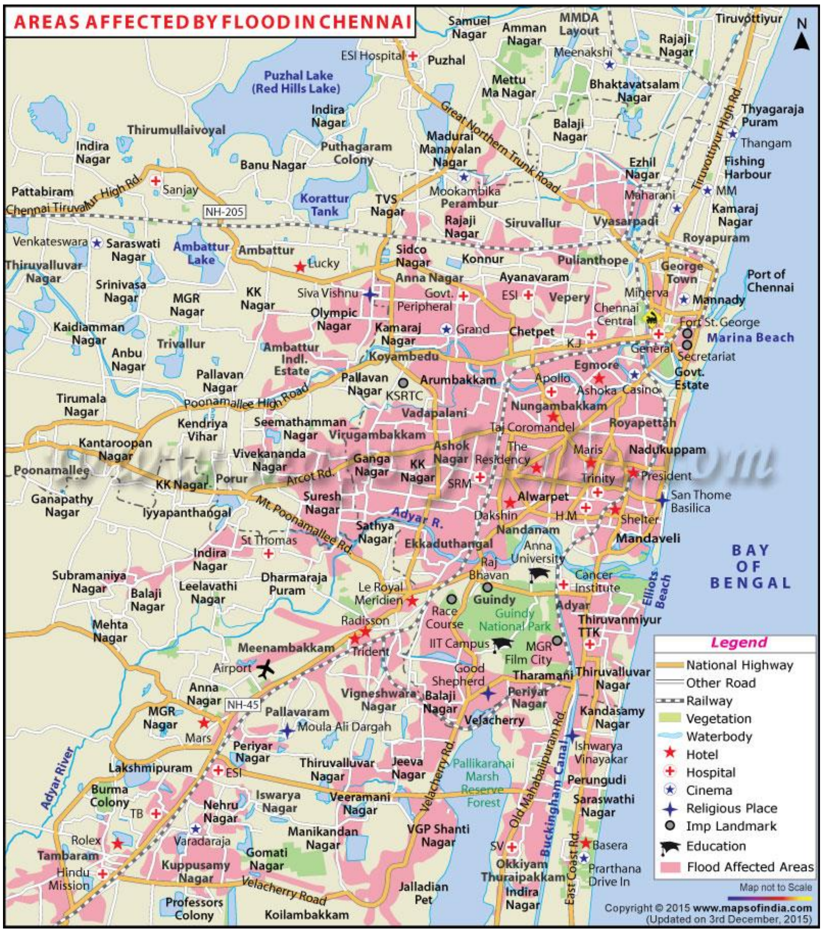


Figure 21: Areas affected by Floods in Chennai on December 3, 2015

(Source: Maps of India, 2015).

As early as December 3, 2016, the Home Minister of India informed the Lok Sabha that rains and floods have claimed 269 lives in Chennai alone until that time (The Indian Express, 2015a). Probably the most shocking news was that of death of 18 patients in MIOT International Hospital, reported on December 5, 2015. The hospital is located close to the Adyar River and the flood waters damaged the power units supplying power to the ventilators (The Hindu, 2015b). The death toll further mounted to 347 (in the entire state of Tamil Nadu) by December

11, 2015, as per the official release from the State Government (The Hindu, 2015c). The Chief Minister of state asserted that a total of 470 lives have been lost in the state of Tamil Nadu during the North East monsoon (The Hindu 2016a). Over 18 lakh (1.8 million) people were displaced because of the flooding event. About 30.42 lakh (3.042 million) families had suffered total or partial damage to their dwellings; 3,82,768 lakh hectares of crops had been lost due to flooding, including over 3.47 lakh hectares of agricultural crops and 35,471 hectares of horticultural crops; roughly 98,000 livestock animals and poultry had died (The Hindu, 2016b). It is reported that more than 100,000 structures were damaged as a result of the floods. Almost 30% of Chennai households have each faced losses between Rs.2 lakh and Rs.20 lakh (DNA, 2015).

It has been asserted by the National Disaster Response Force (NDRF) that the Chennai flooding event was their largest rescue operation (The Economic Times, 2015). A total of 50 rescue teams were pressed into service, starting with 16 teams on December 2, 2015 and reaching up to 50 teams by December 4, 2015. The teams stayed in the field until December 15, 2015. A total of 1715 persons, 194 boats, 1571 life jackets, 1071 life buoys were deployed, along with other essential life-saving equipment, medicines etc. NDRF rescued 22,450 persons and 30 animals, recovered 30 bodies and gave medical treatment to 359 persons. Altogether 2,41,904 food packets and 2,10,372 water packets were distributed.

Many governmental departments (The Coast Guard, the three branches of Indian Armed Forces, The Chennai Corporation, The Chennai City Police, The National Crisis Management Committee and others), non-governmental organizations, civic society groups, industrial houses and very many individuals helped immensely in the rescue and relief operations. Official statements from the State Government indicated that approximately 1.7 million people had been moved to 6,605 relief camps (The Indian Express, 2015b). Majority of these camps were located in Chennai, Cuddalore, Thiruvallur and Kanchipuram districts. The relief operations in Chennai were mostly completed by December 19, 2015. The magnitude of relief operations can be gauged by the following numbers: total number of food packets distributed - 12.8 million; amount of garbage collected - 186,000 tonnes; total number of medical camps - 10,833 and total number of people screened - 1.679 million (The Hindu, 2015d).

As can be expected, people faced much hardship during the days of flooding. Media reports are found to mention acute scarcity of basic necessities such as milk, water, vegetables, candles, fuel, transportation, etc. It was reported that airfares were almost 10 times the normal price.

Also, due to the unique nature of urban flooding, the accessibility issues and considerations for providing immediate relief to the more needy, the relief operations could not be carried out uniformly in all areas (The Economic Times, 2015). Also, in the wake of such an unprecedented disaster event, there was some lack of coordination between different relief and rescue efforts which were being carried out by different departments and organizations in the initial days. Many of the rescue personnel were reportedly from far-off places; hence, they lacked knowledge about local conditions. All this created resentment in some sections of the population and has been part of extensive discussions in social media. These experiences should be taken as an opportunity to learn and improve the effectiveness of disaster relief operations in the future.

Industrial and commercial activities were badly hit by the floods. The Chennai airport was closed from Dec. 1, 2015 until Dec. 6, 2015 as the flood waters inundated the airport and the runways were under water. Industry sources said that major players including Hyundai, Ford, BMW, Nissan, TVS, Renault-Nissan and Ashok Leyland were forced to temporarily shut production during the rain. According to the Auto Component Manufacturers Association (ACMA), more than 50% of the employees have lost their homes and objects (The Indian Express, 2015c). Most of them resumed operations by Dec. 8, 2015. Major Information Technology (IT) companies located in Velachery and Tiruvanmiyur areas were inundated. They had to close their offices due to loss of power and shortage in supply of food and water (Deccan Chronicle, 2015).

Rapid estimates by Confederation of Indian Industry (CII) and Assocham, made as early as December 8, 2016, put the economic loss resulting from the floods at Rs. 15,000 crores due to stoppage of industrial production (Hindustan Times, 2015). However, the state government has put the total loss at Rs 8,481 crore (ZEE News, 2015). Aon Benfield, an UK reinsurance broker has claimed that the floods in Chennai can cost Indian economy a whopping Rs.20,034 crores, making it the eighth most expensive natural disaster in the world during 2015 (DNA, 2015). Table 3 summarises the estimates of economic loss in some sectors as reported in several newspapers.

Table 3: Summary of Estimated Economic Loss

S. No.	Description	Amount in (Rs. Crores)	Source
1	Chennai Real Estate	30,000	http://www.dnaindia.com/india/report-chennai-realty-market-faces-rs-30000-crore-loss-post-floods-2160122
2	Small & Medium Industrial Units (Entire Tamil Nadu)	14,000	http://www.newindianexpress.com/cities/hennai/Flood-hit-Industrial-Belts-Clamour-for-Aid/2015/12/27/article3198021.ece
3	Insurance Companies	4,800	http://indianexpress.com/article/india/india-news-india/hennai-floods-insurance-cos-get-rs-4800-cr-claims/
4	Street vendors	225	http://www.thehindu.com/news/cities/chennai/over-15-lakh-street-vendors-affected/article8023454.ece

8. Response and Recovery

In the aftermath of the flooding event, there was good coordination between the government and the defence agencies during the rescue phase. After the crisis phase passed, there was no direction from the State administration to the Army which led them to figure out as what they were required to do (Frontline, 2015c)

Many volunteers came up with their helping hand during initial stages of the rescue operations. Also, many organisations and youths, split into different groups, joined hands in rescuing people which blurred the cultural differences amongst communities. All the mosques, churches and temples were opened to the flood victims who were also served food (Frontline, 2015c).

Even after the flood water drained out from the arterial roads, many of the low-lying areas continued to be flooded with sewage due to silting and blockage of drains with plastic, mattresses and sundry material. Authorities gathered nearly 25,000 sanitary workers to clean the stinking garbage piled up over the preceding several days to prevent the spreading of diseases. After the floods, piled up garbage piled amounted to 8,000 to 10,000 tonnes. In normal times, it is about 650 tonnes (IBN Live, 2015).

The State government ordered a massive drive to clear illegal encroachments along the rivers. Thatched huts and semi-permanent concrete walled houses were razed down by earthmoving equipment below the Maraimalai Adigal Bridge immediately after flooding across the river in Saidapet (The Hindu, 2015e).

9. Health Impacts

As several media reports suggested and as may be expected, outbreaks of disease and epidemics were much feared in the aftermath of floods (The Huffington Post, 2015). However, timely actions by the Department of health & Family Welfare of the Government of Tamil Nadu averted widespread transmission of disease in the extended metropolis area in the post flooding period (Amalorpavanathan et al., 2016). In fact, there was a drop in the number of cases of Leptospirosis, an infectious disease that could spread through contaminated food, water and soil in 2015 as compared to 2011 (The Hindu, 2016b). It was informed by the Health Secretary of Government of Tamil Nadu that this could be achieved through 24x7 fever surveillance programme and large-scale medical camps. More than ten million capsules of doxycline (used in treatment of Leptospirosis) were in stock.

Many Non-Governmental organizations and Civil Society groups conducted awareness campaigns (Biotechin. Asia, 2015 and Safe Bee, 2015) and cleaning operations (The Hindu, 2015f). Department of health & Family Welfare of the Government of Tamil Nadu put in place static and mobile medical camps for screening, providing treatment and medical needs for illnesses and communicable diseases. The 108 ambulance service was deployed for round-the-clock operation (The Huffington Post, 2015). By December 6, 2015, 216 camps and 92 mobile medical teams were functional in Chennai. These were run jointly by the Directorate of Public Health and Chennai Corporation. Besides these, Madras Medical College deployed 40 mobile medical teams for screening of people in some of the worst affected areas (The New Indian Express, 2016). The Public Health Department started 200 more special medical camps through several medical colleges in the city on December 6, 2015. The State Government started the awareness campaigns on the precautionary measures to be taken by residents re-entering homes that have been ravaged (The Hindu, 2015g).

More than 2000 sanitation workers from all over Tamil Nadu were deployed in Chennai city from December 7, 2015 onwards for cleaning operations (The Hindu, 2015h). State Government ordered 2,000 tons of bleaching powder over and above the existing stocks to spread it on the streets after the drying of water. Bleaching powder packets were also distributed to households for use in their homes and compounds. The Chennai Metropolitan Water Supply and Sewerage Board (CMWSSB) increased the dosage of chlorination for achieving better disinfection not only at the source but also in case of contamination in the distribution network. The chlorine levels at the source and at the supply end were regularly monitored. Government hospitals stockpiled medicines, sufficient for the next three months (Rediff.com, 2015). All the above actions taken by the Department of health & Family Welfare of the Government of Tamil Nadu successfully prevented the outbreak of epidemics, which is highly commendable.

Amalorpavanthan et al. (2016) have suggested a few improvements for disaster preparedness and better coordinated relief efforts in order to minimize level of uncertainty in future. These include (i) avoiding delays in the notification of health advisories, (ii) streamlining the process for drug distribution, (iii) improving the accessibility of emergency hot lines, (iv) providing sufficient and appropriate protective gear for health and sanitation workers, (v) integrating the local expertise for better health care delivery, and (vi) improving the reliability of communication networks etc.

10. Field Visit

On the 16th of March, 2016, a team comprising Mujumdar, Narasimhan, Bhallamudi and Mondal visited five places in Chennai that were affected by the Nov-Dec, 2015 flooding event. The locations of the sites visited are marked in Figure 22. While four of the sites were along the Adyar River, the fifth one was near the Velacheri Lake.

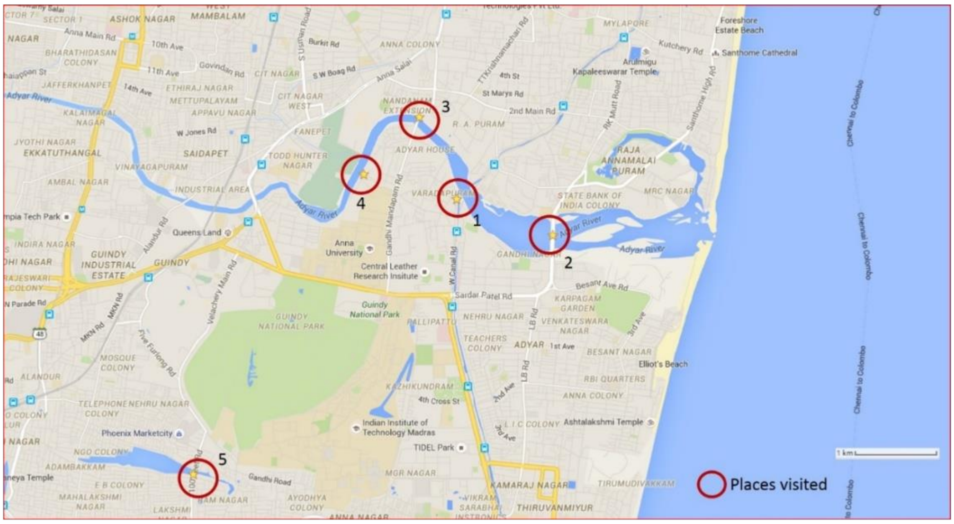


Figure 22: Location of the places visited during the field visit. 1) Meeting point of the Buckingham Canal and the Adyar River, 2) Thiru-vi-ka Bridge, 3) Kottupuram Bridge, 4) Ferry Road near Anna Central Library, 5) Velacheri Lake. [Adopted from Google Maps]

The confluence of the Buckingham Canal and the Adyar River was found to be notably narrow (Figure 23). It was also noted that the Buckingham Canal was constructed for navigation purposes and it was not meant to serve as drainage. The waters were mostly anaerobic in both the Adyar River and the Buckingham Canal, most probably due to sewage discharges.

Figure 23: Confluence of the Buckingham Canal (near) and the Adyar River (far).

This was followed by visits to the Thiru-vi-ka Bridge and the Kottupuram Bridge on the Adyar River. Thereafter the team visited the banks of the Adyar River on the Ferry Road near Anna Central Library (Figures 24, 25). This area seemed to be the worst affected by the flood waters out of all the places visited.

Figure 24: Adyar River near Thiru-vi-ka Bridge.

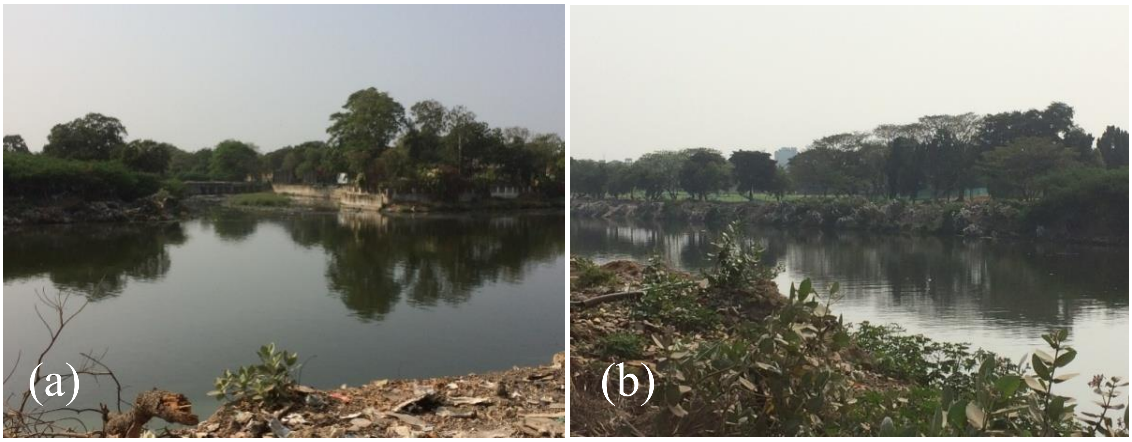


Figure 25: Adyar River close to Ferry Road near Anna Central Library. (a) Storm water drainage outlets can be seen far away. (b) Golf Course in the backdrop. The white-coloured debris on top of the shrubs along the bank on the far side are plastic garbage that were deposited by the flood waters.

Local residents informed that during the earlier floods of 2005 the waters had come only up to ankle length (a few inches above ground) in that area. However, during the floods of 2015, the area was almost 6ft under water. The flood water levels were noted based on feedback from the local people (Figures 26a, 26b). Feedback was received from the local people and the team came to know of an unfortunate death in the area during the floods. As per the eyewitness account, as the water level in the river started rising, the water started surging back through the local drain meant for draining the water out to the river. Ultimately, the river overbanked and further inundated this region. The locals also informed that the flood waters receded within 24 hours.

Embankments have been provided on both sides of the Adyar River in this reach. The banks of the Adyar River in this region had illegal encroachments that were found to be recently demolished by the authorities. In the middle of the rubble from the destruction of the encroaching residences, a storm water outlet was noted in completely blocked and anaerobic condition (Figures 27a, 27b). Encroachments in this area seem to have been haphazardly demolished. However, these particular set of encroachments, which are on the other side of the, embankment did not appear to be the reason for the flooding in this region.

Figure 26: (a) Highest flood water level reached during the flooding event. (b) Banks of the Adyar River near Ferry Road that were under water.

Figure 27: (a) Poor condition of storm water drainage near Adyar River, Ferry Road, (b) Feedback being received from the local residents.

Finally, the team visited the Velacheri Lake and observed a blocked gated (in the past) outlet that was perhaps used for irrigation purposes (Figure 28). It was noted that this region had flooded perhaps because of local waters and not due to release from Chembarambakkam Reservoir, nor due to the overflowing of Adyar River. Flooding in this region seems to be due to poor drainage network and connectivity, chocking of micro drainage with solid waste, aggradation of roads due to constant resurfacing, and lack of adequate cross drainage infrastructure.

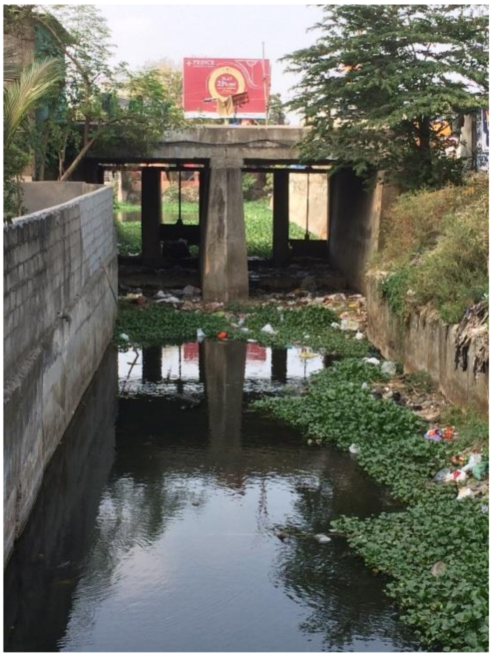


Figure 28: Blocked water outlet from the Velacheri Lake.

11. Recommendations

Many lessons can be learnt from an event of this magnitude to aid better preparedness to face such events in future, not just in Chennai but also in other urban areas in India and elsewhere in developing countries. Herein, some ideas are proposed as recommendations on which attention needs to be focused by the policy makers, administrators and academicians. These recommendations should be considered in conjunction with the guidelines for Urban Flooding prepared by National Disaster Management Authority (NDMA, 2010).

I. **Better Understanding of the Weather**: It is obvious that flood risk can be minimized if one can predict the occurrence of major precipitation events well in advance. This is especially so for cities like Chennai, where major reservoirs are drinking water reservoirs, and one tends to store as much water as possible when the rains come, and little storage is left for flood mitigation. If the reliability of prediction of precipitation magnitude can be improved, especially for an impending high intensity event, it will help operators of drinking water reservoirs to take timely actions and operate them for flood mitigation.

   The present weather forecasting system for urban regions has multiple problems associated with high false alarms, lack of consideration of urban canopy feedback in terms of Large Eddy Simulations (LES) and space-time variability. Spatio-temporal uncertainty in precipitation extremes leads to high false alarms and there is a need for probabilistic forecasts. Furthermore, global forecast systems have significant dry bias on extreme days, as observed in the Global Ensemble Forecast Systems (GEFS) forecasts. This can be improved with regional modelling as discussed in the present report. It is recommended to develop a probabilistic urban extreme rainfall forecasting system with regional ensemble modelling, assimilating Doppler weather radar data, considering urban feedback. The city should set up many more weather/rainfall observation stations, given the high spatial variability in the rainfall in the city,

II. **Water Wiring of Cities:** One of the major issues with regard to management of urban floods in India is the lack of information on them. For example, with regard to flows in major drainage channels during December 2015 floods in Chennai, authors could find data only on the releases from major reservoirs such as Chembarambakkam. Flow data was not available at other locations of the major drainages such as the Adyar River, the Cooum River, or the Buckingham canal. In fact, proper gauging stations are not available on these rivers and continuous flow data is not collected. Also, scientifically collected data on the temporal and spatial variation of depth of inundation during different stages of flooding is not available. It is absolutely essential to deploy sensors at all key locations in the major drainage networks in the Cities and record on-line the temporal variation in water levels and also the flow rates. Sufficient number of telemetric rain gauge stations should be installed. The water level sensors should be not only deployed in channels, but also at key locations in the flood plain and at all major and medium water bodies. All the data should be transmitted to centralized control rooms to provide real time information, flood hazard mapping etc. This on-line data will be useful for: (i) state estimation of surface water system of the city, (ii) on-line operation of the waterways and (iii) planning and design of the control systems in future, using mathematical models.

Major research issues in this context are: (i) development of robust and low-cost sensors / methods for data acquisition,(ii) development of optimization methods for determining sensor locations, (iii) development of technologies for deployment and maintenance of such a large number of sensors, and iv) storage, maintenance and timely dissemination of the collected data for scientific and practical uses.

III. **Development of Urban Flood Models:** Many mathematical models are presently available worldwide for studying urban floods. However, extensive and proper usage of these models in India is hampered by lack of data for their calibration and validation. There is an urgent need to bridge this gap, and to keep ready calibrated urban flooding models for all the cities which get flooded frequently. Such models can be used for designing flood warning systems, on-line control of urban floods and planning water sensitive urban development.

Topographical data at a very fine scale is becoming available for many cities through LiDAR surveys. However, incorporation of the fine scale digital elevation models (DEMs) into hydraulic/hydrologic models for urban flooding leads to complexities due to numerical stability and convergence issues. Research needs to be carried out on development of numerically robust hydraulic models for urban flooding. Also, many times "fine scale" analysis of urban floods is neither warranted nor prudent. Research needs to be carried out on the optimal level of detailing based on the purpose for which simulations are needed.

IV. **System Operation:** Although the Chennai floods 2015 could not have been prevented simply by appropriate operation of reservoirs in the city, there was a possibility of lessening the magnitude of the effect. Therefore, one should revisit the reservoir operation guidelines, and formulate more rational rules for the operation. In any urban area, major natural drainage channels, the storm water drains, the water bodies such as lakes and ponds and the roads (as water conveyance structures for overland flow) act as a single unit during major storm events. Therefore, system dynamics methods should be employed to find out how best to utilize each of these components of the system for minimizing the damage.

V. **Stricter Norms on Roads and Compound Walls:** In the discourse on the effect of urbanization on the floods, major emphasis is usually laid on (i) how the run-off and the peak flow magnitude increases due to decrease in the infiltration component, (ii) how the disappearance of water bodies, small and large, due to land use change, decreases the detention effect of the catchment, (iii) how encroachment of water ways reduces their flood carrying capacity and (iv) how poor solid waste management clogs the storm water drainage system. It has been learnt from Chennai floods that some minor processes can have significant effects, at least locally. As discussed earlier, improper re-laying of roads (thereby increasing their elevation), construction of high and impervious road medians and ubiquitous presence of "compound walls" between adjacent real estate properties alter the over land flow paths and cumulatively affect the location and the depth of inundation. They also prompt uncoordinated acts of local inundation control through breaching of bunds, breaking of compound walls and clogging of culverts.

Administrators should address this issue in detail while according approvals for real estate development. There should be capacity-building in approving organizations so that they can assess any effect a proposed real estate development may have on local surface and subsurface water hydrology.

VI. **Well-planned Peri-Urban Development:** The core parts of most of the cities such as Chennai are already fully developed and in a very unsustainable way. Retrofitting these parts of the city for a water sensitive urban development is almost impossible because of social, political and economic considerations, besides technical reasons. However, peri-urban areas are amenable to policy interventions. Policies must be introduced such that the development is water sensitive and is based on the principles of sustainability [Sustainable Urban Drainage (SusDrain) / Low Impact Development (LID)]. Development should be such that the water bodies in peri-urban areas do not disappear, there is an optimal level of rain water harvesting, and the natural drainage channels are not encroached upon. Development should be based on in-depth analysis of the effects of land use and land cover changes on the hydrology of the basin. Very similar to pollution norms, norms for peak discharge should be developed for new urban development and the developers need to get certification of their design prior to project approvals.

VII. **Urban Flooding Study Group:** Although urban flooding in the scale of Chennai Floods 2015 occurs rarely, the effect of such floods is enormous in terms of loss of life and property. Even the trauma caused by such floods is long lasting. However, coordinated efforts are not being made to collect data on these floods as they unfold, make rapid assessment of events and finally learn from them to make the urban systems resilient to such events. In this context, there is an urgent need to form a national level "urban flooding study group", made up of academicians and practitioners from various institutions. The mandate of such a group is to "rush" to the city affected by the floods, measure spatial and temporal variation in inundation and flows as per a pre-formulated template using instrumentation and crowd-sourcing, gather anecdotal information on the effects of flooding and how the city handled the floods, process the information and prepare the rapid assessment report to be shared with all stake-holders. Such reports will be invaluable for making our cities resilient to catastrophic rains.

VIII. **Maintenance of Drainage System**: One cannot over-emphasize the need for keeping all the storm water drains free from blockages due to indiscriminate dumping of solid waste into them. While keeping the major drains clean could be the responsibility of the urban local body, keeping the minor drains clean should be the responsibility of local population. It is not possible to make the entire drainage system work effectively, unless part of the ownership of the drainage system is taken by the local users. It may be worthwhile to encourage the formation of citizen groups which work in close coordination with government.

IX. **Assessment of Climate Change Impacts:** Uncertainties introduced by climate change need to be addressed in the stormwater drainage designs. It is very likely that the short duration, high intensity rainfalls that cause urban floods will continue to increase in future. The design storm used in the hydrologic designs must therefore be reassessed to account for climate change. It must however be noted that the climate models are currently not reliable for simulation of monsoon precipitation even at daily scale, and therefore disaggregating the climate model outputs to sub-daily scales are burdened with a large uncertainty. The disaggregated outputs must therefore be used with caution. Methodologies are now available (e.g., Chandra Rupa et al., 2015) to quantify uncertainties in the projected sub-daily rainfall intensities, under climate change. City administrations around the world are now assessing climate change impacts on return periods of high intensity rainfall for inclusion in the urban storm water infrastructure designs (e.g., Mehl, 2012, Ministry of Environment, 2010, Nie et al, 2010). Such assessments must be carried out for Indian cities and changes in the designs must be effected if necessary.

X. **Co-ordinated flood relief operations:** Many flood relief workers who come from outside of the area may lack appropriate knowledge of local geography and conditions. This may lead to inefficiencies and inequities in the relief work, as we discuss earlier in this report. Therefore, local government officials should ensure effective coordination between different agencies involved in flood relief operations. Also, proper safety measures should be taken for the health of flood relief workers themselves, especially the sanitation workers.

12. Concluding Remarks

The 2015 floods in Chennai city and surrounding areas in Tamil Nadu have brought to the fore the need for developing a scientific understanding of urban floods to help enhance the engineering, administrative and societal resilience. Therefore, an attempt is made in this report to present issues that contributed to the devastating floods in Chennai city during November-December 2015. Brief discussions on the after-effects of the floods and the responses are also provided. Although much of the material presented in the report is collated from information available in public domain, results from a few preliminary analyses carried out by the authors - especially on estimation of the return period of the rainfall recorded during the period, inferences on the atmospheric drivers and the hydrologic responses - are also included.

Questions related to the influence of global climatic events such as the El Nino on the high intensity rainfall recorded during the event and increasing frequencies of such high intensity rainfall because of climate change and urban heat island effect remain unresolved and require further observations and model-based investigations. However, it is possible to estimate the hydrologic response in terms of the flood inundation in the City for a given intensity of rainfall, if appropriate data is made available to the scientific community. Such estimates will be useful for improving disaster preparedness and management. It is also possible to estimate the impact of urbanization on the occurrence of floods in future so that further development in the City can be made sustainable. Further efforts on improved forecasting of extreme weather events and associated hydrological responses can also aid water management decisions such that the contribution of human regulations (such as reservoir operation) on aggravating the floods can be avoided.

To help timely administrative responses, real time flood alerts with sufficient lead time are necessary. Such flood alerts should be developed by integrating spatially distributed forecasts of high intensity rainfall in the City with hydrological models to simulate overland flow and storm water drainage. Radar measurement of rainfall and monitoring of the flow at critical locations in the rivers running through the City and drainage systems would greatly help in flood forecasting. Also, high resolution terrain data from digital elevation models will be necessary for such an exercise. The real time flood alerts can then be employed to develop Expert Systems to provide decision alternatives for flood management.

With the lessons learnt from the deluge, the scientific community and the administrators of the city of Chennai now have an opportunity to pro-actively demonstrate the effectiveness of scientific and technological interventions in managing urban floods in the country. It is expected that the issues flagged in this rapid assessment report provide a starting point for further in-depth scientific studies.

References

Amalorpavanathan, J., M Ramakumar, S Sivasubramanian, "Preparedness in Disaster Situations Lessons from Chennai Floods 2015", Economic & Political Weekly, February 20, 2016 vol L1, No. 8, pp. 30 – 34.

Balaguru K, S Taraphdar, LR Leung, and GR Foltz. 2014. "Increase in the Intensity of Postmonsoon Bay of Bengal Tropical Cyclones." Geophysical Research Letters 41(10): 3594-3601. DOI:10.1002/2014GL060197.

Bhowmik, Nani, A.G. Buck, S. A. Changnon et al., (1994): "The 1993 Flood on the Mississippi River in Illinois", Illinois State Water Survey, Miscellaneous Publication, 151.

Biotechin. Asia (2015), https://biotechin.asia/2015/12/05/health-concerns-dos-and-donts-after-chennai-floods/.

CMDA, "Second Master Plan", Chapter X, http://www.cmdachennai.gov.in/volume3. html,pp. 214-237.

COC, http://chennaicorporation.gov.in/departments/storm-water-drain/.[Accessed on April 21, 2016]

Coles, S., 2001. "An introduction to statistical modelling of extreme values", Springer.

Deccan Chronicle (2015), http://www.deccanchronicle.com/151203/nation-current-affairs/article/when-chennai-was-logged-out-and-how

DNA (2015), http://www.dnaindia.com/money/report-chennai-floods-losses-estimated-at-rs-20034-crore-to-the-india-s-economy-says-aon-benfield-report-2154521

Emanuel, K. A. (1987) “The dependence of hurricane intensity on climate”. Nature 326, 483-485 .

Emanuel, Kerry (2005) "Increasing destructiveness of tropical cyclones over the past 30 years." Nature 436.7051 : 686-688.

Frontline (2015a), http://www.frontline.in/cover-story/when-chennai-went-under/ article 7965 575.ece.

Frontline (2015b), http://www.frontline.in/cover-story/the-monsoon-story/article7965640 .ece

Frontline (2015c), http://www.frontline.in/cover-story/sunk-by-negligence/article7965695 .ece.

Hindustan Times (2015), http://www.hindustantimes.com/business/chennai-rains-may-have-sunk-businesses-worth-thousands-of-crores/story-dCUi5GHoQPmdddpRk2rLQM.html

IBN Live (2015), http://www.news18.com/news/india/as-water-recedes-chennai-braces-to-check-outbreak-of-diseases-1174026.html.

IWS. (2007). “Microlevel Study: Chennai Basin. Vol-I”. Institute for Water Studies, Tharamani, Chennai.

King, Andrew D., et al. (2016), Emergence of heat extremes attributable to anthropogenic influences .

Knutson, T. R. & Tuleya, R. E. (2004), “Impact of CO2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization”. J. Clim. 17, 3477–3495 (2004).

Knutson, Thomas R., et al. (2010), "Tropical cyclones and climate change." Nature Geoscience 3.3 : 157-163.

Maps of India (2015), http://www.mapsofindia.com/mapinnews/areas-affected-by-flood-in-tamilnadu/

Murawski, M (2015), “Sustainable development in the peri-urban regions of Chennai: Spatial analysis using optical remote sensing data”, unpublished report presented to Indo-German Center for Sustainable Development (IGCS), IIT Madras, Chennai, 2014-2015.

Narasimhan, B. (2016). “Storm water drainage of Chennai- Lacuna, Assets, and Way Forward”. Presentation made at “Resilient Chennai: Summit on Urban Flooding” hosted by 100 Resilient Cities in partnership with the Corporation of Chennai.Feb.1-2, 2016.

NDMA (2010) ,”National Disaster Management Guidelines – Management of Urban Flooding”, NDMA, Sep. 2010

(http://www.ndma.gov.in/images/guidelines/management_urban_flooding.pdf)

NDTV (2015), http://www.ndtv.com/chennai-news/a-month-before-chennai-floods-the-met-office-had-issued-a-warning-1250581

Ramasamy, N “Macro drainage system in Chennai Metropolotan area”, Second Master Plan 2026 – Proceedings and Recommendations, Session-III, Page 138; www.cmdachennai.gov.in/SMPS/SMPS.html]

Rediff.com (2015), http://www.rediff.com/news/interview/how-chennai-is-trying-to-keep-an-epidemic-away/20151216.htm

Safe Bee (2015), http://www.safebee.com/outdoors/how-stay-safe-and-healthy-after-chennai-floods

Shastri, Hiteshri, et al. (2015) "Impacts of urbanization on Indian summer monsoon rainfall extremes." Journal of Geophysical Research: Atmospheres 120.2 : 496-516.

Swamy, G.S.N.V.K.S.N., and Nagendra, S.M.S., (2016) "Study of Urban Heat Island (UHI) Formation in Chennai City Area", Poster presented at Indo-German Conference on Sustainability : Exploring planetary boundaries and their challenges and opportunities", 27 - 28 February 2016, Indo-German Center for Sustainability, IIT Madras, Chennai, India.

The Economic Times (2015), http://articles.economictimes.indiatimes.com/2015-12-31/news/69426970_1_ndrf-flood-rescue-rescue-operation

The Hindu (2015a), http://www.thehindu.com/news/cities/chennai/chennai-floods-a-wrong-call-that-sank-the-city/article7967371.ece

The Hindu (2015b), http://www.thehindu.com/news/cities/chennai/miot-hospital-deaths-patients-relatives-in-shock-clueless-about-cause-of-death/article7949838.ece

The Hindu (2015c),http://www.thehindu.com/news/national/tamil-nadu/death-toll-in-floods-mounts-to-347/article7973293.ece

The Hindu (2015d), http://www.thehindu.com/news/cities/chennai/chennai-rains-chennai-corporation-to-spend-rs-110-crores-on-road-restoration/article8044455.ece

The Hindu (2015e), http://www.thehindu.com/news/cities/chennai/removal-of-huts-along-adyar-river-begins/article8043536.ece?ref=relatedNewsThe Hindu (2015f) ;http://www.thehindu.com/news/cities/chennai/muslim-group-cleans-floodhit-temples/article7959652.ece

The Hindu (2015g),http://www.thehindu.com/news/cities/chennai/tamil-nadu-government-lists-out-8-steps-to-safety/article7953813.ece

The Hindu (2015h), http://www.thehindu.com/news/cities/chennai/tamil-nadu-rains-devastation-unfolds-as-flood-recedes article7955293.ece

The Hindu (2016a),http://www.thehindubusinessline.com/news/national/northeast-monsoon-claimed-470-lives-in-tamil-nadu-jayalalithaa/article8064661.ece

The Hindu (2016b), http://www.thehindu.com/news/cities/chennai/no-disease-outbreak-after-floods-claim-health-officials/article8122149.ece

The Huffington Post (2015); http://www.huffingtonpost.in/2015/12/04/tamil-nadu-health-epidemic_n_8716576.html

The Indian Express (2015a),http://indianexpress.com/article/india/india-news-india/ chennai-flood-death-toll-crosses-260-home-minister-says-situation-very-alarming/#st hash.kuq2OuBX.dpuf)

The Indian Express (2015c), http://indianexpress.com/article/india/india-news-india/chennai-floods-industries-crippled-suffer-huge-revenue-loss/

The Indian Express (2015b), http://indianexpress.com/article/india/india-news-india/ jayalalithaa -urges-pm-modi-to-declare-chennai-floods-as-national-calamity/

The National (2015), http://www.thenational.ae/world/south-asia/20151213/letter-from-chennai-saving-a-home-from-the-floods

The New Indian Express (2016),http://www.newindianexpress.com/cities/chennai/200-More-Special-Camps-to-Tend-to-Flood-hit-Chennai/2015/12/06/article3

The News Minute (2015), http://www.thenewsminute.com/article/chennai-floods-what-happened-chembarambakkam-negligence-or-nature%E2%80%99s-fury-36675

The Times of India (2015a), http://timesofindia.indiatimes.com/tech/tech-news/IT-companies-suffer-60-million-loss-due-to-Chennai-floods/articleshow/50060374.cms.

The Times of India (2015b), http://timesofindia.indiatimes.com/city/chennai/Flood-Chennai-corpn-learned-little-from-CAG-advice/articleshow/49852204.cms

The Wire (2015), http://thewire.in/2015/12/09/how-official-negligence-turned-a-natural-crisis-into-a-human-made-catastrophe-16938/

TNUIFSL. (2014). Tamil Nadu Sustainable Urban Development Project: Integrated Storm Water Drainage Project for the Expanded Areas of Chennai Corporation. Storm Water Drains Department, Corporation of Chennai. 53p.

TNUIFSL. (2015). Tamil Nadu Sustainable Urban Development Project: Storm Water Drains for the Selected Areas of Corporation of Chennai. Storm Water Drains Department, Corporation of Chennai. 66p.

ZEE News (2015), http://zeenews.india.com/business/news/economy/chennai-floods-financial-loss-may-exceed-rs-15000-crore-says-assocham_1829598.html

Zubair, Lareef, and Chester F. Ropelewski. (2006), "The strengthening relationship between ENSO and northeast monsoon rainfall over Sri Lanka and southern India." Journal of Climate 19.8 : 1567-1575