CS (AR) / 2009-10

A study on spatial and temporal hydrological aspects of Kakinada city

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Kakinada
2010

Preface

In Andhra Pradesh the percentage of urban population has increased from 9.65 % in 1901 to 27.08 % in 2001. By 2001, a population of about 20.5 millions out of a total of 75.7 million are in urban areas in the state. In 1961, only 6.3 million was the urban population of the state. Thus urbanization is taking place at good pace of late and has a striking impact on the natural resources and especially on hydrology of the urban areas. It is fact that urbanization and industrialization are the cause for modification in urban ecosystem and its environment.

As cities grow, not only hydrological regime of river through the city but also magnitude and variation of smaller flows in man-made water-related infrastructure and on paved surfaces is of interest. Moreover, it must be possible to predict these flows in advance, even before the new construction is built. Hence, any construction of urban water-related infrastructure, channels, pipes, conduits and even shaping of streets must be based on good knowledge of what will be the effect of these structures on water flows in the city and what is necessary to avoid damage on man-made constructions. Rainfall is the driving force of all hydrological processes and it constitutes the most important input to any runoff calculations and modeling procedures. However, because of the usual lack of rainfall data representative of temporal and spatial variations of the natural rainfall process, the rainfall input is often a weak point. In India, emphasis is being laid for some years now on urban hydrological studies, especially to understand the spatial and temporal aspects of rainfall, floods, etc.,

As part of this study short duration rainfall of the Kakinada city was monitored by establishing a network of gauges, since such short duration data is not readily available. The data from NIH Regional Centre's observatory was also used. Rain gauges were procured and installed at 7 locations in the city with collaboration of Municipality and other authorities. As part of the network 2 digital rain gauges with tipping bucket and logger, 2 tipping digital rain gauges with tipping bucket and display of cumulative rainfall and 3 ORG's were established at 7 locations in the city. The rainfall – intensity for different short durations of rainfall during 2007 to 2009 is analysed in this study. Depth – Area –Duration analysis was also undertaken for most severe storms by plotting DAD curves for storms of 5 to 30 minute duration. The intensity duration frequency relationship is derived from only 3 years of observed data using partial duration series (PDS) from about 40 events using peak over threshold (POT) model at 2 locations for short duration rainfall event of 1 to 30 minutes. Such relationships are useful in hydrological design of urban infrastructure and roof water harvesting structures that require a 2 to 100 years return period rainfall as input.

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Abstract

It is well known that changes in land use have direct effect on the hydrology any watershed. Among such changes, the urbanization is the most forceful one that affects the water balance of any system under study. Urbanization can have a great effect on hydrologic processes, such as surface-runoff patterns. Neglect of the hydrology of the region while undertaking planning and developmental works in an area will have serious consequences. Apart from the non-availability of drinking water, the other problems of concern of urban areas and rural housing projects, due to this negligence, are the inundation of dwelling areas during rainy season due to improper roadside drains and storm water drains; flooding of low-lying areas etc.,

A detailed study on hydrological aspects of Kakinada city was undertaken with the objective to understand short duration rainfall characteristics as input for use in water resources planning and management. The highest amount of rainfall recorded in one, two and three hours at Kakinada are about 70 mm, 120 mm and 135 mm respectively from the hourly IMD Data. The intensity of rainfall is about 200 mm/hour for about 15 minutes during October 2005. The maximum 1, 5, 10, 15, 30 and 60 minute rainfall intensity recorded up to 2009 was during 30th August 2009. During the intense storm of 30th Aug 2009 an intense rainfall of 20 cm/hr over 5 minutes; 16.5 cm/hr over 15 minutes; 11.5 cm/hr over 30 minutes durations occurred in the city. Also, it is noticed that rainfall intensities were higher for storms of lower durations during the study period. It is to be mentioned that 2009 is a deficit rainfall year of recent decades. From the DAD plots, the area of core of storm centre was 37.7 Ha for 30 minutes duration with rainfall of about 26 mm in the middle parts of the city during the August 2008 storm event. Analysis of less or small rainy events indicated that rainfall intensity of 1 (0.25 mm) to 2 tips (0.5 mm) in 15 minutes might initiate runoff from RCC surfaces.

From the groundwater investigations aspect, it is observed that the deficient rainfall of 2008 has resulted in large EC of groundwater during post-monsoon of 2008 in the eastern half of the city and is very high compared to the EC of Post monsoon of 2007. It is observed that at Madhava Nagar, which is adjoining good recharge area like JNTU campus and Medical college sports grounds extending up to district sports authority campus experience a rise of 1.2 m for every 300 mm of uniform rainfall under wet conditions indicating a storage coefficient of 25%, which is a standard for alluvial aquifers. In areas on the west, north- west of city where groundwater is potable the groundwater table has dried up and the situation is alarming. There is need to rejuvenate such aquifers using artificial recharge techniques to supplement the decreasing natural rainfall recharge using roof water harvesting for sustainable development of the water resources in the city.

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1.0 INTRODUCTION

Understanding the science of hydrological cycle and its engineering application through hydrologic design of different systems of water resources especially of societal orientation is of importance to any developing society. Coastal and deltaic areas of east coast of India experience frequent cyclonic storms during which extraordinary rainfall occurs. This heavy precipitation added to the drainage congestion problems of streams and drains in flat plains results in inundation of water submerging low-lying areas, dwellings, communication facilities etc., for sufficiently long periods causing lot of inconvenience to the public and strain to the authorities.

India is a part of the global trend towards increasing urbanization in which more than half of the world's population is living in cities and towns. Over 27 per cent of India's population (285 million) lived in urban areas by 2001. India's urban system is the second largest in the world. In India, the percentage of urban population having access to safe drinking water has increased from 82 per cent in 1991 to 90 per cent as of now. However, only 63 per cent people have access to potable water within their premises. For Indian cities to become growth-oriented and productive, it is essential to achieve a world class urban system. This, in turn, depends on attaining efficiency and equity in the delivery and financing of urban infrastructure (PIB, 2002).

In Andhra Pradesh the percentage of urban population has increased from 9.65 % in 1901 to 27.08 % in 2001. By 2001, a population of about 20.5 millions out of a total of 75.7 million are in urban areas in the state. In 1961, only 6.3 million was the urban population of the state. Thus urbanization is taking place at good pace of late and has a striking impact on the natural resources and especially on hydrology of the urban areas. It is fact that urbanization and industrialization are the cause for modification in urban ecosystem and its environment.

It is well known that changes in land use have direct effect on the hydrology any watershed. Among such changes, the urbanization is the most forceful one that affects the water balance of any system under study. Urbanization can have a great effect on hydrologic processes, such as surface-runoff patterns. It can be visualized as below.

In a natural environment, the land in the watershed adjacent to a stream can be thought of as a sponge (more precisely, as layers of sponges of different porosities) sloping uphill away from the stream. When it rains some water is absorbed into the sponge (infiltration) and some runs off the surface of the sponge into the stream (runoff). An assumption of occurrence of a storm lasting one hour and 50% of its rainfall entering the stream and the rest is naturally absorbed by the surroundings (sponges). Due to gravity the water in the sponges will start moving in a general downward direction, with most of it seeping out and into the stream banks during the next day or two. Now, imagining that roads and buildings have replaced most of the watershed surface, the changes in this process can be different. When any rain occurs, it can't infiltrate the impervious surfaces. It will runoff directly into the stream, and also very quickly. The result is a very quick and short-lived urban flood, rather than a gradual rise and fall in the river. Thus, a storm lasting even 10 minutes is enough to flood the infrastructure in an urbanized watershed (Fig.1).

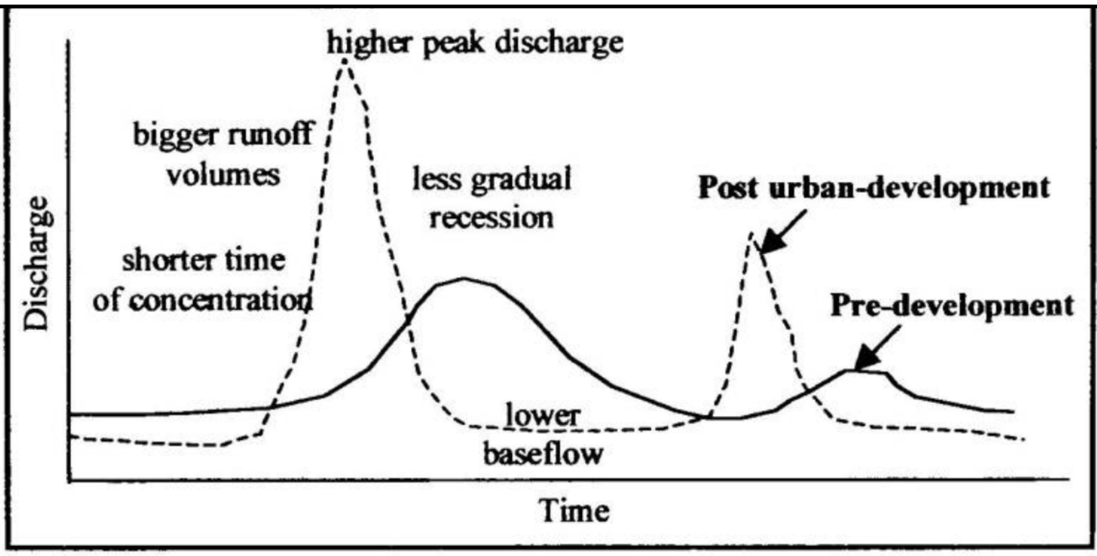


Fig. 1. Effect of urbanisation on the characteristics of runoff hydrograph (adapted from Schueler, 1987)

In modern times, As cities grow, not only hydrological regime of river through the city but also magnitude and variation of smaller flows in man-made water-related infrastructure and on paved surfaces is of interest. Moreover, it must be possible to predict these flows in advance, even before the new construction is built. Hence, any construction of urban water-related infrastructure, channels, pipes, conduits and even shaping of streets must be based on good knowledge of what will be the effect of these structures on water flows in the city and what is necessary to avoid damage on man-made constructions. Even more: increasing imperviousness of the city area with generation of storm water flows may significantly influence the flow regime in the entire river downstream. All these influences must be quantified by analysis of hydrological data and calculations before any construction is built.

Computerized runoff modeling has become a standard method for planning, design and analysis of storm water systems in many cities. But when the input data used are weak, further development of hydrological models will not bring any progress. Thus, future development of models is only justified to the degree motivated by possible increase in accuracy and availability of hydrological data.

Modeling of storm water flows in a city has recently become a standard routine performed in order to design the city and its infrastructure so that possible damages to the city itself and to the entire river basin downstream are minimized. Additional target of rainfall-runoff modeling is to minimize the costs of constructing storm water-related infrastructure. Measured local flow data constitute the necessary base for meaningful urban hydrological calculations and modeling. Simultaneously measured rainfall and runoff data are necessary for calibration of mathematical models.

Effects of development on urban hydrology

According to Shaw (1994), after a major urban development in a originally rural area of a drainage basin, following differences of the flow regime can be identified: there is a higher proportion of rainfall appearing as surface runoff; for a specific rainfall event the response of the catchment is accelerated and thus time to peak and lag time are reduced; flood peak magnitudes are increased (except for very extreme events and when rural runoff coefficient is greater than 50%); in times of low flows discharges are decreased since groundwater storage replenishment is less; water quality in streams, drains is degraded by effluent discharges.

According to Tikoo (2002), in India, till now very little emphasis has been laid on research on hydrology of urban areas. Taking into account that the trends of urban population concentration increase will continue in the future, a programme for encompassing all hydrological, ecological and socio-economic aspects of future urban planning and management needs to be taken up in right earnest. This would require improvement in the management of existing urban drainage systems, disseminate knowledge of integrated urban water management, identify the impact of urbanization on surface and ground water quality through point and non-point sources, to study impact of storm water (wastewater discharges) on ecosystem health of receiving water courses and to establish experimental urban catchments.

2.0 REVIEW

Though the ‘Earth’ is covered two-thirds by water the non-availability of enough potable drinking water, for most of the populations of the nations of the world called ‘developing countries’, is a persistent problem. With the ever increasing charm of living in urban areas there is a need for more efficient and sustainable water management methods to protect local water resources, to optimize the use of surface and groundwater, to help create attractive urban environment. Urban water resources systems deal with quantitative and qualitative aspects of water resources and include water and waste water systems along with systems for reuse or multiple use of water (Ramaseshan, 1988).

Need for Urban hydrological data

Niemczynowicz, J (1999) discussed in detail about urban hydrology and water management of present and future Challenges. All planning and development of urban areas, design of man-made structures and all water management activities in cities should take into account local climatologically and hydrological conditions and possible interactions with rural areas around the city. Hydrological conditions, i.e., size of a river basin, location of area in question in a river basin, proximity to water divider, size and character of surface water bodies, characteristics of groundwater table, etc. often constitute determining and limiting factors for possible development and growth of a city. These natural, local prerequisites determining location and development of cities must be taken into account in planning of new developments in city and in a river basin. Such planning must be based on local data. Thus, gathering of reliable and adequate hydrological data is an important task of urban hydrologists all over the world.

The rainfall is a driving force of all hydrological processes and it constitutes the most important input to any runoff calculations and modeling procedures. However, because of the usual lack of rainfall data representative for temporal and spatial variations of the natural rainfall process, the rainfall input is often a weak point (WMO, 1982; Niemczynowicz, 1991). The reasons for performing discharge measurements have shifted during the process of human development. From ancient times, river and its water was used for drinking, transportation and perhaps the most important use of river water, for crop irrigation. People wanted to know what variations in water availability can be expected, what magnitude and timing of flood and draft events may be expected. Such reasons for monitoring of river flow are still valid. To achieve these goals it is necessary to measure flow and its variations in time. Development of cities with their infrastructure brought additional needs and reasons for flow monitoring.

Neelakantan and Pundarikanthan (1999) analysed the existing urban water supply system for Chennai city and the problems are described along with the proposals. Precipitation is the decisive input variable for a large number of dimensioning methods and models in urban hydrology. Due to the small catchment areas and the shorter flow paths, the runoff processes are characterised by a high degree of dynamics. Giesecke (1998) described the methods used in Germany for supplying precipitation data, and reference is also made to alternatives that may be used in cases where the database is insufficient.

National Institute of Hydrology (NIH), Roorkee initiated urban hydrological studies in the year 1993 in the Nazafgarh drainage basin in the city of Delhi (CS(AR) –140). The methods available for computing runoff hydrographs have been reviewed in the NIH report titled ‘Storm drainage estimation in urban areas’ (TN-49) and another report titled ‘Effects of urbanization on runoff’ (TN-92). NIH has published status reports on urban hydrology in India and elsewhere (SR-15 and SR-4/98-99). These studies highlighted the need of advanced scientific studies on urban hydrology in India.

Methods and models:

During the last century the hydrologic design procedures have improved due to the studies and research undertaken at various academic and governmental institutions though their field application is limited due to a number of reasons.

Empirical methods:

In the initial days due to non-availability of flow records for most of the streams a number of empirical methods to estimate flood flow for design purpose like Ryve’s formula, Dicken’s formula, Nawaz Jung Bahadur formula etc., were evolved for different regions of the country. They are still being practised in the designs though a number of developments have taken place, just because no real data is required except the catchment area. A number of coefficients are proposed for different regions. In the Rational method along with area, rainfall intensity is also input.

Unit hydrograph (UHG) method:

An improvement to empirical formulae is the concept of unit hydrograph introduced by an American engineer Sherman, which states that a T-hour UHG is a hydrograph resulting from unit (10mm) ‘effective’ rainfall occurring in T-hours over the catchment. Since many design problems require the development of relationships at points where flow data are not available, Snyder suggested a group of equations for different components of UHG and is called a ‘synthetic’ UHG. SCS method is another approach to formulate synthetic UHG.

Statistical methods:

The procedure requires all the observed data to be assembled. By undertaking flood frequency analysis and regression analysis, peak flows for urban areas can be estimated and thus flood volumes. Regression equations can be used to estimate flows at ungauged sites.

Hydrologic models:

Computers and numerical models running on them have revolutionized the manner in which hydrologic computations are now performed. A number of operational models for urban areas are developed all over the world. Operational models are generally available and can be acquired and successfully implemented by new users. Bedient and Huber (1989) briefly listed some of the models. The important models are SCS method model TR 20 (SCS, 1986); ILLUDAS (Terstriep and Stall, 1974); HSPF (Johanson et al., 1980); STORM (HEC, 1977); SWMM (Huber et al., 1981; Roesner et al., 1981; James and Robinson, 1984); USGS model (Alley and Smith, 1982a, 1982b). The choice of selecting a model depends on model support and documentation, familiarity with techniques, computer and data available. The last factor is most important in general. The results are going to be bad with a bad input data applied to a very good model.

3.0 METHODOLOGY

The objective of the present study is to demonstrate the importance of spatial and temporal aspects of precipitation of short duration on the urban hydrology of surface water and groundwater in planning and management. Preparation of rainfall intensity relationship of 1 minute to 60 minutes duration is required for use in hydrological design of storm water drains, water storage structures, water conservation measures and roof water harvesting structures. As per the drainage pattern of the city, automatic rain gauge sites were procured and established. The same are monitoring for short duration rainfall using data loggers. Rainfall intensity plots for 1 minute to 60 minutes duration were prepared along with DAD plots, IDF relationships using some severe storm events. The groundwater recharge from rainfall is also to be studied from the aspect of urban development and increasing impervious area by undertaking ground water monitoring from a network of observation wells in the city. The procedures for the same are discussed next.

There is a necessity to properly predict the urban storm water flow to design efficient and effective urban storm water drainage facilities. Such predictions require data and information on rainfall, runoff, soils and land use, evaporation, infiltration etc., , In other words different components of hydrological cycle need to be quantified by observation or estimates. When erroneous assessment of components happens, it is reflected in the under design of any urban storm water system and other urban infrastructure suffers. Some times it may lead to over design of system and results in excess costs and a burden on the public purse. So, there is a necessity to select appropriate design practice and also to evaluate different components of urban hydrological cycle by improving their evaluation methodologies as well to improve the quality of observation data. The same is discussed in details here.

Rainfall

For the proper design a rainfall event is to be identified and then is to be used in generating resultant storm hydrograph. The rainfall event is either an actual one or an artificial one, which are used in general for quantifying the volume of runoff and peak flood respectively. The artificial rainfall, termed a design storm used in the design of urban storm water system, is determined based on the depth - duration - frequency (DDF) analyses of historical data.

DDF method is the traditional method of design where in the DDF curves are used to quantify the depth of design storm of a required duration and specific return period. Then the point rainfall is modified to spatial rainfall considering areal effect. The modified depth is split using an assumed time distribution of rainfall to determine design hyetograph. The hyetograph is the input to many runoff models. Some of the problems while undertaking the DDF method are as below.

In developing DDF curves from historical records, the rainstorm events should be independent. For which auto-correlation analyses can be performed for various rainstorm durations to determine the time lag between rainfall periods such that there is no significant statistical correlation between them. Another way of establishing independence is (Restrepo-Posada and Eagleson, 1982) is to identify the minimum time interval of dry period between two successive rainstorms during which average rainfall is nil or nearly zero. In this approach, two successive events statistically belong to each other if they are separated by a dry period less than the identified minimum dry period. Based on the assumption that Poisson process describes the completely random arrival of storm events, the value of dry period corresponding to a coefficient of variation equal to unity can therefore be determined and considered as the minimum dry period necessary to separate any two successive rainstorm events into statistically independent events.

The traditional DDF analysis is based on the assumption that rainfall depths within a given duration have variate values which come from a single probability distribution function (PDF) and accordingly the records of rainfall depths are normally fitted to a selected single variate PDF.

The DDF curves provide a way to estimate the average rainstorm depth for a specified duration and required return period over a catchment. The effect of rainfall spatial and temporal variabilities over small size catchments is normally ignored in the traditional methods in the urban storm water design. However, the studies indicate that runoff from a rainstorm event varies with not only depth of rainfall but also by spatial (Schilling, 1983) as well as temporal (Akan and Yen 1984) variations of the event over the catchment. Such assumptions may be a source of error in storm water runoff predictions. So, point rainfall depths should be reduced to account for such considerations. These reduction factors vary inversely with both size of catchment and return period for a given duration of the event point rainfall. As the duration of rainfall increases these factors also increase.

In general, the return period of the runoff for a given rainstorm is assumed as that of the rainstorm itself. This is subjected to the characteristics of the other hydrological processes and time lag in between occurrence of rainfall and production of runoff. In an urban area where runoff is fast and quick time of concentration is a minimum and the losses from rainfall are less and hence the assumption may be valid. Nouh (1990) compared the return periods of rain storms and the return periods of corresponding runoff generated using SWMM Model for semi-arid region. The effect of area (A); constant infiltration capacity (fc); A measure of spatial rainfall variation taken as ratio of the time average rainfall intensity of a hyetograph at the centre of a rainstorm to the average rainfall intensity of the rainstorm of over the catchments (SRV); a measure of temporal rainfall variation, taken as the average ratio of time to peak intensity of hyetograph of the total duration of the hyetograph over the catchments (TRV); total rainfall depth in mm (D) and average daily variation of temperature over catchments in degree Celsius (P) are studied to understand the return period of rainstorm and corresponding peak and volume of storm flow.

The procedure selected for time distribution of rainfall depth or the shape of hyetograph also can bring in errors in estimation of storm flow in some regions. Akan and Yen (1984) and many others have concluded that different shapes of hyetographs of same rainfall depth produce different hydrographs.

Evaporation

The urban storm flow paths have short duration processes and hence the effect of evaporation is neglected in traditional method of design. But in arid and semi-arid regions and during summer the evaporation rates are high and significant.

Infiltration

Infiltration is an important rainfall abstraction in arid and semi-arid climates. The infiltration rate is a function of soil. Soil permeability and initial soil moisture content are the soil parameters in estimation of infiltration rate. In general, unless the test results are available, the infiltration rate is a guess work. Some times, a change in ion concentration due to major rainfall and runoff events or due to some form of surface pollution may alter the soil permeability. A significant error is possible in the hydrograph if the infiltration is not accounted for properly. In the design of urban storm water systems infiltration is accounted by the following methods.

American Society of Civil Engineers, ASCE and WPCF proposed standard infiltration curves for sandy soils, residential areas and industrial and commercial areas (ASCE, 1970). These curves have deficiency that they don’t account for soil water storage which is important in arid climates.

Equations such as Horton, Green and Ampt etc., that describe the infiltration process are used. Viessman et. al. (1989) reviewed such equations to determine the infiltration rates realistically.

SCS procedure of USDA is also practiced (USDA, 1975). In this method the initial soil abstraction is assumed as one fifth of catchment storage. This assumption may not be valid in arid regions where the initial abstraction is about one fourth to four tenths of the catchment storage.

In addition to the above difficulties in determining the infiltration in arid regions, there is a problem of recovery and the problem of high temporal and spatial variations of infiltration capacity. The recovery problem arises when rainfall ceases and there is a recovery of infiltration capacity with time and the extent of recovery at any point in time depends on the dryness of the period. Such condition can be modelled using the SWMM continuous simulation. The problem of spatial variability of infiltration rate can be overcome by simulating flow over smaller sub-divisions.

4.0 STUDY AREA

Understanding the science of hydrological cycle and its engineering application through hydrologic design of different systems of water resources especially of societal orientation is of importance to any developing society. Coastal and deltaic areas of east coast of India experience frequent cyclonic storms during which extraordinary rainfall occurs. This heavy precipitation added to the drainage congestion problems of streams in flat plains results in inundation of water submerging low-lying areas, dwellings, communication facilities, agricultural fields etc., for sufficiently long periods causing lot of inconvenience to the public and strain to the authorities. The worst affected or the densely populated urban areas.

Kakinada town in coastal Andhra Pradesh with a population of about 18,000 in 1870 has grown to about 300,000 by 1991 and is expected to touch 1000,000 by 2040 (Vijayakumar, 2002). To undertake a detailed study on hydrological aspects for systematic water resources planning and management in urban areas like Kakinada, which is recently upgraded to Corporation status, it is planned to take up this scientific study. As the required input of data on rainfall and other geographical information system is lacking, it is felt that a systematic study in project mode is necessary to understand the urban hydrology of a typical coastal urban area and to plan and manage its surface and ground water along with the natural water bodies, swamps and vegetation for the sustainable development of a coastal city. The location map of the study area is shown at Fig. 2.

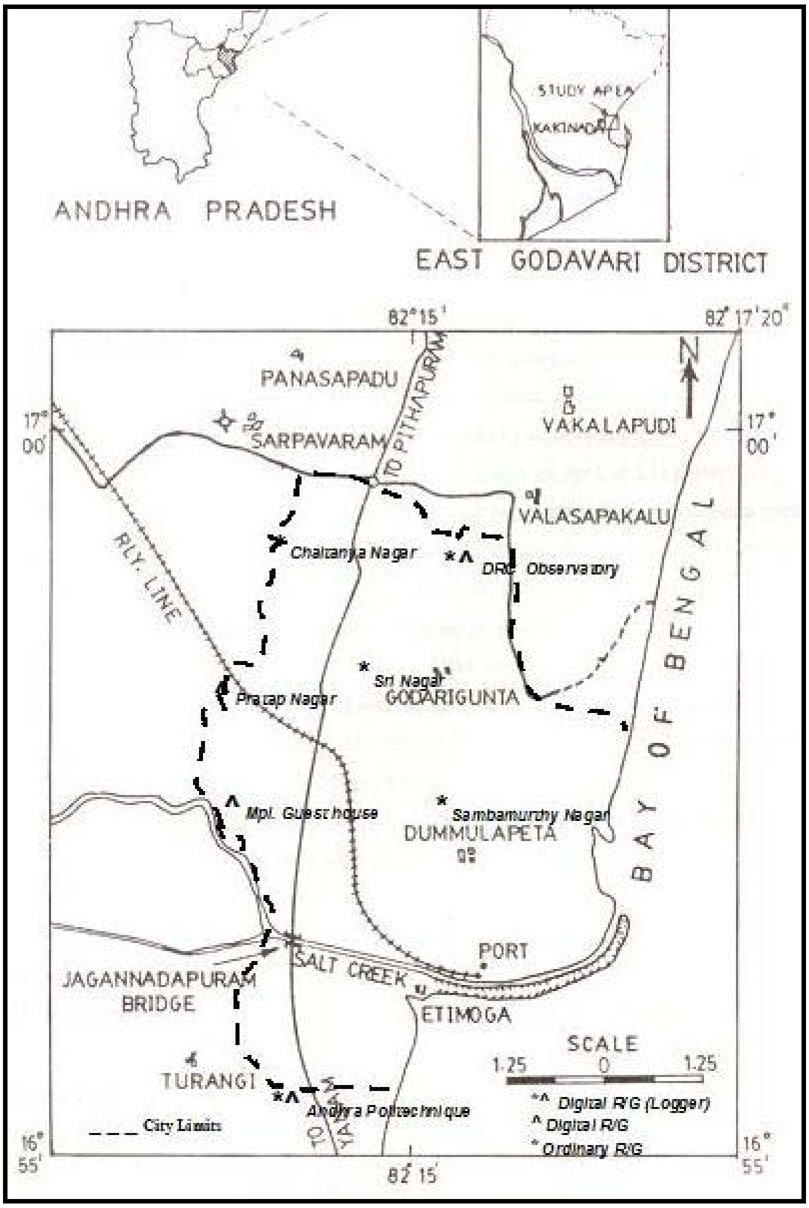


Fig. 2. Location Map of the study area

During 8th to 11th of May 1995 coastal plains of East Godavari district of Andhra Pradesh experienced an average rainfall of 330 mm due to a cyclonic storm over Bay of Bengal, whereas the monthly normal is 47 mm. Kakinada town recorded 342 mm of rainfall in 24 hours during this storm, which is more than the 50 year 24 hour storm precipitation for the region. Due to this storm streams in and around Kakinada flowing into Kakinada Bay experienced catastrophic floods, which exceeded their capacities causing breaches due to overtopping of banks thus resulting in inundation of vast expanses of deltaic plains. The same is the experience during heavy rainfall during every monsoon season and of the subsequent cyclone events of 1997, 2003 and 2005. As with flat coastal and deltaic plains, the excess water lead to inundation of low-lying areas (Fig. 3). As with flat coastal and deltaic plains, the excess water lead to inundation of low-lying areas.

Fig. 3. Some of the flooding scenes around Kakinada City in October 2005

Water Supply

The source of supply is the Godavari eastern delta canal system at Samarlakota of the Samarlakota canal and Aratlakatta of the Kakinada canal and is drawn through a pipe by gravity. The geographical area of this well planned Municipality is about 30.51 sq. km. and is bounded by Kakinada Bay on the East. Urbanisation is taking place at a fast rate into adjoining northern and western rural areas, which are fertile agricultural lands under Godavari delta canal system. The water works namely 'Victoria Water Works' of the town were commissioned in 1909. It slowly developed into a supply system having nearly 12000 domestic taps, 2000 street posts, which run with water for 2 to 3 hours in a day and are catered through elevated service reservoirs (ELSR) located in eight different areas of the town and a treatment plant of capacity of 4.7 MGPD (million gallons per day) which works round the clock. NIH (2000) presents the detailed description of the system.

Drainage

The roadside drainage including storm water drainage of Kakinada is an open one and typical of any Municipality in the Region. The smallest dimension of a first order drain of 0.3 X 0.3 m section is seen along the internal streets of any colony. Such drains join a medium drain of section 0.8 X 0.8 m at junction of important roads. Such drains increase to a size of 1.0 X 1.0 m depth large drains which join major drain of size1.6 X 1.6 m. These used to flow in low-lying areas and along railway track to join Salt creek, the natural drainage that enters the Kakinada bay. Now these are reconstructed with sections, which increase from a section of 2.0 X 2.0 m at inlet to 2.7 X 2.1 m at outlet. The outlet of Railway drain that falls into Salt Creek is shown in fig. The drainage area at outlet of the drain is about 2.575 sq. km i.e, 257.5 Ha. The drainage area is of 3 major land uses. In the upper parts it is 50% urbanized, in the middle it is 90 % urbanized and towards outlet it is 75% urbanized. The major drainage congestion occurs in the middle parts near Municipal Corporation office. Another major drain draining in the city is 'Cheedilapora' drain that joins the 'Gaderu' drain, which has catches agricultural drainage and surface runoff from the adjoining rural areas surrounding the city. The Gaderu also joins the Salt Creek on the west of city.

Data & Analysis

While undertaking the study various types of data like rainfall and groundwater of the Kakinada city are observed, as such short duration data is not readily available. The historical hourly rainfall data of IMD for important storms a period of 1976 to 1997 was analysed and shown in Table 1. The data from NIH Regional Centre's observatory being monitored from 1997 was also used (Fig. 4 and Fig. 5). The one, two and three hour rainfall from IMD, Kakinada was analysed and its graph plot is shown in Fig. 6. season wise daily rainfall and number of rainy days from 1996 to 2008 is shown in Fig. 7. Rain gauges were procured and installed at 7 locations in the city. As part of the network 2 tipping bucket loggers, 2 tipping digital rain gauges and 3 ORG's were established at 7 locations in the city with collaboration of Municipality and other authorities. The locations were Jagannaickpur, Ramaraopeta, Pratap Nagar, Chaitanya Nagar, Siddharth Nagar, Srinagar and Sambamurty Nagar (Fig. 2). The data has been recorded from July 2007 to November 2009. The data from 2 loggers located about 8 km apart in the study area provides not only storm movement but also its time distribution. The data obtained during monsoon season from loggers is unique and help measure every tip of rain and its occurrence. The data at two loggers recorded for the time of occurrence of each tip that measures a rainfall of 0.254 mm (0.01 inch). Such recorded data has been converted into one minute duration rainfall and the accumulated rainfall for 5, 10, 15, 30, 60 minutes duration is found during large storms. The daily observed data at other locations is used for distributing the rainfall into short duration rainfall at these gauges for respective storms. From such distributed short duration rainfall depth-area-duration (DAD) curves were plotted for peak storms of 21st September 2007 and 5th August 2008. Weekly rainfall at such locations is used to correlate the corresponding groundwater recharge at specified monitoring stations.

Groundwater Monitoring

Groundwater levels were observed from Open Wells at L B Nagar, Gaigolpadu, Madhura Nagar, Kondayyapalem, Gandhi Nagar, Main Road, Suryanarayanapuram, Jagannaickpur, Toorangi, Fragerpeta, Madhav Nagar and RR Nagar. Water levels were monitored weekly and fortnightly during monsoon and post monsoon periods respectively during 2007 and 2008.

5.0 ANALYSIS AND RESULTS

Hourly rainfall of Kakinada IMD site is analyzed for important storms from 1976 to 1996 and is shown in Table 1. The 1, 2, 3 hour rainfall in mm is 70, 120 and 135 mm respectively and is also shown in Fig. 6. Further, some more events were analyzed from SRRG Charts of DRC Observatory. 15-minute duration rainfall for an intense October 2005 event is analyzed from SRRG chart. The intensity of rainfall is about 200 mm/hour for about 15 minutes on 14th October 2005.

Table 1. Severe 1, 2, 3 hour rainfall in mm over different storms at Kakinada

Interval	Rainfall in mm	recorded rainfall in mm @
Max 3 hr	135.10	09/05/1995 19:00
Max 3 hr	124.80	14/07/1996 15:00
Max 2 hr	119.80	14/07/1996 15:00
Max 2 hr	96.60	09/05/1995 18:00
Max 3 hr	87.40	16/06/1996 08:00
Max 3 hr	86.20	10/05/1990 21:00
Max 3 hr	80.60	12/05/1979 13:00
Max 2 hr	78.00	08/05/1990 22:00
Max 3 hr	76.50	16/10/1987 01:00
Max 2 hr	76.40	16/10/1987 01:00
Max 1 hr	75.00	14/07/1996 14:00
Max 3 hr	73.20	20/11/1977 18:00
Max 3 hr	70.00	25/11/1979 14:00
Max 2 hr	68.40	20/11/1977 18:00
Max 2 hr	67.90	16/06/1996 08:00
Max 3 hr	66.90	02/11/1987 22:00
Max 2 hr	66.80	02/11/1987 22:00
Max 1 hr	66.70	08/05/1990 22:00
Max 3 hr	65.00	09/10/1995 05:00
Max 2 hr	59.70	12/05/1979 12:00
Max 2 hr	59.00	25/11/1979 14:00
Max 3 hr	55.60	04/11/1976 22:00
Max 2 hr	53.50	09/10/1995 05:00
Max 1 hr	51.90	02/11/1987 22:00
Max 1 hr	50.00	09/05/1995 04:00

Short duration rainfall

During the 2007, the events of 19th (21 mm of 15 min most intense rainfall), 21st September (150 mm of most accumulated rainfall) and of 23rd October (56 mm of 3 hours rainfall occurred at southern parts of the city only) are analyzed. The rainfall – intensity for different short durations of rainfall during 2007 to 2009 is carried out and the highest intensities observed at DRC station and APT station 6 Km away on 30th Aug 2009. Depth – Area –Duration analysis was also undertaken for most severe storms of 2007 i.e., of 21st Sep 2007; in 2008 i.e., of 5th Aug 2008 and in 2009 30th Aug 2009 in the city. The first storm lasted for about 10 hours; second one was for about 90 minutes. The storm in 2009 was most intense short duration storm and lasted only for 75 minutes.

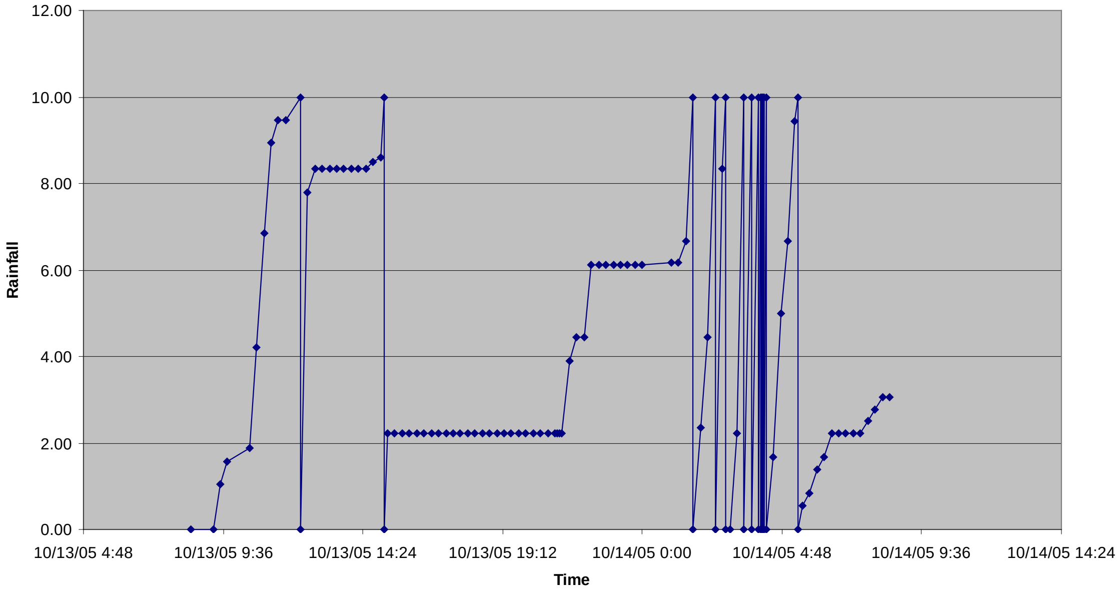


Fig. 4. Digitised SRRG chart for analysis

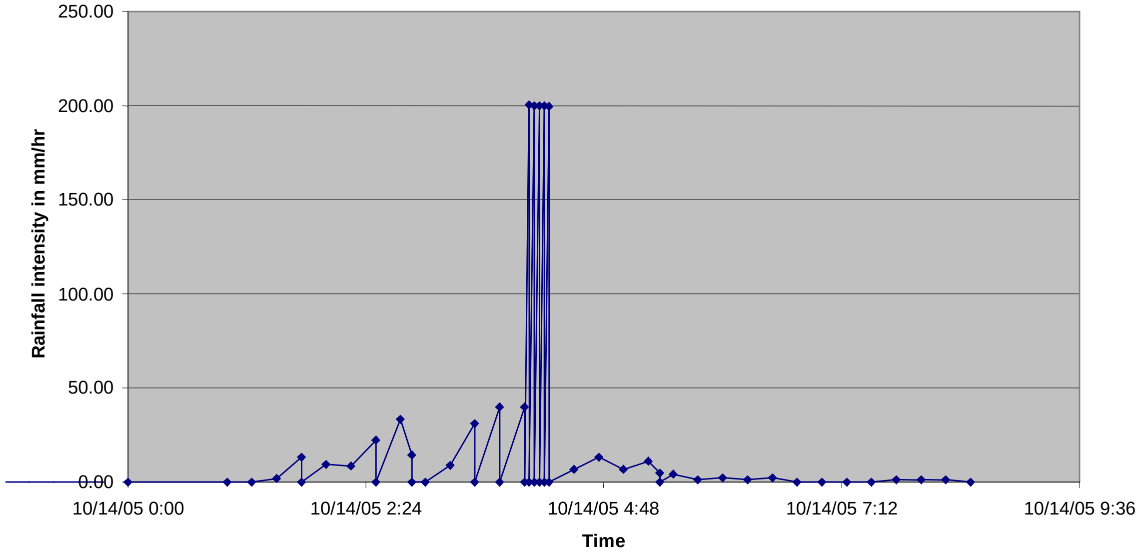
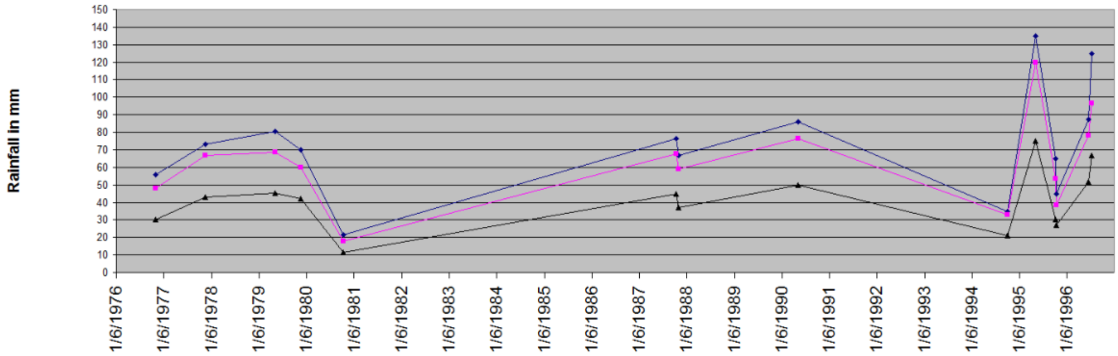


Fig. 5. Intensity of Rainfall during 14th October 2005

Fig.6 Plot showing 1, 2, 3 hour duration rainfall over storms of 1976 to 1996 at Kakinada



	5/9/1995 19:00	7/14/1996 15:00	6/16/1996 8:00	5/10/1990 21:00	5/12/1979 13:00	10/16/1987 1:00	11/20/1977 18:00	11/25/1979 14:00	11/2/1987 22:00	10/9/1995 5:00	11/4/1976 22:00	10/15/1995 14:00	10/4/1994 11:00	10/17/1980 17:00
in 3 hours	135.1	124.8	87.4	86.2	80.6	76.5	73.2	70	66.9	65	55.60	45	34.8	21.6
in 2 hours	119.8	96.6	78	76.4	68.4	67.9	66.8	59.7	59	53.5	47.90	38.4	33	17.8
in 1 hour	75	66.7	51.9	50	45.5	44.9	43	42.2	36.90	30.3	30	27	21	11.3

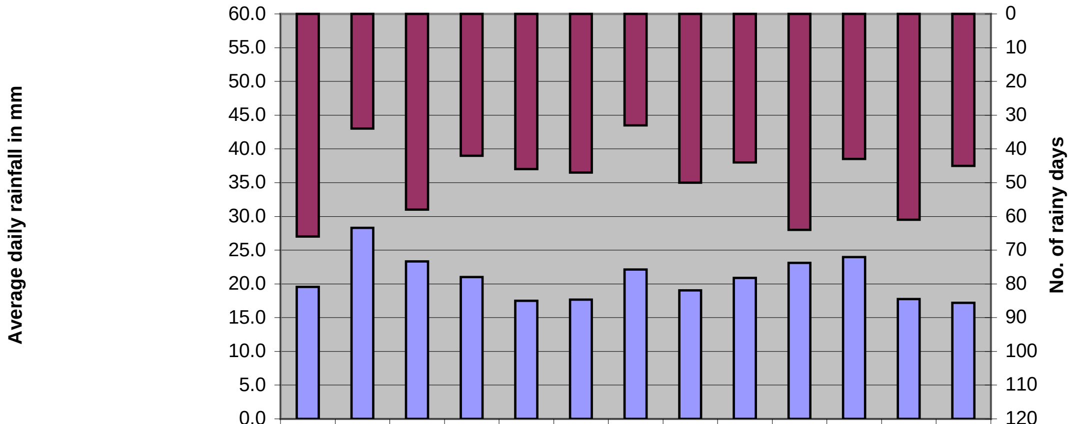
Storm date

in 3 hours in 2 hours in 1 hour

Short duration rainfall analysis

The five-minute duration rainfall for 21st Sep 2007 storm is shown in Fig. 8. The maximum rainfall intensity for above duration during different storms are compiled and plotted as intensity duration curves. The intensities of maximum rainfall recorded over one to 60 minutes duration storms is shown in Fig. 9. The 15-minute duration rainfall observed is about 50 mm at Kakinada on 13th October 2005 and it is the most intense 15-minute rainfall, measuring about 20 cm/hour, so far observed. During the

Fig. 7. Average daily rainfall and rainy days at Kakinada from 1996 to 2008



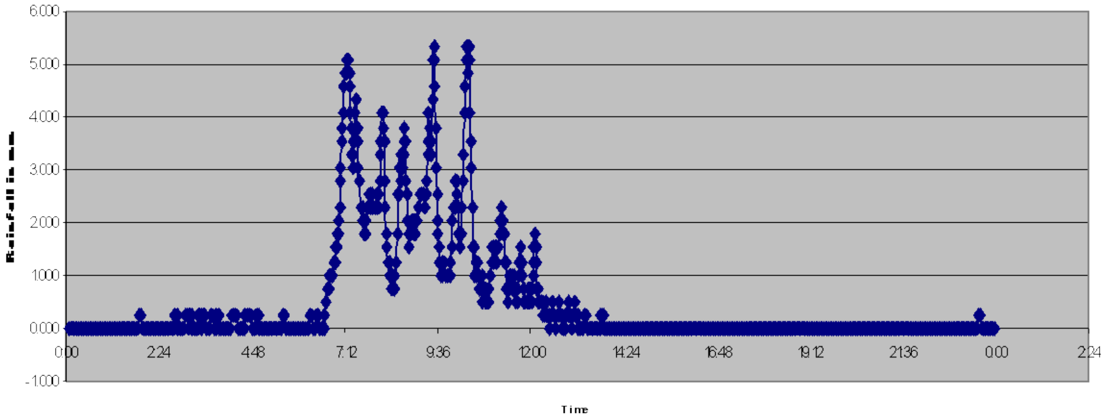
	June-Oct-96	June-Oct-97	June-Oct-98	June-Oct-99	June-Oct-00	June-Oct-01	June-Oct-02	June-Oct-03	June-Oct-04	June-Oct-05	June-Oct-06	June-Oct-07	June-Oct-08
Average daily rain in mm	19.5	28.3	23.3	21.0	17.5	17.7	22.1	19.0	20.9	23.1	24.0	17.7	17.2
No. of rainy days	66	34	58	42	46	47	33	50	44	64	43	61	45

Period

Average daily rain in mm No. of rainy days

2007, the events of 19th (21 mm of 15 min most intense rainfall), 21st September (150 mm of most accumulated rainfall) and of 23rd October (56 mm of 3 hours rainfall occurred at southern parts of the city only) are analyzed.

Fig. 8. Five Minute Cumulative Rainfall in mm during Storm of 21st September 2007



The heaviest intensity of rainfall observed in the study area for 1, 5, 10, 15, 30, 60 minutes duration in 2007 is 13.72, 11.28, 10.52, 8.33, 7.37, 4.88 and in 2008 it is 15.24, 11.58, 9.14, 7.72, 6.55, 4.57 cm/hour respectively. The heaviest intensity of rainfall observed in the study area for 1, 5, 10, 15, 30, 60 minutes duration in 2007 is 13.72, 11.28, 10.52, 8.33, 7.37, 4.88 and in 2008 it is 15.24, 11.58, 9.14, 7.72, 6.55, 4.57 cm/hour respectively. The maximum 1, 5, 10, 15, 30, 60 minute rainfall intensity recorded up to 2009 was during 30th Aug 2009 and is the most intense storms at Kakinada is 25.91, 20.73, 18.29, 16.76, 11.53 and 6.63 cm/hour. The maximum 1 to 60 minutes duration rainfall observed at Kakinada during 2007 to 2009 is shown in Table 2. The intensities of the same are shown in Table 3. Analysis of less rainy events indicated that rainfall intensity of 1 (0.25 mm) to 2 tips (0.5 mm) in 15 minutes might initiate runoff from RCC surfaces depending on the diurnal and seasonal effects while designing roof water harvesting.

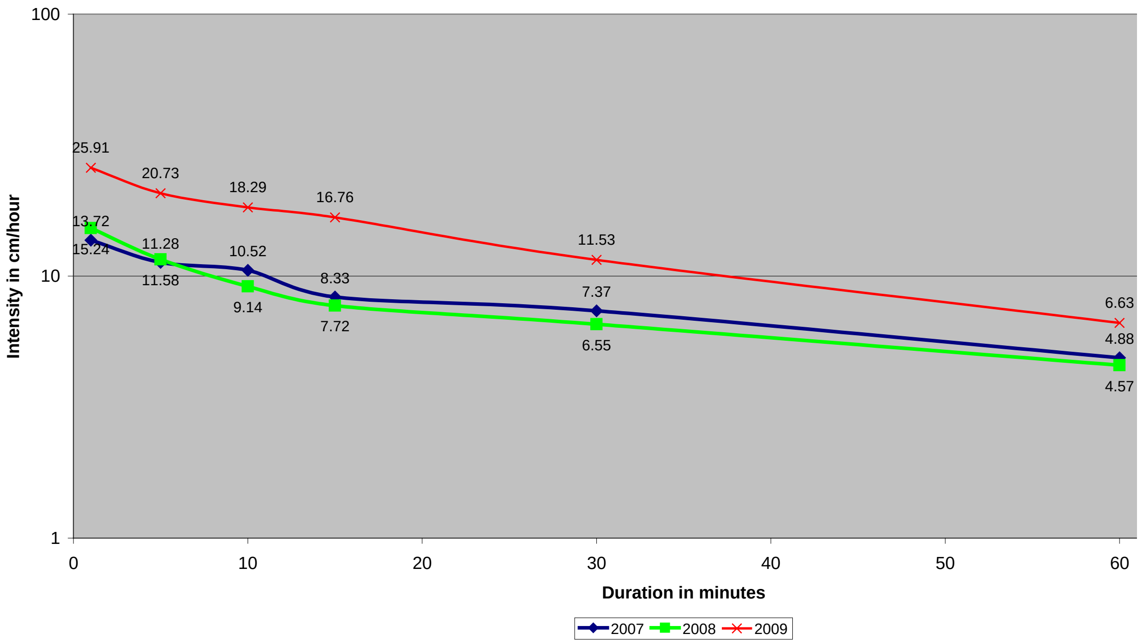
Table 2. Annual maximum rainfall for different short durations in 2007 and 2009 at Kakinada
(Duration in Minutes; Rainfall in mm)

Duration	2007	2008	2009
1	2.29	2.54	4.32
5	9.40	9.65	17.27
10	17.53	15.23	30.48
15	20.83	19.30	41.91
30	36.85	32.75	57.66
60	48.80	45.70	66.29

Table 3. Annual maximum rainfall intensity for different short durations in 2007 and 2009 at Kakinada
(Duration in Minutes; Rainfall intensity in cm/hr)

Duration	2007	2008	2009
1	13.72	15.24	25.908
5	11.28	11.58	20.7264
10	10.52	9.14	18.288
15	8.33	7.72	16.764
30	7.37	6.55	11.5316
60	4.88	4.57	6.6294

Fig. 9. Intensity - Duration curve for short duaration rainfall of peak storms from 2007 to 2009 in Kakinada City



The rainfall – intensity for different short duration rainfall during 2007 and 2009 and the maximum of both years are shown as graph plot at Fig.9. Depth – Area –Duration analysis was also undertaken for most severe storms of 2007 i.e., of 21st Sep 2007 and 2008 i.e., of 5th Aug 2008 in the city. The first storm lasted for about 10 hours and the second one was fort about 90 minutes. The daily observed rainfall data at six other locations in the city is converted into short duration using the short duration rainfall data from 2 digital loggers installed at NIH and APT. The spatial plots for each duration of the storm from 1, 5, 10, 15, 30 and 60-minute rainfall are plotted using the short duration rainfall calculated at eight locations in the city. Such spatial plots for 1,5,10,15,30 minutes and 1 hour duration rainfall for the storms of 2008 and 2009 are shown from Fig.10 to Fig 21 respectively. From these plots, the areas for rainfall depth isohyets are measured using digital planimeter. The DAD plot arrived at for the storm of 5th August 2008 is shown in Fig. 22. The same is also shown in tabular format at Table 4. From the DAD plots, the area of core of storm centre was 37.7 Ha for 30 minutes duration with rainfall of about 26 mm in the middle parts of the city during the storm of 2008 which was of about 90 minutes duration.

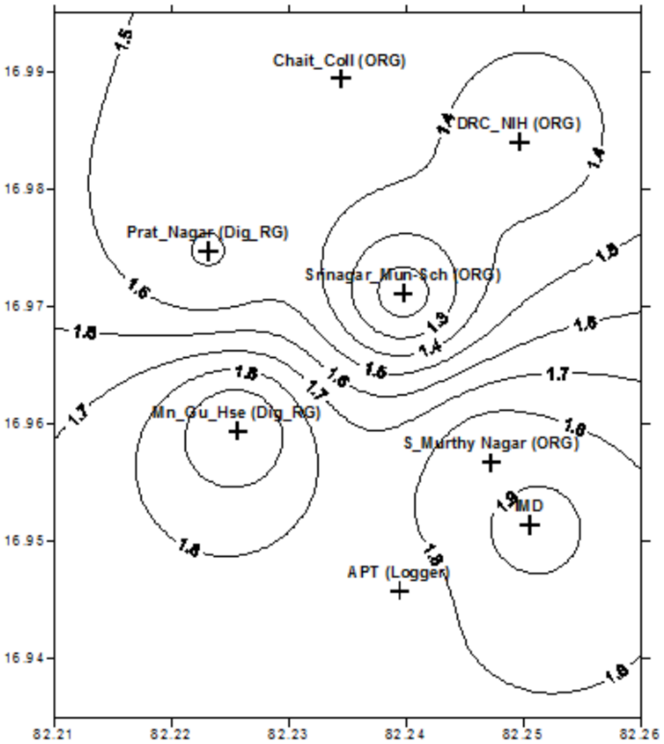


Fig. 10. One minute Rainfall of storm on 21st Sep 2007 around Kakinada and surrounding area

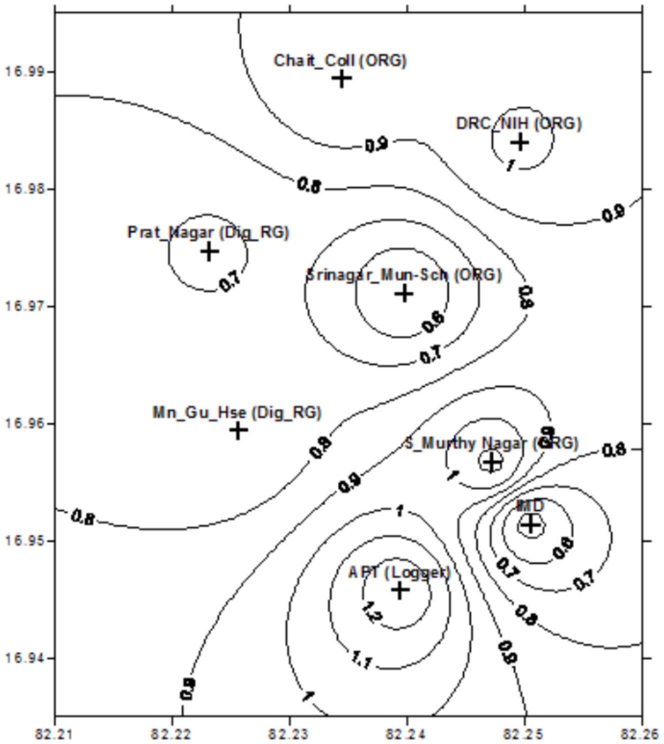


Fig. 11. One minute Rainfall of storm on 5 Aug 2008 around Kakinada and surrounding area

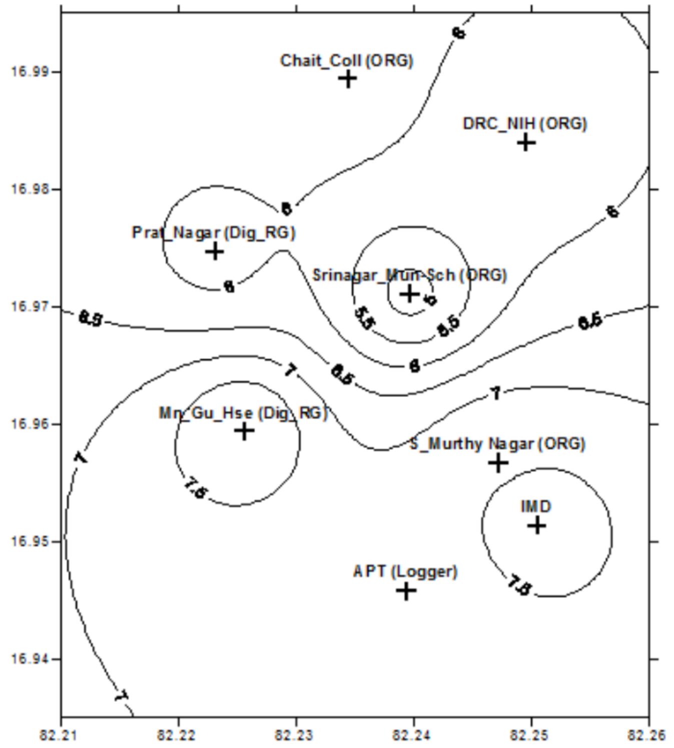


Fig. 12. Five minute Rainfall of storm on 21st Sep 2007 around Kakinada and surrounding area

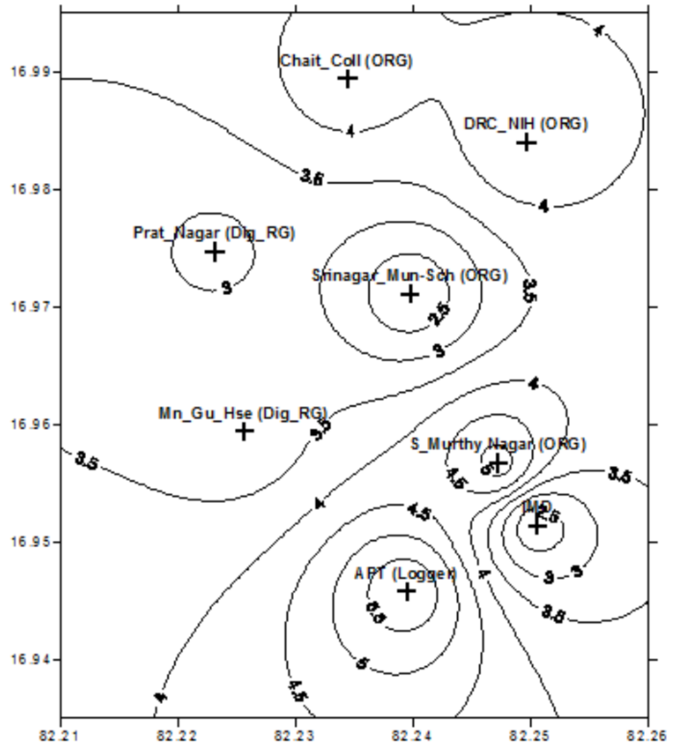


Fig. 13. Five minute Rainfall of storm on 5 Aug 2008 around Kakinada and surrounding area

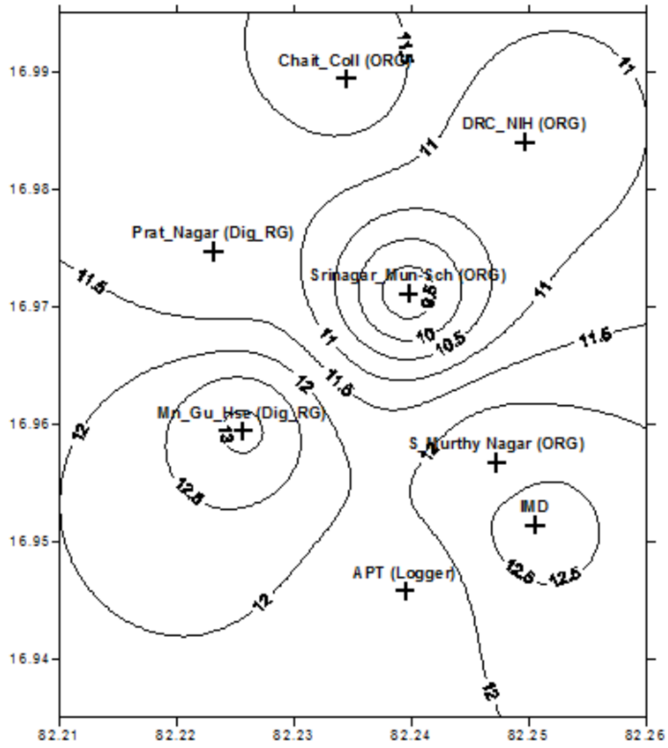


Fig. 14. Ten minute Rainfall of storm on 21st Sep 2007 around Kakinada and surrounding area

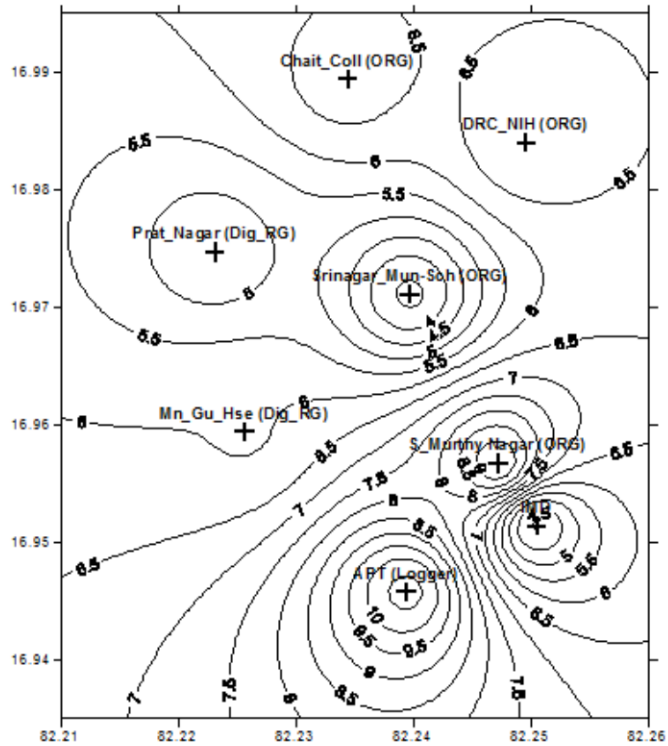


Fig. 15. Ten minute Rainfall of storm on 5 Aug 2008 around Kakinada and surrounding area

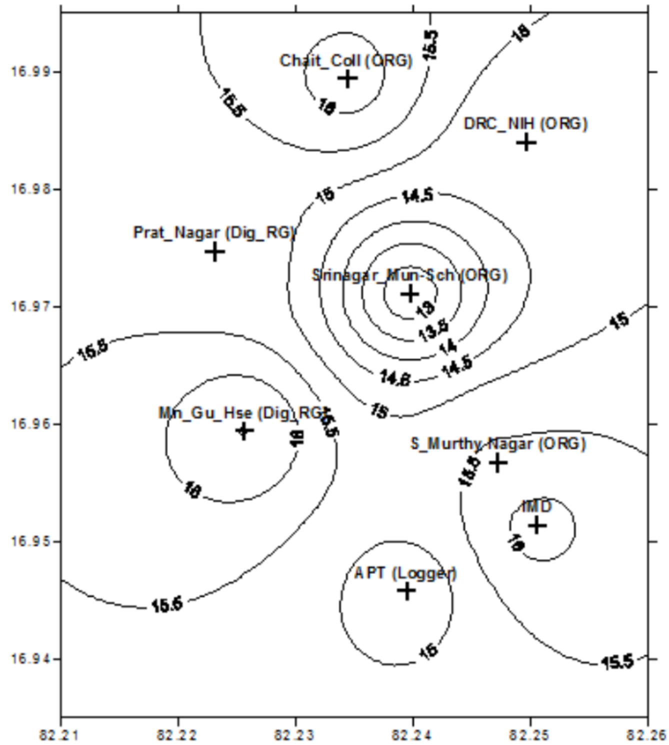


Fig. 16. Fifteen minute Rainfall of storm on 21st Sep 2007 around Kakinada and surrounding area

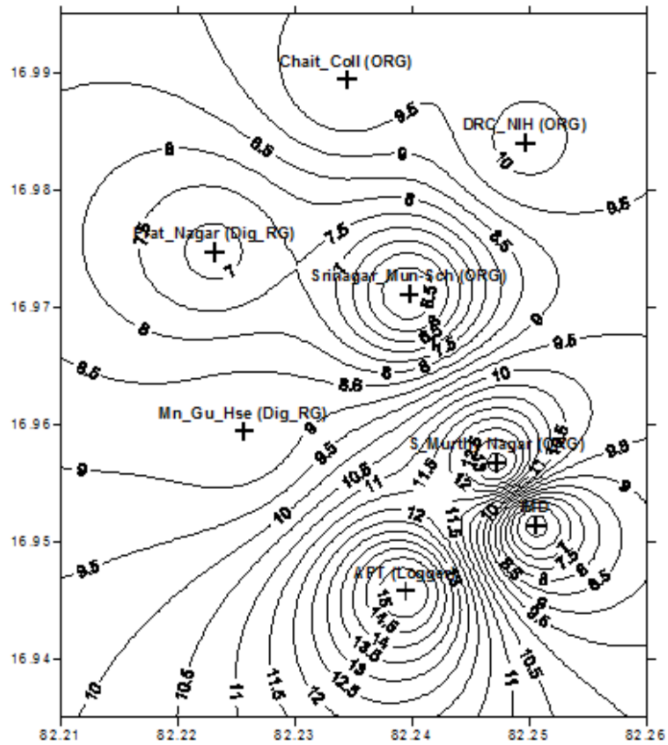


Fig. 17. Fifteen minute Rainfall of storm on 5 Aug 2008 around Kakinada and surrounding area

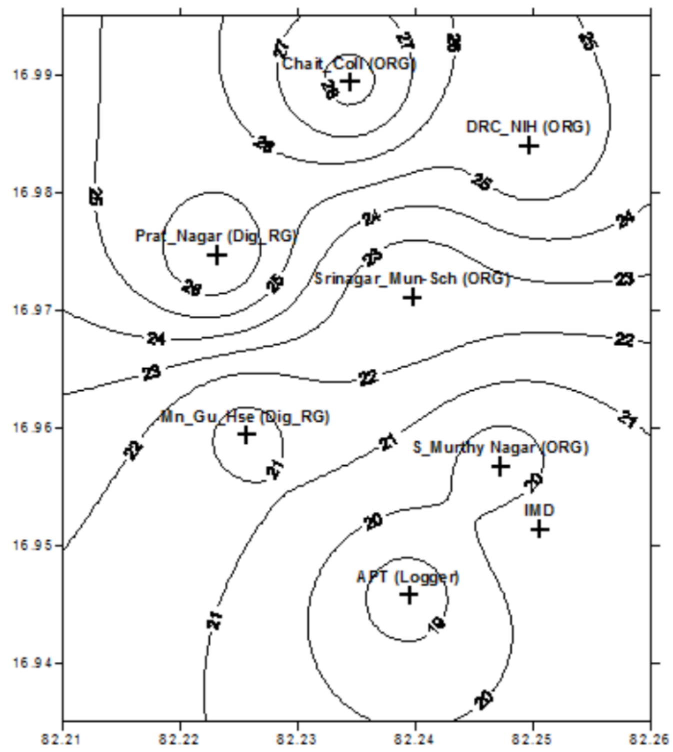


Fig. 18. Thirty minute Rainfall of storm on 21st Sep 2007 around Kakinada and surrounding area

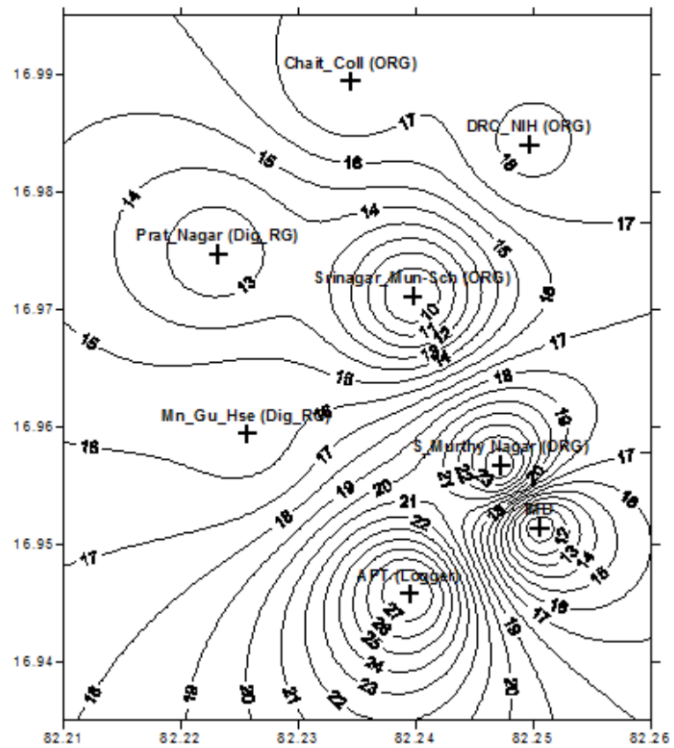


Fig. 19. Thirty minute Rainfall of storm on 5 Aug 2008 around Kakinada and surrounding area

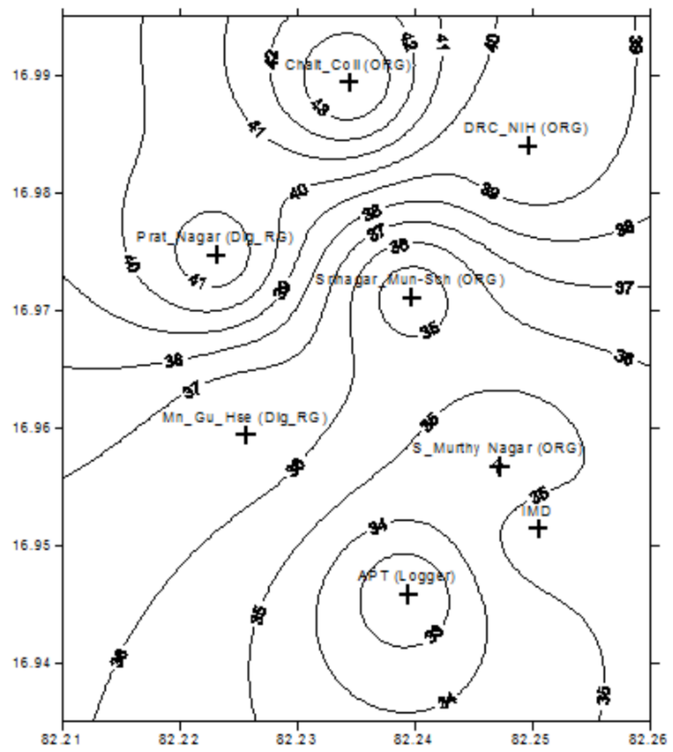


Fig. 20. One hour Rainfall of storm on 21st Sep 2007 around Kakinada and surrounding area

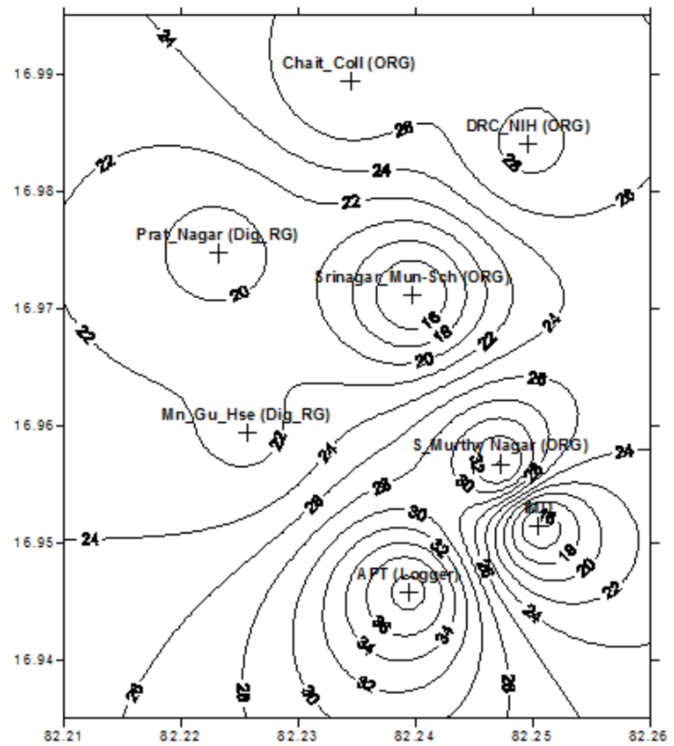


Fig. 21. One hour Rainfall of storm on 5 Aug 2008 around Kakinada and surrounding area

Downloading of rainfall data from digital raingauge using data shuttle is shown in Fig. 23. From the studies on short duration rainfall taken up and explained above, it is observed that that during the intense storm of 30th Aug 2009 an intense rainfall of 20 cm/hr over 5 minutes; 16.5 cm/hr over 15 minutes; 11.5 cm/hr over 30 minutes durations occurred in the city. Also, it is noticed that rainfall intensities were higher for storms of lower durations during the study period, may be a phenomena of climate change effect. 2009 is a deficit rainfall year of recent decades.

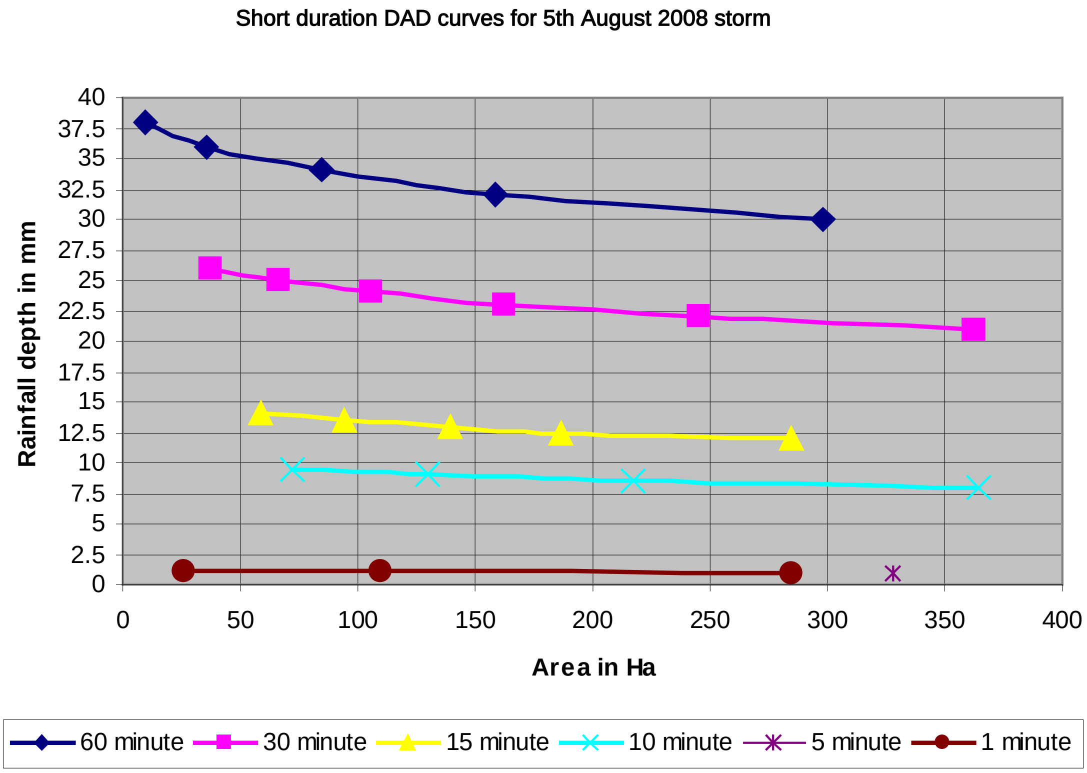
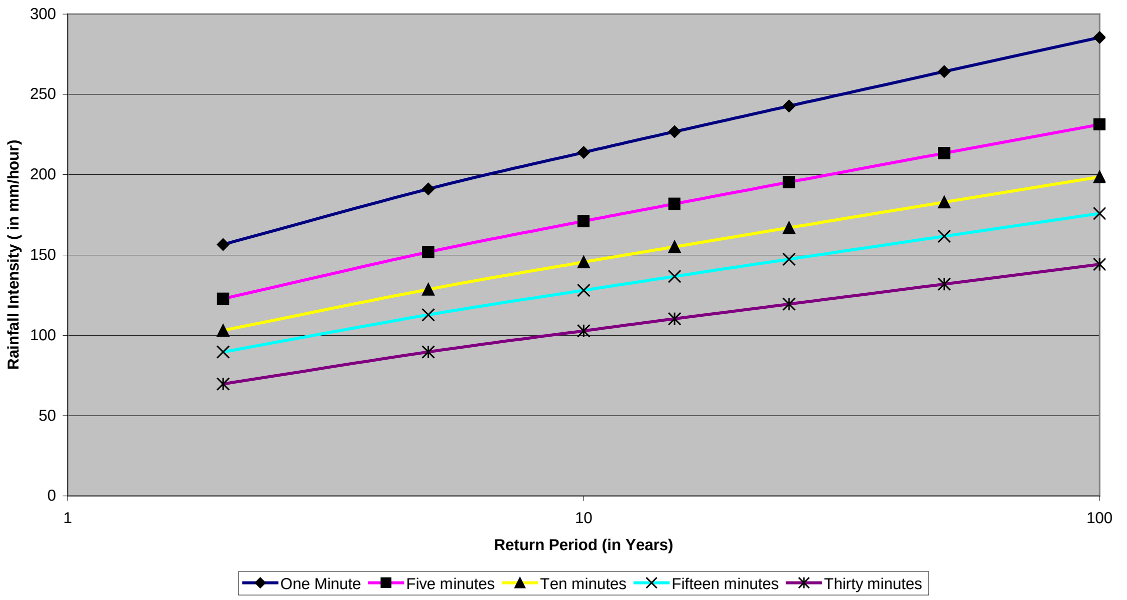


Fig. 22. Short duration DAD Curves for 5th August 2008 storm

Table 4. Depth - Area - Duration for 5th August 2008 storm at Kakinada		
Duration in Minutes	**Rainfall depth in mm**	**Area in Ha**
1		
	1	284.7981
	1.1	109.3926
	1.2	26.4051
5		
	4.5	328.1779
	5	116.9370
	5.5	30.1773
10		
	8	364.0134
	8.5	216.8992
	9	130.1395
	9.5	71.6710
15		
	12	284.7981
	12.5	186.7219
	13	139.5699
	13.5	94.3040
	14	58.4685
30		
	21	362.1274
	22	245.1904
	23	162.2029
	24	105.6205
	25	66.0128
	26	37.7216
60		
	30	298.0006
	32	158.4307
	34	84.8736
	36	35.8355
	38	9.4304

Fig. 23.
Down loading data through shuttle from Digital rain gauge

Fig 24. **Intensity duration frequency (IDF) relationship for one to thirty minutes duration rainfall at DRC, Kakinada**



The intensity duration frequency relationship is derived from only 3 years of observed data using partial duration series (PDS) from about 40 events using peak over threshold (POT) model at 2 locations for short duration rainfall event of 1 to 30 minutes. The same is plotted and is shown at Fig. 24. Such relationships are useful in design of urban infrastructure and roof water harvesting structures with return period of 2 to 100 years.

Rainfall vs. Groundwater recharge

On 21st September 2007, the city witnessed a severe storm and some of the scenes of inundated area are shown in Fig. 25. To understand the rainfall recharge characteristics of urban area, groundwater monitoring is undertaken for water levels and quality at 12 locations in the city (Fig. 26). Groundwater levels were collected every week during the monsoon season. The samples are also collected to know the variation of its EC and pH. Weekly rainfall are correlated with rise in groundwater table and it is observed that groundwater levels reacted very quickly for most rainy events in highly urbanized and discharge areas. The maximum depth to groundwater table during the study period is shown in Fig. 27 and from the same, it is observed that the groundwater table is falling at some places gradually over the last three years in this city. The groundwater level plot of the study area for pre and post monsoon 2007 is shown in Fig. 30. The groundwater table is at a depth of 1.5 to 3.5 m during pre monsoon and rise to 1 to 2 m by post monsoon.

Rainfall recharge

The weekly rainfall for September 3rd week of 2007, is shown as spatial plot in Fig. 28. The weekly rainfall for different storms of 2007 is shown as graph plot in Fig. 29. From this it can be noticed that September 21st storm has resulted in a weekly rainfall of 200 to 300 mm in the city. The wells located at discharge locations like Suryannarayanapuram, Jagannaickpur, Toorangi and close to drains like LB Nagar, RR Nagar and those located at highly urban areas like Surya Rao peta (main Road) are responding quickly to heavy precipitation and recording high water tables immediately. The wells located at elevated areas like Madhva Nagar, Gandhi Nagar, Rajendra Nagar, Frazer peta, Madhura Nagar and Dwaraka Nagar are responding gradually to rainy events.

Fig. 25.
A view of inundation of flood water (21st Sep 2007) in Kakinada.

Right: Tilak street

Below: Cinema road near Municipal complex

Fig. 26. Monitoring GW levels after a storm of September 2007

Fig. 27. Maximum DTW of all wells monitored at Kakinada

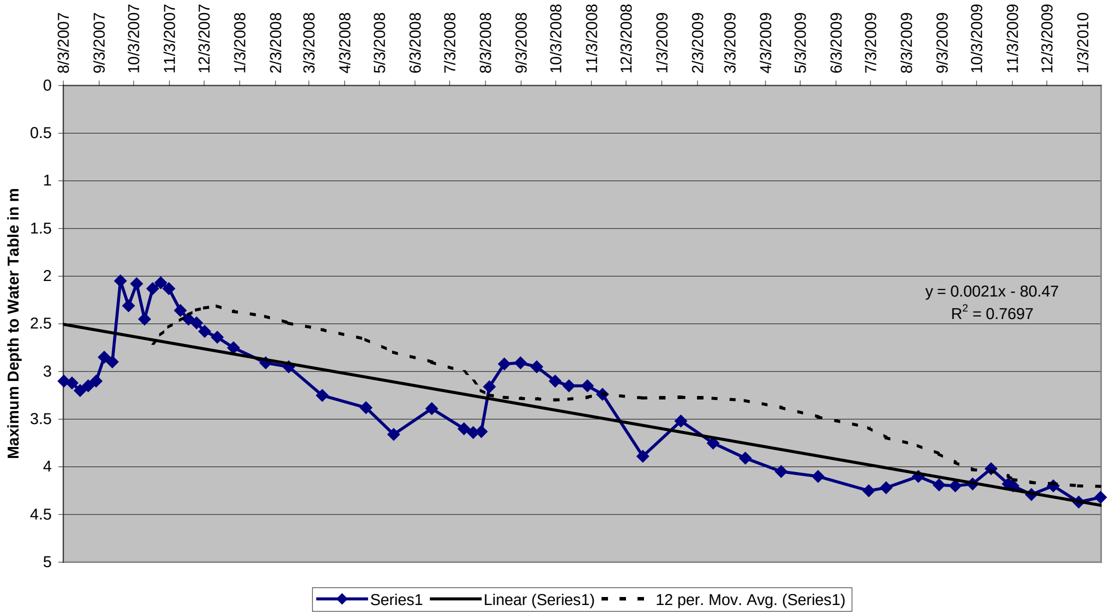


Fig. 28. Spatial plot of weekly rainfall at different stations in mm in Kakinada during 3rd Week of September 2007

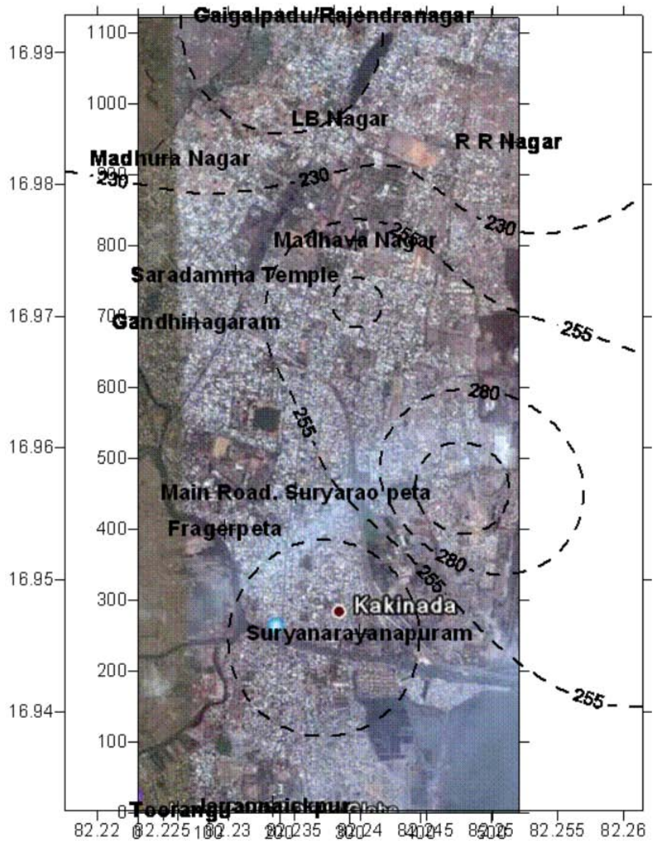


Fig. 29. **Nth largest weekly rainfall at different locations in Kakinada city during monsoon of 2007**

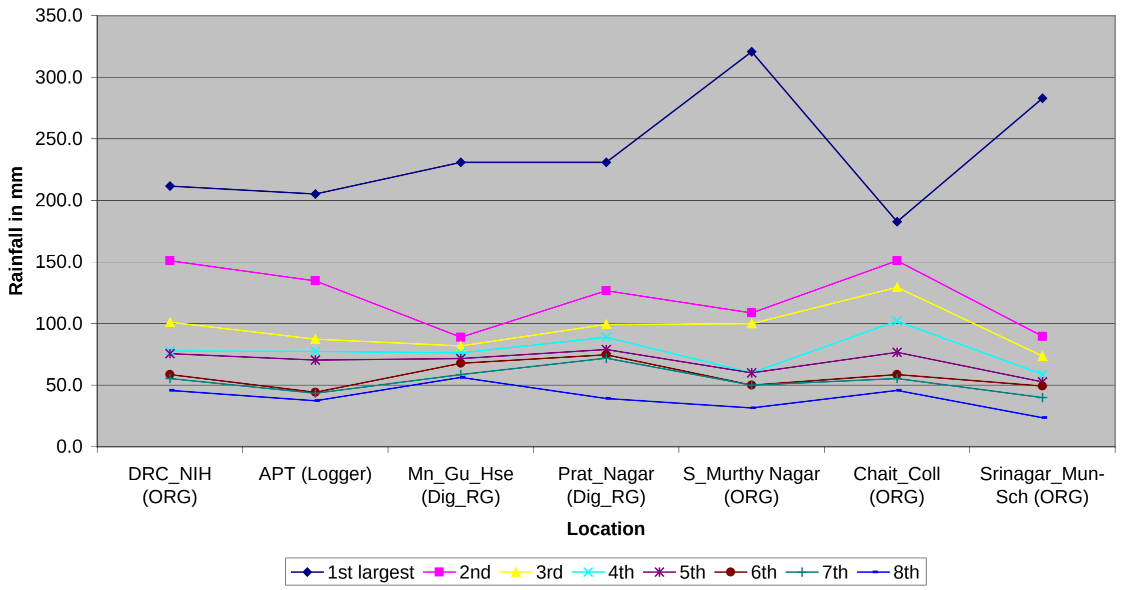


Fig. 30. Groundwater level w r t MSL in m in Kakinada in 2007

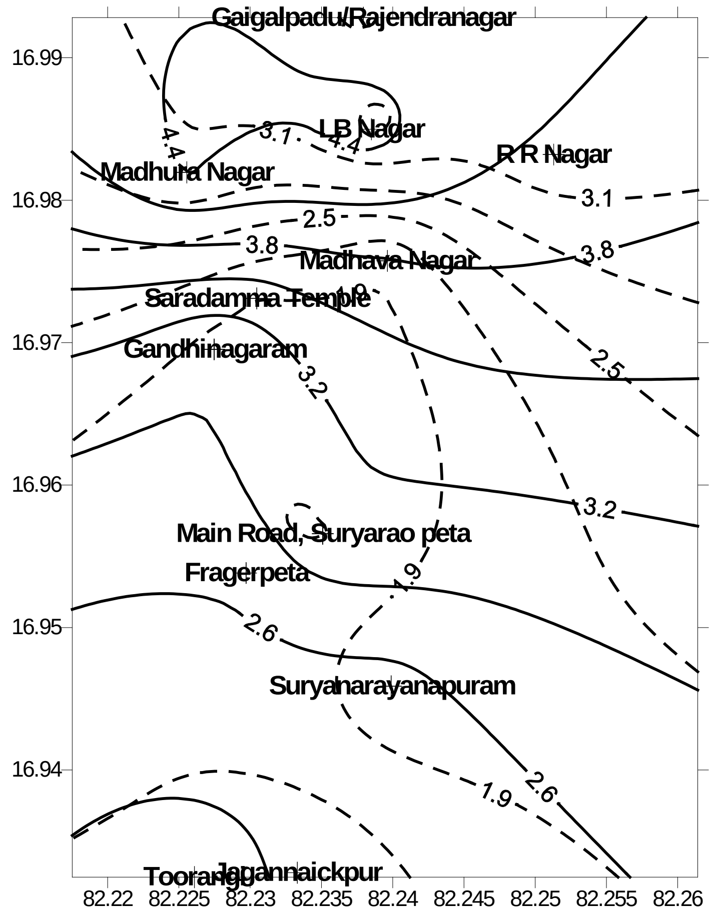
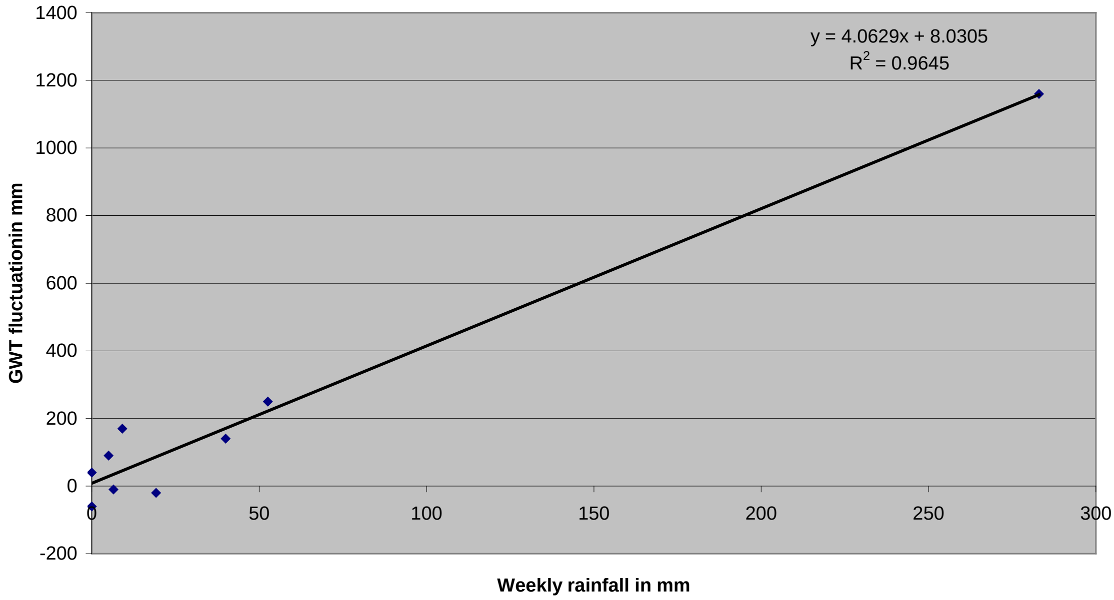


Fig. 31. Fluctuation of GWT at Madhava Nagar w r t rainfall at Srinagar school



The weekly fluctuation of groundwater table at Madhava Nagar with respect to corresponding rainfall is shown as a rainfall vs. groundwater fluctuation plot in Fig. 31. It is observed that at Madhava Nagar, which is adjoining good recharge area like JNTU campus and Medical college sports grounds extending up to district sports authority campus experience a rise of 1.2 m for every 300 mm of uniform rainfall under wet conditions indicating a storage coefficient of 25%, which is a standard for alluvial aquifers.

The Depth to groundwater table for October 07 (post monsoon 07) and April 08 (pre monsoon 08) and Sep 08(Post monsoon 08) is studied and presented as contour plots in Fig. 32. The EC of groundwater in October 07 (post monsoon 07) and April 08 (pre monsoon 08) and Sep 08(Post monsoon 08) is contour plotted is shown in Fig. 33. This indicates that influence of the impact of seasonal recharge in areas north, Central and eastern parts of the city. The seasonal change in EC of groundwater in the city is shown in Fig. 34. The change in EC of non-monsoon season of 2007-08 and monsoon season of 2008-09 indicates the influence of the impact of seasonal rainfall recharge. It is observed that the less rainfall of 2008 has resulted in large EC of groundwater during post-monsoon of 2008 in the eastern half of the city and is very high compared to the EC of Post monsoon of 2007.

Fig. 32. Variation in depth to Groundwater table in m in Kakinada city in Oct 07, Apr 08 and Sep 08

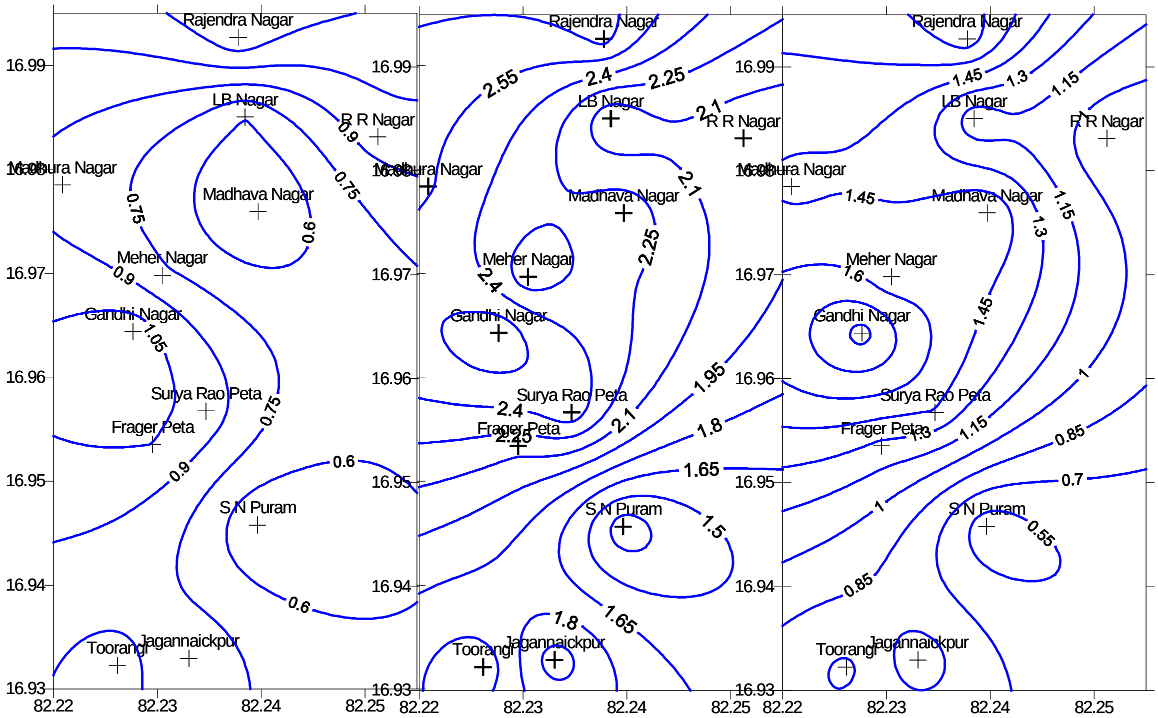


Fig. 33. **Variation of EC in Oct-07, May-08 and Sep-08**

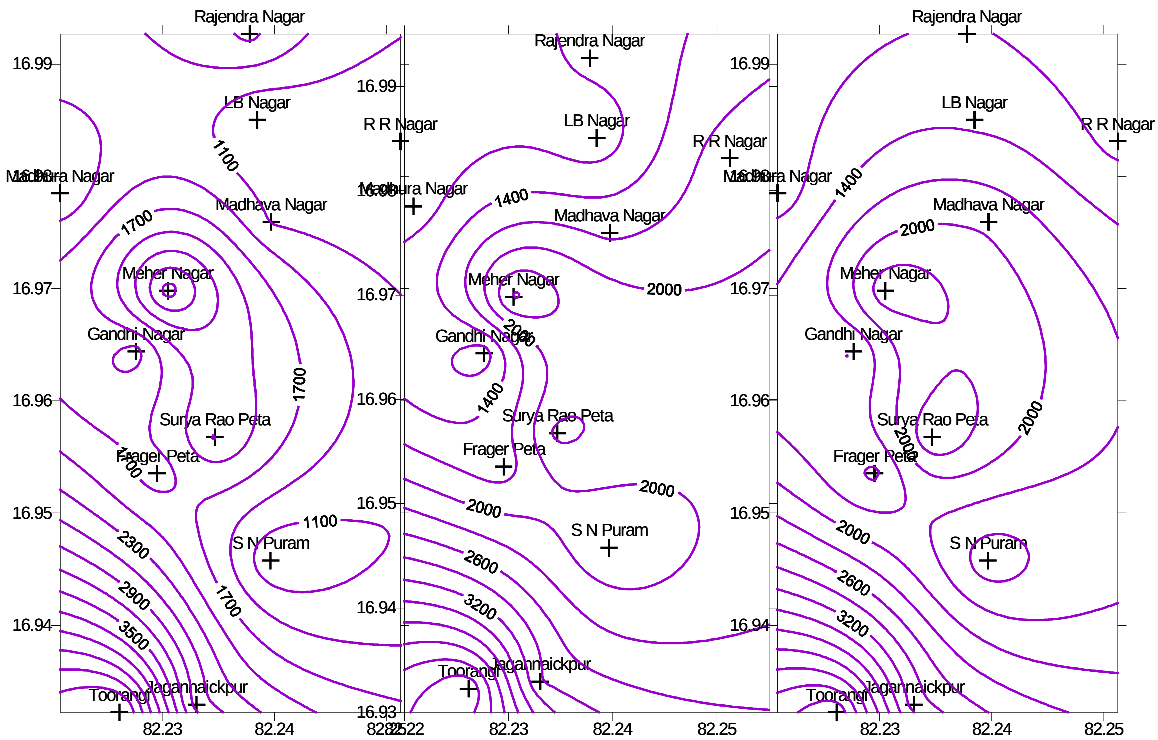
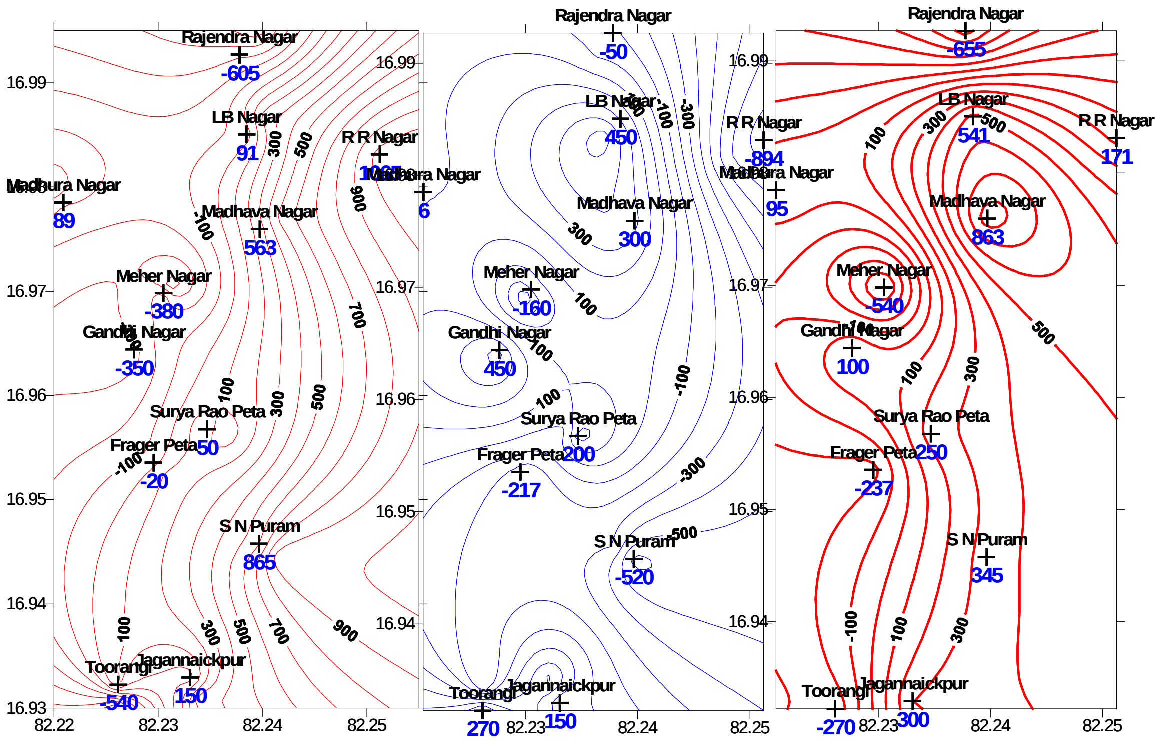


Fig. 34. Seasonal change in EC Oct 07 to Apr 08, Apr 08 to Sep 08 and Oct 07 to Sep 08



The seasonal fall in depth to groundwater table from 2007 to 2009 is shown in Fig. 35. The change in depth to groundwater table with respect to daily rainfall during 2007 is shown in Fig. 36. The damage caused to raingauge by miscreants at Srinagar observatory is shown in Fig. 37. In areas like Gandhi Nagar, Madhra Nagar, Meher Nagar and Frazer pet on the west, north- west of city where groundwater is potable the groundwater table has dried up and the situation is alarming. During the Laila cyclonic storm in third week of May 2010 a rainfall of 6 inches (150 mm) helped in rise of groundwater table by 12 to 15 inches. There is need to rejuvenate such aquifers using artificial recharge techniques to supplement the decreasing natural rainfall recharge using roofwater harvesting for sustainable development of the water resources in the city.

Fig. 35. Fall of Groundwater table from post monsoon to pre-monsoon during 2007-2009 in Kakinada

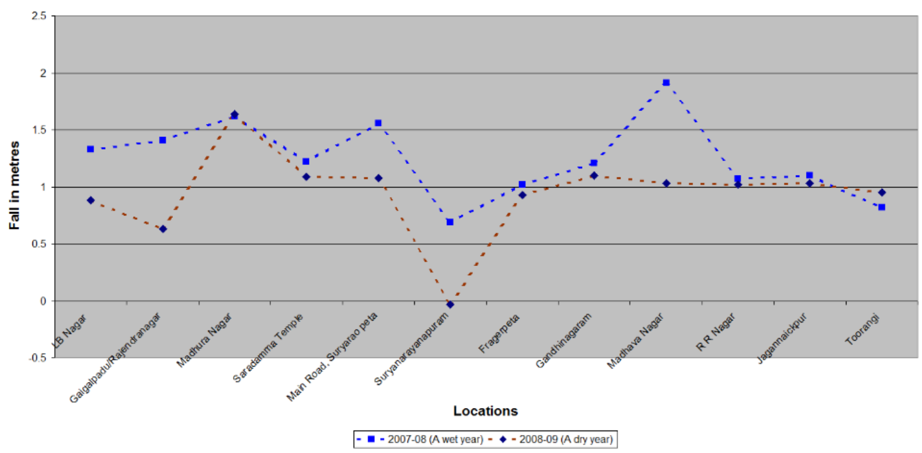


Fig. 36. Rainfall and Depth to GWT at observation wells in Kakinada during 2007

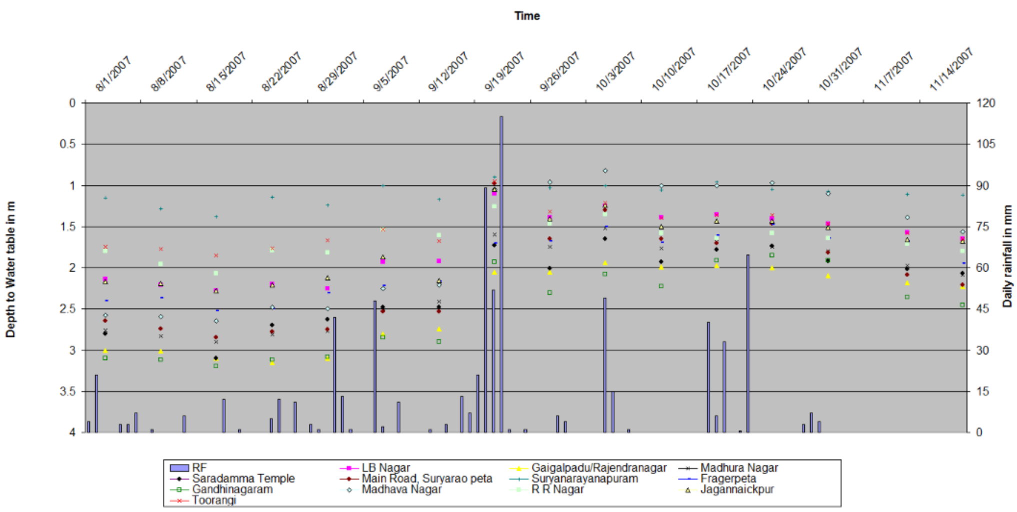


Fig. 37. Damage to ORG at Srinagar Municipal School by miscreants

Fig. 38. Outlet of Rly. drain joining the Salt creek

Fig. 39. A view of Budampeta Railway drain

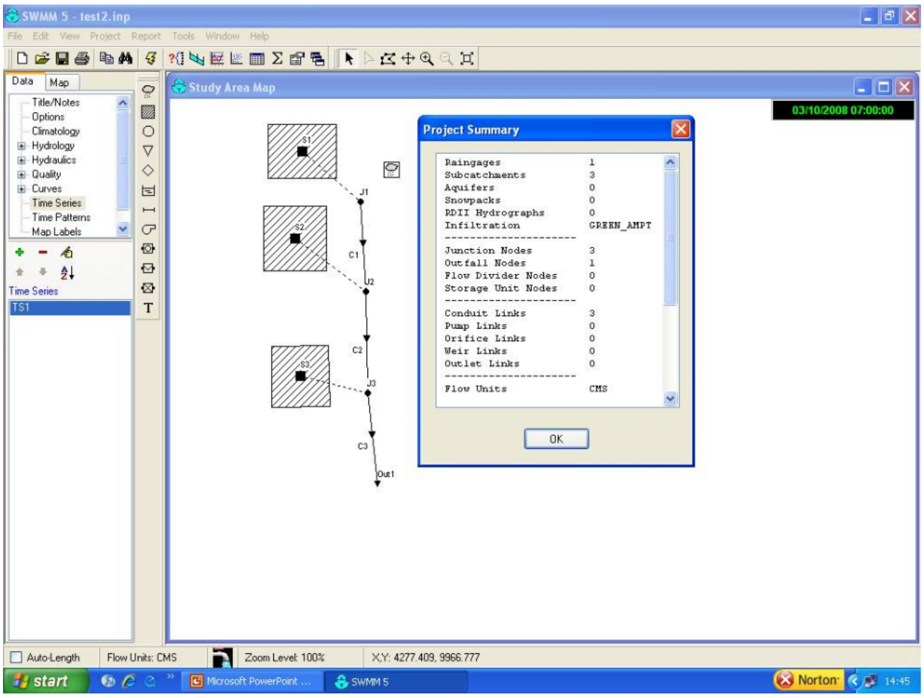


Fig. 40. Conceptualised Drains for SWMM 5 for Kakinada City

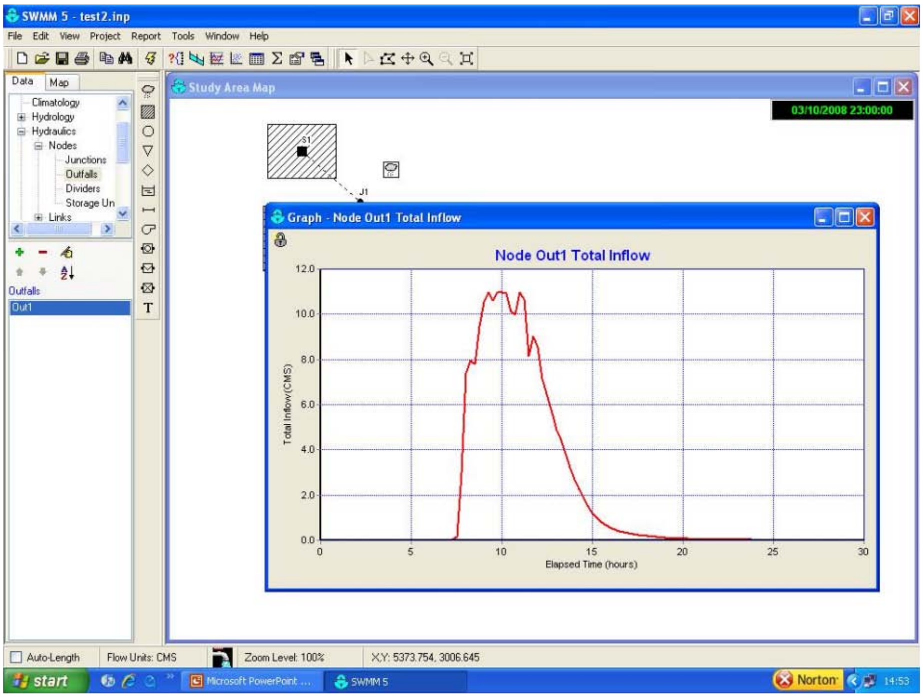


Fig. 41. Simulated runoff at railway drain during for 21st Sep 2007 storm

Application of SWMM model

SWMM is a useful conceptual rainfall runoff model for use in simulating runoff from urban watersheds. On 21st September 2007, the city witnessed a severe storm and some of the scenes of inundated area are shown in Fig. 25. In the study rainfall and runoff process is simulated for this event for the Railway Drain, a major drain having watershed area completely urbanized and explained in detail in previous sections. The aerial view of the railway drain and its sectional views middle and outlet is shown in Fig. 38 and 39. The conceptual structure of the model and sub-catchments of the watershed is shown in Fig. 40. The simulated hydrograph is shown in Fig. 41. The simulation resulted in a peak discharge of about 11 cumecs in just 90 minutes of time to peak, which is, much more than the design discharge capacity of the drain. The overflowing water added to drainage congestion of inlets has caused inundation of large commercial area in the city including Municipal corporation complex, Main Road, Cinema Road. Photos of the some of the inundated areas are shown is shown at fig. no. Such simulations help in analyzing the urban runoff and in proper design of relevant infrastructure.

6.0 CONCLUSIONS

In this study rain gauges were procured and installed at 7 locations in the city with collaboration of Municipality and other authorities. As part of the network 2 digital rain gauges with tipping bucket and logger, 2 tipping digital rain gauges with tipping bucket and display of cumulative rainfall and 3 ORG's were established at 7 locations in the city. The rainfall – intensity for different short durations of rainfall during 2007 to 2009 is analysed in this study. Groundwater is monitored at 12 locations for its level and quality in the city and to understand its relationship with rainfall. Depth – Area –Duration analysis was also undertaken for most severe storms by plotting DAD curves for storms of 5 to 30 minute duration. The intensity duration frequency relationship is derived from only 3 years of observed data using partial duration series (PDS) from about 40 events using peak over threshold (POT) model at 2 locations for short duration rainfall event of 1 to 30 minutes. Such relationships are useful in hydrological design of urban infrastructure and roof water harvesting structures that require a 2 to 100 years return period rainfall as input.

7.0 REFERENCES

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