Jalvigyan Sameeksha, Vol. 13, No. 1-2, 1998

REMOTE SENSING IN URBAN HYDROLOGY

S.K. JAIN, S.K. MISHRA and K.S. RAMASASTRI
National Institute of Hydrology, Roorkee, Uttar Pradesh

Abstract *The use of remote sensing in studies related to urban hydrology has been widely recognized since the inception of these techniques, particularly in the last two decades, which have seen tremendous urbanization globally. As a result, a bulk of literature is available on the subject. This paper provides in brief a gist of the current applications of remote sensing in urban hydrology, particularly in Indian context, and addresses a range of issues related to urban hydrological systems with a greater emphasis on determination of impervious areas and runoff volumes and rates.*

INTRODUCTION

About one-fourth of India's population living in towns/cities is designated as 'urban'. However, none of the large cities in India, which are among the 100 largest cities of the world, is adequately provided with basic amenities (Manmen, 1991). Since urban settlements pose several problems to planners, managers, environmentalists, its planning requires an adequate knowledge about the location and extent of various categories of land utilization over space and in time. Conventional surveys are expensive and time consuming and by the time the survey is completed, there is a considerable change in the utilization of land, and therefore is of little use. Aerial photographs, on the other hand, are viable alternative in mapping the urban land use/land cover changes. These photographs, however, fail to provide necessary information about the ongoing developments in time for several known/unknown reasons. The remotely sensed data from space-borne sensors are most relevant, perhaps the cheapest means of acquiring information in near real time about urban land use/land cover with reasonable accuracy. The added advantages include the provision of synoptic view, repetitive coverage, and digital data amenable to computer analyses besides creation of Geomorphological Information System (GIS) database to incorporate new information from time to time.

REMOTE SENSING

Remote sensing techniques provide the land cover and land use information. Over the years, the satellite (remote sensing) sensors have significantly improved in spectral and spatial resolution. The repetitive nature of satellite remote sensing has always been handy to monitor temporal phenomena for change detection. The mapping by using conventional technique has its own advantages. But the information derived from remote sensing suffices for many hydrological applications. For example, the land use maps derived from satellite imageries are widely used in determination of the direct runoff from a catchment.

Many satellites e.g. Landsat, SPOT, IRS satellite series have sensors on boards operating in these remote sensing windows. These sensors acquire digital data in multispectral mode and these data are available for digital processing, and also displayed or hard copy of the data can be prepared in color mode by combining three spectral channels. In standard False Color Composites (FCC) of these data, many objects are easily identifiable. For example, water, vegetation, urban area, fallow/ barren areas, sand have black to blue, red, cyan, green/ yellow/ dark/ white/ cyan and white colors, respectively. Linear features e.g. roads, rail, canals, rivers, embankments are often visible. The rails and canals run rather more straight than roads. Canals need not pass through towns, villages, and cities. This feature enables to distinguish canals easily from transportation networks. Similarly, rivers have meanders/crenellations, urban/human settlement areas have approaching pattern of roads/rails, and texture and sizes are other properties useful for visually identification of various land uses on the satellite FCC.

Landuse Mapping

Land use map is required for various applications such as planning, water resources management, flood management, drainage design etc. The quantity of runoff and peak discharge from a watershed depends on the land use. Land use mapping requires a land use classification system. In a land use classification system, land use classes are listed and clearly defined. If possible, a hierarchical classification can also be designed. There are many land use classification systems available e.g. United States Geological Survey (USGS) classification system, waste land classification, and other individual classification systems.

The open-ended USGS classification system is a hierarchical classification designed for use with remotely sensed data. Level I and level II land uses are rigid whereas other levels can be user defined. Level I is a broad classification with classes urban or built up land; agricultural land including cropland, pasture, orchard etc.; rangeland etc. At the level II, the urban land is classified into residential, commercial and services, industrial, transportation, communication and utilities, industrial and commercial complexes, mixed urban and built up land, and other urban and built up land. The mixed urban land use is a blend of urban land use categories non-separable at the mapping scale. These categories typically include the development along transportation routes etc. Industrial and commercial complexes are areas where mainly industrial and commercial activities take place and these are followed by other related uses. These can be further reclassified into levels III and IV using additional data, ground survey etc. Commercial, residential and industrial classes at level II are obvious classes. The coarse resolution satellite data can be used for level I land use mapping, and high altitude aerial photograph (altitude >12400 m and scale 1:80000) for level II land uses.

The availability of information in time about the changing pattern of urban land use plays a significant role in urban land use planning and sustainable urban development. The mapping and monitoring of urban land use/land cover requires a land use classification system. Anderson (1971) developed the first comprehensive land use classification system for aerial photo-interpretation in 1971. Several attempts have since been made to modify it to meet the requirements of varying data base situations. After consultation with Urban Development Authority (UDA), Town and Country Planning Organization (TCPO) and several other users departments, National Remote Sensing Agency (NRSA) developed in 1986-89 an Urban Land use Classification System for use with satellite data.

Several studies on land use/land cover mapping have been completed using both aerial photographs and satellite imageries. The contributions of Human settlement Analysis Group, IIRS, and Space Application Centre to this end are both commendable and creditable. Using large scale aerial photographs and Landsat TM, SPOT and IRS LISS-II data, the former has undertaken land use/land cover mapping of Jaipur (1983, 1989); Coimbtore (1984); Ujjain (1985); Rohini, Delhi (1987); Kanpur (1988); Delhi, Dehradun, and Lucknow (1989); Bhubaneshwar (1990); Saharanpur (1992); Bangalore (1994); and Jammu (1995). The Space Application Centre has undertaken the land use/land cover mapping of Bombay (1989), Ahemdabad (1991), and Calcutta (1992); and NRSA of Chennai (1990) and Hyderabad (1994) under the Remote Sensing Applications Mission of the Department of Space (Pathan, 1989, 1991, 1992; NRSA, 1990, 1994; Raghvaswamy et al., 1994).

Urban Change Detection

Analogous to dynamic 'organisms', cities never remain static. While ground methods identify certain urban processes and changing forms, the easiest and least expensive way of deriving urban information systems that could correlate spatial and physical changes in the city is by remote sensing techniques. The information derived from sequential aerial photography and orbital remote sensing helps urban planners and decision makers in detecting land use conversions from agricultural to non-agricultural, urban fringe activities, loss of greenery and water bodies, developments along the transport corridors and drainage lines, and the changing quality of urban environment. Furthermore, the remote sensing techniques also help derive an integrated urban development plan and a suitable strategy for its implementation. Urban planners always look for reliable information about the rate and direction of the growth in the physical limits of a city. Several studies have established the potential of remote sensing techniques in obtaining synoptic and repetitive coverage of the cities necessary in monitoring the patterns of urban growth and urban fringe activity, and the gobbling of agricultural lands by the growing cities. The early studies on urban growth/sprawl were carried out using large-scale aerial photographs. The Landsat TM, SPOT HRV and IRS LISS-II data with improved spatial resolution since early 1980's provide an opportunity to make use of the remote sensing techniques in mapping and monitoring urban sprawls and its impact on surrounding rural areas. For example, the urban built-up area in Bangalore city and its surroundings has been found to be at the cost of agricultural land and surface water bodies (Behera et al., 1985). A similar study has identified the encroachment of the margins of Dal Lake as a consequence of the urban sprawl of Srinagar (Raghvaswamy et al., 1992). The gobbling of agricultural land as a result of rapid urban growth have also been detected in Hyderabad, Madras, and Nagpur (NRSA, 1990 and 1994). In addition, the mapping of the urban sprawl of Jaipur, Delhi, and Lucknow have been completed by Human Settlement Analysis Group, IIRS, and of Allahabad and Port Blair by NRSA (NRSA, 1990; and Sokhi et al., 1989).

URBAN HYDROLOGY

Urban hydrology is defined as the interdisciplinary science of water and its interrelationship with urban mankind. Other definition of urban hydrology involves the study of hydrological processes occurring within the urban environment. Urban hydrology can also be defined as the study of impact of change of landuse pattern due to human activities on peak and volume of runoff from the basin. A more complex definition of urban hydrology may include the study of hydrological processes both within and outside the urban environment influenced by urbanization.

Urban hydrology is relatively a young science, and bulk of knowledge on the subject has accumulated since early 1960s. The beginning of urban hydrology can be traced back to the time shortly after the Industrial Revolution when automobile became the major means of transportation in the world. The result was rapid creation of large impervious area and drainage congestion. The science of urban hydrology actually evolved due to necessity to understand and control these problems.

SOME ISSUES

The major issues, which urban hydrology needs to deal with, can be the water supply for urban settlement, urban water pollution or water quality, and urban storm-water runoff disposal. As urban areas are growing rapidly, it has become imperative to search for new sources of water. The remotely located source of water may lead to competitiveness or dispute for water utilization among adjacent cities and/or neighboring States.

It is of common experience that the health of a community depends on the adequate water supply of good quality. The main sources of urban water pollution could be the point-source pollution, and non-point source pollution, such as turbidity from erosion-prone urban watersheds, agro-based chemical pollutants from agricultural croplands draining into lakes or rivers. An efficient urban storm-water drainage system helps in quick disposal of urban storm-water runoff (Chakraborti, 1991).

Urban Surfaces and Runoff

As the land surface is developed for urban use, a region is transformed from the natural state to a totally man-made state. New structures add to the large amount of impervious areas to watershed, leading an increase in surface slope and reduction in water storage capability.

Landuse Changes due to Urbanization

Landuse changes due to urbanization, as described by Stankowski (1972), starts with the occupation of rural lands by small and closely spaced communities with concentration of houses, schools, and commercial facilities. Further growth is by way of large residential subdivisions, shopping centers and a large network of streets and sidewalks. The process continues until all such structures and developments occupy all or most of the former rural land.

Savini and Kammerer (1961) divided the process of urbanization into four stages, rural, early urban, middle urban, and late urban. The rural stage refers to the area under virgin stage, under cultivation or in pasture. Early urban landuse is characterized by city type houses built on large plots with pre-existing vegetation cover remaining intact. The middle urban stage concerns the construction and growth of large-scale housing developments, shopping centers, schools, streets and sidewalk. Finally, the late urban stage results due to excessive development activities causing complete loss of vegetation cover, and the available land is occupied by the man-made structures.

REMOTE SENSING APPLICATIONS

The modern remote sensing techniques including air-borne and satellite-based systems are capable of providing data pertaining to a number of hydrology related attributes. The remote sensing from space has provided new dimensions to information and mensuration based water resources. The remote sensing data can be characterized as follows:

- Synoptic coverage of wide geographic regions including urban settlements in a single- or multiple-image frame.
- Real time data gathering by an automated space-borne orbiting system.
- Computer compatibility of display, analysis, processing, and retrieval of data.
- Integration of thematic outputs in GIS.

Remote sensing applications can be made to the issues discussed above. To date, most uses of satellite remote sensing data have consisted of relatively straightforward expansions of photogrammetry. The issues like water quality, landuse and impervious factor etc. have been discussed in the following paragraphs.

Sources of water pollution, dispersion and dilution pattern of pollution in a water body can be assessed using spectral, spatial, and temporal characteristics of water and water quality. While qualitative nature of many water quality parameters like water colour, turbidity, eutrophication, and surface temperature can be obtained by spectral response of water in visible, near infrared, and thermal infrared regions of electromagnetic spectrum, quantitative information requires statistical correlation of these spectral response with in-situ water sampling (Chakraborti, 1991).

Runoff can not be directly measured by remote sensing techniques. The role of remote sensing in runoff calculations is generally to provide a source of input data. Alternatively, remote sensing aids in estimation of model parameters. Urbanization alters the physical characteristics of basins and, in turn, changes the response. A number of hydrological models have been proposed in the past to model the urban rainfall-runoff process. These include empirical models relating runoff to the basin and climatic factors, conceptual models relating to storage and conveyance characteristics of basins, and simulation models relating various components of hydrological cycle (Roy and Draper, 1983). As discussed earlier, some of the modeling parameters including landuse and impervious factor can be conveniently extracted from remote sensing data.

The percent imperviousness is an important parameter in modeling urban rainfall-runoff processes. It is usually determined using manual methods such as random sampling method or conventional accounting method. Regardless of the method, studies have shown a strong correlation between basin response and amount of impervious area in the basin.

In the Landsat approach, the percent of impervious area is estimated by assigning a representative land coverage value to each category. These values are summed to obtain the watershed's overall impervious value, generally utilized in hydrologic models to (a) compute/predict urban runoff using Soil Conservation Service Curve Number (SCS-CN) equation or any other method and (b) develop frequency information for planning and storm water allocations for future design studies. Impervious areas can be readily identified on most types of remotely sensed data.

Landuse and landcover are the most important characteristics of a basin, which govern various hydrological processes such as infiltration, evapo-transpiration, soil moisture status and so on. The dynamic nature of these features over space and in time makes it very difficult to get real time information by conventional means. Space imageries obtained from satellites are especially useful in landuse mapping. Urban landuse consisting of buildings, transportation networks, business, parks, and a variety of mixed uses represents high frequency details. One of the earliest investigations into the utility of Landsat data in urban hydrologic studies was a landcover inventory prepared for the Anacostia river basin in Maryland. High resolution images from the second- generation satellites such as Landsat TM, IRS LISS II and SPOT are more suitable for extraction of urban landuse information. In addition, GIS has proven over time to be of great use in the study of various aspects of urbanization. Different types of data can be easily integrated in GIS environment.

Estimation of Runoff from Urban Areas

Empirical formulae

Jackson in 1975 developed an equation for estimating the percentage of urban area from Landsat data. The percentage of impervious areas is expressed as exp{1.45-2.16 × [ratio of band (0.8-1.1 μm)/ band (0.5-0.6 μm)]}.

The rainfall is converted to runoff as:

$$R = CA\,(P-D) \tag{1}$$

where R is runoff volume for time increment (say 1 hr); C is runoff coefficient percentage of impervious area; A is area; D is available depression storage; and P is rainfall volume.

Carter in 1977 also developed an equation for urban watershed of Washington D.C. taking impervious factor into account as:

$$Q/K = 223A^{0.85}\,T^{-0.45} \tag{2}$$

where $K = \dfrac{0.3 - 0.3(\frac{I}{100})}{0.3} + 0.75(\frac{I}{100})$ in which I is percentage of imperviousness; and

$T = C\,(LS^{-0.5})^{9}$ in which C is coefficient reflecting the degree of urban development; L is stream length; and S is channel slope.

The Soil Conservation Service (SCS) procedure, which came into common use in 1954, is the product of more than 20 years of studies of rainfall-runoff relationships for small rural watersheds. The conceptual and empirical procedure was developed to provide a rational basis for estimating the effects of land treatment and land use changes on runoff resulting from storm rainfall. The SCS runoff equation is expressed as:

$$Q = \frac{(P - 0.25)^2}{(P - 0.8S)} \qquad (3)$$

which is subject to the restriction that P> 0.2S. Here, P is rainfall amount; Q is the direct surface runoff; and S is the potential maximum retention.

Parameter S (mm) is related to the curve number CN by the following relation:

$$\text{CN} = \frac{25400}{\text{S} + 254} \qquad (4)$$

where CN is a function of watershed's hydrologic landuse/landcover, hydrologic soil type; antecedent moisture conditions. Estimation of CN and, in turn, runoff Q is possible using satellite-derived landuse/landcover and soil information.

Hydrologic Simulation Models

University of Texas Watershed Simulation Computer Program The University of Texas Watershed Simulation Computer Program is a continuous moisture accounting model. Precipitation falling on the watershed is taken as initially abstracted by interception storage that is dissipated by evaporation. After interception storage requirements are met, further precipitation flows down to the ground surface, which is either impervious (contributing directly to stream flow) or pervious in nature. The pervious area is divided as depression storage and overland flow storage. Infiltration into soil profile occurs from both overland flow storage and depression storage. The moisture percolates down into the intermediate zone and then to groundwater storage. Some portion of moisture from intermediate zone and ground water zone also reaches the stream. Therefore, runoff in the stream channel is composed of (i) volume of water from impervious area, (ii) volume of overland flow contributing to stream, and (iii) volume lagged through interflow and groundwater storage.

Based on the instantaneous unit hydrograph concept, the model has the input requirements of precipitation, pan evaporations, transpiration, stream flow, physical characteristics of watershed and the constants used in infiltration, unsaturated permeability, soil moisture tension equations, size of soil zones, interflow and outflow from groundwater storage to stream.

TRRL Hydrograph Method The TRRL hydrograph method is widely used in the United Kingdom. It calculates the runoff hydrograph from the characteristics of catchment and rainfall. A novel feature of this model is that it computes the flood hydrograph considering the runoff only from paved areas directly connected to sewer system(s). The rainfall input into the model is a recorded storm, and the surface hydrograph is routed using the storage concept. In the storage routing, the minimum storage is taken as the volume occupied by water in the sewers at the peak rate of runoff.

If P and Q are the rates of routed and unrouted runoff, respectively, and R is the total volume of water in storage at time t, then total runoff from routing is given by the following solution of reservoir equation:

$$P\text{-}Q = \frac{dR}{dt} \tag{6}$$

The solution of this equation requires a relationship between Q and R. Therefore, it is assumed that at any given instant, the ratio of the depth of water to the maximum depth is the same for all pipe systems.

TVA Continuous Daily Streamflow Model The Tennessee Valley Authority (TVA) daily streamflow model was designed for applications involving studies on the effect of landuse changes on water quality transport or storm water runoff. The time unit of a day was taken for reasons of easy availability of daily rainfall and streamflow data. With the time unit used in this model, it is possible to identify separate storm events. It is also sufficiently so long that data management problems do not arise.

The continuous daily streamflow model is basically a simple water budget book-keeping for the watershed. Daily rainfall is budgeted among a series of conventional cascading compartments or reservoirs. This feature distinguishes from the available several flow models. The non-incorporation of outflow and inclusion of only a single soil moisture reservoir is taken for simplicity reasons. These simplifications were made to minimize the number of parameters and intercorrelations among them. Input consists of daily rainfall, streamflow, and monthly evapotranspiration for analyses. Output from the system consists of daily, monthly, and annual streamflows, along with an annual allocation of the streamflow (TVA, 1976).

CURRENT RESEARCH IN INDIA AND ABROAD

Several researchers have investigated the effect of urbanization on runoff. Ferguson and Sucking (1990) in their study on changing rainfall-runoff relationships in the urbanizing Peachtree Creek watershed Atlanta, Georgia, reported that the increasing urbanization was accompanied by both increasing runoff in wet years and declining runoff in dry years. The reason of intense runoff in wet years was because of the fact that the large and intense rainstorms led to large short-term runoff adding significantly to annual rainfall. Wallace (1971) modeled individual Peachtree Creek flow events and found that with increasing urbanization short-term flood peaks tended to increase, and time to peak to decrease. As urbanization increased, the average annual direct runoff increased in relation to precipitation, the magnitude of short-term peak flow increased and entire hydrographs were faster.

Colwel (1970) used high altitude imagery to detect urban features such as vegetation, non-vegetation and water, and separated nine different landuses. Ragan and Jackson (1980) compared the landcover determinants and the estimates of percent impervious areas as obtained using conventional and Landsat-based techniques in a 342 km^2 watershed. Later, Ragan et al. (1980) estimated the runoff curve number (CN) based on Landsat MSS digital classification of urban landuse/cover categories and showed that these compared well with those obtained using the conventional approach. Draper and Rao (1986) used a single linear reservoir hydrograph model with a precipitation excess equation based on the percentage of impervious area, storm rainfall, area covered by ground moraine deposits and an antecedent rainfall index. Using the high altitude aerial photographic interpretation, they demonstrated the two computerized methods for determining the impervious area. The study of Rohini, Delhi (Chakraborti, 1989) revealed the urban drainage index to be of the order of 5.5 cumec/sq. km for a given rate of urbanization expected to increase from 55 to 84 percent. Using remote sensing technique and SCS method, Shukla and Singh (1994) revealed an increase in peak discharges from 74 cu. m/sec in 1972 to 110.3 cu. m/sec in 1989 with increase in the impervious area of Najafgarh drain, N. Delhi. Ramaseshan (1983) reported that urban hydrologic problems of India differ from those of developed countries in several important respects such as lateral rather than vertical development, limited amounts of paved area, preference for open drains over closed ones, limited availability of continuous records of streamflow and water quality, low fiscal priority for drainage investment, limited number of sewer connections and limited capacity of financial investment.

Ferguson and Sucking (1989) compared rainfall-runoff relations for early and late periods of the Peachtree Creek's urbanization. In another study, Wallace (1971) reported that over a period of two decades, the impervious area of Atlanta, Georgia, (area about 356 sq. km) increased from 1.7-31 percent, the storm runoff increased in dry months, baseflow decreased in wet months, and peak runoff due to summer storms increased significantly.

REMARKS

There exists a potential scope for use of remote sensing in tackling with the hydrological problems of urban areas. Some of the potential applications include the estimation of changes in peak flows and baseflows among others due to urbanization. The studies reported indicate that the flow peaks increase abruptly with increasing urbanization, two to four times that of undeveloped areas with steep rising and falling limbs of the hydrograph. Several studies on the effect of urbanization on baseflow has reported that with the increase in impervious area, runoff volumes increase in dry months and baseflow decreases in wet months, which possibly because of the decreasing groundwater recharge.

Remote sensing can also play an important role in determination of some of the crucial parameters required in urban hydrological studies. The remote sensing product can effectively supplement conventional maps, and for many parts of the world, these products may be the only source of map type of information. However, the real impact of remote sensing will not be in providing data to hydrologists, rather in providing new types of data to improvise the state of the art of the hydrologic data bank. The works to date on determining landuse and impervious factor exemplify the vital application of remote sensing. Further, the introduction of latest technique of GIS/LIS and photo mapping can improve the process in terms of quality, cost, and time.

The tremendous increase of India's (a) population from 109 million in 1971 to 156 million in 1981 and (b) number of towns with population over 20,000 from 536 in 1951 to 957 in 1971, and in turn, the urban population has increased its impervious area considerably. As a result, the designed capacities of the urban drains have also exceeded. Consequently, the problem of flood hazards has increased significantly. This problem is more acute in cities located near river banks, for the rivers are unable to accommodate all the flood water during high flood periods. Under these circumstances, even if the drainage system of a city is adequate, it may not drain the floodwater to the nearby river due to reasons of backwater effects. Most of the hydrological models available in literature however ignore this phenomenon. Further research is therefore needed on this important aspect of urban hydrology. A close monitoring of urban runoff at suitable outlets, especially in metropolitan cities, is imperative for better and safe living in these cities. In India, this problem is complicated and needs immediate attention. The urban instrumentation network both in terms of assessing quantity and quality of urban runoff is very poor and needs attention.

REFERENCES

Anderson, J. R. (1971). Photogrammetric Engg., 37(4), 379-387.

Behera, G. (1985) Growth of Banglore city since 1900 based on maps and satellite imagery, ISRO Technical report, ISRO-EOS-TR-55-85.

Carter, V. (1977) Proc. 11th. Symp. Remote Sensing Environment. Ann. Arbor, MI, 301-323.

Chakraborty, A.K. (1982) Proc. Int. Symp. Remote Sensing Environment, Egypt, 1003-1012.

Chakraborty, A.K. (1989) Urban storm water runoff modelling-A case study in Rohini Delhi, WRD, IIRS, Dehradun, Report 1989.

Chakraborty, A.K. (1991) Urban storm water runoff projection, NNRMS Bull. No. NNRMS (B)-14, ISRO/DOS, Bangalore.

Colwell, J.E. (1970) Multispectral remote sensing of urban features, Willow Run Laboratories, Univ. of Michigan, Ann Abror, Michigan, USA.

Ferguson, B.K. and Suckling, P.W. (1990) Changing rainfall-runoff relationships in the urbanising peach tree creek watershed, Atlanata, Georgia. Wat. Resour. Bull., 26(2).

Jackson T.J. (1975) Proceeding Workshop on Environment Appl. Multispec Imaging, ASP Ft Belvoir, Virginia

Lazaro, T.R. (1979) Urban hydrology- A multidisciplinary perspective, Ann Arbor Science Publishers, Ic., Ann Arbor, Michigan, 142-165.

Mishra, S.K. and Singh, V.P. (1999) Another look at SCS-CN method. ASCE J. Hydrolog. Engg., 4 (3), 257-264

Moglen, G.E. and Hartman, G.L. (2001) Resolution effects on hydrologic modeling parameters and peak discharge. ASCE J. Hydrolog. Engg, 6 (6), 490-497

Mannen, J. (1991) Urban realities, The Hindu, July 7, 1991

ISRS (1989) Special bulletin of Photonirwachak, 17(3).

NRSA (1990) Mapping and monitoring of urban sprawl of Madras, unpublished project report, 1-50.

NRSA (1994) Mapping and monitoring urban sprawl of Hyderabad , project report, 1-85.

Pathan, S.K. (1989) Urban landuse mapping and zoning of Bombay metropolitan region using remote sensing data, Photonirvachak, 17(3), 11-22.

Pathan, S.K. (1991) Urban land use mapping: A case study of Ahemdabad city and its environs, Photonirvachak, 19(2), 95-112.

Pathan S.K. (1992), Urban land suitability analysis: A case study of Calcutta Metropolitan Area, Photonirvachak, 20(2&3), 72-84.

Pathan, S.K. and Bhandari, R.J. (1996) Usefullness of IRS 1C data for Urban land use Planning and Development, Ahemdabad, RSAG, Space Application Centre, 1-7.

Ragan, R.H. and Jackson, T.J. (1980) Runoff synthesis using Landast and SCS model, ASCE J. Hydraul. Div., HY5, 667-678.

Raghavaswamy, V. (1992) Landuse/cover mapping and monitoring urban sprawl using IRS data: A few examples, in: Natural Resources Management in space technology and Geography, Hyderabad, NRSA, 295-323.

Ramaseshan, S. (1983) Progress since 1979 in India, Section II, International Symposium on urban hydrology, Edit by J.W.Delleur and H.C. Torno, Urban Water Resource Research Program, ASCE, New York.

Rathore, D.S. and Jain, S.K. (2001) Application of remote sensing for urban hydrological studies in Delhi areas, unpublished report, NIH, Roorkee.

Roy, S.G. and Draper, S.E. (1983) Estimation of percent imperviousness of urban basins using remote sensing and remote data transmission, August, 1983, IAHS Pub. No. 145.

Shukla, M.K. and Singh, H. (1994) Urban watershed modelling a comparative study, A case study of Nazafargarh drain, NIH report.

Soil Conservation Service (1975) Urban hydrology for small watersheds. Technical Release No. 55, Engg. Div., Soil Conservation Services, U.S.Department of Agriculture.

Sokhi, B.S., Sharma, N.D. and Uttarwar, P.S. (1989) Satellite remote sensing in urban sprawl mapping and monitoring: A case study of Delhi. Photonirwachak, 17(3), 57-69.

Stankowski, S.J. (1972) Population density as an indirect indicator of urban an suburabn land surface modifications, U.S. Geol. Surv. Prof. Paper 800-B, GPO, Washington, D.C.

TVA (1976) Urban hydrology: A system study of Knoxville, Tennessee Valley Authority.

Wallac, J.R. (1971) The effect of land use changes on hydrology of an urban watershed, School of Civil Engg., Report ERC-0871, Georgia Institute of Technology, Atlanata Georgia, GGPP and UNESCO Press.