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# Use of GIS in optimal spatial network of hydrological data in Betwa river catchment

Ritu Ahlawat[1]
1- Miranda House, University of Delhi
ritu.ahlawat@gmail.com

## ABSTRACT

The ultimate design for any kind of hydrological data network must evaluate all possible alternatives before rationalising the task of data collection at an optimal level. Wherever different kinds of data collection centres duplicate the measurement of same parameters in close proximity, efforts should be to integrate the entire process of data processing at one place. The extent to which the spatial aspect of data needs to be compromised is examined in this paper at sub-catchment/watershed level of Betwa river, one of the important southern tributaries of River Yamuna after Chambal. An integral design of various kinds of hydrological data has been attempted using spatial multi-criteria module within Geographic Information System (GIS) framework. Basic concept of geographical domain has been utilised to derive optimum network of hydrological data.

**Keywords:** Optimality, spatial variation, multi-criteria, feasible weights, integral design

## 1. Introduction

Data on hydrologic processes are used to better understand the space-time variations and probabilistic nature of these processes. They act as direct input into hydrologic simulation models for design, analysis and decision-making. A rapid expansion of hydrologic data collection worldwide was fostered by the International Hydrologic Decade (1965-1974), and it has become a routine practice to store hydrologic data on computer files. Recent advances in electronics allow data to be measured and analyzed as the events occur (Chow, 1988).

Now, intelligent decisions about hydrological data station location and duration of data have become necessity (WMO, 1994). Only in the last five decades has the concept of a well-defined network of data collection activities begun to impact types, quantities and qualities of the data that are available to aid in making water resource decisions (Langbein, 1972). The specifications for optimum network should include the following (Moss, 1985):

i) The number of sites at which data are to be collected;
ii) Their locations;
iii) The types of data which are to be collected at each site;
iv) The frequency and duration of collection of each data at each site;
v) The equipment and techniques, which will be used to collect the data.

The 1990s has seen the launch of a new initiative by the WHO to provide timely, and if possible real-time, quality-controlled data. World Hydrological Cycle Observing System (WHYCOS) uses satellite communications to link strategically selected new and existing stations reporting water levels, discharges, water quality and meteorological variables. Thus, automation, telemetry and remote sensing have revolutionized data collection.

Further, the search for theories and models in hydrological network design has enhanced the need for precision in observation and analysis. With the availability of remotely sensed data and Geographical Information System (GIS) facility, modelling in the field of hydrological design has acquired new dimension. Various kinds of networks and their optimum designs, which require accurate measurement of distances, evaluation for long-term data, spatial relationships, visualization in three-dimensional model of terrain need data inputs obtained by aerial photographs and satellite imageries. They can now can be analysed and simulated for experiments on computers installed with GIS software. Utility of GIS in watershed modelling, water quality monitoring networks, and digital terrain models has been demonstrated and applied by various scholars (Singh and Fiorentino, 1996). Application of spatial multi-criteria evaluation concepts and methods to support identification and selection of proper landfill sites for disposal of wastes in a town of Columbia has demonstrated the utility of GIS module for decision-makers in a very simplest manner (Sharifi and Retsios, 2004). Remote sensing and GIS have really widened the horizon of analysis of uncertainty in hydrological events and in estimation of geographic parameters in a catchment. Use of fuzzy sets to represent geographical land-cover data has considerable potential in visual exploration of the multi-dimensional space of a catchment. Fuzzy sets and memberships may be unfamiliar to many users of remotely sensed imagery wherein Boolean logic is used in many cases. But, it can be more easily introduced and explained by the use of familiar metaphors such as the spectral signatures (Bastin, Wood and Fisher, 1999).

However, there is a dearth of data network-based studies particularly, in India. The only much-studied parameter is temporal variability in rainfall. Few studies have been completed by hydrologists or hydro-meteorologists. But, the multi-use network is attempted only recently because the task of data collection is considered to be the domain of government office. Some private users/companies/organizations seeking to have their own database are given limited access to data monitoring site. Record of hydrological data is fragmented among different central institutes and various state government organizations. The least studied aspect of the data collected by these organizations is their timely communication and publication of data. Economists have mainly studied economic aspects whereas, geographers have used the optimum solution programme, emphasizing the end use of hydrological data in the field of irrigation and agriculture. The traditional domain of geographers, *i.e.* location of sites for hydrological data collection has been ignored, and even if it is attempted, the use of advanced spatial statistics is limited. It is in this context that the present study is undertaken to analyse and design an integrated optimum network of hydrological data in a river basin.

## 2. Study area

The catchment area of Betwa river, marked by diverse hydrological and physiographic characteristics, is selected for the case study. The catchment area is bounded by northern alluvial plains and southern. It extends from 22°20' to 26°0' North latitudes and 77°10' 80°20' East longitudes and covering most of Bundelkhand districts of southern Uttar Pradesh and northern Madhya Pradesh till Vindhyan plateau. The River Betwa is the life-line for the region through which it flows and has an important role to play in the all round growth and development of the region. It serves as the source of drinking water to huge population of the region especially to Raisen, Vidisha, Basoda and Kurwai. It is the major source of irrigation for the area known for the production of high quality wheat, gram and soya bean in the country. Journey and life of Betwa can be still imagined as revolving around towns and villages (Fig.1). But, the catchment area suffers from differential levels of uneven agricultural and irrigational development. It has been affected by the paucity and wide spatial network of hydrological data (Ahlawat, 1999). Hence, any type of design and planning for water resource development gets affected by deficient and irregular data network even after launch of Hydrology project in plateau region. Therefore, the study of hydrological data network and its optimality becomes important in the region dominated by seasonal tributaries.

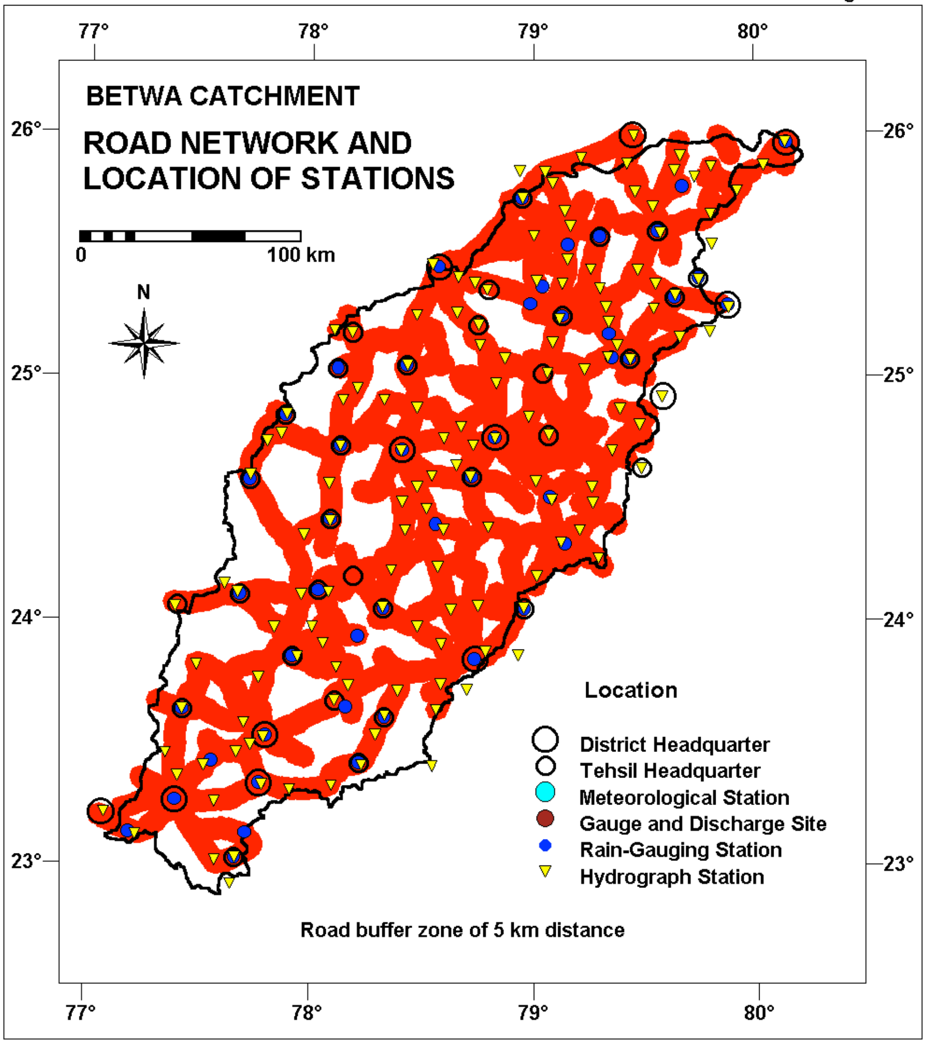



**Figure 2:** Accessibility of the study area

## 3. Methodology

The analysis is based on data collected mainly from secondary sources - Indian Meteorological Department (IMD), Central Water Commission (CWC), Central Ground Water Board (CGWB) and Central Pollution Control Board (CPCB). Besides annual data, monthly data from these and other state-level organisations were also collected. Base maps were drawn using toposheets of Survey of India and plates of drainage and water resources series of National Atlas Thematic Mapping Organisation (NATMO). According to latest published records and data availability from various offices, stations having long-term record were included to get estimates of mean values of various hydrological parameters.

Before proposing a well-defined integral design, field visits in different years (1999-2004) were undertaken at more than 30 places in the catchment area. Useful information could be gathered by interacting with locals and farmers. An assessment about requirements and problems at sites could be made through informal discussions. Scores based on other secondary socio-economic information and landuse data were also given relative weightage. Hierarchy of stations and the multi-purpose nature of stations were ascertained through composite scores derived by combining spatial multi-criteria maps after adopting appropriate standardisation and weightage procedure in a GIS-based system (ILWIS). Accessibility index to roads and administrative headquarters was determined by drawing buffer zones of 5 and 10 km around these areas. A random grid of proposed stations and error map obtained from kriging estimates was overlaid on these criterion maps to identify suitable zones. This feedback information was then integrated with the statistical-cum-mathematical analysis of long-term record of spatial data in ILWIS and SPSS (Statistical Package for Social Scientists) for one of the sub-catchment. Thus, a feasible solution has been attempted for all types of proposed hydrological locations. The trade-off among all scientific (spatial, temporal and seasonal variation) factors could be achieved when all possible criteria and constraints were analyzed together in Spatial Multi-Criteria Evaluation (SMCE) module of ILWIS 3 (ILWIS - Integrated Land and Water Information System) for each alternative design of hydrological data collection stations. The input for this application was a number of raster maps of the catchment all prepared by Author (Ahlawat, 2007) like rainfall isohyetal maps, pixel-wise water balance maps, digital elevation map (DEM) for meteorological and rain gage stations; data; hydrograph network map for ground water morphometry maps for runoff data stations; (so-called 'criteria' or 'effects' incorporating maps as factors and maps as constraints).Based on these input maps, a criteria decision tree was formed containing the grouping of criteria, their standardization methods and weightings (Fig.2).

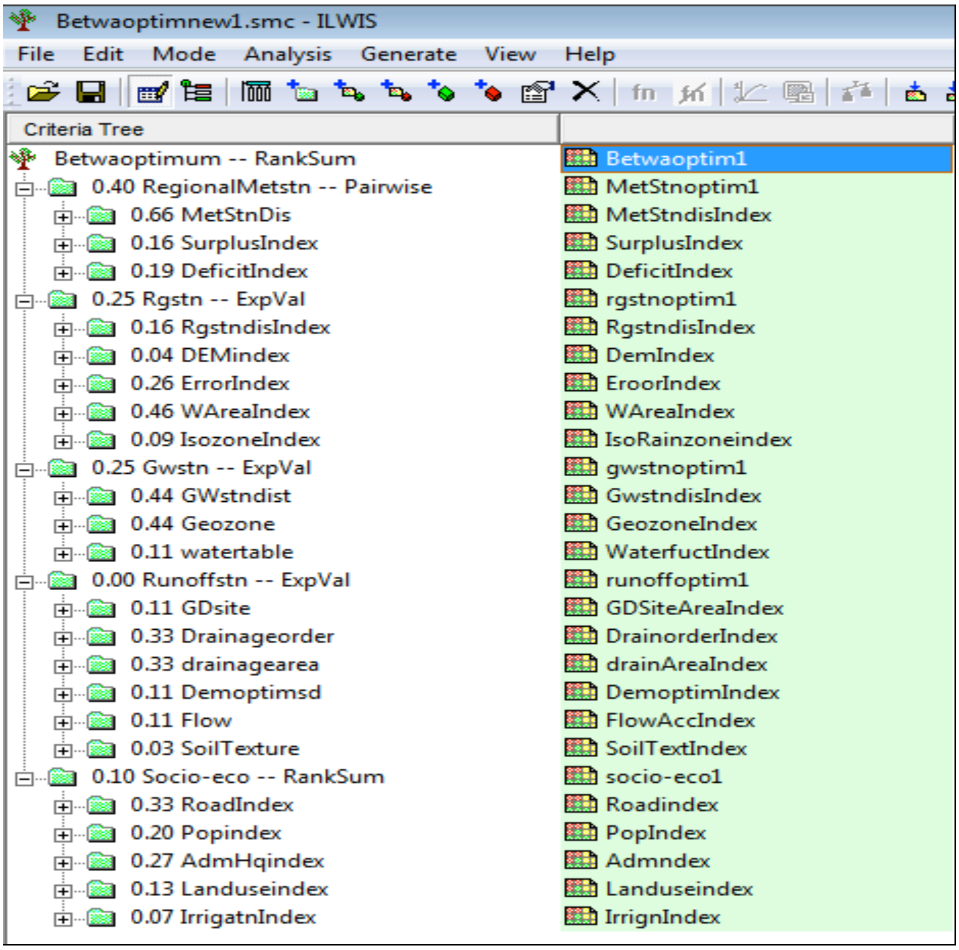



**Figure 2:** ILWIS Screen shot - Decision tree of spatial multi-criteria design (Abbreviations used for raster input maps in field names)

Weights were determined based on their subjective importance in field. The output is one or more maps of the same area (the so-called 'composite index' maps) that indicates the extent to which criteria are met or not in different areas in terms of pixel values ranging between 0 and 1, and thereby supporting planning and/or decision-making for water resource monitoring sites. Finally, an integrated strategy for this hydrological network design has also been discussed and described with respect to its use, impact and associated problems.

## 4. Results and discussions

As hydrological data in the region are collected and maintained by different departments, therefore, integrity and usefulness of the network need to be reviewed; firstly, from their perspectives. At the national level, Indian Meteorological Department (IMD) has developed a good network of class I and II observatories for climatological and hydro-meteorological data for a considerable long period of time. Gauge, discharge, silt-load and water quality measurements are done at sites maintained by Central Water Commission (under the Ministry of Water Resources). Water quality is monitored on regular basis by Central Pollution Control Board under the Yamuna Action Plan and Global Environmental Monitoring System (GEMS) programme. Ground water quality, water table level fluctuations, *etc.* are recorded through a network of hydrograph stations of Central Ground Water Board. Besides national level sites, respective state governments have also set up their own sites for monitoring ground and surface water quality (with state government centres at Bhopal), and for recording water level (gauge sites maintained by State Irrigation Departments). An additional data on rainfall during monsoon season (1 June-15 Sept) is collected by State Land Record Department under its routine revenue process at all tehsil headquarters. Various agricultural universities and forest departments have also set up their own agro-meteorological observatories for recording rainfall and soil moisture data.

Total number of rainfall stations varies from 29 to 45 according to data given in state climatological report, weekly rainfall report respectively in case of Betwa catchment alone. There exist only very few class I observatories in the Betwa catchment with sunshine recorder facilities and the result for these at nearby observatories is also not published so frequently along with other parameters.

Spatial and temporal variations in the data collected at these sites affect any estimate needed for water resource planning and development at different territorial levels. Coordination among several departments, consistency and precision of available record further aggravates the problems for both planners and users in general. A closer examination of each type of data network can suggest some compromise between scientific design of optimum standard and socio-economic rationality.

Although different kinds of data network require different locational settings, still, it was found that some of the data collection process can be combined at same locations, *e.g.* at gauge and discharge sites, rainfall, groundwater level and water quality measurements can be integrated. At least, a common local head office can be identified even if exact site requirements are not met with. Coordination among different agencies can be achieved to avoid same measurements, by exchange of data in digital format.

If location of all kinds of existing data stations is compared just with district/tehsil/block headquarters and towns, then a close similarity was observed in the case of 30 stations in Betwa river catchment (Fig.1). Hence, administrative hierarchy can be considered for hydrological data linkage, too. For proposed stations as well, a preference can be established with respect to potential administrative/urban centres.

At present, this administrative hierarchy of station headquarters is not designed catchment-wise for supervision of hydrological data network. Even in the case of gauge and discharge sites, it is according to nearby division /zone and for each circle an engineer is made responsible. Similarly, network of meteorological stations has its own regional nodal centre at Nagpur for different sub-divisions. Bhopal, being the state capital, has best labs for water quality and other data processing facilities related to hydrological information like Regional Remote Sensing Centre. But its links with Betwa river catchment are restricted to its vicinity zone in state. Water quality monitoring standards at Mandideep, located at few km away from Bhopal are also not taken care of their implementation.

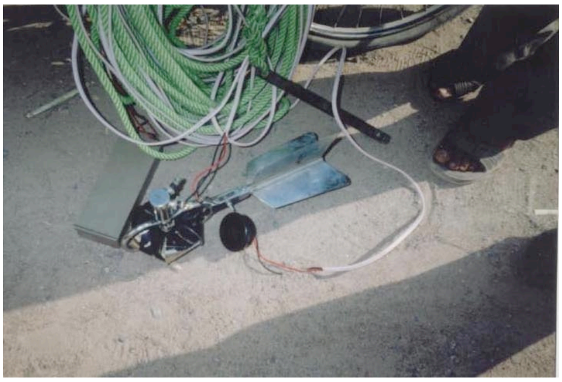
In the light of above problems in coordination, it is suggested that Jhansi and Hamirpur in U.P, and Bhopal and Vidisha in Madhya Pradesh can be considered as regional centres for coordinating the process of hydrological data collection in Betwa river catchment. Further, sub-regional/local level selection of stations can be done if their relative accessibility and other practical aspects of field operations are taken into account.

### 4.1 Water Resource monitoring sites - A field view

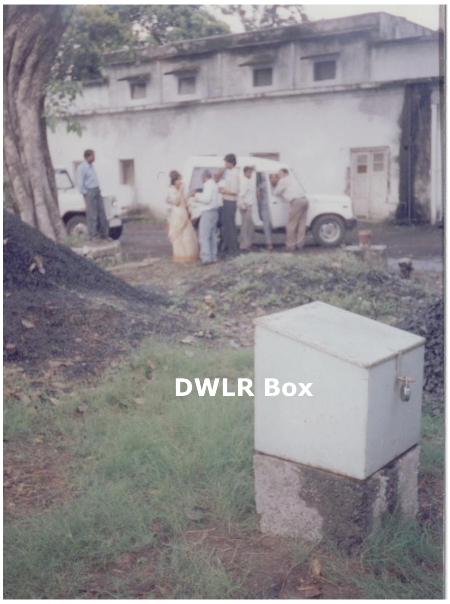
A field survey at 30 places in the Betwa catchment provided real view of operational aspects of integrity in hydrological data network design. The nature and status of instruments at selected sites in the basin itself points towards several limitations. There are very few automatic data collection centres. Automatic and digital records are yet to be in place. At present, the task of data collection is quite difficult especially at some of the GD sites during monsoons. An observer has to reach the site daily on bicycle and take observations for about 1-2 hour. If the instrument is not working properly, then obviously missing record remains in place for several days/months. Most of these sites are under supervision of junior engineer and a paltry sum is meant for maintenance and repair. Moreover, the work is not just over with data collection but a manual entry and processing of data in a specified format requires several approximations. The situation is grim in the case of lower level meteorological observatories, which are maintained by part-time staff. Again, a lump sum meagre payment @ Rs. 200-300 per month is made to one of the official responsible for maintaining these records daily. He is just assisted by one messenger who sends fax to nearest regional meteorological centre. The automatic rain-gauge recorders at places like Nowgaon, the oldest observatory in the catchment was not found to be functional at the time of visit. Again, it takes time to get these instruments replaced or repaired after inspection by IMD staff. Further, subjective judgment about visibility and cloud pattern is used. For groundwater depth measurements, observation wells are not properly maintained. Some of these have dried up and are not in use. Measurements are usually done with steel-tape and electric sounder. But, these wells are quite large in number and database becomes difficult to store on daily basis. However, at some of these sites a digital logger (DWLR) is in place (Plate 1).

Further, primary information about utilisation and planning of water resources in villages was collected from eight selected villages located in upper, middle and lower reaches of Betwa river catchment revealed reality of developmental work. Villages located in close vicinity of big dams like Rajghat and Barwa Kalan near Matatila also do not get enough water and electricity supply. The benefits of dam go to distant areas in cities and dam colony. The largest newly built Rajghat dam being a joint venture of two state governments and central government has to allocate water and electricity between two respective states. Canals going through this village land that was acquired long ago in 70's do not provide any benefit to these villagers. The information on water use and sharing is not provided to local villagers and other outsiders. Photography is also strictly prohibited in all reservoirs. However, in some cases like in Parichha, Betwa canal head has proved to be a boom for villagers and their economic uplift. Prior to that, this area like any other region in Bundelkhand had abundance of dacoits. Villages in interior areas of Uttar Pradesh Bundelkhand still have this tendency mainly because of frustration among villagers. Hamirpur-Mahoba plain has best network of canals but the villages at tail end do not get much benefit. It clearly shows lack of proper planning and management of water resources. The data base, if shared with villagers, then perhaps, can reveal real picture and from this intermediate solution can be arrived.

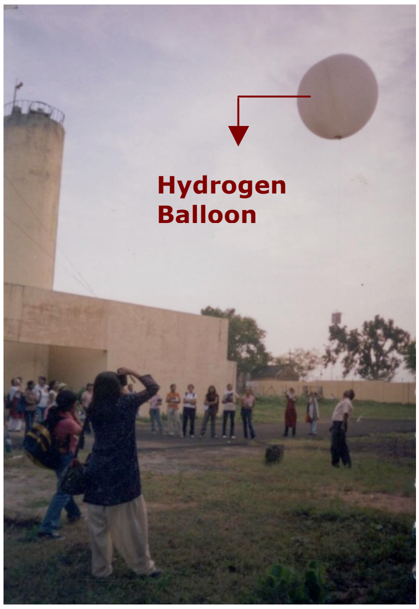
(a) Automatic Rainfall Recorder at Part-time Nowgaon Station, Chattarpur District



b) Current Meter at CWC's Gauge and Discharge Sites on Betwa - Sahijina, Hamirpur District




c) DWLR at Misrod Hydrograph Station




d) Hydrogen Balloon with *Radiosonde*

**Plate 1:** Important Instruments at Monitoring Stations
(Courtesy Author)

## 4.2 Socio-economic factors in network design

The above survey thus emphasised the need for incorporation of socio-economic information into integral design of hydrological data network. Role of different factors like accessibility to road, use of land, requirement and use of water was found to be important.

### 4.2.1 Accessibility

Accessibility to data collection centres from nearby roads, railway lines, administrative headquarters and bridge/reservoir was found to be important aspect of data network in field. Hence, all proposed and existing stations have been ranked according to their scores. Most of the existing stations in the Betwa catchment already lie in close vicinity of the important roads (Fig. 1).

Approach road to interior stations can also be considered over a period of time in a phased manner and satellite-based telemetry facilities can be extended to at least all existing 2$^{nd}$ order stations. Moreover, centres that are quite approachable can be considered as potential location for proposed stations so as to minimize infrastructure costs. Approachability in terms of time is most important factor nowadays. A shortest route map covering all major nodes in the catchment reveals that it takes about one to two day visit to inspect all stations. Stations located near existing stations and irrigation projects have either been already closed (like Rajghat GD site after construction of dam) site or are being operated for few observations only in order to reduce cost and time involved.

### 4.2.2 Landuse

Besides accessibility, landuse has been considered as one of the important criteria for justification of location of hydrological stations in different categories. Proposed landuse planning, specially based on irrigation will require additional stations. A rain gauge amidst forests; runoff and groundwater quality monitoring station in irrigated belt will provide additional information not only for localised use but also for analysing trend in long-term changes. Existing network also shows close correspondence with irrigated area. Spatial variation in different watersheds, although calculated on *pro-rata* basis from block level landuse data, is quite significant in case of surface water irrigation. Groundwater irrigation in the entire Betwa catchment constitutes major proportion ranging from 42% to 68% but its spatial variation being lesser requires extension of groundwater monitoring stations network to limited locations only. Even distribution of cultivable wasteland requires attention for location of proposed station in watersheds. Areas having uncultivable wasteland, however, can be avoided to minimize cost factor in the location of full-fledged monitoring stations. Only seasonal monitoring will suffice in these zones to account for overall regional hydrological estimates.

### 4.2.3 Areal and demographic coverage

Besides area, population of the catchment also necessitates the requirement of hydrological data stations in specific zones. Total population of about 15 million living in 70 towns and 7,904 villages is dependent upon water resources of Betwa river and its tributaries (Table 1).

An examination of the existing hydrological data network reveals that there exists little correlation with population density in the case of rain-gauge network and no relationship with hydrograph stations. Surface water quality stations maintained by State government, however, are located close to major towns and industrial units. Smaller size watersheds like Newan, Sagar, Naren do not have even one rain-gauge in spite of their high population density (mostly rural). These areas have, therefore, been selected for location of additional stations.

**Table 1:** Population density and number of optimum hydrological data stations

| Watershed | Total population (2001) | Area ($km^2$) | Density (Persons /$km^2$) | Rain gauge | Hydro-graph stations | Surface water quality stations | Discharge sites |
|---|---|---|---|---|---|---|---|
| Uppermost Betwa | 369,801 | 621.41 | 595 | 1 | 2 | 1 | -- |
| Kaliasote | 1,748,903 | 735.14 | 2,379 | 2 | 1+1 | 1 | +1 |
| Halali | 520,724 | 1,160.30 | 449 | 1 | 3 | 1 | +1 |
| Newan | 862,445 | 348.38 | 785 | +1 | +1 | 1 | -- |
| Baen | 599,056 | 1,148.76 | 521 | 1+1 | 3 | 1 | +1 |
| Sagar | 862,445 | 840.91 | 1,026 | +1 | +2 | 1 | +1 |
| Upper Betwa | 688,663 | 1,976.72 | 348 | 2 | 6 | 1 | 1 |
| Upper Middle Betwa | 788,241 | 2,342.43 | 337 | 2+1 | 6 | 1 | 1 |
| Bina | 803,747 | 2,820.55 | 285 | 4 | 6 | 1 | +1 |
| Narain | 751,287 | 1,338.98 | 561 | 1 | 2 | 1 | +1 |
| Kevtan | 637,555 | 1,098.88 | 797 | +1 | 2+1 | 1 | +1 |
| Naren | 862,445 | 799.70 | 2,476 | +1 | 3 | 1 | --- |
| Kethan | 670,947 | 1,347.82 | 498 | 2 | 4+1 | -- | -- |
| Lower Middle Betwa | 694,383 | 4,654.67 | 149 | 4 | 15 | 1 | 1 |
| Orr | 345,806 | 1,974.59 | 175 | 3 | 5 | -- | +1 |
| Jamni | 960,225 | 4,780.43 | 201 | 3+1 | 16 | 1 | +1 |
| Upper Dhasan | 954,627 | 4,908.49 | 194 | 3+1 | 16 | 1 | +1 |
| Lower Dhasan | 733,390 | 6,266.85 | 117 | 9 | 21 | -- | 1 |
| Lowermost Betwa | 266,134 | 1,424.97 | 187 | 2 | 10 |  | 1 |
| Birma | 472,268 | 2,542.25 | 186 | 5 | 11 | 1 | +1 |
| Betwa total | 14,593,092 | 43,132.23 | 338 | 44+9 | 132+6 | 16 | 5+11 |

Note. (+) Additional location proposed besides more sites at existing headquarters

### 4.2.4 Composite scores

Higher-level stations have already been identified among existing towns/block/tehsil/district level headquarters. While deciding location for new lower order stations, different parameters are found to have varying impact/influence. The relative weightage of each factor is taken care of while calculating composite score at each place (Fig. 3).

A composite picture of all socio-economic parameters, *viz*. accessibility to road, town, landuse, area, population and other amenities like education, medical, banking, communication and sources of water supply at all villages in Betwa catchment brought out three significant factors. Nearly, about 120 locations scored a value lying in upper quartile. Now, among these a station each in the middle of 3rd order watershed; and at upstream and downstream locations in 4th and 5th order is suggested for proposed stations. These potential sites at both town and village locations have preferential advantages in terms of cost of setting up a new station.

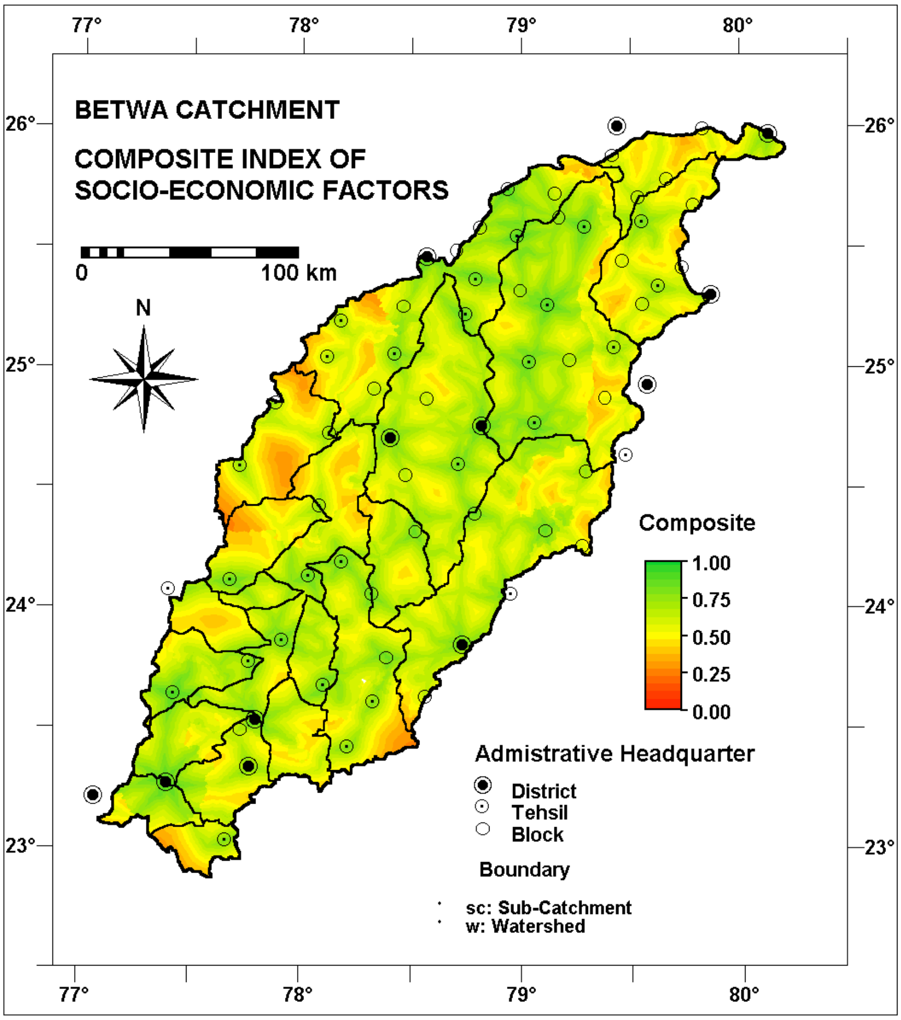



**Figure 3:** Socio economic composite index

### 4.3 Choice of alternative sites

Choice of alternative sites for each kind of network was seen through application of different weight factors in spatial multi-criteria criteria module of ILWIS. For each set of maps, composite score was calculated and mapped in Fig. 4 to 7. New possible sites, identified on the basis of their non-spatial attributes in SPSS, were also considered for relative suitability.

#### 4.3.1 Proposed data network (Sub-Catchment and watershed level)

Lastly, an illustrative attempt is made to formulate an optimum integral design of hydrological data network for one of the sub-catchment of Betwa river, falling between two gauge and discharge sites, *i.e.* Basoda (upstream) and Rajghat (downstream). An analysis of long-term data on rainfall and runoff, current landuse status on paper as well as on satellite imagery, digital elevation model with smaller pixel size of 100 meter, district-level geological maps and socio-economic data at village level resulted into identification of potential sites through their relative scores (Fig. 8). A detailed hydrological network of each kind was suggested at watershed level, too.

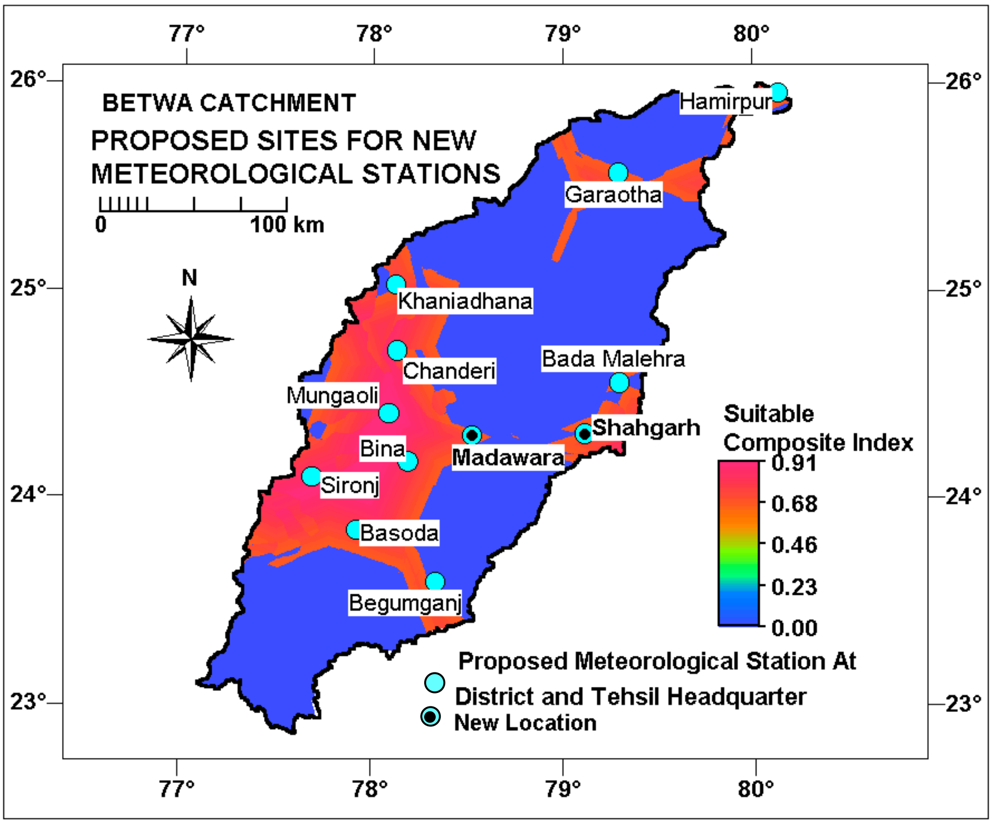



**Figure 4:** Meteorological Stations: Composite index and sites

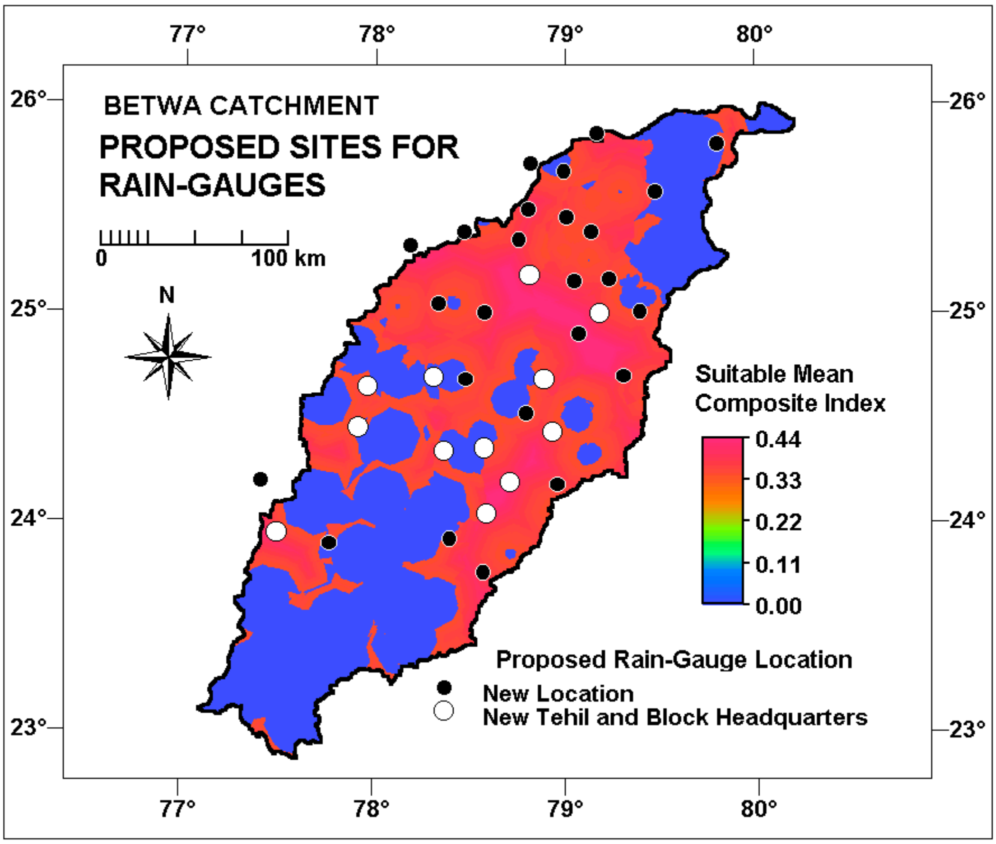



**Figure 5:** Rain Gauge stations: Composite index and sites

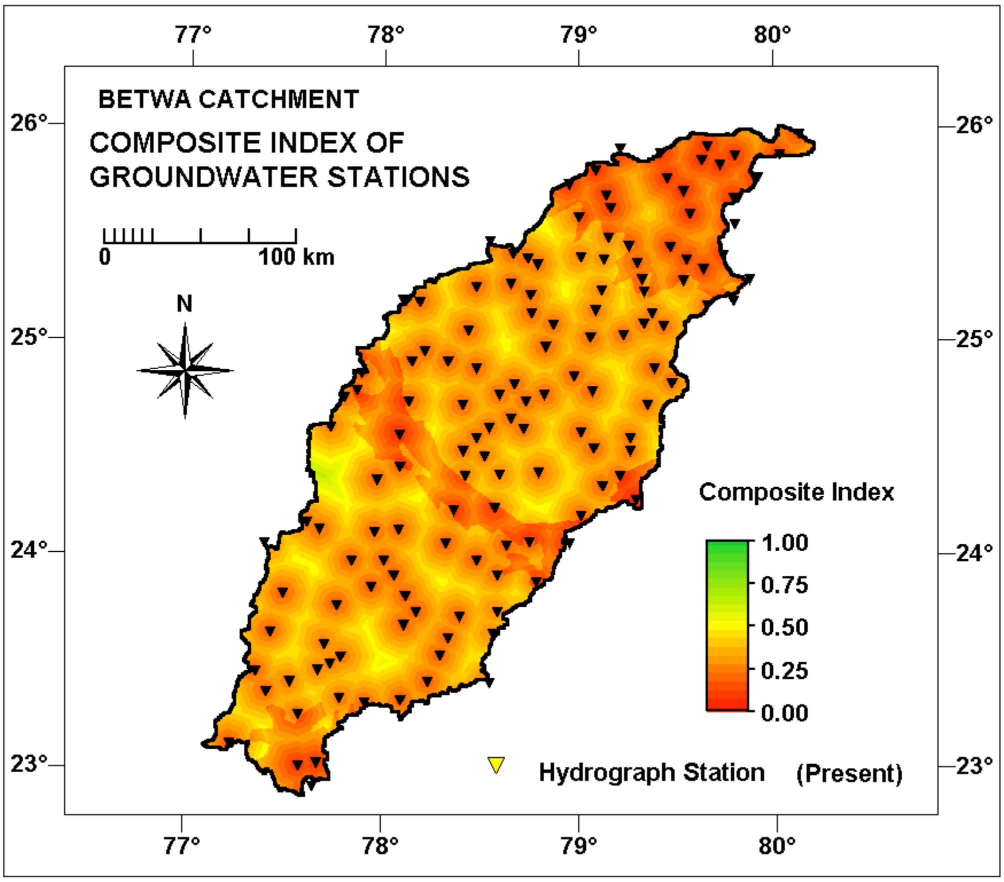



**Figure 6:** Groundwater stations: Hydrograph sites and composite index

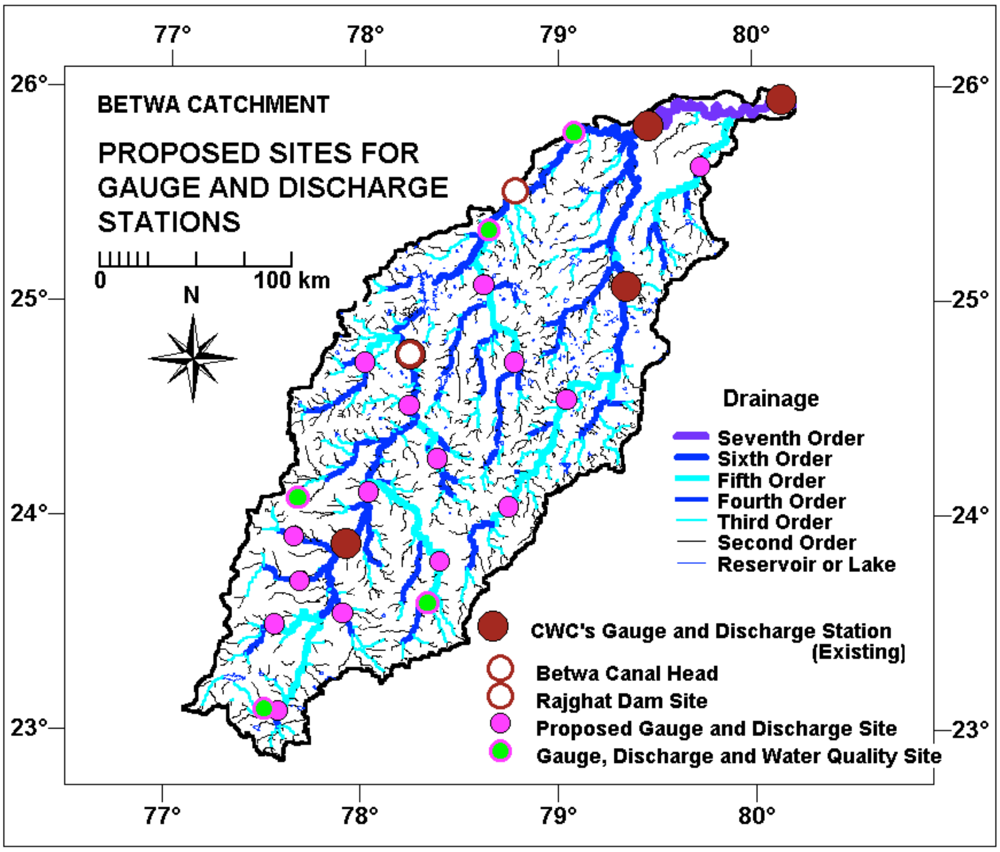



**Figure 7:** Hydrological stations: Drainage network and sites

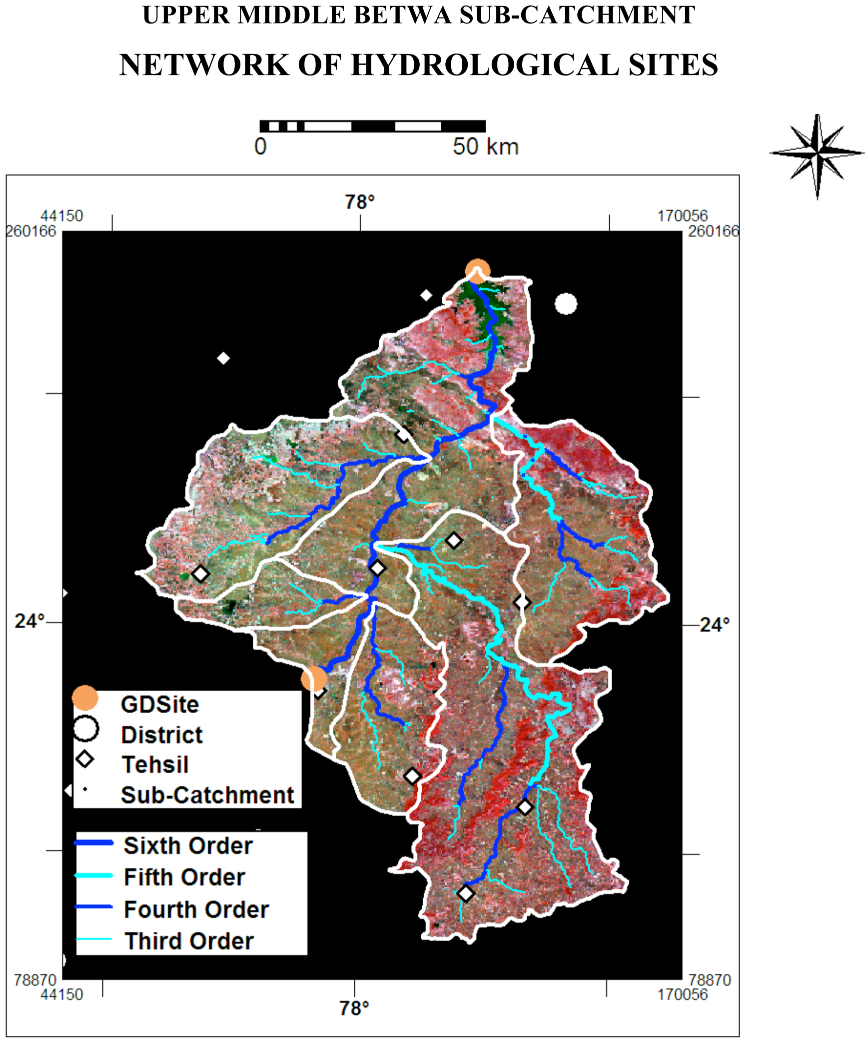



**Figure 8:** Drainage order-wise hydrological sites and administrative headquarters

## 5. Conclusion

A brief survey of the existing hydrological data collection stations not only helped in the understanding of the process of measurement, but also in conceptualizing the real problems before designing an optimum network. The site of stations, accessibility, cost and maintenance of the data record are thus essential parameters. Automatic data collection instruments, electronic storage, and relative ease of their use in remote areas are still a proposition of scientists. The current density of all types of data network especially full-fledged climatological stations, gauge and discharge sites and water quality stations is much lower than the minimum standards.

A combination of socio-economic information with the physical criteria in hydrological design provided significant practical choices not only for their location but also for their relative importance and utility. With the availability of detailed information at micro-level through satellite images, an appropriate strategy of rationalisation of hydrological data network can provide a long way in water resource planning. Pixel-size, real-time monitoring and stochastic behaviour of hydrological phenomena have demonstrated their effect both at sub-catchment and watershed level.

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