Designing Representative Groundwater Sampling of Mahakalapara Block, Odisha: A Comprehensive Hydro-geologic Analysis by GIS Approach

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***Abstract* – Representative groundwater sampling points to the approximation of subsurface aquifer systems cardinally with respect to identifying and monitoring the extent of human or natural contamination. The present study takes into account the hydrological, topographical and geological setting of the area of interest in establishing the sampling locations. Besides these natural influencing factors, the study looks into the cultural set up of the human habitats and its interrelationship with the subsurface water elemental variation. Analysis of the existing geological record of Geological Survey of India and the Shuttle Radar Topographic Mission DEM information coupled with the reconnaissance survey of the area, the research proposes 88 discrete sampling locations which can replicate the subterranean water chemistry of the concerned aquifer systems.**

Key Words – Groundwater, Sampling, Aquifer, Hydrology, Topography, SRTM

I. INTRODUCTION

Water is one of the vital natural resources influencing the development as well as destruction of human civilization [1,2]. It is beyond the fact of establishment that water is the cardinal factor behind the economical prosperity as well as the ecological diversity of the adjacent human habitat [3]. The world water estimate points to approximately 97.4% as saline type trapped in the vast oceanic expanses, while out of the rest 2.6% of fresh water, only 0.592% occur as groundwater in subterranean aquifers. However, from the point of view of portability with regard to domestic, irrigation and industrial human activity, the exploitation of this natural resource has seen an ever increasing significance with both space and time.

Groundwater hydrology is the study of occurrence, distribution and movement of subsurface water while hydrogeology gives a greater emphasis on the geology of the terrain concerned [1]. It is a very important cog in the hydro-geochemical cycle and is of prime importance with respect to human engineering, geologic and water supply endeavors [1,4]. Therefore, the quality evaluation of groundwater assumes a greater significance which needs the measures of chemical, physical, biological and radiological to be established. This in turn, points to the proper sampling procedures as well as the concerned evaluative analytical protocols to be established of which, the former is the basic step towards the groundwater quality survey and monitoring program [1].

The present research deals with the subsurface aquifer systems of Mahakalapara block, Kendrapara district, Odisha along the east coast of India with regard to the groundwater quality survey. The area of interest belongs to the vast flood plains of the Mahanadi delta and the coastal alluvium deposits along the Bay of Bengal. As the groundwater quality is influenced by both natural such as the geologic and hydrologic conditions and anthropogenic factors, we have analyzed the Shuttle radar Topographic Mission (SRTM) Digital Elevation Model (DEM) data for hydrologic interpretation, existing geologic conditions and the cultural set up of the study area in establishing the representative sampling locations of the area as a first step towards the geochemical evaluation of the concerned aquifer systems. The aquifer systems of the area are assumed to be very dynamic with regard to spatial elemental variations as it sits by one of the major industrial hubs of the state of Odisha as well as having a very close proximity to the confluence point of River Mahanadi with the Bay of Bengal. To the best of our knowledge, no research has been undertaken till date for the establishment of representative sampling sites with respect to the above terrain.

II. REPRESENTATIVE GROUNDWATER SAMPLING

Although, the need for specific scientific basis for groundwater sampling is felt for years, much of it has been designed during the last few decades primarily by the United States Geological Survey and the United States Environmental Protection Agency [5,6,7,8,9,10,11,12]. Whereas the bulk of the research has been in relation to the monitoring strategy, the fruitfulness of the different methodologies has attracted little attention [13]. Much of the groundwater dynamics study in western countries have been based on the monitoring well data as well as the logging data of various sources which can be very time consuming and expensive as well. In contrast to this, the Indian scenario fundamentally differs from the outset itself due to the different socio-economic as well as hydrogeologic conditions.

Groundwater sampling points to the collection of certain volume of water along with its constituents from subsurface which can be interpolated to define the physical, chemical or biological characteristic of the concerned aquifer system depending on the project objective [14]. However, the physico-chemical or biological evaluation of the subsurface aquifer system is rather more complex and uncertain than that of the surface water systems [14]. Representative groundwater sampling is one of the cardinal aspects in any system characterization which governs the accuracy, precision and quantization of the final result [14]. In other words, this points to the basic step of defining the aquifer system itself which is very qualitative and scale dependent [14]. In general, most aquifers are locally isotropic but are rather anisotropic on a regional scale and the former characteristic is desired for various assumptions in order to properly evaluate the concerned groundwater basin and dispersion phenomena [14]. As each body of water, whether static or mobile, has its own characteristic associated set of dynamism, establishment of single sampling site will not suffice the proper interpretation of the whole system [15]. Hence the statement of Mudroch and MacKnight regarding sediment sampling which states *"There is no formula for design of a sediment sampling pattern which would be applicable to all sediment sampling programs"* can also be extended to the subsurface water systems as well [16].

However, collection of "representative" samples is very difficult when there is a higher emphasis on the reliability and for subsurface water systems it should accurately point towards the *in situ* conditions of the aquifer at the time of sampling [13]. The two criteria for representative sampling are (a) a prior knowledge about the system in concern and (b) the comprehensiveness of the sampling and analytical procedures to be followed [13].

III. Study Area

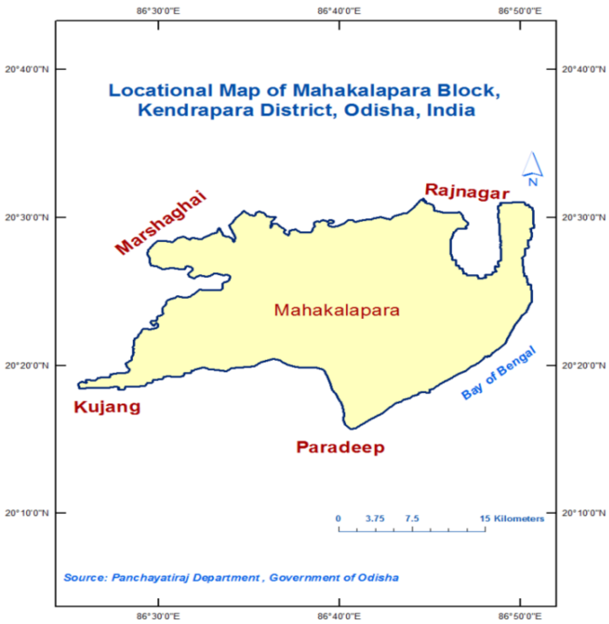

Fig. 1 Physical and political setup of Mahakalapara block, Kendrapara district, Odisha, India

The present research deals with the aquifer systems of Mahakalapara block, Odisha along the east coast of India (Fig. 1). The area encompasses an area of approximately 600sqkm. having a perimeter of about 195km. It lies to the north of the Mahanadi River which merges with the sea in a short distance and also engulfs the total area of the concerned region within its vast expanse of floodplain. Opposite to the area of interest along the Mahanadi River, situated is the Paradeep port to the southeast side which is one of the major industrial hubs of Odisha. In contrast to Paradeep, Mahakalapara has not witnessed the development of a single industry till date and most of the population depend on the port services and agriculture for their livelihood. The study area is bounded by Kujang block of Jagatsinghpur district on south-west and Marshaghai and Rajnagar block of Kendraparadistrict on northwest and northeast respectively. The area has an extent of approximately 86.26^0E to 86.51^0E longitude and 20.16^0N to 20.31^0N latitude. The Bay of Bengal forms the east coast of the study area facilitating the growth of mangrove forests along the coast line.

IV. Materials and Methodology

Representative groundwater sampling points to the collection of discrete samples which accurately and precisely reflect the geochemical properties of the aquifer system in concern. First and foremost is the purpose of the geochemical investigation of the groundwater which is primarily carried out in order to identify the contamination of the subsurface water that may harm the public health. Therefore, the cultural set up of the study area assumes a greater significance for representative sampling and this aspect can also point towards the anthropogenic influence as well. However, as the groundwater flows very slowly underground it gets a greater time to interact with the rock and soil particles than the surface waters [1,4,14]. Hence the geology of the study area is of utmost importance in relation to the chemical constituents present within the groundwater and is the cause of natural contamination if any. Finally, While the subsurface conditions govern the distribution and movement, it is the hydrologic conditions that furnish water to the subsurface aquifer system [1]. This is the reason why, water table normally corresponds to the water level of local hydrologic features such as lakes, streams etc. and its fluctuation to the region's rainfall, temperature, pressure, pumping rates etc. [4]. Similar to the surface streams which require slope for its movement, the water table needs hydraulic gradient for the set up of subsurface flow and most often than not, follows the overlying surface topography [4]. Hence looking at the above explained groundwater occurrence, distribution and flow characteristics, the following criteria were considered for the selection of sites for representative groundwater sampling:

1. Cultural set up
2. Geology
3. Hydrologic condition
4. Topography

A. Cultural Set Up

Looking at the cultural set up of India, we firmly believe that the representative groundwater sampling should be carried out from active tube wells (used by public on a daily basis) of the encompassed villages/towns of the individual basins which are concurrently used for public utilization. This aspect is categorically different from the followed practice of the western countries and the Unites States where the sample collection is primarily done from the purged established monitoring wells. One of the cardinal aspects to remember here is that, the monitoring wells are always pumped for a specific period of time before the sample collection in order to increase the related area of draw down or the cone of depression which forms around the monitoring well within the subsurface. This is the process by which the samples are assumed to be representative of a broader area of aquifer system eliminating the microscopic and local heterogeneity of the system both laterally and vertically as well. But, for the present area of interest, the active wells of the villages/towns hold greater significance than the establishment of monitoring wells as it is a highly populated area and unlike the more developed urban regions of the country there exists little public water supply systems for the use of local population. Moreover, we strongly believe that, the use of public active tube wells for sampling collection for geochemical evaluation of the aquifer system will have a greater representativeness as they will have a greater drawdown area or the corresponding cone of depression of the system because of their continuous pumping for the public use. Besides, the selection of multiple active public tube wells at the time of peak demand will account for the aquifer heterogeneity in a significant manner. This also holds true for the contamination aspect of the aquifer system as there exists no industry making any short temporal variation of water quality parameters negligible.

Looking at the physiographic and geomorphologic as well as the land cover and land use map of the study area and interpretations from a preliminary reconnaissance survey of the block it was found out that the northern and northeastern region are covered by vast tracts of mangrove forests and coastal sand dunes (Fig. 2). Hence for the selection of representative groundwater sampling, the above two parts of the study area were not taken into consideration.

B. Geology

The concentration of dissolved material in groundwater is normally greater than that of the surface waters due to their greater exposure to geologic strata [1]. The type and concentration of the salts do depend on the mineralogical characteristics of the aquifer and their solubility as well. A detailed analysis of the geologic setting of the study area was done based on the geological map which has been established by the Geological Survey of India for the state of Odisha (Fig. 3). The map displays the presence of primarily three types of geologic formations covering the total study area including Kaimundi Formation, Burahbalang formation and the Bankigarh formation. All the three types of formations belong

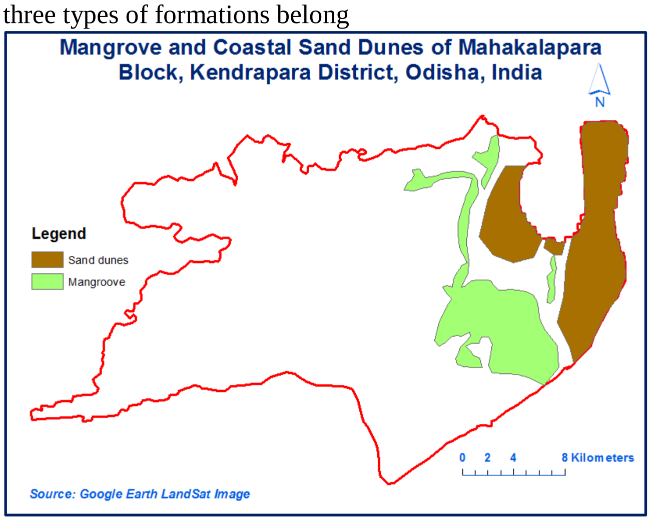

Fig. 2 Land Cover map of Mahakalapara block, Kendrapara district, Odisha, India

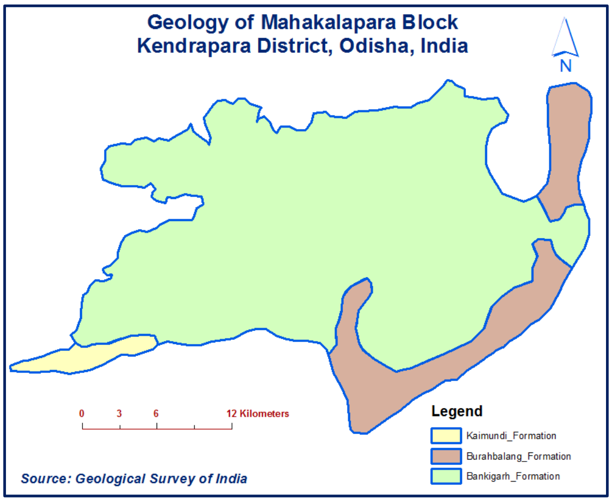

Fig. 3 Geological map of the study area

to the fluvial and marine type of sedimentary alluvial deposits. The Kaimundi or Sijua formation consists of hard greyish green clays with calcareous nodules. Clay is one of the common aquicludes present in the sedimentary deposits. The Bankigarh formation occupies a considerable part of the study area and consists of old sand dunes, marine clay, fluvial silt or clay and deltaic deposits. The eastern region of the study area points to the presence of two distinct belts of Burahbalang formation where the lithology is of sand silt in alternating flood plain layers, recent sand dunes and marine deposits. There have been research reports of salt water intrusion of the study area by various government agencies as well as different independent researchers. Hence, most of the tube wells for public use have been installed by the concerned government department and the approximate depth of the tube wells is 700ft to 800ft (as told by the local people). Therefore it can be safely assumed that the active tube wells account not only for the lateral heterogeneity but also for the layered vertical lithological variations too. As the Bankigarh formation of the extreme north eastern side is devoid of any human habitat and lies along the sea coast, it was not considered for the representative groundwater sampling. However, the rest of the formations are assumed to influence the aquifer geochemistry in a significant manner and hence were given due priority for the selection of sampling site in combination with the hydrologic basins present within the study area.

C. Hydrology

The hydrology of the study area was analyzed from the shuttle Radar Topographic Mission (SRTM) data acquired from the CGIAR Consortium for Spatial Information, United States (CGIR-CSI) [21]. The SRTM data acquired is a level 4 resampled Digital Elevation Model (DEM) of the study area with a resolution of 30m X 30m. This DEM was analyzed with the spatial Analyst environment in ArcGIS 10 for the depiction of hydrologic basins present within the area of interest. The extension calculates the flow direction of a drop of water for each cell taking into account the elevation value of that particular cell in relation to the surrounding cells. From the estimated number of cells contributing the water to an individual cell, it generates the flow accumulation values for each cell which finally gives rise to the production of different stream paths present within a corresponding basin (Fig. 4) beyond a threshold value.

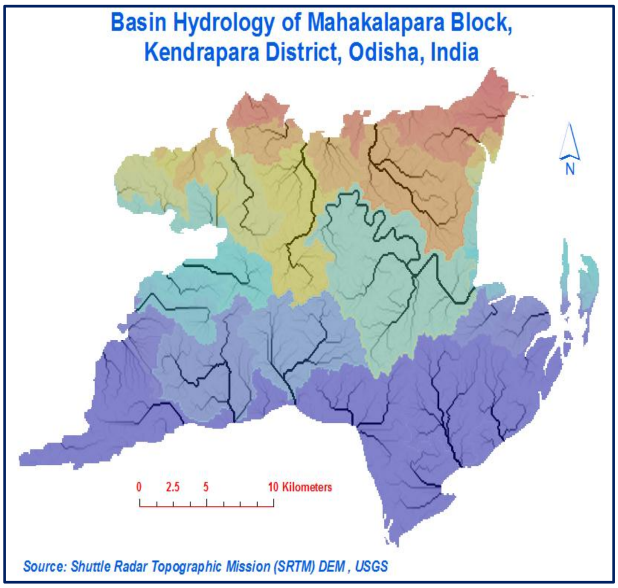

Fig. 4 Hydrological basins of study area

The hydrological basins of the study area were also demarcated based on the flow direction values of each cell within the DEM.

D. Topography

The topography of the area was established from the elevation values of the SRTM DEM. In GIS environment the different elements of the topography including slope, aspect and curvature of the terrain were established. The slope map of the terrain depicts the gradient or inclination of the place between two points. A look at the elevation map from the DEM illustrates the study area to be a very low lying area (Fig. 5). This fact is amply supported by the slope map with two predominant minimum and maximum values of 0^0 and 90^0 (Fig. 6). The lowest values represent the stream channels whereas the maximum value close to the vertical is displayed by the flat lying areas.

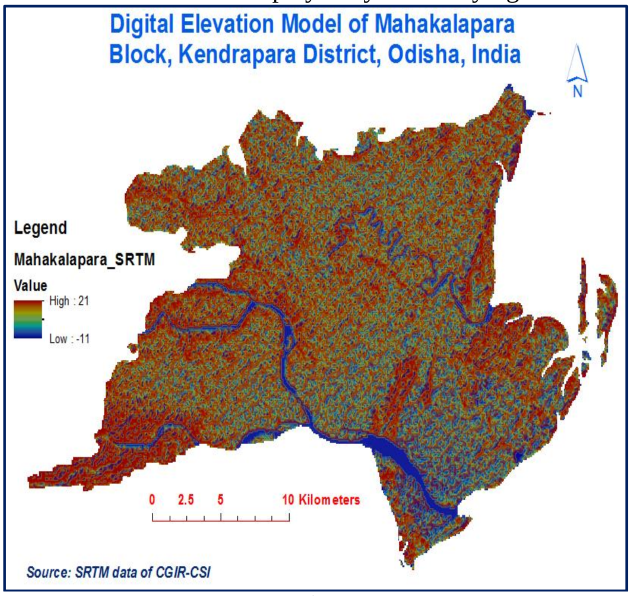

Fig. 5 Elevation map of the study area topography

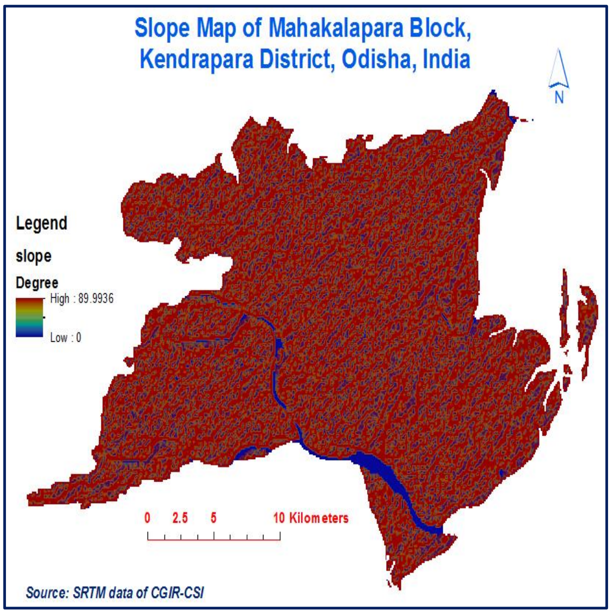

Fig. 6 Slope map of study area topography

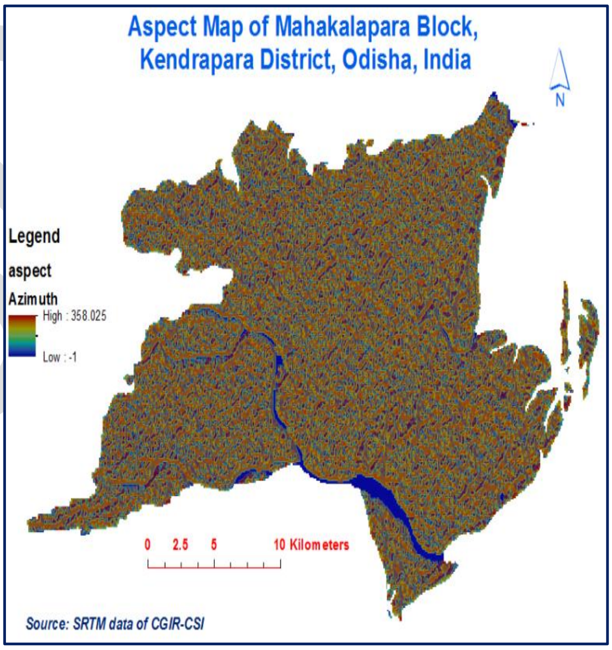

Fig. 7 Aspect map of study area topography

The aspect map of Mahakalapara also gives a similar trend as that of the slope map with a prominently east facing topography which is evident from the physiographic setting of the terrain (Fig. 7).

The curvature map depicts the second derivative of the slope of the topography or in other words it points to the acceleration or deceleration of the flow of water along the slope. This third element of the topography also gives a similar view to that of the slope and aspect of the terrain. The curvature map of the terrain gives a very homogenous or isotropic view of the study area (Fig. 8). In a nut shell, the three elements of the topography points towards a very gently sloping eastward facing terrain merging with the Bay of Bengal in the east.

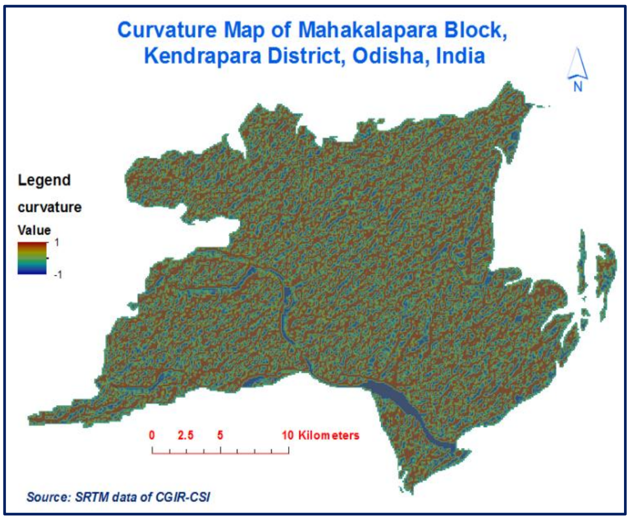

Fig. 8 Curvature map of study area topography

V. RESULTS AND DISCUSSION

Based on the type of occurrences, the unconsolidated alluvial aquifers are categorized as water courses, buried valleys and intermontane valleys [1]. The area of interest for the present study classifies itself into the first category as the aquifers form and underlie the various distributaries of the river Mahanadi as well as forming its floodplain too. Permeable strata bordering the streams are recharged in a significant manner due to the infiltration from the streams to the underlying aquifer system [1]. Hence the adjacent areas of the streams can be assumed to be maximally prone to natural contamination if any and can be treated as possible representative groundwater sampling sites for water elemental variation. However, as discussed above, the number of sampling locations can be evaluated based on the relative volume of the corresponding hydrologic basin.

The common three types of geologic strata encountered during groundwater flow evaluation are (a) porous media; (b) fractured media and (c) fractured porous media [13]. An analysis of the various lithological units present within the study area points to the existence of porous aquifer systems within the terrain. The primary lithological units are sand, silt and clay, both of fluvial as well as marine origin. This geological setting of the study area points to the sampling of each type of formation in concordance with the hydrological set up to properly represent the groundwater chemistry. Of significant importance will be the clayey formation at the southwestern part of the study area as well as the selection of deep bore well within a densely populated site. While the former can give clue about the possible presence of any perched aquifer system, the latter can account for the vertical heterogeneity of the subsurface strata with a wider cone of depression.

As discussed above, the water table follows the surface topography in low frequency areas (topographic variation is less). As depicted from the topographic maps (discussed in the previous section), the study area is devoid of high undulations and water table can be assumed to replicate the topography with greater lateral homogeneity (looking at the alternating sand and silt layers in the flood plain). However, the associated vertical heterogeneity should be accounted by the selection of multiple sampling sites with deep tube wells.

Keeping all these aspects in mind a reconnaissance survey of the study area was carried out with a Garmin Nuvi 250 Global Positioning System (GPS) to acquire the positional information of the potential representative sampling locations. The reconnaissance was done according to the Survey of India toposheets (F45U45 and F45U11) as well as with the help of few local people of the region. Various thematic GIS maps prepared from the existing geological records of GSI and from the analysis of the SRTM DEM data were overlaid to get a perspective synoptic view of the hydrological and geological setting of the area and their interrelationship with the existing cultural set up. As displayed by the land cover map of the study area (Fig. 2), the eastern as well northeastern part of the research site is scarcely populated and moreover inaccessible for groundwater sampling. The same is also somewhat the

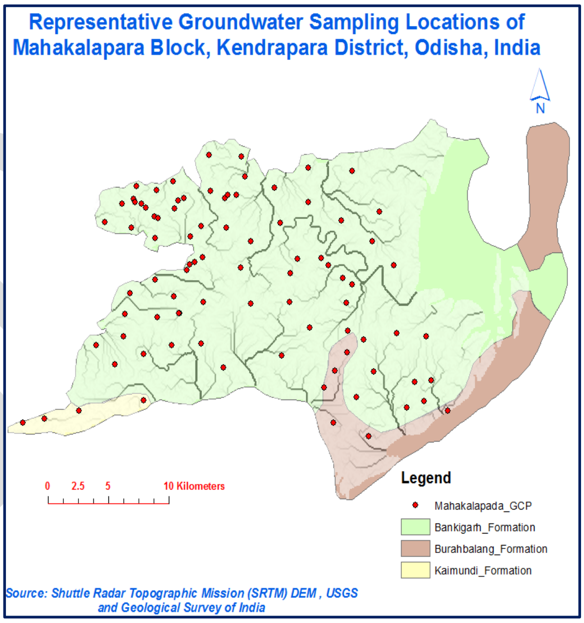

Fig. 9 Representative sampling locations of study area

case for southeastern portion of the study area which is kind of detached from the mainland and hard to access. Hence, the above mentioned two regions were not selected for representative sampling due to the scarcity of deep tube wells and the sea water intrusion of the shallow aquifers from the existing literatures as well [23]. The clayey formation of the study site occur in the form of a linear lensoid outcrop towards the extreme southwestern part and hence four sampling locations were selected in a east west direction to represent the geochemistry of the subsurface aquifer system. Rest of the study site is underlain by the Bankigarh formation and representative sampling locations were selected within the heart of the cultural set up i.e. villages or towns having proximity to any kind stream channels, canals or water bodies. A total of 88 sampling locations were identified for the water chemistry prospecting of the subsurface aquifers which have been plotted against the hydrological and geological setting of the study area (Fig. 9).

VI. CONCLUSION

The present research looks into the selection of representative groundwater sampling locations for the geochemical analysis of groundwater in Mahakalapara block, Kendrapara district, Odisha. The analysis took into account the geological setting of the study area (based on geological map of Odisha acquired from GSI), hydrological aspect as derived from SRTM data as well as the topographical elements, in identifying the representative sampling locations. The study establishes the use of active public tube wells (as opposed to the monitoring wells) within the densely populated area for the collection of samples. Looking at the hydrology as well as geology of the individual basins, it is proposed that collection of samples from deep tube wells from the surrounding flood plains of the stream channels can account for the microscopic as well as vertical heterogeneity of the aquifer system.

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