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Subsurface Contaminant Transport Analysis for Flowpath Direction in Katni Watershed, Madhya Pradesh, India Using GIS and Groundwater Modeling Approach

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Abstract

The current study aims to identify the pathways of pollutants and travel time of contamination using Remote Sensing and GIS approach. In sight of this, to evaluate hazard, groundwater contaminant transport is analyzed by using the ground water model in Katni River watershed. Darcy flow and velocity have been used for contaminant transport analysis, which is one of the components of Arc GIS in Groundwater module extension. Modeling tools such as Kriging, Darcy Flow/Velocity and Linear Directional Mean were used to identify the groundwater path lines and travel time. The analysis was done by taking into account of vulnerable areas, the location of contaminant sources and infected wells and their well field. The hydro-geological properties of underlying rocks along with surface and groundwater elevation are also considered by simulations, found that flow lines intersect with the Katni River in numerous places and flow lines converge towards wells in the study area, implying contaminated water is carried to these areas from all directions. Consequentially, the quality of the surface and groundwater is determining the quality of water in the wells

Keywords: Contaminant Transport Analysis, Pathways and Travel Time, Groundwater Flow Model, Darcy Flow, GIS, Kriging

Introduction

Water is the most essential natural resource for human existence. Therefore, the need for managing water resources is decisive and even more pressing since there is an enormous development in industrialization within and around cites (Andualem and Demeke, 2019; Jha *et al.*, 2010). Joji *et al.* (2022) studied the Characterization of typical complex Hydrogeological condition of structurally disturbed shear zone areas of Palakkad district in Western Ghats Region, Central Kerala. The hard rock terrains have been structurally controlled by shear a zone, which facilitate to develop numerous fractures and becomes potential repositories of groundwater Groundwater contamination is a hidden surface-subsurface process, which is not directly visible from the surface. It can be noticed only once a spring or a well becomes contaminated, or the contaminant is released into surface waters (Jang *et al.*, 2017). The method to envisage the groundwater flow rate and direction and contaminant transport in the aquifer systems, further facilitates the planning and implementing of contaminated aquifers (Limaye, 2003). Singh *et al.* (2015) studied the Groundwater contamination and vulnerability in urbanized areas are of major concern and need proper attention. Several models including the modified-DRASTIC/DRASTICA model are used to evaluate groundwater vulnerable zones to pollution where anthropogenic contamination is high, particularly in and around urban centers. Several researchers have investigated subsurface aquifer parameters, hydrogeochemistry and groundwater contamination assessment using GIS based Modeling approaches (Maqsoom *et al.*, 2021; Singh *et al.*, 2015; Naghibi *et al.*,2017).The groundwater models may act as a prognostic tool to perform analysis of the subsurface groundwater regime to determine the impact of present scenario as well as the future conditions. These tools can be used for developing management standards and guideline as screening tools in autocratic mode (Bedient *et al.*, 1994). The similar studies are already undertaken by various researchers to prepare a groundwater flow and contamination transport model to comprehend a groundwater regime for various part of India such as upper Palar basin, Dindigul town, Tamil Nadu (Mondal and Singh, 2005). Groundwater models are affected by choice of interpolation method and by sample size of which the interpolation is based on. In addition to the elevation of the geological layers, the data from the groundwater wells was used for simulation of the groundwater models. For the wells with

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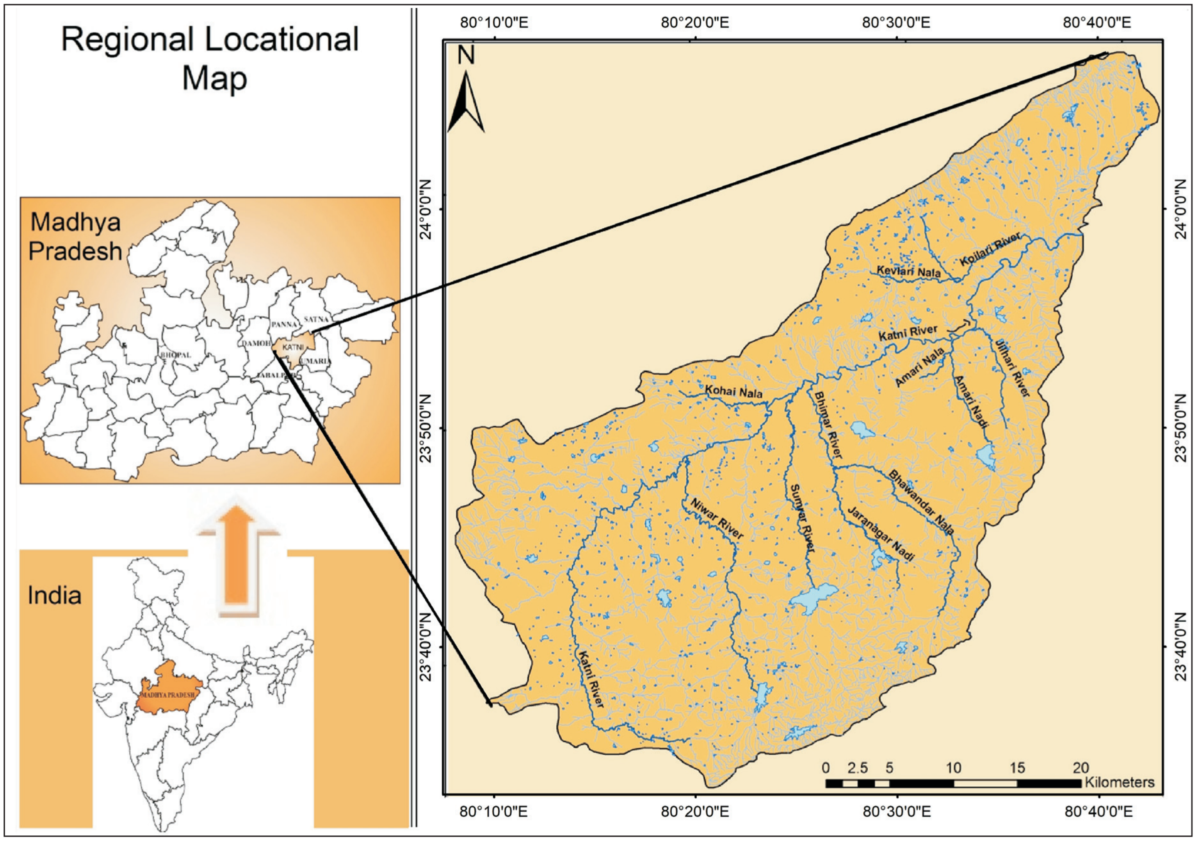

Fig.1. Location Map of the study area

several measures of groundwater level, the mean value was used for defining the groundwater level in the models (Agerberg, 2020).

Remote sensing is a valuable tool in the acquisition of spatially distributed data for groundwater modeling (Ganapuram *et al.*, 2019). It facilitates mapping of faults and dikes, litho types, geomorphological units *etc* (Doll *et al.*, 2000; Danielsen *et al.*, 2003; Jorgensen *et al.*, 2003). This information is very useful to prepare realistic conceptual models with regard to the aquifer system (Al-Adamat *et al.*, 2003). GIS is another valuable tool in developing conceptual models to solve any groundwater flow and contaminant transport analysis (Ibrahim and Ahmed, 2016). GIS offers enormous tools for data management and spatial analysis that gives extensive inputs in groundwater modeling (Naghibi *et al.*, 2017; Pourghasemi *et al.*, 2012).

This study intends to understand the echelon and trend of contamination and travel time of contaminants as well as to delineate the path lines of contamination. As surface and groundwater are intimately linked to each other, there might be leakage from the highly polluted Katni River.

The depth and pumping rate of usable wells pertain to quality of well water in such areas. The Katni watershed is densely fractured by lineaments. As a consequence, permeability and transmissivity of rock matrix are high, facilitating accidental and/or deliberate introduction of contaminants into the aquifer (Iwanoff, 2006). The subsurface features, *i.e.* porosity, permeability, saturated thickness, hydraulic conductivity and transmissivity of existing litho units of an area are key indicators for simulations of contaminant transport analysis (Tenalem *et al.*, 2005). By analyzing these parametric modeling of dispersal of contaminates has been the pursuit of generating surfaces in GIS environment by using Kriging interpolation model. Although, Contaminant transport analysis model has been generated using Darcy Flow-Velocity in GIS Environment.

The current study can be functional in constructing a working model for solving similar problems elsewhere in the country as well as establishing precautionary strategies and control further expansion of groundwater contamination. Therefore, contaminant transport analysis in wells which are evidently susceptible by increasing industrial waste or other likely activates is not only a timely speculation but also a robust tool in resolving issues of safe drinking water.

Materials and Methodology

Data and Study Area

The study area comprises watershed of river Katni which flows in the Katni district and further meets within the Mahanadi River, covers an area of 1480.4 sq km, between 23°34'53" N to 24°06'07" N latitudes and from 80°10'29" E to 80°41'38" E longitudes (Fig. 1). Geologic map of the study area is prepared by the visual interpretation of satellite IRS 1C LISS III data of October 2015 keeping in the view district resource map of Jabalpur district prepared by the Geological Survey of India.

Fourteen observation wells of the Central Ground Water Board (CGWB) fall in the study area. Groundwater samples from these wells are collecting and chemically analyzing by CGWB every year. This Periodic groundwater quality data from the year 2007 to 2017 has been considered. There are sixty six open-cast mines lie in the study area, out of which most of them are of limestone and dolomite excavation and few of fireclay, bauxite and Laterite. These data have been collected from the Directorate of Geology and Mining, Katni, M.P. The rainfall data provided by the Indian Metrological department, Hydro-Metrology division, New Delhi is utilized to analyze amount of precipitation. The data related to ground water level, subsurface geology and thickness of the stratum for the well locations referred from the Central Ground Water Board (CGWB), Bhopal and Public Health Engineering (PHE) Katni, Madhya Pradesh.

Methodology

In pursuit of the overall objectives, the present study followed scientifically approved procedures and measures for on-screen mapping and strategic explanation that focused on literature review and appraisal of preceding studies, field work that include site observation and verification of previous geological map, including structural features of the area and its hydro-geological setting, post-field work that encompassed revision of geological and hydro-geological maps and evaluation of all data.

Hydro-geological Settings

To study of groundwater contamination, various measures have been taken place by using temporal data of all possible parameters from year 2007 to 2017. As Katni area having Ca^{++} and Mg^{++} rich underlying rock like dolomite, limestone, laterite and clay with caliche concretions *etc*, consequently, allows salts to seep through porous media and increase the hardness of water. Moreover, the excavation of limestone, dolomite, bauxite and laterite is posses susceptible for high values of Ca^{++}, Mg^{++} and TH (Total Hardness) in groundwater leads to pollution. Therefore, groundwater contamination is assessed by considering Ca^{++}, Mg^{++} and TH (Total Hardness). The present study covers the location of fourteen observation wells along with different mines overlaid on underlying geological formations (Fig.2).

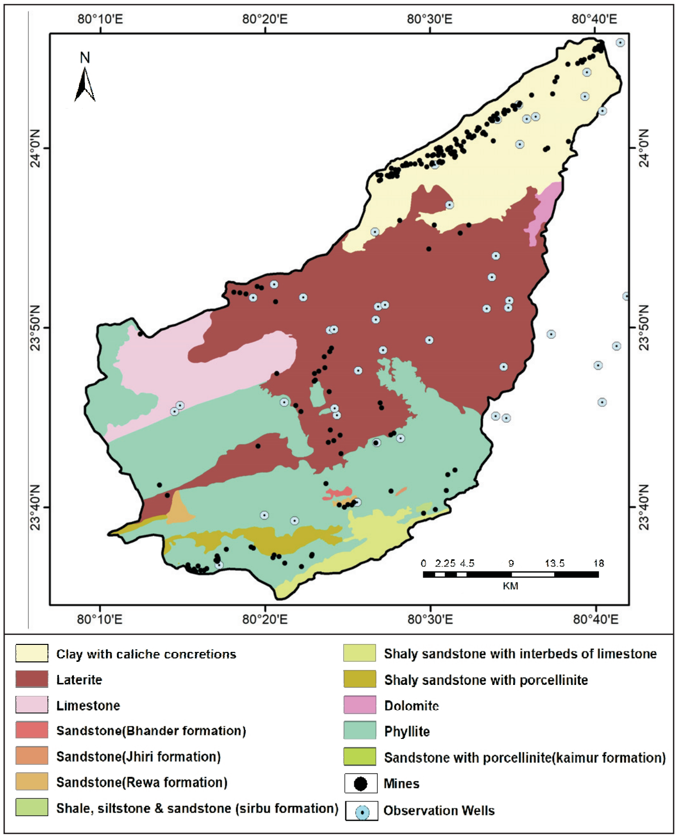

Fig.2. Lithology overlaid by Mines and Industries

The amount of precipitation affects the amount and rate of percolated groundwater and dissolved chemicals, which is directly related to extrapolate the risk of contamination in aquifers. 3D Digital Elevation Model of the study area constructed from SRTM map using an Arc scene module of ArcGIS software for topography and groundwater flow direction analysis (Fig.3a) and the comparison of ground surface elevation and elevation of ground water level at respective well location of the area that have spatial variant (Fig.3b).

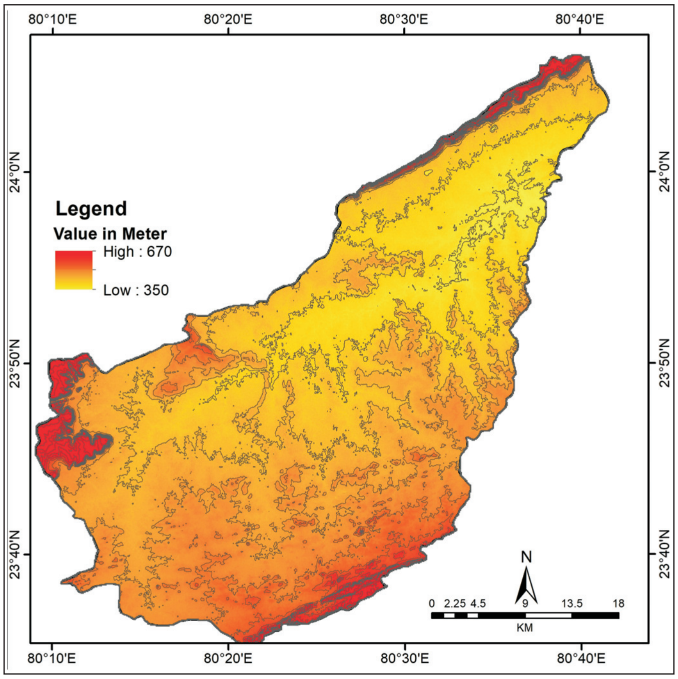

Fig.3a. 3-D Digital Elevation Model shows relation of topography.

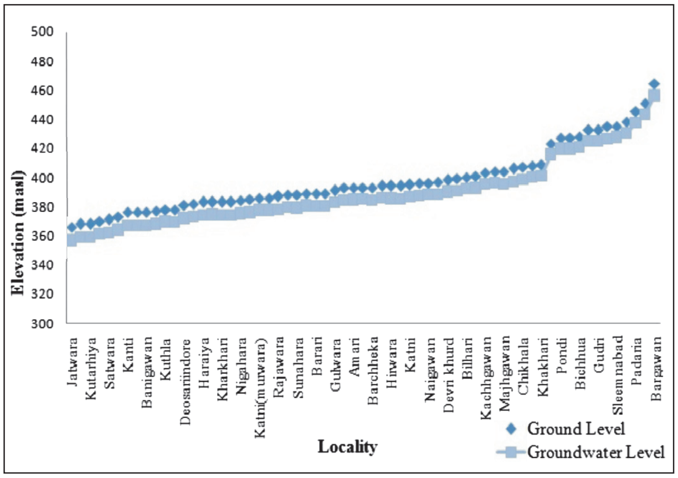

Fig.3b. Comparison between Surface Elevation and Groundwater level

Table 1: Temporal variation of values of Ca^{++}(Calcium), Mg^{++}(Magnesium) and TH(Total Hardness) (*After* Department of Public Health and Engineering (PHE), Katni, Madhya Pradesh, 2017)

Village	Ca^{++} values(mg/l)						Mg^{++} values(mg/l)						TH values(mg/l)					
	2007	2009	2011	2013	2015	2017	2007	2009	2011	2013	2015	2017	2007	2009	2011	2013	2014	2017
Deogawan	110	118	132	122	12	58	24.5	16	25.7	20	75	26.8	375	395	400	385	340	255
Katni	54	104	68	65	18	46	15.9	15.9	19.5	17	44	45.0	200	325	250	210	225	300
Majhgawan	38	36	20	12	14	32	15.8	6.1	3.7	7	9	48.7	160	115	65	60	70	280
Piparia	92	54	116	104	20	110	24.4	4.9	26.9	7	32	10	330	155	400	290	180	300
Barchheka	48	66	50	42	22	18	3.7	1.3	1.3	4	17	60.8	135	170	130	120	125	295
Basadi	48	62	34	8	14	66	13.4	2.5	3.7	1	4	20.8	175	165	100	25	50	250
Barhi	100	120	170	100	12	44	28.1	24.5	14.8	35	75	57.2	365	400	485	395	340	345
Kewlari	82	80	84	60	12	80	26.8	24	22	38	62	32	315	327	300	305	285	330
Lakhapateri	124	68	40	44	22	22	30.5	8.6	11	10	44	11	435	205	145	150	235	100
Umariapan	50	150	120	137	82	112	9.8	30.6	35.4	42	49	37	165	500	445	475	512	250
Sleemnabad	36	70	54	74	14	54	21.9	18.3	20.7	16	47	34.1	180	250	220	250	230	275
Rithi	204	114	234	58	8	28	120	52.4	72.0	18	133	15.8	324	500	880	220	565	135
Ubra	65	80	80	86	26	46	9	14.7	20.8	6	62	34.1	220	260	285	240	320	255
Badwara	22	42	14	62	12	50	3.2	5	7.31	26	74	28.0	47	52	65	260	335	240

Chatterjee *et al.* (2022) analysed major ions to understand the influence of geochemical processes on groundwater quality in Bamanghaty Subdivision of Mayurbhanj District, Odisha, India using Geospatial Technology. The Groundwater examined data of observation wells is collected for ten years, *i.e.* 2007 to 2017 (Table 1). The geospatial analysis has been conducted for Ca^{++}, Mg^{++} and Total hardness by Kriging interpolation model in GIS environment for considered years. The evaluation of interpolated surfaces provides an apparent image of areas having high grade contamination and area possessed risk in future and further used in modeling for groundwater contamination analysis. Rokade *et al.* (2022) stated that the hydrogeological system of the area is determined by its hydraulic parameters and aquifer recharge and discharge. In evaluation of the hydrogeological parameters of an aquifer, the storativity and transmissivity are the most important field parameters for quantitative understanding of the problems in hydrogeological regime. To identify the pathway and final destination of pollutants, it is necessary to describe the porosity, permeability, saturated thickness, hydraulic conductivity and transmissivity of litho units at well locations. The standard porosity values have been considered in the present study. Saturated thickness varies from 4.01m to 18.09m which depicts low values in the southern area and high values in northern and central area (Table 2).

Modeling Approach

Contaminant transport analysis was conducted by constructing Groundwater model in GIS. It is a three-layered process followed one after another. Firstly, to generate raster surfaces through vector data sets using "Kriging Interpolation module". Preceded by using these layers as input to create ground water flow vectors by using "Darcy Flow/Velocity module" and then lastly used "Linear Directional Mean module" to get overall flow direction in the study area.

Kriging

The Groundwater model is governed by driving the ground water elevation, formation porosity, saturated thickness and formation transmissivity using kriging interpolation model using Arc GIS-10.5.

Darcy Flow/Velocity Module

It is a two-dimensional model which works in regard to ensure the steadiness of groundwater datasets to generate flow vectors. The output raster calculates the flow field using Darcy's Law in GIS environment. Here flow is governed by variation between adjacent cells to create raster data set.

Linear Directional Mean

The overall flow direction has been derived by using Linear Direction Mean, an automated module in Arc-GIS.

Contaminant Transport Analysis

Darcy flow and velocity have been used for contaminant transport analysis, which is one of the components of Arc GIS in Groundwater module extension. It is assumed in Darcy flow path, that fluid properties are homogeneous and concentration changes do not significantly affect fluid density or viscosity and hence fluid velocity. Rate of pollution attenuation depends on the geology, local

Table 2: Hydrogeological Data (*After* Central Groundwater Board (CGWB), Bhopal, Madhya Pradesh, 2017)

Well S.No.	Water Level (m)	Saturated Thickness b (m)	Hydraulic Conductivity k (m/d)	Transmissivity T (m^2/d)
1	2.4	10.38	10^{-3} - 10^{0}	5.2
2	1.39	9.94	10^{-4} - 10^{0}	4.97
3	1.56	15.44	10^{-7} - 10^{-3}	0.008
4	1.36	9.34	10^{-7} - 10^{-3}	0.005
5	1.6	13.92	0.001 - 0.15	1.05
6	6.89	10.18	10^{-4} - 10^{0}	5.1
7	0.82	18.09	0.001 - 0.15	1.37
9	6.96	4.71	10^{-7} - 10^{-3}	0.002
10	6.55	9.44	10^{-3} - 10^{0}	4.73
11	2.35	6.68	10^{-3} - 10^{0}	3.34
12	2.84	7.66	10^{-3} - 10^{0}	3.83
13	3.22	4.01	0.001 - 0.15	0.303
14	4.2	6.3	10^{-4} - 10^{0}	3.15
15	5.84	9.36	10^{-4} - 10^{0}	4.68
16	1.92	6.21	10^{-3} - 10^{0}	3.11
17	2	5.53	10^{-3} - 10^{0}	2.77
18	1.4	11	0.001 - 0.10	5.5

hydro-geological situations, geochemical processes, and the type of pollutants. Contaminant migration facilitates by the weathered rocks along with associated structures which allows contaminant to reach the water table with percolating water especially in rainy season. Phenomena deplete the groundwater quality which conversely degrades surface water quality and vice versa. The study area telling the same story as the Katni River downstream is flowing from the main Katni city, where river bed is higher than ground water level, besides the cluster of industries exists too. Therefore, the area is highly susceptible to allow effluent to leach into the ground through fractured plains (AAWSA *et al.*, 2000). The pH, EC, TDS and Ca^{++} concentration in the groundwater also reflect the influence imposed by polluted surface water, implying the strong seepage of surface water into the groundwater system.

In the study, the significance is also given to slope as it determines the rate of runoff and degree of infiltration. Areas with gentle slopes like the central part of the study area are highly vulnerable to groundwater contamination. All possible sources of contamination like pulp, paper, pigments, brewing, textile, food processing, and meat packing factories; dairy farms, open-air slaughtering, quarries, lime kilns, dense settlements and open markets are widespread in the area. The Kaimur area (North East region under the present study) is a highly fractured, porous and permeable rock sequences, located on elevated topography posses much drinking water dug wells as well as boring wells. The site is being used as a limestone active mines and water filled excavated quarries. ACC cement and Everest India cement industries located on the way to Kaimur road adjacent to the Koilari and Kevlari streams. It is usually observed that quarry filled by cyan color water and release effluent to the stream, then crosses through the vast agriculture field then meets with the main stream. Similarly in the central part of the study area near Sumer and Bhirawar streams; where many industries release effluents, sewage line and sanitation system are also present which discards pollutants into the main Katni River.

The travel time for pollutants in the Katni watershed has been calculated by Darcy velocity, which uses Darcy flow to calculate the flow field. A flow field is a vector field of ground water seepage flow velocities. The present work clearly depicts the ground water path lines and overall path direction in the study area (Fig. 4).

Results and Discussion

The normal concentration of calcium in groundwater ranges from 10 to 100 mg/l (Nag, 2009). The basic sources of calcium are carbonate rocks, *i.e.*, limestones and dolomites, which are dissolved by carbonic acid in groundwater. The chemical breakdown of calcic-plagioclase feldspars and pyroxenes may be responsible for calcium in the groundwater (Ganyaglo *et al.*, 2010). In the study area, due to the high concentration of $Ca^{++}$and Mg^{++} deposits, the observation wells of Katni, Barhi, Umariyapan and Ubra villages depicts high values of Ca^{++}, Mg^{++} and TH (Total hardness).The village Rithi lies on the underlying rocks of sandstone of the Bhander Formation and depicts highest values of Ca^{++}, Mg^{++} and TH(Total hardness). These rocks are essentially made up of sandstone, shale and minor limestone with high primary and secondary porosity. These sedimentary rocks are also dominated by $CaCO_3$ component, fine to medium grained with minor shale intercalations which leads groundwater percolation (McFarlane and Bowden, 1992). Deogawan also depicts higher Ca^{++}, Mg^{++} and TH (Total hardness) along with the underlying shales with interbeds of stromatolitic limestone of the Sirbu Formation. Another major geologic unit is quaternary Laterite of recent to Pleistocene Cenozoic period. This Laterite rock is mostly a type of earthy soil, but it hardens into solid rock in the air. Some lateritic rocks (bauxite) deposit in vicinity of caliche depositions. The mining is usual here because some of bauxite has highest aluminum contents. These formations have extensive water-holding capacity, depending on the depth of the formation. Dissolution of primary mineral is there while percolation of water, which causes suspension of soluble elements such as sodium, potassium, calcium, magnesium, and silicon (GSI, 2010). Therefore, Barcheka, Pipariya, Basadi and Majhgawan depict very low values of Ca^{++}, Mg^{++} and TH (Total hardness) concentration in groundwater.

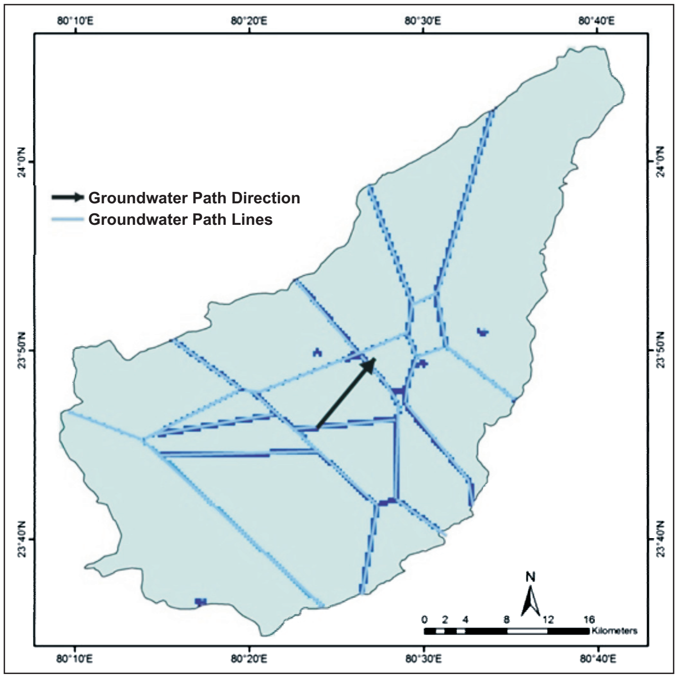

Fig.4. Groundwater Contamination flow Path

Depth to ground water varies from 0.82 to 6.96 (mbgl), which is very high in the northern part where mining and industrial sites present to large scale. The ground water flows from the Katni River towards NE portion and follow the topography of the area. The velocity ranges from 0.00006 to 0.004 meters per day. It is about 0.0007 m/d and 0.0004 m/d in the northern and southern parts, respectively. It is relatively high in the central part where aquifer posses high levels of pollutants. In most area they seem in a mixture of gradients of velocity vectors. Furthermore, in this areas ground surface exist with gentle gradient and litho units characterized by higher hydraulic conductivity or permeability. All factors collectively make possible the easy movement of contaminants in area. In Kaimur area, where maximum lime industries and water filled abundant quarries exist; factors like, the intercalation of limestone and sandstone with an intensive network of fractures and their close spacing allows easy groundwater circulation and contaminant migration in the area. In addition, due to high gradient slope, intensive erosion activities are prompt; there is a poor soil development on most of the parts of the slope which proves the lack of defense line to hydrogeological system. Therefore, the danger zones are the areas of rock exposures with no soil coverage and faulted zones. The Katni River shows wide channel and slow flow velocity that allows enough time for percolation of contaminants. The alluvial sediments of this area are also characterized by high water porosity and permeability. Therefore, the percolated contaminated water can move into the water table as well within the aquifer. Hence, there is the higher risk of contamination in shallow wells from the Katni River. The shallow groundwater level is susceptible to contamination. In the long run, the lowering of the water level due to pumping will change hydrological conditions at the bottom of the river and percolation of polluted water will increase in this area. Groundwater monitoring in the area shall be conducted considering their spatial distribution and proximity to the wells and how long the contaminants take to arrive at the well locations. The frequency can be dispensed as half of the travel time. Therefore, one can have at least half to a quarter of its full travel time to control the contaminant before it pollutes the whole aquifers.

In addition, if pollution is noticed in one area, the nearest wells should not be stopped because they can be used to control the pollution. Stopping pumping of polluted wells will let contamination in surrounding areas. Instead of stopping pumping, their discharge, under the preventive measure should be encouraged to disconnect the polluted water from aquifer system. However, the effect of contaminant migration is currently not at such large scale, the model developed in this study clearly depicts that contamination of the wells in the study area is forthcoming, unless strong scientific actions will taken by creating comprehensive groundwater protection policy followed by aquifer management strategies. The groundwater modeling can extensively use to analyze contaminant transport not only in existing as well as future scenarios, but also helps in town planning and simulate changes in concentration of contaminants.

As result it can be summarized that the Katni River has direct impact on the nearby wells that tap water from the alluvial layer as indicted by the intersection of contaminant path lines with the water level. In the study area, the groundwater flow lines converge towards central and north-east portion of the study area, implying that any contaminants are carried to these areas from all directions. Therefore, the quality of the surface and groundwater will determine the quality of water in the wells. The intensive pumping of groundwater from those areas will result in a rapid decline of groundwater levels, leading to disturbance in the steady state flow system of the groundwater, eventually higher the groundwater flow velocity.

Conclusions

This present study indicated that the wells of the Katni watershed are highly vulnerable to contamination from surface water and groundwater. This study potentially facilitates the rapid flow of contaminated water from upstream sections of the aquifer to the wells. However, the model indicates that water flow path lines with contaminated water injected at contaminant sources upstream will reach in the wellness field in less than 20 years time. Flow is not linear throughout the system. Although, it is more rapid where porosity and transmissivity are high and depends upon the orientation of tectonic fractures. In view of tackling the actual and potential contamination risks of the study area more effort should be made to conduct contaminant transport analysis considering chemical reactions, attenuation and multiple layer aquifer; effort should be made to create closed–loop water supply systems of industrial enterprises involving effluent reuse; to implement strict environmental policy with regard to industries. The comprehensive groundwater policy can control activities in potential polluted pockets and their buffer areas and closely monitor the chemical quality of groundwater in the watershed.

Authors' Contributions

D. Bhatnagar: Writing Original Draft of manuscript, Data Collection, Analysis and Interpretation of Results, Software Validation, Editing. **V. Singh:** Writing- Editing and Reviewing, Modify Original-Draft of Manuscript, Formal Analysis and Interpretation of Results. **S. Goyal:** Support, Conceptualization. **S. Tignath:** Supervision, Visualization. **D.K. Deolia:** Supervision, Visualization

Conflict of Interest

There is no conflict of interest involved in the present research work.

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