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Assessing the Risk of Arsenic Transport in the Upper Dupi Tila Aquifer of Dhaka City from the Surrounding Shallow Aquifers

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Abstract

Dhaka depends heavily on groundwater for urban water supply. Due to diminished recharge and over abstraction groundwater level has been declining alarmingly over the last two decades. Groundwater elevation contour maps depict a number of cones of depressions at heavy abstraction areas where regional groundwater flows are converging from all sides. Shallow groundwater in the districts surrounding Dhaka contain high concentrations of geogenic arsenic and as the groundwater level elevation is higher in these areas there is a risk of encroachment of arsenic enriched water to Dhaka city shallow aquifers. This study was conducted to assess the risk of arsenic transport to Dhaka city aquifers from the surroundings by way of conducting logistic regression modeling of arsenic transport. The study focused on in-depth assessment of hydrostratigraphy and surface geological information by way of using lithologic bore logs and GIS layers. Arsenic concentrations data have been used from available studies. Logistic regression approach based on relationships between surface data, hydrostratigraphic maps, depth and measured groundwater arsenic data is used to assess the relative importance of the indicators in the possible transport of arsenic contaminated groundwater towards Dhaka city. Initial 2D and 3D models developed indicate varying risk of arsenic transport in groundwater of the different parts of the city. Risks are relatively high in the areas to the southern and northern parts of the City where Holocene aquifer is present. Immediate management actions are needed to protect the currently arsenic safe aquifers from encroachment of arsenic risk groundwater from the surrounding districts.

1. Introduction

In terms of exposed population, groundwater arsenic contamination in Bangladesh is reported to be the biggest calamity in the world. It is estimated that 97% people depends on groundwater for drinking purpose while more than 70% irrigated area is served with groundwater sources (Hoque et al., 2007). The safe water access has fell down from 07% to 80% and has emerged as a matter of mass scale public health concern since arsenic has detected above Bangladesh Drinking Water Standard (BDWS) 0f 50μg/L (Hasan, 2008). Long term drinking of arsenic enriched water causes arsenicosis, melanosis, keratosis and progressively leads to cancers of skin and other organs (UN, 2001; Kapaj et al., 2006). Arsenic contaminated water is still preferable to rural people for drinking purpose to avoid the pollution with pathogens and other inorganic pollutants in surface water.

The Holocene alluvial fan deposits and Pliocene Dupi Tila sands serve the major aquifers in the country (after Uddin & Lundburg, 1998). The Holocene shallow aquifers at the lower reach of Ganges-Brahmaputra-Meghna (GBM) river systems are severely affected of arsenic compared to other geological settings. Through reduction dissolution of ferric oxyhydroxides, arsenic has entered the groundwater, to which it was absorbed during fluvial transport. Arsenic concentrations are associated with fine-sands and organic rich sediments. Near the water table, concentrations are low and it increase to a maximum 20-40 m below ground surface and fall to very low levels between 100-200 m (Ravenscroft et al., 2005). Arsenic enriched groundwater is detected in 60 districts of Bangladesh above WHO provisional guide line value of 10µg/L by the national surveys (BGS/DPHE, 2001; BAMWSP, 2002). The southern regions of the country covering the districts of Chandpur, Comilla, Noakhali, Munshiganj, Faridpur, Madaripur, Gopalganj, Shariatpur and Satkhira are the most contaminated parts. Contamination has also been found in the SW, part of NW, NE and North central regions.

Dhaka, the capital of Bangladesh, is located in the central part on the bank of River Buriganga. The city is the fastest population growing mega city in the world. The current population is in excess of 15 million, and by 2015 this may have risen to more than 20 million people (United Nations, 2010). For the urban water supply, Dhaka is depended on groundwater. 82% of the total supply (close to 1.25 mm^3/day), is provided by groundwater (William et al., 2011). With the increasing water demand groundwater abstraction is rising drastically in the recent decades. Extensive exploitation of Dupi Tila aquifer causes severe water level decline which has detrimental effect on groundwater quality (Ahmed et al., 1999). Rate of the depression in the piezometric surface has become nonlinear in recent years. All of the temporal contours indicate radial flow of groundwater from peripheral zone to the city centre (Hoque et al., 2007). In the year 2002, the maximum decline increased to about 46 m below the datum.

The Dupi Tila aquifer contains arsenic free groundwater. But the shallow aquifers in most of the area surrounding the city are highly contaminated with arsenic. Due to groundwater mining and formation of a huge cone of depression, arsenic may transport from the peripheral areas to the city by groundwater movement to the depression.

The study deals with the occurrence and distribution of arsenic around Dhaka and risk of arsenic transport in Dhaka city shallow groundwater in relation to the geological and hydrogeological aspects. It has been undertaken with a view to assess the probability of arsenic transport in the shallow aquifers (that is Holocene and Dupi Tila aquifers) in Dhaka city. The depth-wise arsenic distribution of the shallow aquifer as well as hydrogeology were measured to prepare the regression model of the groundwater. Through this research work, geostatistical logistic regression model is introduced, which is applied for the very first time in Bangladesh.

Recently, a research has been done using geostatistical model to detect arsenic pollution in the deeper aquifer in Hanoi city, Vietnam where Holocene aquifer was already contaminated to arsenic and now a day contamination is started to go further downward and pollute the deeper aquifer. Hanoi Pleistocene aquifer has already contaminated by arsenic which is a result of excessive pumping, not the hydro chemical reason. It has been suggested previously that oxidized sediments in Pleistocene aquifers have a significant capacity to attenuate arsenic over hundreds of years because of adsorption. But Vietnam research results indicate that this assumption might be proven wrong in situations where groundwater abstraction is pronounced (Berg et al., 2011).

Similar geological settings and depositional environments are observed in Bangladesh. In Hanoi City, groundwater extraction from the deeper Pleistocene aquifer began some 50–70 years earlier than in Bangladesh. Dhaka extracts groundwater from Dupi Tila aquifer which is of Pleistocene time and arsenic safe. The only difference is that Holocene aquifer of Dhaka is not contaminated to arsenic yet. But excessive groundwater extraction may contaminate the Dhaka city shallow aquifer by arsenic water from the surrounding area.

2. Study Area

The concerned area is Dhaka which is the 9th largest city in the world and also 28th among the most densely populated cities in the world (World Bank, 2010). The city is located in the central Bangladesh and is bounded by four rivers. It covers an area of more than 360 km² with a population of approaximately 16 million in 2011 (BBS, 2008). Dhaka is almost flat with some depressions. The central part of the city is occupied by the southern half of the Pleistocene Madhupur Tract. The rest of the area is covered by the recent floodplains of the Jamuna, Padma and Meghna Rivers. The surface elevation ranges from 1.5 to 15 m above the mean sea level. The city is well linked with the surrounding big dendritic patterned rivers by the interconnecting streams, streamlets, retention lakes ponds and canals (Sultana, 2009). DWASA is responsible for drainage and water supply of Dhaka city. According to EPC/MMP (1991), unconsolidated aquifer materials are terminated by the faults and Dhaka seems to be uplifted as a horst block. The rivers and streams flowing through these fault systems could have cut through the overlying clay aquitard and in some places may be connected with the aquifer by semi-permeable materials (Ahmed et al., 2009).

Hydrostratigraphy of Dhaka city is distinct like its geology. The Pleistocene Dupi Tila Formation serves the main aquifer that acts as a multilayer leaky aquifer effectively confined by semi pervious Madhupur Clay layers. The average thickness of this main aquifer is about 140m. A discontinuous clay layer divides the Dupi Tila system into two aquifers: an upper fine-grained aquifer (The upper Dupi Tila aquifer), 30–50 m thick, and a lower coarse-grained aquifer (The lower Dupi Tila aquifer), 80–100 m thick. The upper Dupi Tila aquifer is also subdivided into two zones in the most of the parts of Dhaka. The aquifer contains very good quality of water. However, conditions in the Plio–Pleistocene Dupi Tila sands of the Dhaka region are pervasively oxidizing, and arsenic concentration in groundwater from the Dupi Tila aquifer of Dhaka is less than 3µg/L (BGS and DPHE, 2001).

The aquifer of Dhaka city is mainly recharged by deep percolation of rainwater, direct infiltration and surface runoff during wet season. In addition, recharge across the city area will be influenced by the effects of urbanization and huge thickness of Madhupur clay layer above the aquifer. Groundwater abstraction is the main discharge. Dhaka WASA is tapping water from aquifers at depth between 50-220 m from the ground surface. Now DWASA is producing 1800 million litres per day as urban water supply through 575 deep tube wells (DWASA, 2011). The groundwater level of the upper Dupi Tila aquifer is decreasing day by day. Groundwater hydrograph of the Upper Dupi Tila aquifer demonstrates a steady downward slope and the depletion rate is about 2.5-3.5 m/year (IWM, 2008). Over abstraction changes the aquifer characteristics from semi confined to unconfined nature generating a mining situation. Groundwater moves in the direction of minimum hydraulic head and thus groundwater of Dhaka city moves towards the centre of city from the peripheral areas. The huge depressions in the water level exist within the city, centering in the abstraction areas, like Dhanmondi and Motijheel (Hoque et al., 2007).

3. Methodology

To fulfill the purpose, the study was carried out to use GIS technologies for constructing different maps (location maps, point maps, depth-wise surface geology maps etc.) to interpolate the hydrostratigraphy of the study area, to correlate the geology with the arsenic concentrations and to run the logistic regression models effectively, to analyze the outputs of the model and to interpret the results of the models.

47 borelogs were taken in the area where three logs were hypothetical ((logs made by manual cross-section) because there are some places where no scientific borelogs are available. 227 arsenic concentration points were considered for this area. The lithologs were converted to the hydrostratigraphic units. Only 150 m depth was considered because high arsenic

concentration is found in the shallow aquifer of which depth is less than 150 m. Based on the specific lithologs of the study area, the geology was interpolated at every 5 m intervals from 0 m to 100 m and 10 m intervals from 100 m to 150 m. And on every geologic layer arsenic concentrations were also included. These maps were used in the model as input parameters.

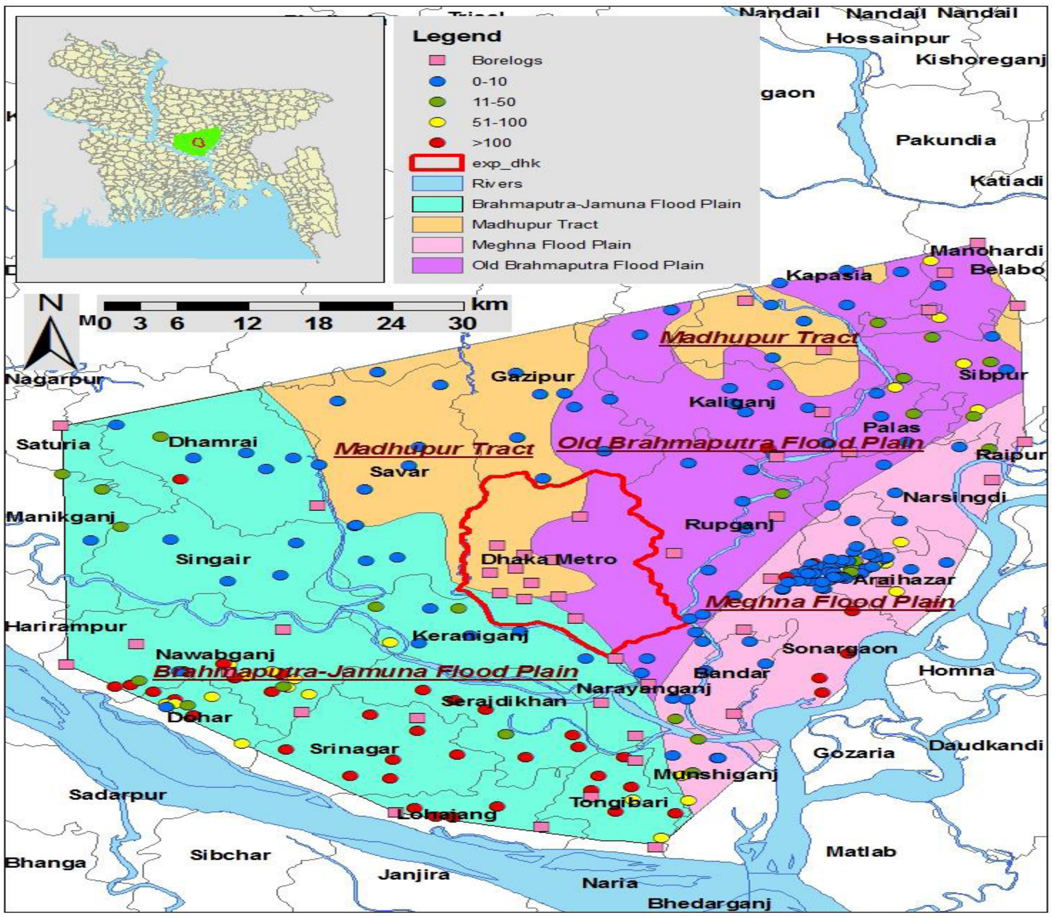

Fig.1. Map of the study area and the surroundings with the bore logs, geology and As-concentrations.

In statistics, **logistic regression** is used for the prediction of probability of occurrence of an event by fitting data to a logistic curve. Logistic regression is a non-linear regression method. It uses a set of binary distributions, such as presence or absence of a characteristic, to derive coefficients for an equation that calculates the probability that a new case is of a certain class (Amini et al., 2010).

Let P denote the probability that arsenic concentration exceeds the WHO guideline value. In logistic regression the ln(odds) is defined as the ratio of the probability that an event occurs to the probability that it fails to occur (or ln(P/ (1- P))), as a linear combination of independent variables.

$$Log\ (odds) = C + \sum_{i=1}^{n} \lambda i . Xi$$

where, C is the intercept of regression, Xi are influencing variables, and λi are the regression coefficients that are obtained using a maximum likelihood optimization procedure. According to the calculated odds, for example, the probability (P) of having arsenic concentration larger than the WHO guideline value is calculated as follows:

$$P = \frac{exp(C+\sum_{i=1}^{n}\lambda i.Xi)}{1+exp(C+\sum_{i=1}^{n}\lambda i.Xi)}$$

Arsenic prediction models were obtained by: (i) binary coding of Arsenic groundwater concentration data (dependent variable), using the WHO guideline value for arsenic in drinking water (10 μgL−1) as a threshold; (ii) conducting logistic regression; and (iii) calculating the probability of arsenic contamination based on the threshold value. Well depths were expressed relative to the mean sea level (Winkel et al., 2011).

Four models were developed where two were 2-dimensional and two were 3-dimensional. Arsenic concentration was considered as a dependable variable; Hydrostratigraphy, depth and surface information were considered as independent variables. For each model, variables were different. On a regional scale, two different aquifers have been identified to the depth of 150 m where high concentration of arsenic has been found in the Holocene aquifer. The Pleistocene aquifer was found virtually arsenic safe. Three Quaternary aquitards were identified within the 150 m depth based on lithology dominated by clay layers and occasionally intercalated clay lenses.

For sensitivity checking of the outputs of the models, ROC-curves (Receiver Operating Characteristics) are used. It is a technique for visualizing, organizing and selecting classifiers based on their performance. By taking tp-rate (true positives) on Y-axis and fp-rate (false positives) on X-axis, ROC-curve is constructed. An important point about ROC graphs is that they measure the ability of a classifier to produce good relative instance scores (Fawcett , 2005).

4. Results

From the depth 0m to 150m, seven hydrostratigraphic units were identified and those are aquifers and aquitards. Arsenic concentration data were included in every depth interval hydrostratigraphic maps. There is arsenic with very negligible amount at the surface and up to 10 m. At the depth of 20 m very few points show the high concentration of arsenic. From 25 m depth, the concentration increased and continued up to 60 to 65 m. At the deeper part the concentration followed the decreasing trend up to 150 m.

Several models were run for the study and four significant models were taken into consideration. Some of the regression co-efficient used to assess the risks i.e. beta values, Wald and p-values, odds etc. The negative beta values indicate fewer risks and the positive values indicate the high risk. According to that Holocene aquifer shows the high risk of arsenic transport. Wald and p-values (Sig.) indicate the significance of the variables. Wald values give the relative importance in percentages and p-values the absolute significance, where a value <0.05 indicates a significance of at least 95%. Variables that were not statistically significant ($p > 0.05$) were not considered in the modeling. The odds also indicate the risks with the specific values. Holocene aquifer shows the significantly high risk in all the models.

Table 1: Model performance

Models	Accuracy
2D-Model without depth	77%
2D-Model with depth	76%
3D-Model without depth	80%
3D-Model with depth	85%

The accuracy shows the model performance in the table. Greater than 70% seems to be excellent. All of the models show the excellent model performances. From the model classification table, 1-specific value and sensitivity were used to create the ROC-curve which showed the accuracy of the model. By putting the 1-specific values which are false negatives in X-axis and sensitivity values which are true positives in Y-axis, ROC-curves were found that indicate good accuracy of the model. In the figure, ROC-curves for 3D and 2D-models are presented all together.

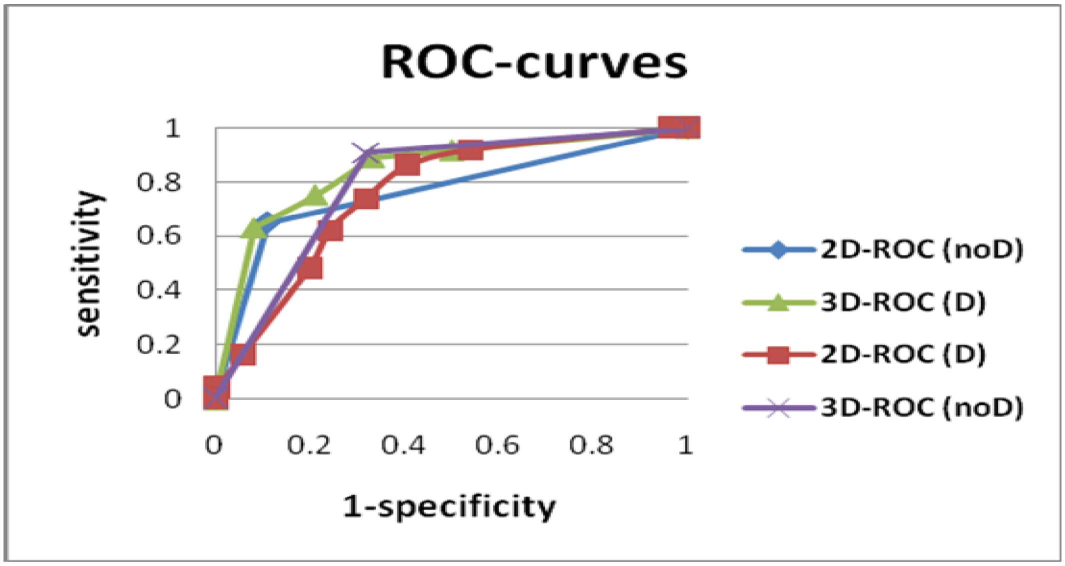

Fig.2. ROC-curves for models' accuracy checking.

The accuracy of ROC-curves ranges from 76% to 85%. In the four models, 2D-model without depth was the simplest; It was given the 77% accuracy which is quite good result. Moreover, 3D-model with depth which is more sophisticated was considered all the variables and was given 85%. More sophisticated model seems to give better results than the simple one, what it gives. But the simplest model also gives the good results. So it is clear that, if there has only surface information of any area, it would be possible to assess the probability that would be close to accurate.

For every 5 m interval (up to 0-100 m) and 10 m interval (up to 150 m), 26 probability maps were constructed for each of the model. The probability maps for 3D-models present nearly similar probability for all depths between 100 and 150 m. Rest of the maps show different probabilities at different depths. The individual probability maps (at given depths) locally indicate probabilities up to 0.815. Some significant risk maps are shown below.

All the maps were combined in one map by taking the mean values of each pixel. The highest probabilities are found where Holocene sediments are present including in the eastern and southeastern parts of Dhaka city, in the 20-40 m depth range given below.

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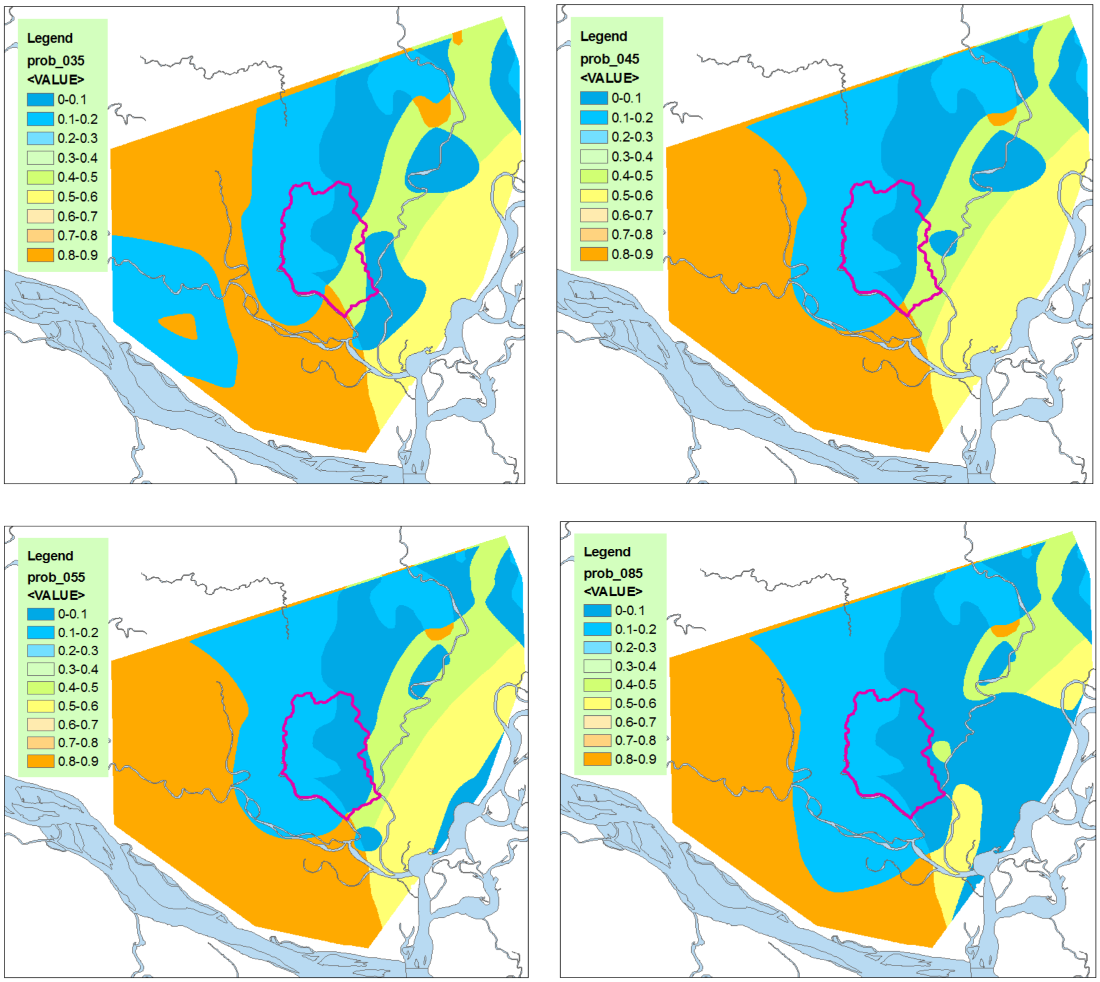

Fig.3. Results from model including surface and subsurface geology: risk map at 35m, 45m, 55m and 85m below surface.

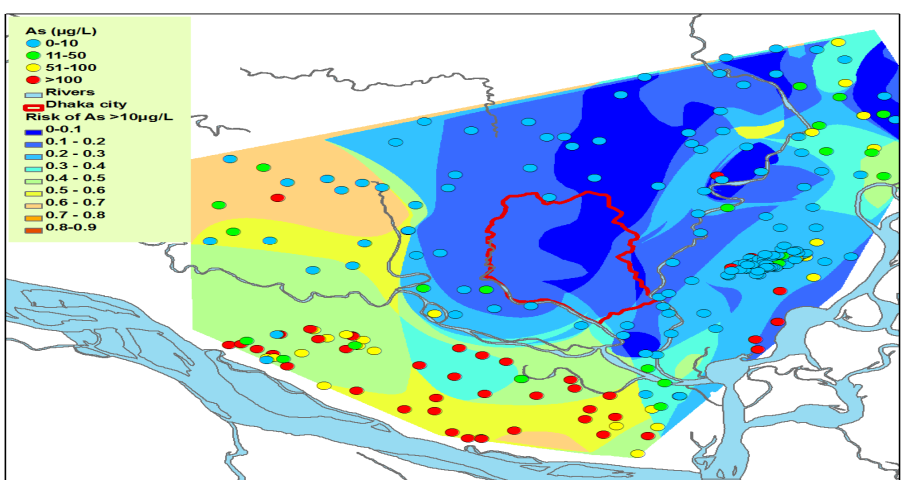

Fig.4. A combined depth-integrated risk map.

5. Conclusions

By using logistic regression model, it is clear that some parts of the Dhaka city lying on the floodplains such as eastern and southern parts; having the Holocene aquifer has higher probability of transport of arsenic enriched water. The results also confirm that the Pleistocene aquifer is free from arsenic at least for the present. There is a potential risk of arsenic occurrence at certain depths in certain areas within the city boundaries. It can be concluded that logistic regression model is a useful tool to determine the risk of contaminant transport by developing 2D and 3D models. These models are fast, robust and simple compared to conventionally use dynamic models. Moreover with this statistical approach, 3-dimensional risk modeling would ideally be complemented with dynamic hydrological models that could indicate flow directions and changes of flow.

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