# Assessment of Potential Exposure Pathways in Karst Groundwater Systems in Vega Alta, Puerto Rico using Geographic Information Systems

**Katherine M. Steele-Valentín**
University of Puerto Rico, Mayagüez, Puerto Rico, ksteele1@gmail.com

**Ingrid Y. Padilla**
University of Puerto Rico, Mayagüez, Puerto Rico, Padillai@uprm.edu

## ABSTRACT

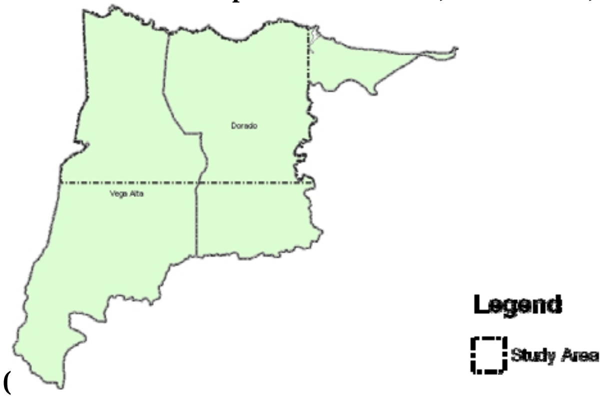
The North Coast Karst Aquifer System of Puerto Rico is the most productive aquifer of the island, serving as a significant source of drinking water and supporting important ecosystems. The same characteristics that make karst groundwater system highly productive, makes them highly vulnerable to contamination. Water quality surveys in Puerto Rico have shown a vast contamination of the aquifer. This research assess, potential path for exposure of contaminants in the karst groundwater system of northern Puerto Rico, using geographic information system (GIS) technologies. A methodology to delineate the pathway is explained and used. The results show that the pathway of contaminants from the superfund site goes toward the Atlantic Ocean and cover a considerable lateral extension. Contaminants could discharge in wells, wetlands and streams. Several wells with VOC data were contained inside the delineated pathway. GIS is a powerful tool in the integration and visualization of the existing data. It helps to visualize the extent of a contamination and the potential points of exposure. Future research will be done to improve methods for predicting human exposure through karst aquifers using GIS.

**Keywords:** Groundwater, GIS, Karst, Chlorinated solvents

## 1. INTRODUCTION

Karst terrains are underlain by soluble rocks, primarily limestone and dolomite, which undergoes considerable dissolution of joints, fractures, bedding planes, and other openings in which groundwater flow. These terrains are characterized by high permeability and well-developed conduit porosity, which provides important freshwater resources for human consumption (Ford and Williams, 2007). Those same characteristics that make karst aquifers highly productive make them highly vulnerable to contamination (Göppert and Goldscheider, 2008), and impart an enormous capacity to store and convey contaminants from sources to potential exposures zones. As a result, karst aquifers serve as an unfortunate route for contaminants exposure to humans and wildlife.

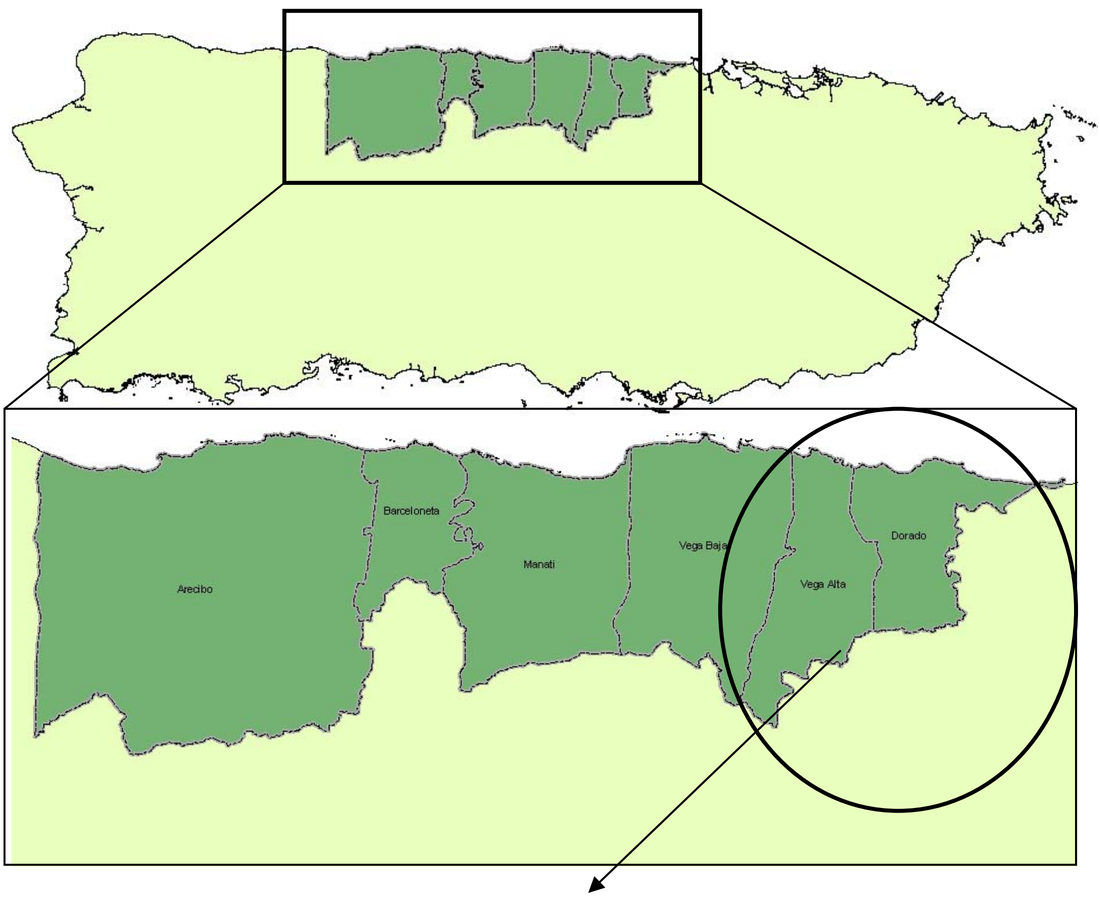
**Water quality surveys in Puerto Rico have shown a vast contamination of the northern karst aquifer (Guzmán-Ríos, et al., 1986; U.S. Geology Survey, 2008).The contamination of chlorinated chemicals has been of great concern, having been detected in a large percentage of sample wells. Among heavily affected areas is the La Plata-Arecibo hydrologic system in northern Puerto Rico. This area includes the Municipalities of Arecibo, Barceloneta, Manatí, Vega Baja,**




**Vega Alta and Dorado (**

Figure 1). The area contains a wide range of land uses including residential, industrial, and agricultural. It is overlain by the North Coast Limestone Aquifer System.

The North Coast Aquifer System consists of an unconfined aquifer (upper), a confining unit, and a confined aquifer (lower). The upper aquifer is very vulnerable to contamination and can provide several routes of potential exposure to contaminants. It is physically accessible for groundwater extractions and it is an important source of potable water in the region. In year 2004 it represented 52% of water production (DRNA, 2008). Also, it is hydraulically connected to surface features which can serve as potential exposure routes.



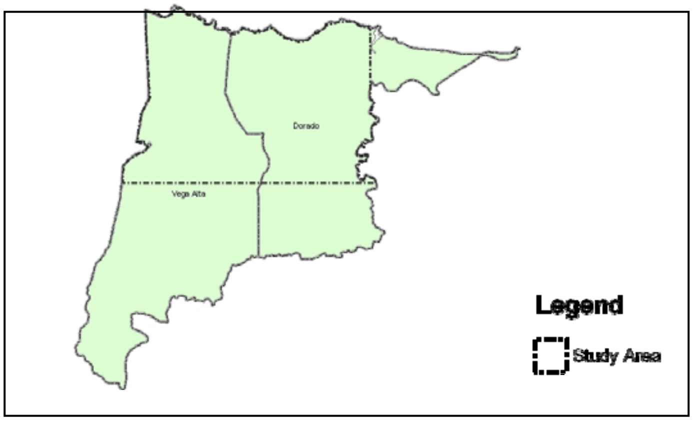



**Figure 1: From up to bottom: Puerto Rico map, Municipalities from Arecibo to Dorado, Vega-Alta Study Area**

Water and soil quality surveys (Guzmán-Ríos, et al., 1986; U.S. Geology Survey, 2008; U.S. Environmental Protection Agency, 2008a) have shown vast contamination in the La Plata-Arecibo study area. Sources of contamination in the study area include: superfund sites, landfills, dry cleaners, pharmaceutical industries, and other sites impacted by toxic release. Serious contamination has prompted inclusion in the National Priority List (NPL) of 10 sites within La Plata-Arecibo hydrologic region. The NPL is the list of national priorities among the threatened releases of hazardous substances, pollutants, or contaminants throughout the United States and its territories (EPA, 2008b). Five of these sites (Barceloneta Landfill, Scorpio Recycling, Upjohn, Vega Alta Public Supply Wells, and Vega Baja Solid Waste Disposal) have been contaminated with chlorinated solvents. This paper emphasizes the Vega Alta-Dorado region, where a large amount of volatile organic compound (VOC) was released; ending up with the inclusion of the site in the NPL as the Vega Alta Public Supply Wells (PSW).

To drink safe water is of utmost importance, as water pollution is one of the leading worldwide causes of deaths and diseases. Developing countries suffer from poor drinking water treatment (if any), making people susceptible to waterborne diseases, and exposing them to hazardous contaminants. But, this is not an exclusive problem for developing countries, industrialized countries also struggle with water pollution problems. The pertinent authorities are working on solutions to give people safe water. The agencies in charge of it in Puerto Rico are the Environmental Quality Board (EQB) and the Environmental Protection Agency (EPA). Those agencies ensure people that the water they are drinking is complying with high water quality standards.

Geographic Information Systems (GIS) is a tool that can be used in developing countries and industrialized countries to study water pollution and to help finding solutions. GIS has already been used in the development of, monitoring schemes (Bajarska et al., 2004), relation of contamination to health risks (Kamilova et al., 2007; Harris, 1997), and assessment of vulnerability for contamination and exposure risk in groundwater (Antonakos and Lambrakis, 2007; Dixon, 2005; FDH, 2003). This paper will show the methodology used to assess potential path for exposure of contaminants in the karst groundwater system of northern Puerto Rico, using GIS.

## 2. METHODS

The primary goal of the research is to reconstruct potential contamination paths for exposure of chlorinated contaminants released from Vega Alta superfund site in the karst groundwater system. This aim was attained through integration of hydrogeology, hydrologic, and contamination data in a spatial analysis, using ArcGIS 8.3.

In order to reconstruct the potential contamination pathway from Vega Alta PSW superfund site, it was necessary to create several layers of data collected on water levels, hydraulic conductivity, porosity, and wells with chlorinated hydrocarbons. Once gathered and revised, the data was incorporated in the ArcMap database and segregated into layers for spatial analysis. Spatial Analyst extension for ArcGIS was used in order to perform the necessary analysis. Several routines were performed to obtain Darcy velocity, groundwater flow direction and average interstitial velocity maps with Spatial Analyst. These maps formed the base to establish criteria for assessment of potential contamination path for exposure from the superfund site. For the analysis, it is assumed a steady-state scenario in an isotropic and vertically homogeneous aquifer. Values are assumed constant over time. Karst aquifers behave different than aquifers of porous media, but in this paper it will be treated as a porous one.

### GROUNDWATER MOVEMENT

The first map created was the Darcy velocity map. This map was done using the raster calculator from Spatial Analyst. This calculator performs any type of mathematic operation to raster layers. If the layer in which is wanted to perform an operation is not a raster (e.g. shapefile), it is necessary to convert it before the calculation. Darcy velocity was calculated using the following equation:

$$q = -K\frac{dh}{dl} \quad \textbf{(1)}$$

Where $q$ is the Darcy velocity (ft/d), $K$ is the hydraulic conductivity (ft/d), $dh/dl$ is the hydraulic gradient. The negative sign indicates that the flow of water is in the direction of decreasing head (Todd and Mays, 2005). To calculate Darcy velocity, two layers were needed: head layer and hydraulic conductivity layer; $dl$ was set as the cell size in feet.

The first created layer was the Head layer, which also gave the direction of groundwater flow. To obtain the layer, it was necessary to perform an interpolation. This was done in ArcGIS using Spatial Analyst extension. The program gives several method of interpolation, and the one selected was the spline method. This method gives smoother results and is better when applying to water table maps (ESRI, 2001). Once this layer was created it was proceeded to create the hydraulic conductivity layer.

Information about hydraulic conductivity (K) was extracted from USGS Water-Resources Investigation Report (WRI) 97-4170 (Sepúlveda, 1999). In the report, the aquifer was divided in several layers, thus information of K was in all layers. Each hydraulic conductivity layer was digitized in ArcGIS in order to calculate the equivalent hydraulic conductivity. Figure 2 shows the first layer digitized with the *Editor* tool. After digitizing all layers, they were converted to raster in order to be able to use it in the raster calculator. Since, flow direction was parallel to the layers and it was assumed that each layer was individually isotropic and homogeneous; the equivalent horizontal hydraulic conductivity was calculated using the following equations:

$$K_{eq} = \frac{K_1 z_1 + K_2 z_2 + \ldots + K_n z_n}{z_1 + z_2 + \ldots + z_n} \quad \textbf{(2)}$$

Where, $K_i$ is the hydraulic conductivity of each layer, $z_i$ is the thickness of each layer and $n$ is the number of layers. But, because the thickness of all layer were the same, the equation could be simplified as follows:

$$K_{eq} = \frac{K_1 + K_2 + ... + K_n}{n} \quad \textbf{(3)}$$

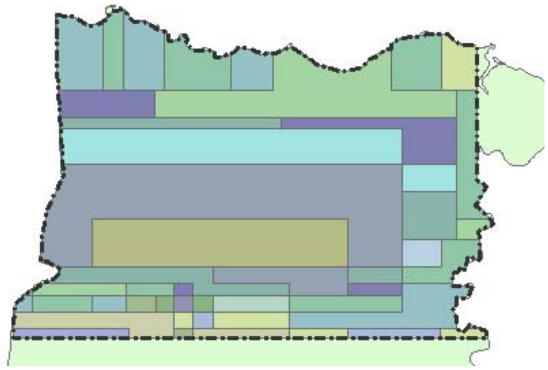


**Figure 2: Hydraulic conductivity from first layer**

With the resulting layer and the heads layer, both in raster format, it was possible to calculate Darcy velocity. This velocity and the effective porosity layer were used to create the velocity map, using equation 4 in the calculator.

$$v = \frac{q}{\alpha} \quad \textbf{(4)}$$

Where $v$ is the average interstitial velocity (average linear velocity) (ft/d), $q$ is the Darcy velocity (ft/d) and $\alpha$ is the effective porosity. A porosity layer had to be edited from WRI 97-4170 (Sepúlveda, 1999), and then converted to raster. When the porosity layer was ready, equation 4 was set and the velocity map was created.

Groundwater flow direction can be determined with the head layer. The elevation at any point on the water table equals the energy head and, as consequence, flow lines lie perpendicular to water table contours (Todd and Mays, 2005). In order to have those directions it was necessary to vectorize the head layer in Surfer (computer software). The vector map resulted from Surfer was then exported to ArcGIS. The resulting layer represents the direction of groundwater flow.

### ADVECTION-DISPERSION TRANSPORT MECHANISM

The principal solute transport mechanisms are advection, diffusion, dispersion, sorption, and decay (Delleur, 1999). Because the purpose of the study is to determine the potential pathway, instead of modeling the contaminant transport, the only mechanisms to be considered are advection and dispersion.

Advection is the transport of a solute by the bulk groundwater flow (Delleur, 1999). Basically, it moves with the groundwater flow and follows its direction. This mechanism was the base to obtain the longitudinal direction of the path. As the source of contamination was already established, it was set as the starting point of the spread (i.e. superfund). The expected longitudinal direction of contamination followed the direction groundwater flow. In order to delineate this direction it was used the groundwater direction layer and the head contour layer. The latter was created by converted the head raster layer to a shapefile.

Dispersion is the spreading of the plume that occurs along and across the main flow direction due to aquifer heterogeneities (Delleur, 1999). The study of dispersion phenomena involves the application of probability theory for predicting the spatial distribution of tracer particles with time in a porous media (Batu, 2006). The distribution of contamination in the plume will follow a Gaussian distribution, thus the extension can be represented with the standard deviation of the distribution (Fetter, 1999).

The next step in the procedure was to determine the transverse dispersion coefficient. This coefficient can be determined with the following equation:

$$D_T = \alpha_T v_i + D^* \qquad \textbf{(5)}$$

Where $D_T$ is the hydrodynamic dispersion of the coefficient perpendicular to the principal direction of flow (transverse) ($ft^2$/d), $\alpha_T$ is the transverse dynamic dispersivity (ft), $v_i$ is the average linear velocity (ft/d), and $D^*$ is the molecular diffusion (Fetter, 1999). In this study the molecular diffusion was neglected, only mechanical dispersion ($\alpha_T v_i$) was considerated.

The transverse dispersivity ($\alpha_L$) used in this research was set to 5 meters (Dassargues and Derouane). Now, with the velocity previously calculated the transverse dispersion coefficient was determined. Then, it was proceeded to calculate the time it takes a particle to travel from one point to another. This was done dividing the length between the points by the average linear velocity. After, the dispersion coefficient and time was calculated, it was possible to calculate de standard deviation of the plume with the next equation.

$$\sigma_x = \sqrt{2D_T t} \qquad \textbf{(6)}$$

Standard deviation was calculated in several points through the longitudinal direction. In many practical problems a simple and adequate estimation of the width of a dispersing cloud is 4σ (Fisher et al., 1979), this represents 95.44% of the total area under the Gaussian curve (Ott and Longnecker, 2001). For every point, the extent of the spreading will be calculated as 4σ. Even though diffusion, sorption and decay, help in the attenuation of the contamination, for this purpose the longitudinal direction was extended up to the coast. Once, the longitudinal direction and spreading extension was calculated and converted in layers, the potential pathway map was created in ArcGIS.

## 3. RESULTS

Results from this study are presented in a set of figures that were developed using ArcGIS. These figures present the results obtained with the methodology used to delineate the potential pathway of the contaminants released by Vega Alta PSW superfund site.

The first map created was Darcy velocity. For this, two layers were needed: head layer and hydraulic conductivity layer. Shows the head layer, it was the result of an interpolation technique using ArcGIS. It illustrates the aquifer’s water table elevation. This layer was then exported to Surfer and it was vectorized. The same figure shows the groundwater flow direction (results from the vectorization) overlaid on top of the head layer. With this layer and the hydraulic conductivity layer, Darcy velocity map was created as seen in Figure 4. This figure shows in the upper left, the hydraulic conductivity layer created with the *Editor* tool. In the upper right it can be seen the head layer, and in the bottom of the figure, the resulting Darcy velocity map.

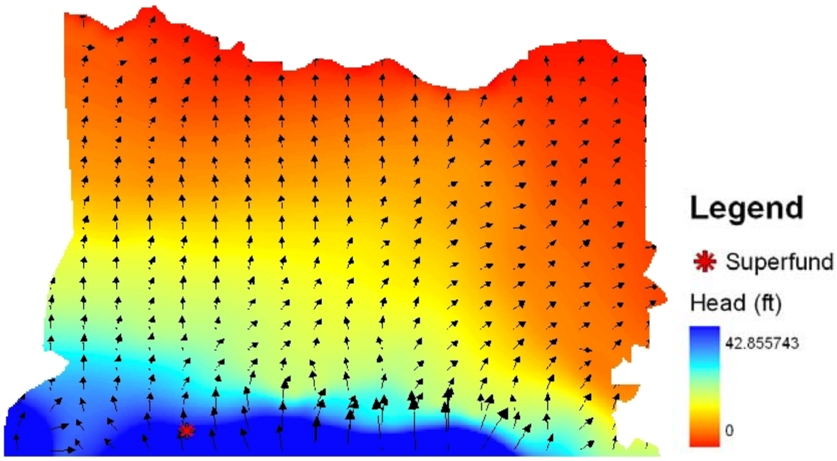



**Figure 3: Head vectors layer from Surfer with head layer**

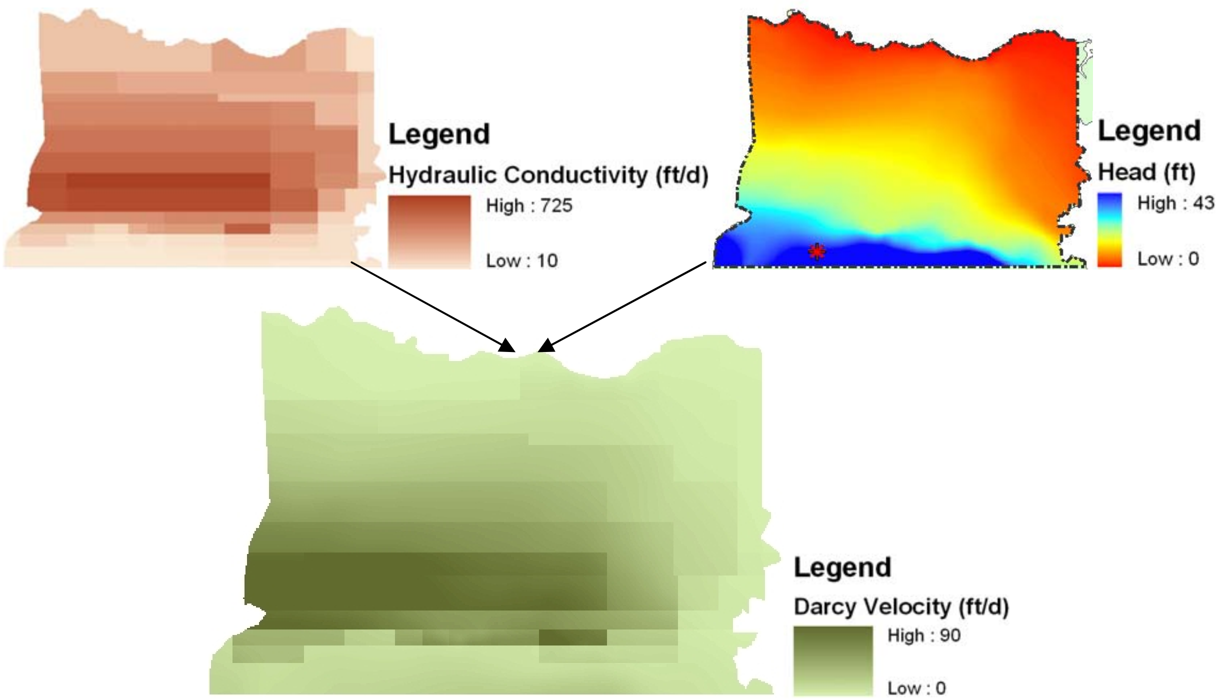



**Figure 4: Hydraulic Conductivity layer (upper left) and Heads layer (upper right) were used in the calculation of Darcy Velocity (bottom)**

Darcy velocity has a range that goes from 0ft/d to 90ft/d, with a mean of 49.40ft/d. This map was used, along with the porosity layer, to create de Average Linear Velocity map. Figure 5 illustrates the creation of this map. In the upper left it shows the porosity layer, which was digitized with the *editor* tool in ArcGIS. In the upper left shows the Darcy velocity layer, and in the bottom is shown the Average Linear Velocity map. This velocity has a range that goes from 0ft/d to 726 ft/d, with a mean of 230.63ft/d.

With the groundwater flow direction map and the heads contours maps, the advective flow direction was delineated in ArcGIS, as shown in Figure 6 (left side). This figure illustrates the longitudinal direction of the contaminant from the superfund site. When already delineated the longitudinal direction with a line, the average linear velocity map was used to calculate the transverse dispersion coefficient and the travel time of a particle from two given points of that line, to determine the transverse dispersion of the contamination.

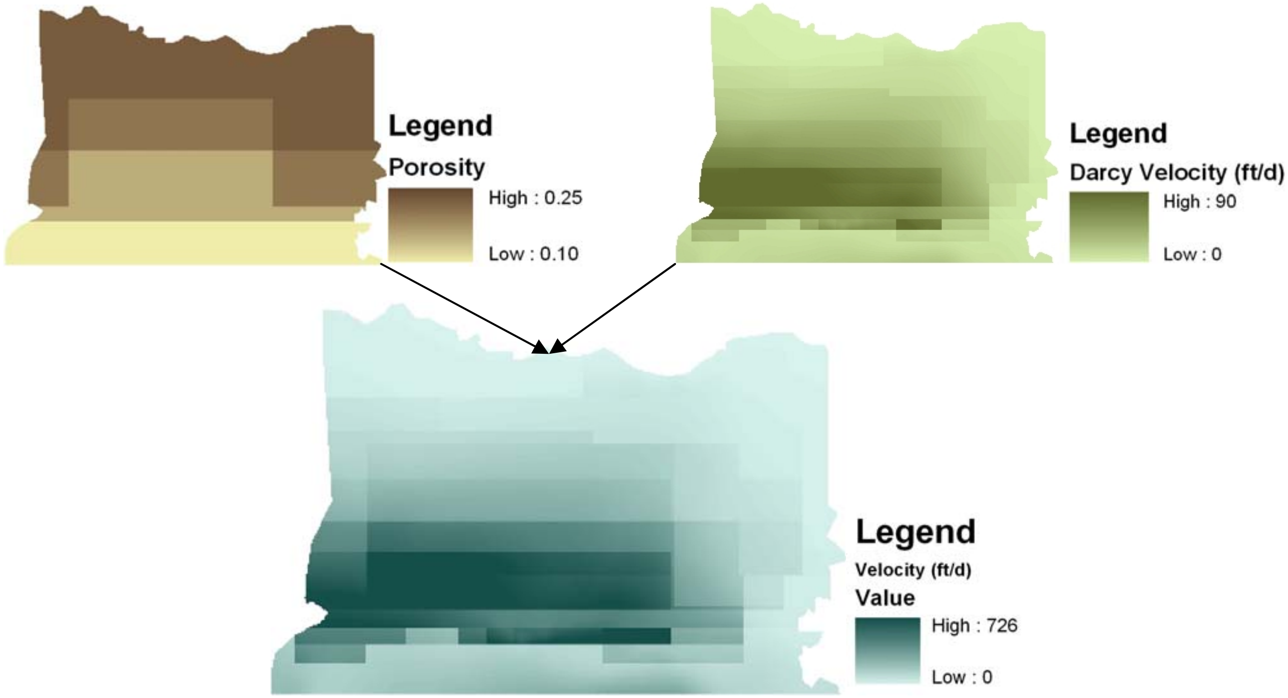



**Figure 5: Porosity layer (upper left) and Darcy Velocity layer (upper right) were used in the calculation of Average Linear Velocity map (bottom)**

Figure 6 (right side) illustrates the contamination spread from the superfund site. Here, concentrations and type of contaminant is not taken into consideration. This figure shows only direction of the contamination pathway and the extent of the exposure. In the figure is also seen the distribution of wells with Chlorinated VOC in the study area.

## 1. Discusion and Conclusions

In Vega Alta – Dorado area, groundwater enters the system through surface infiltration and direct injection of runoff into karstic conduits (e.g., sinkholes), and it generally flow northward toward the Atlantic Ocean. Discharge is principally to wells, coastal wetlands and streams (Renken, et al., 2002). This can be seen in Figure 3, as the head vectors represents the groundwater flow direction, which flow toward North (where the Atlantic Ocean lies). This pattern will make the release of contaminant to travel toward wetlands and the ocean.

In karst aquifers, contaminants entering the system are subjected to multiple events of rapid mobilization during conduit storm flow followed by slower diffuse flow during baseflow conditions (Padilla and Steele, 2008). Over time, variable flow regimes cause significant dispersion of contaminants in the aquifer, extending the zones of potential exposure. If hypothetically, it was a contaminant with no attenuation, the lateral extension will cover a considerable area (where wells, wetlands and streams exist). These contaminants may contaminate the potable water from the wells. This could end up threatening human health, as many of these wells are not receiving any kind of water treatment (Martí et al., 2004).

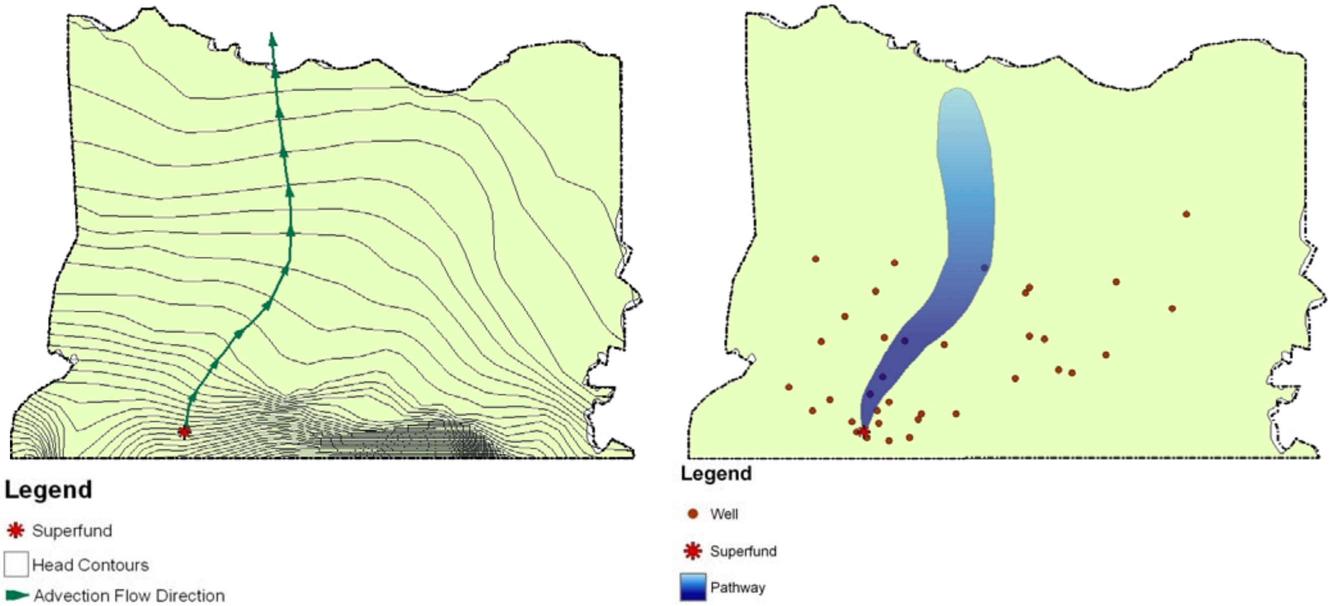



**Figure 6: Longitudinal path (left side) and spreading extent (right side) of contamination from superfund site.**

Figure 6 (right side) illustrates the wells with VOC data in the study area. Some of the wells are contained inside the pathway extension area with concentrations that ranges from 4μ/L to 142μ/L. For most of the contaminants of concern in this research, the maximum contaminant level permitted by the Environmental Protection Agency (EPA), are 5μ/L (EPA, 2008c). From the wells inside the area only one didn't exceed this level.

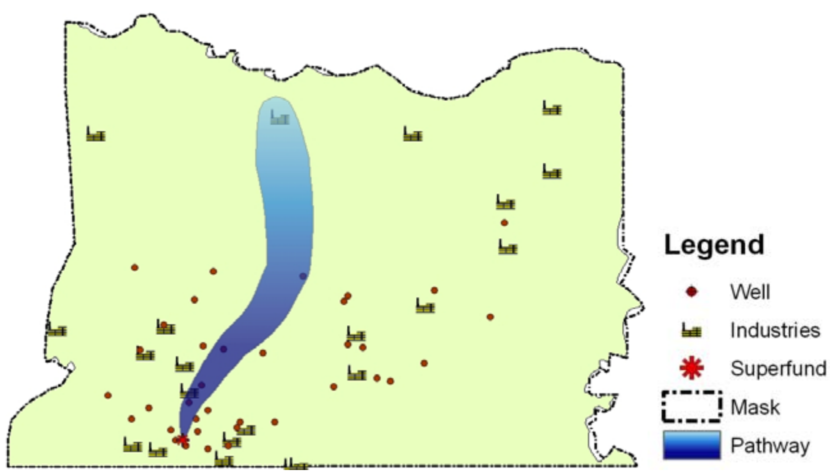



**Figure 7: Map of potential pathway of contamination. Wells with VOC data lie inside the pathway and the surrounding areas. Industries and commerce of the region can be other potential source of contamination.**

Figure 7 shows a large number of wells that are not covered by the pathway extension. This can be explained with the fact that many industries and commerce lies in the surrounding areas. These industries are potential sources of contamination. Dry cleaners are not included but they are other kind of potential sources of chlorinated solvents. A factor that could end in error of the model is that in its preparation, several assumptions were made. The most important one was that the aquifer was considered a porous media instead of karstic. This could end in conclusions that could differ with the real situation.

ArcGIS and Spatial Analyst extension were significant tools for the construction of the contaminant pathway for this research. They were a powerful tool in the integration and visualization of the existing data. Information that normally will be difficult (if not impossible) to overlay, can be done easily in GIS. A large number of data are accessible and already digitized. This is of great help when modeling, because it saves time and money. It allows rapid integration of new data and avoids tedious, error-prone text editing of model input files (Watkins, 1996). A geographic information system helps in the visualization of potential exposure and it may assists decision-makers when a contaminant release occurs. Future research will be done to improve methods for predicting human exposure through karst aquifers using GIS.

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