DEVELOPMENT OF METHODOLOGIES FOR KARST GROUNDWATER VULNERABILITY AND CONTAMINATION RISK MAPPING FOR THE PROTECTION OF KARST AQUIFERS IN MIDCONTINENT UNITED STATES

Final CCF report

1. INTRODUCTION

Vulnerability mapping of an area in Big Creek basin, Newton County, Arkansas (Fig 1.) was performed in order to define the vulnerability and susceptibility of the area to groundwater contamination.

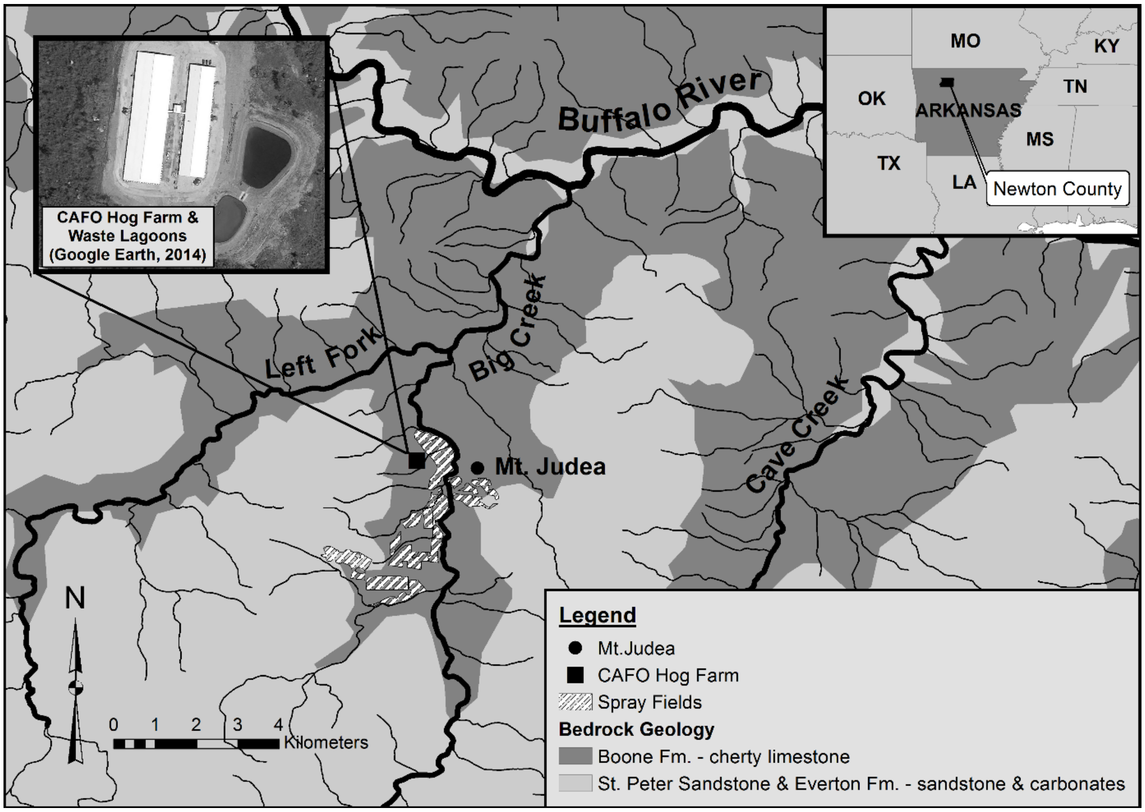

Figure 1 Vulnerability mapping area

The Slovene Approach to vulnerability mapping was used to perform the vulnerability and risk assessment of the area. The Slovene Approach was chosen because it presents a methodology that combines surface and groundwater source and resource protection. Additionally, it includes a risk analysis which considers intrinsic vulnerability, contamination hazards and the importance of the source or resource (Ravbar and Goldscheider, 2007). It also integrates a so called K factor that assesses the karst groundwater flow within the saturated zone, in order to address the protection of karst water sources.

The study was performed in two parts. First, vulnerability mapping was performed to develop resource and source vulnerability maps. These two maps help define: a) the resource protection, which aims to protect the whole aquifer and, b.) the source protection which aims to protect a particular spring or well (Goldscheider and Popescu, 2004 in Ravbar and Kranjc, 2007). Here it should be noted that the term "protection" is used in contrast to the term "vulnerability". The term "protection" focuses on the natural protection of a hydrological system against contamination, while “vulnerability” indicates the liability of a hydrological system to contamination, and its ability to neutralize and attenuate that contamination (Ravbar and Kranjc, 2007). The resource vulnerability map focuses on the intrinsic vulnerability of the watershed, based on the natural characteristics of the environment which determine its ability to reduce negative influences of contamination and to re-establish the equilibrium of the environment (Ravbar and Kranjc, 2007).

The source vulnerability integrates the K-factor, by overlaying it on the resource map, in order to target specific springs and wells. Due to the complexity of karst groundwater systems and the difficulty in delineating karst aquifers, the Slovene Approach K-factor assessment is based on groundwater flow velocities, connections, and contributions to the source (Ravbar and Kranjc, 2007).

The second part of the study consisted of hazard analysis/mapping and risk assessment. Maps of hazards, their hazard level, and a total risk map were developed.

2. VULNERABILITY MAPPING

The three factors used to develop the resource vulnerability map included:

- geology and soil structure (O factor; Fig. 2),
- catchment area (C factor, Fig. 3),
- precipitation (P factor, Fig. 5)
-

2.1 O factor

The O factor considers the protection provided to the aquifer to attenuate the potential contamination (Daly et al., 2002; Vias et al., 2002 in Ravbar and Kranjc, 2007) and is divided into two separate sub-factors, the os sub-factor and the ol sub-factor.

The os sub-factor considers the soil’s thickness and structure. To define the os-factor, we used data from U.S. Department of Agriculture (USDA) web application named Web Soil Survey and USDA Hydraulic Soils Groups definitions (2007).

The hydraulic group of the area’s soils, as defined by USDA, was chosen as the most appropriate parameter to use for characterizing/delineating the os sub-factor. The USDA hydraulic soils grouping defines the water transmissivity and conductivity of soils based on the characteristics of saturated soils. The hydraulic group of the area’s soil was chosen as the most appropriate parameter to use for characterizing/delineating the os factor. The soils with hydraulic group C and D are defined as sandy and clayey, and for the purposes of this vulnerability mapping were characterized as less protective, while the soils with the hydraulic group A and B are defined as silty and loamy and were considered more protective. This may initially appear to be counter intuitive considering clay’s low intrinsic permeability. However the author of the Slovene Approach concludes that although clays may be more protective when wet, they are far less protective than loam when dry due to the potential for cracks in the soil structure. This potential for cracking exists due to the fact that the clays in karst areas are often present in well drained environments subjected to frequent wet and dry cycles.

In order to determine if mapping results would change significantly by using alternative soil parameters to define the os sub-factor, we also characterized the soils based on the texture description in the USDA soil database. Both the original and the alternative maps produced identical results; therefore the hydraulic group division was selected for os sub-factor mapping.

The ol sub-factor is a measure of the protection provided by the lithology and is a multiplicative factor of the confined value and the layer protection index. According to the geologic map of the study area, the Big Creek Basin is underlain by a single lithology, the Boone Formation (Fig. 1), which is a heavily karstified limestone with nodular to bedded chert. The estimated thickness of the Boone Formation in the study area is 73m. Overlying the Boone Formation is a 0.5m thick clay and chert-rich regolith. Based on these characteristics the Slovene Approach yields a layer protection index of 2.

Because the bedded chert in the Boone Formation can often act as a confining unit for groundwater, we consider the system to be semi-confined. The Slovenian method specifies a value of 1.5 for semi-confined systems.

Ol= layer index × confined conditions (cn)

Therefore based on the equation above, the ol sub-factor is assigned a value of 2.5.

The two sub-factors (os and ol) were then added together resulting in combined O-factor values representing primarily low to moderate vulnerability, with the exception of few a highly vulnerable areas. These results are depicted on the O factor map (Fig. 2).

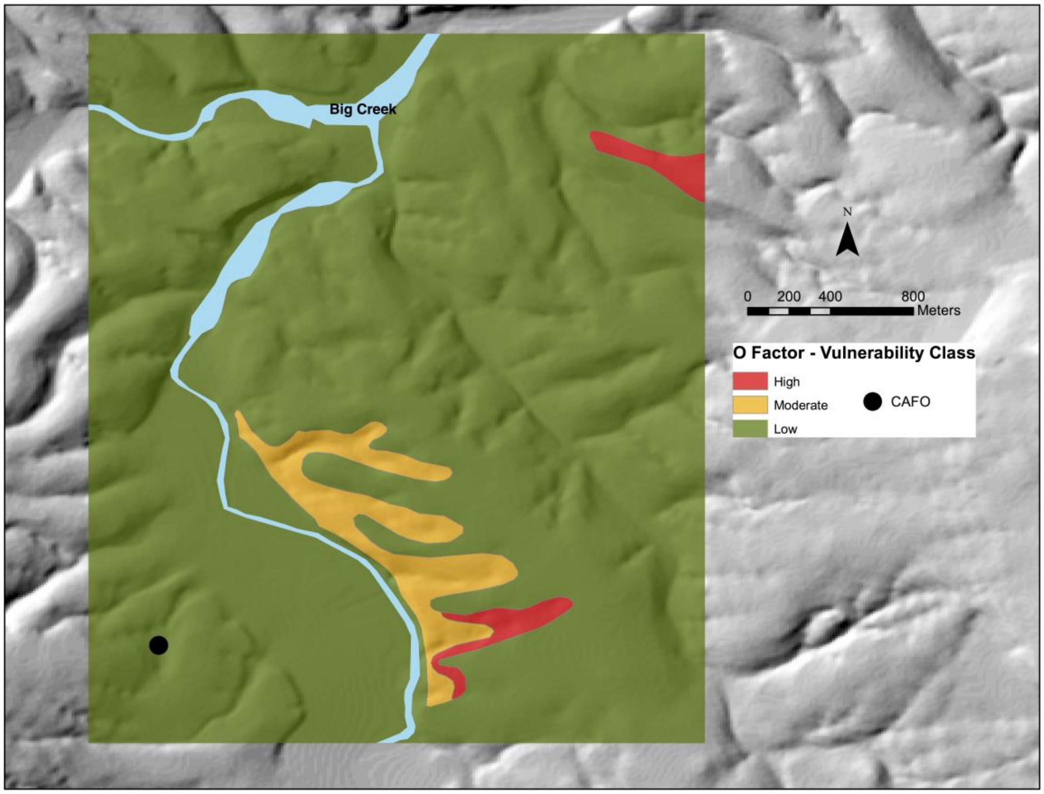

Figure 2 O factor map

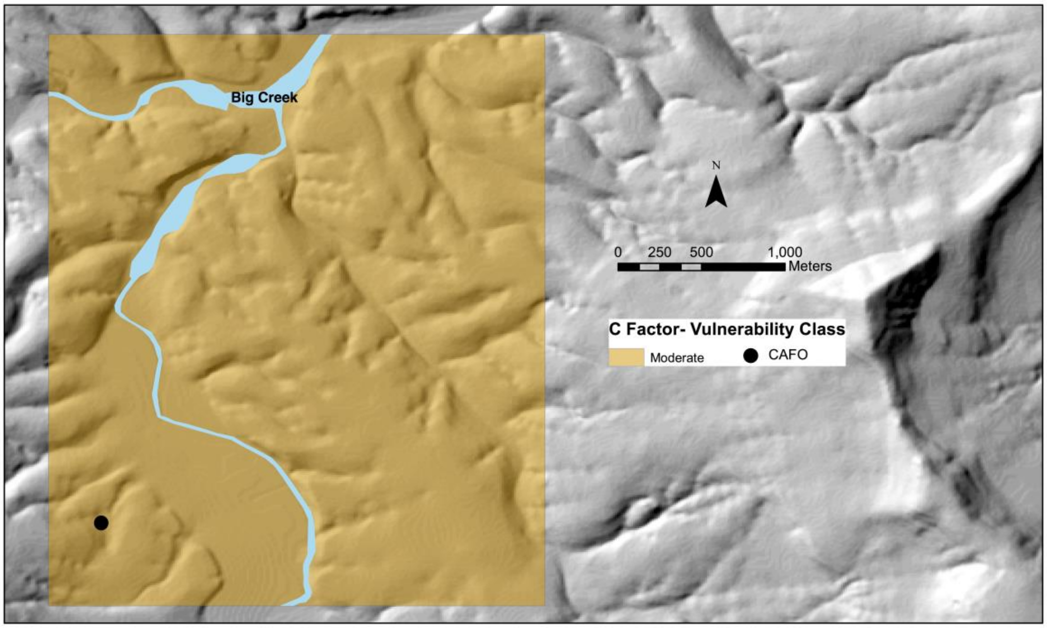

Figure 3 C factor map

2.2 C factor

The C factor expresses the degree to which the protective cover is bypassed by lateral surface flow. In the Slovene Approach it considers the recharge area of a sinking water body (e.g. river or lake) (Ravbar and Kranjc, 2007). The C factor is comprised of five sub-factors which include: the distance to swallow holes (dh), distance to sinking water bodies (ds), temporal variability (tv), slope and vegetation (sv), and surface morphological features (sf). Because the study area does not have any swallow holes, only slopes and vegetation, and surface morphologic features were included in calculation. Based on the final results the area was ranked in the moderate vulnerability class (Fig. 3), with C score of 0.52.

2.3 P factor

The P factor is addressing the precipitation regime of the studied area. To determine the P-factor, daily precipitation data for a 30-year period were analyzed and characterized based on two sub-factors; the rd sub-factor which indicates rainy days (rain quantity of 20-80 mm/day) and the se sub-factor which indicates when intensive storm events occur (rain quantity of < 80 mm/day). The P factor is derived by multiplication of both sub-factors.

To define the study area P factor we used 30 year precipitation data for the following weather stations: Jasper, Harrison and Gilbert. The locations were chosen because of their proximity to the studied area (Fig. 4). The resulting P factor for all locations was defined as low vulnerability.

After all three factors (O, C and P) are determined and mapped, the overall Resource map is created by overlaying all three factors (Fig. 6).

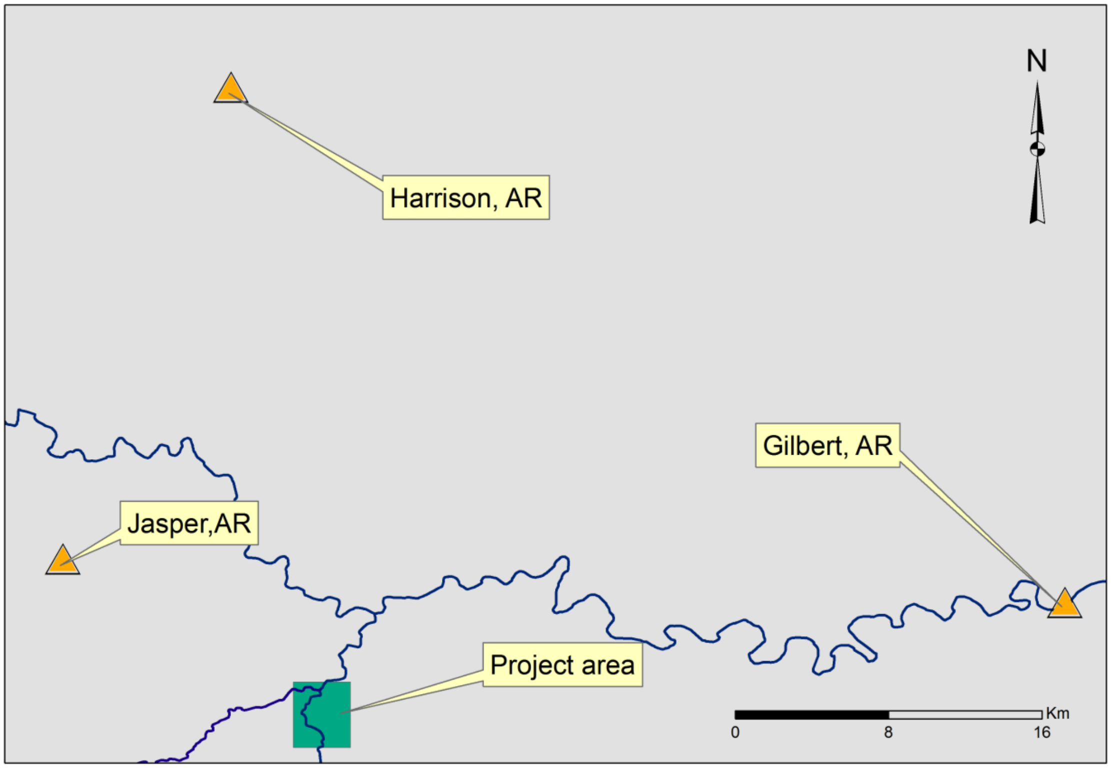

Figure 4 Meteorological stations used to define P factor

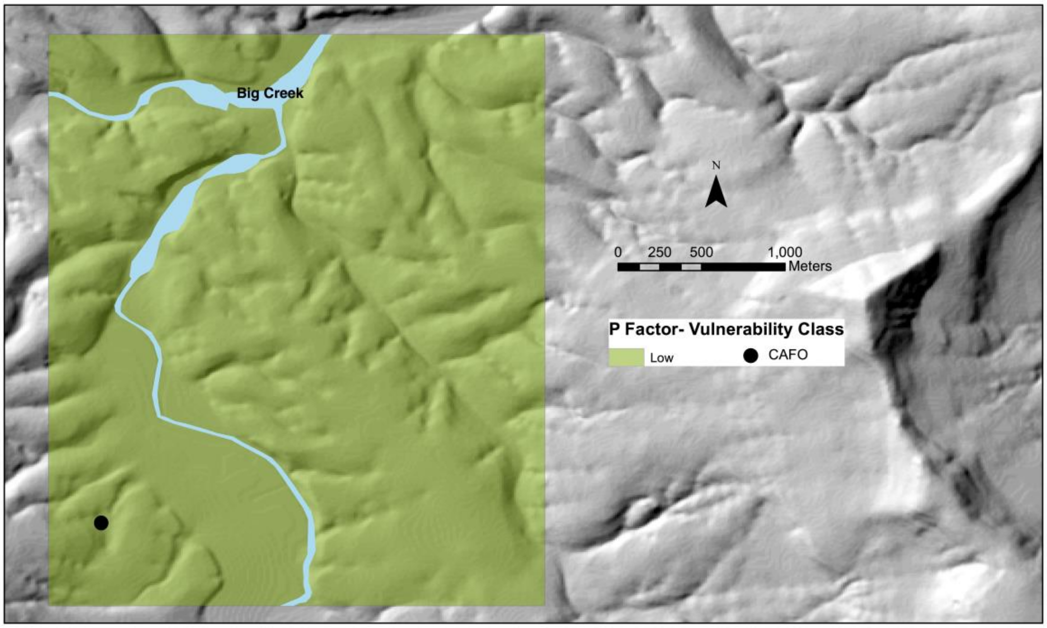

Figure 5 P factor map

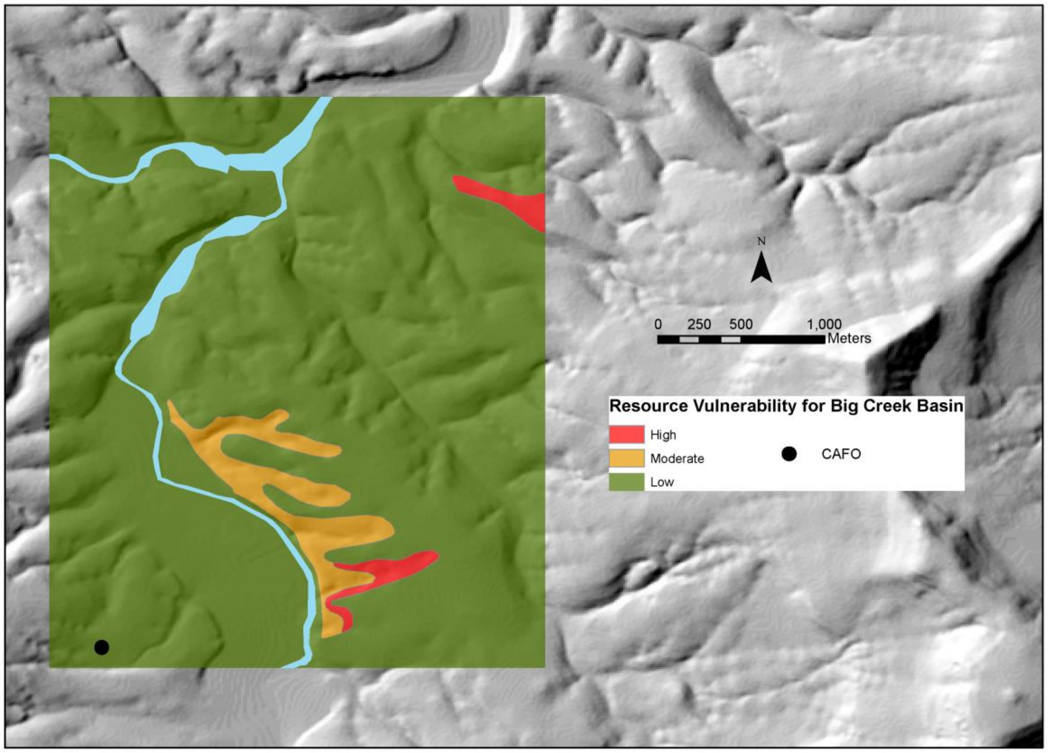

Figure 6 Resource vulnerability map for Big Creek basin

2.4 K-factor and source map

As explained in the introduction, the source vulnerability map addresses the protection of karst water sources. In order to develop the source vulnerability map, the K factor which characterizes the extent of karst network development, is overlaid on the resource map (Fig. 8). The K factor in the Slovene Approach is defining the karst groundwater horizontal flow path in the saturated zone (Ravbar and Kranjc, 2007). To define the K factor three sub-factors must be considered. The t sub-factor (travel time) is based on the groundwater flow velocities within the saturated zone and is independent from the drainage system within the unsaturated zone. The n sub-factor (information on karst network) indicates the presence of active conduit network, and the r sub-factor (connection and contribution) which indicates parts of the aquifer system that either always or rarely contribute to the source and are either directly or indirectly connected to and drained by the source (Ravbar and Kranjc, 2007).

Because of inaccessibility to private properties in the study area, dye tracer tests could not be performed as part of this study. However, several tracer tests were performed in the area, by the Karst Hydrogeology of the Buffalo National River (KHBNR) project group prior to this study. Therefore results from tracer tests performed by KHBNR were used for the vulnerability mapping study. In the chosen tracer test the dye (Fluorescein) was injected into a well, located approximately 530 m from Confined Animal Feeding Operation (CAFO) waste lagoons and in proximity of a spray field. The well is located approximately 575 m from the spring in Big Creek which shows positive dye tracing results. (Fig. 7). The visual detection of the dye occurred after 42 hours.

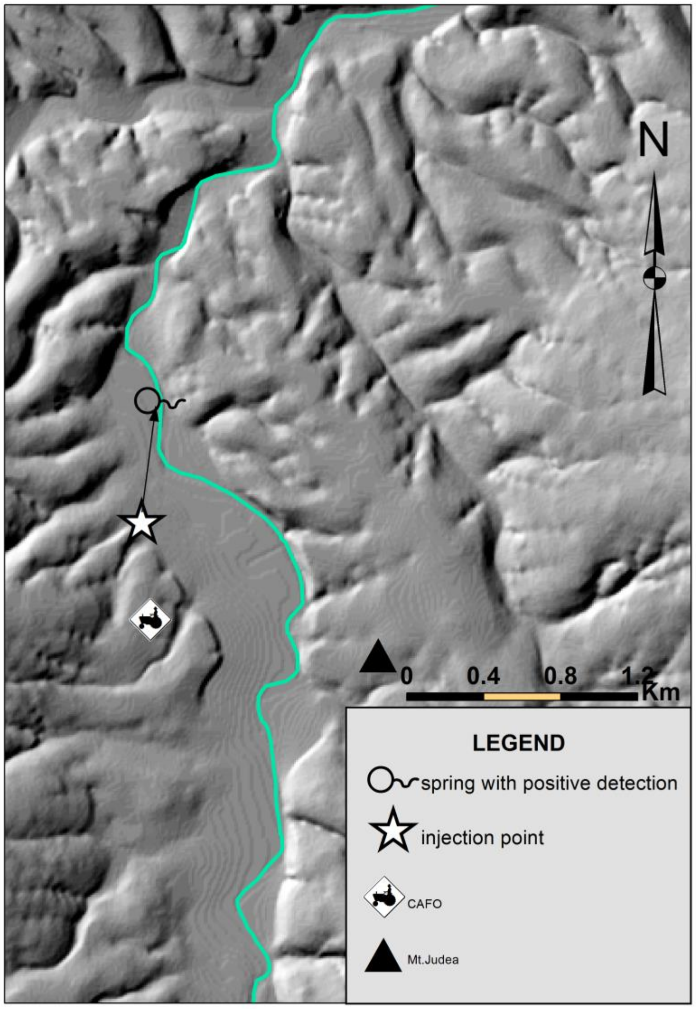

Figure 7 Well (injection point) and spring location from KHBNR tracer test

Based on the dye tracer test results, we defined the karst system as intermediate (n sub-factor), with 1%-10% contribution and connection factor within the system (r sub-factor), and with a groundwater travel time of 1-10 days (t sub-factor). All these criteria fall into moderate vulnerability class, therefore the K-factor (Fig. 8) defines the area as moderately vulnerable.

The K-factor was then added to resource vulnerability map in order to create the source vulnerability map (Fig. 9). This source map defined the area as low to moderately vulnerable, with the exception of a few areas that were defined as highly vulnerable

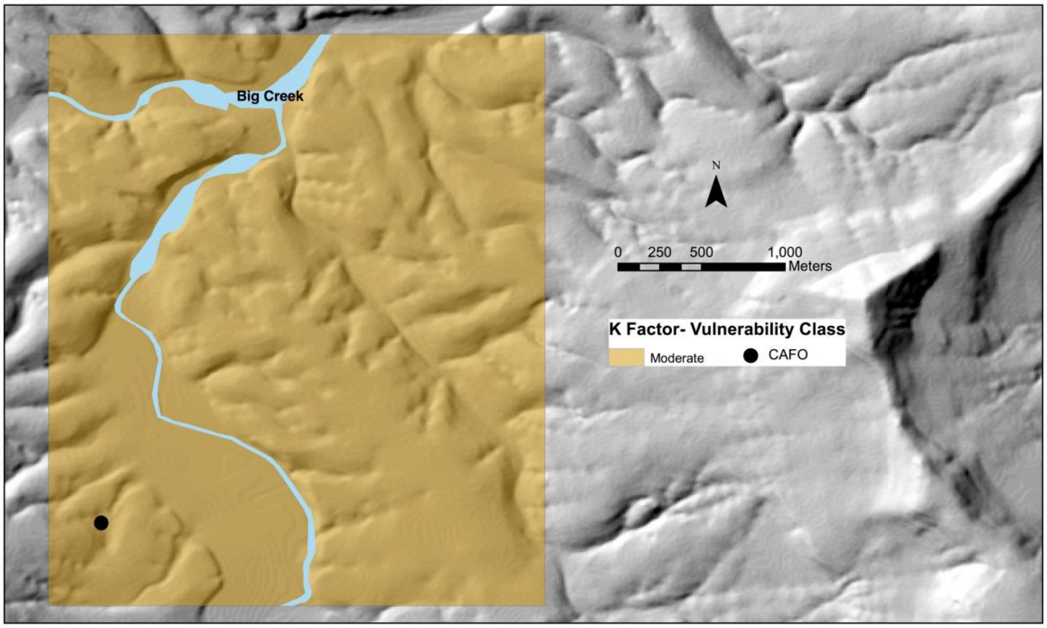

Figure 8 K-factor

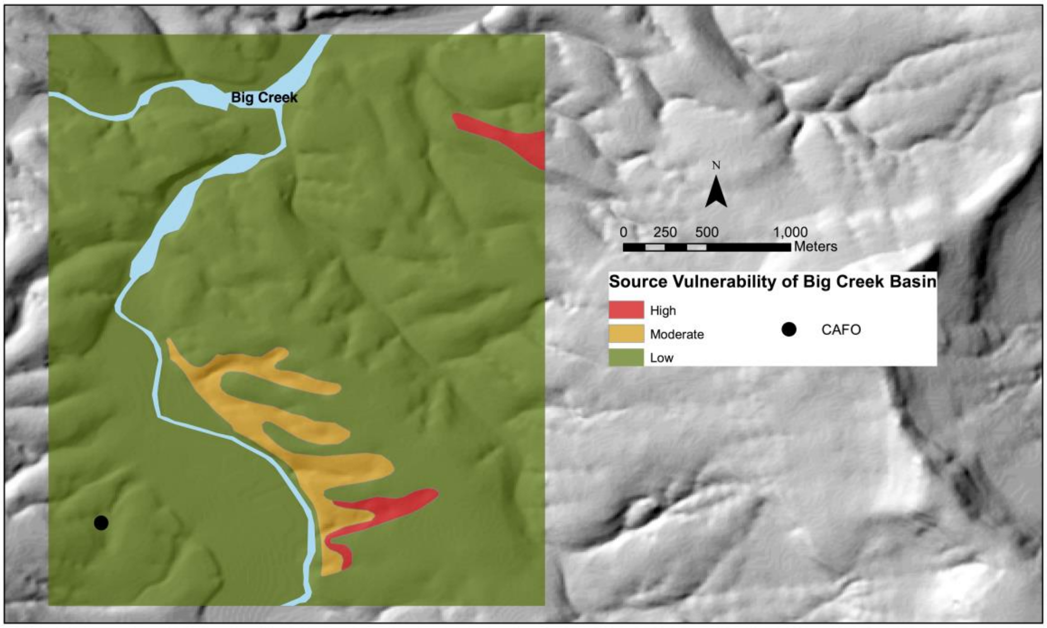

Figure 9 Source vulnerability map of Big Creek basin

3. HAZARD AND RISK ASSESMENT MAPPING

3.1 Hazard mapping

The first step in hazard mapping process was to assess all potential sources of contamination or so called hazards in the area which are presented in Figure 10. Hazard assessment considers the potential degree of harmfulness for each type of hazard (Ravbar and Kranjc, 2007).

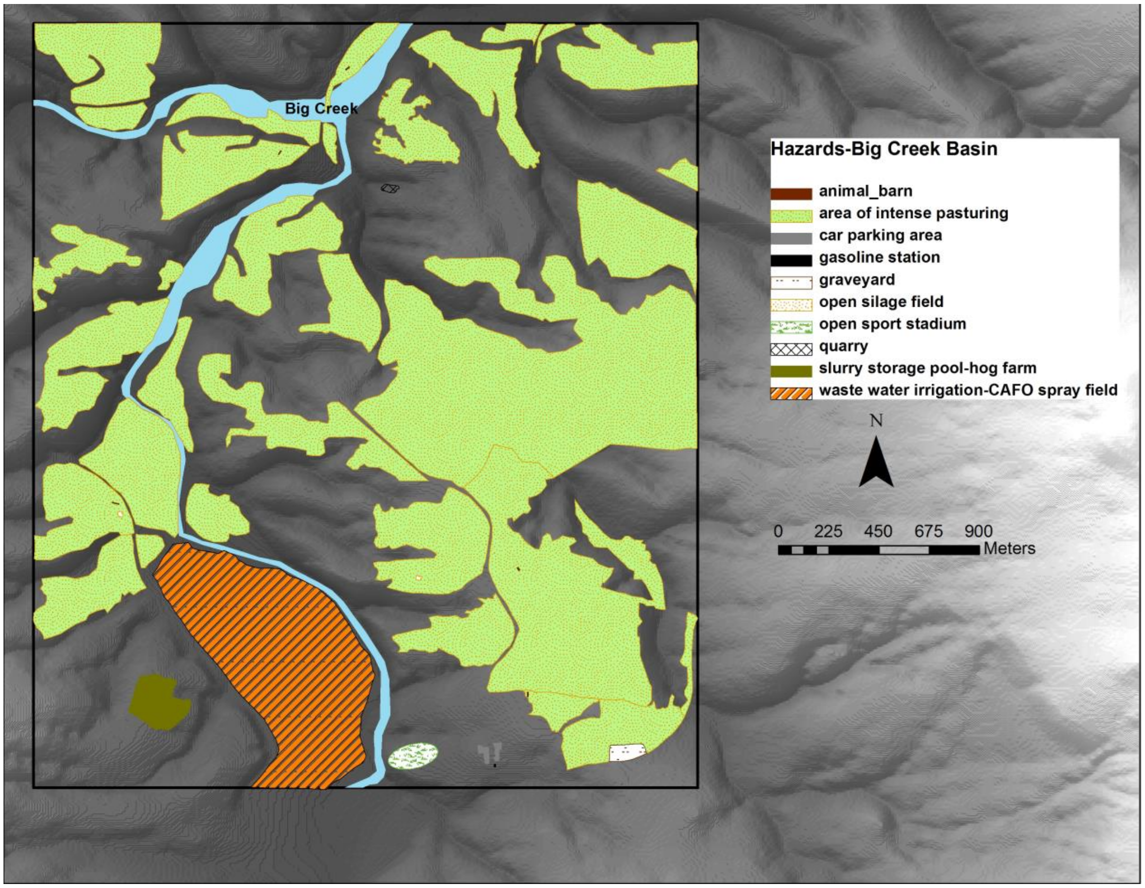

Figure 10 Map of hazard in the Big Creek basin

Hazards are primarily classified into three main types of land use: infrastructure, agricultural and industrial activities, and are later subdivided based on the specific nature of activity e.g. runoff from paved surface, pasture, animal barn, cemetery, quarry, and many more. A weighting value (H) which consists of a qualitative comparison of potential damage to the groundwater or source (Ravbar and Kranjc, 2007) is applied to each of the hazards in order to define the potential harmfulness of hazard. After defining the weighting factor (H), then a ranking factor (qn factor) is applied, which enables a comparison between hazards of the same type. The Ranking factor is defined based on sets of classification criteria for each hazard, e.g. population density, volume of waste disposal or applied nutrients, number of cars or trains/day, and several others. The third element of the hazard evaluation is the reduction factor (rf), which assesses the probability for a contamination event to occur. Upon characterizing the area's hazards for these three parameters, a final hazard score can be calculated by using the formula below, and a hazard map can be developed (Fig. 11).

Hazard score = Hazard index (H) + Ranking factor (qn) + Reduction factor (rf)

The hazard map characterized the majority of the study area as having very low and low hazard scores, with the exception of the spray fields and the CAFO location which were defined as areas with moderate to high hazard.

Following the completion of the hazard map, the importance score of the area was defined, which is needed in order to perform the risk assessment. The importance score considers resource/ source social importance (si sub-factor), economic importance for either agricultural or other activities (agri sub-factor (focusing on agricultural activities) and acti sub-factor (focusing on other activities e.g. tourism, industry)), and ecologic importance (bi sub-factor). The si sub-factor is defined based on the number of inhabitants that are supplied by the water source. The agri sub-factor is determined by the intensity of agricultural activities supplied at a respective source (livestock density and intensity of irrigation). The acti sub-factor is determined based on the average annual amount of used water m³, and the bi sub-factor is based on an evaluation of the springs and especially valuable ecosystems (Ravbar and Kranjc, 2007). These sub-factors are considered cumulatively and an importance score is calculated based on following equation.

$$\boxed{\text{Importance score} = si + agri + acti + bi}$$

The karst aquifer in the area is used as a supplementary source for irrigation, and supplies drinking water to less than 100,000 people; however because the aquifer has a high ecologic importance due to the documented presence of the Ozark blind cavefish, the area was assigned an importance score of 2 which is classified as "highly important".

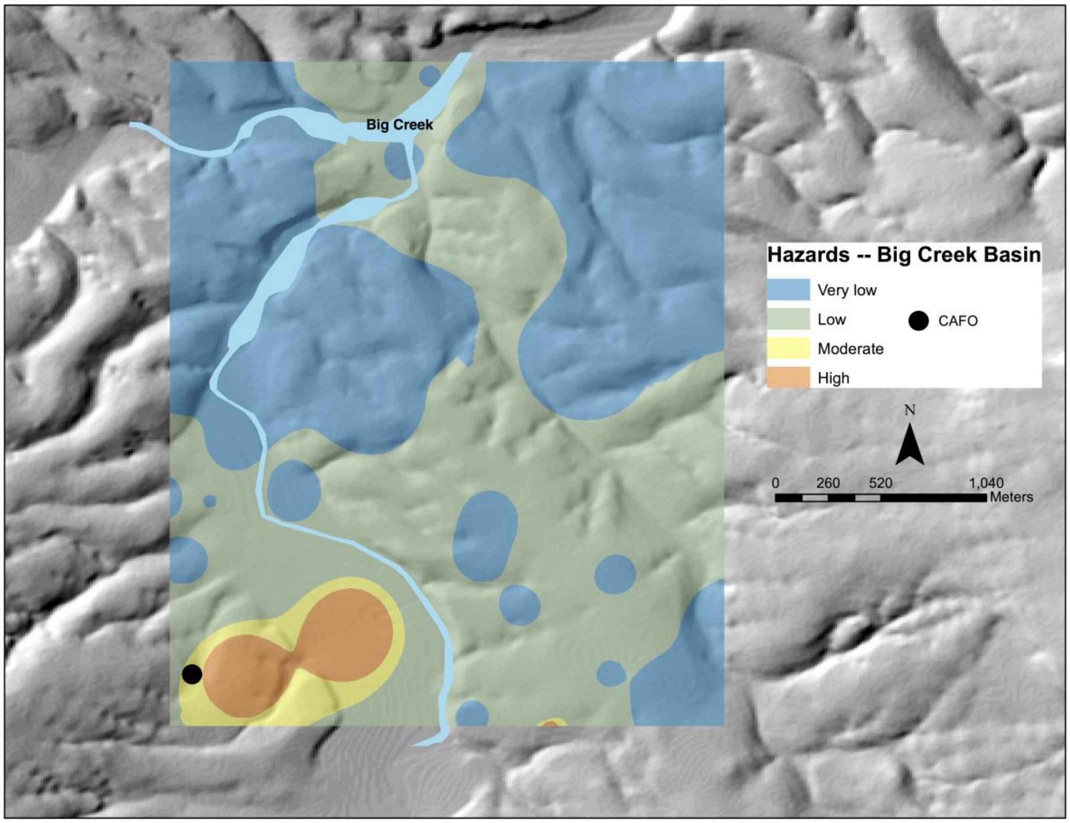

Figure 11 Hazard level map

3.2 Risk assessment

The risk analysis identifies the existing or potential hazards and exposure to contamination that need to be addressed in order to provide the basis for taking action to ensure groundwater source protection (Daly et al., 2004 in Ravbar and Kranjc, 2007).

First the risk intensity needs to be defined. The risk intensity evaluation identifies those surfaces on which contamination is likely to occur and estimates the processes that can lead to reduction of contamination ((Ravbar and Kranjc, 2007). The risk intensity index was defined through combining the source vulnerability index and the hazard index, using the equation below. The equation allows for the use of either the source vulnerability index or the resource vulnerability index. The source vulnerability index was chosen for this study because it combines all the aspect of intrinsic vulnerability and the K factor thus provides a more comprehensive assessment of the risk intensity.

In order to define the risk intensity the following equation was used:

Risk Intensity = Source Vulnerability Index or Resource Vulnerability index + Hazard Index

Where the source vulnerability index is defined as:

Resource index + K-factor

Based on these equations the risk intensity index is ≤ 7 and defines the area as low risk intensity. Once risk intensity is defined the total risk assessment can be performed. Total risk is a linkage of the degree of a potential contamination event with the evaluation of the consequences if the event actually occurred (Hötzl, 2004 in Ravbar and Kranjc, 2007). The total risk is defined by combining the risk intensity index and the importance index. The total risk map defined the study area as being very low to moderately prone to risk (Fig. 12).

Total risk = Risk Intensity index + Importance index

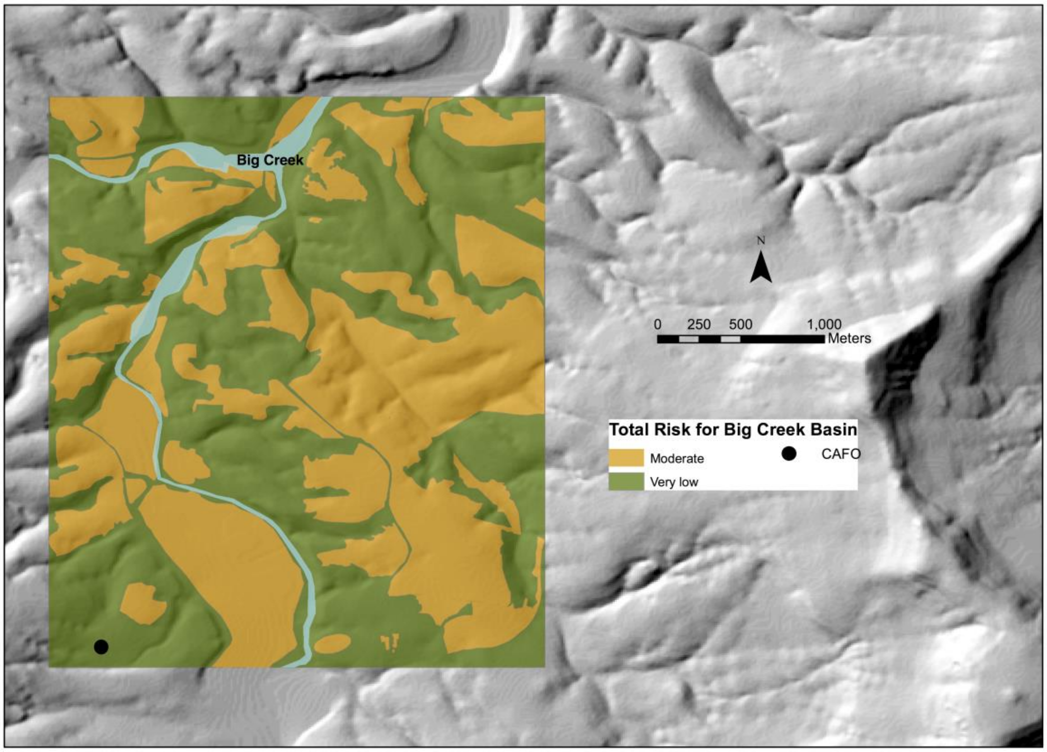

Figure 12 Total risk map for Big Creek basin

4. DISCUSSION AND CONCLUSIONS

The Slovene Approach to vulnerability mapping is a method that was developed for use in karst areas. However, because the method was designed for mapping of Slovene karst which covers alpine and classical karst that fall into the group of bare karst (with little to no overlying soils), the method does not perform well for mantled karst areas and/or highly agricultural areas.

The main disadvantage of the Slovene Approach in mantled karst areas is that the method assumes that thicker soil cover (including topsoil and subsoil) improves the self-cleansing processes. Self-cleansing processes apply to the natural attenuation processes i.e. physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater (United States Environmental Protection Agency, 1999). However these processes may be very complex and may work individually or in combination with other processes to provide varying degrees of attenuation. These reactions depend on site specific soil and aquifer characteristics as well as on geochemical properties of each pollutant (Gogu and Dassargues, 2000).

The method also puts much emphasis on the presence and location of swallow holes, which are often absent in mantled karst terrains.

The study area in this project has a considerably thick soil layer; which should enable self-cleansing processes, e.g. biodegradation; dispersion; dilution; sorption; volatilization;

radioactive decay; and chemical or biological stabilization, transformation, or destruction of contaminants (United States Environmental Protection Agency, 1999). However, due to agricultural activities, which include cattle farming, spraying fields from a CAFO, and open waste lagoons, the soils are likely saturated with nutrients (particularly Nitrogen) and may therefore be incapable of self-cleansing mechanism.

The Slovene Approach does consider the degree of the anthropogenic impacts and if they have already reached or even exceeded the natural self-cleaning capacity of karst aquifers/sources (De Ketelaere *et al.*,2004 in Ravbar and Kranjc, 2007). These considerations are reflected in the Hazards levels map (Fig. 11) which identifies the spray fields and waste lagoons as areas of high hazard. However, when the source vulnerability index is added to calculate the risk intensity and total risk, these areas are defined as having a moderate risk intensity due to the fact that the Slovene Approach considers intrinsic vulnerability of the studied area protective enough to reduce the risk of spraying and intensive farming.

However, the studied area has a shallow water table, the soils are believed, as stated above, to be rich with nutrients, and additionally the area is surrounded with a losing stream, therefore all the nutrients washed into the stream likely reach the groundwater quite rapidly.

In order to verify the possibility of quick introduction of nutrients from spray fields and pastures into groundwater, a surface tracer test was performed. It aimed to simulate the travel time of water on fields where manure is sprayed by applying dye on the surface of a pasture and measuring the travel time of dye from the injection site to a spring. Due to inaccessibility to the study area because private property, the tracer test was performed on an alternative location in the area of the Savoy Experimental Watershed, owned by the University of Arkansas. This site was chosen because it shares similar hydrogeological characteristics/conditions as the studied Big Creek Basin, and because it enabled us to safely perform uninterrupted dye tracing using a field fluorometer. The area is mainly used to study long-term impacts of sustainable animal production on karst land, and has a well-defined watershed of karst aquifers. Thus, it enabled us to perform a controlled tracer test considering that the groundwater connections were already known.

The dye (Rhodamine WT) was applied directly to the soil surface in a linear drainage swale located approximately 10 m away from Langle spring where a field fluorometer was deployed. The swale bypasses the spring and continues towards a surface stream. Therefore the assumption was that the dye would bypass the spring and flow directly to the stream. No additional anthropogenic water input was used thereby simulating the application of manure on spray fields. The soil thickness in the Savoy Experimental Watershed is ranging between 34 cm to 210 cm. Thickness is defined based on past drilling activities. In the area of dye application the soil thickness should range between 35 cm to 90 cm.

A rain event occurred one day after the dye application. The field fluorometer reported a detection of the dye at the spring in less than 10 days after injection. Because the dye application area lies in very cherry part of the Boone Formation, with continuous thin chert layers the dye was likely perched between these layers, and diverted laterally toward the spring.

The positive trace from the pasture to the spring indicates that the substances applied on the surface can reach the groundwater, without significant dilution in the soil, if the hydrological conditions are suitable. Hence, the nutrients from cattle fields and spray fields can be directly introduced into groundwater even if there is a soil cover, which, according to the Slovene Approach, should prevent contaminant transmission through the soil zone.

Another feature that the Slovene Approach may not adequately address from a risk perspective are waste lagoons. Several studies have shown that waste lagoons tend to leak even if lined with a clay protection layer (Field, 2012; Ham, 2002; Hutchins et al., 2012; Mallin and Cahoon, 2003). Therefore the nutrients and manure can be steadily introduced directly into the subsurface.

Additionally, leachate waters from landfills and other similar sources, can potentially enhance the dissolution of limestone in the vadose zone. In her studies that focused on the percolation of contaminates and dissolution rates of limestone in the vadose zone, Kogovšek (2011) suggests that these activities can lead to the formation of localized permeable fissures that rapidly route infiltration containing contaminants through the vadose zone to underground watercourses and on to karst springs (Kogovsek, 2011).

Based on these studies, an experiment is currently being developed to observe the dissolution rates of limestone tablets covered with soil, water and manure. This experiment will help determine if manure application on spraying fields influences the dissolution rates of underlying limestone bedrock.

To conclude, the study showed that the Slovene Approach, although specifically developed for karst areas, may not be a suitable method for mantled and highly agricultural karst areas. Vulnerability mapping is most effective when developed site specifically, in the same way as the Slovene Approach was developed for Slovene karst. Following this mapping project, it remains uncertain if this kind of vulnerability mapping is a method that should be fostered in the future in order to assure karst protection.

These thoughts and findings will be further developed in an upcoming publication by Springer entitled Karst Water Environment: Advances in Research, Management and Policy.

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