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Efficacy and Challenges of Using Springs for Early Detection of Contaminant Release from Waste Disposal Facilities Constructed in Karst Terranes

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Abstract

Early detection of groundwater contamination from waste disposal facilities is challenging in karst terranes. First, one needs to demonstrate that the groundwater system at the study site is monitorable. Both springs and wells are potential monitoring locations if they are effectively connected to the groundwater system, and they are not impacted by any other disposal facilities. Second, due to dynamic responses to recharge events, particularly discharge and chemical constituents at karst springs, multiple-parameter, long-term, and high-frequency monitoring may be required to collect background data. Sampling and analysis plans should be designed to reflect the unique characteristics of the monitoring locations. Characterization of the natural variations in water quality may require sampling efforts under different flow conditions. Third, evaluation of the potential impact of waste disposal units on the groundwater system requires an effective statistical evaluation program. Due to heterogeneity of karst aquifers, intra-locational comparison is generally preferred to inter-locational comparison. Sufficient groundwater monitoring data prior to construction of waste disposal units are required to develop the intra-locational statistical evaluation. In the case study presented in this paper, procedures to address these above-mentioned challenges were presented for two springs using seven dye tracing tests, two spring instrumentations, nine background sampling, flow-weighted concentrations, and an innovative statistical evaluation method were presented. These procedures were developed to evaluate potential contaminant release from a solid waste disposal facility constructed in a relatively isolated karst terrane. Although the specific procedures may not be duplicated, the overall technical approaches discussed in the paper may shed light on groundwater monitoring programs in other karst areas.

Keywords

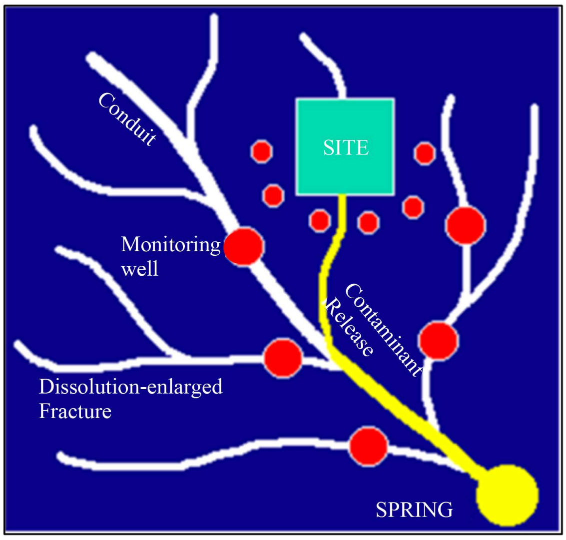
Karst, Spring, Dye Tracing, Flow-Weighted Concentration, Waste Disposal, Statistical Evaluation

1. Introduction

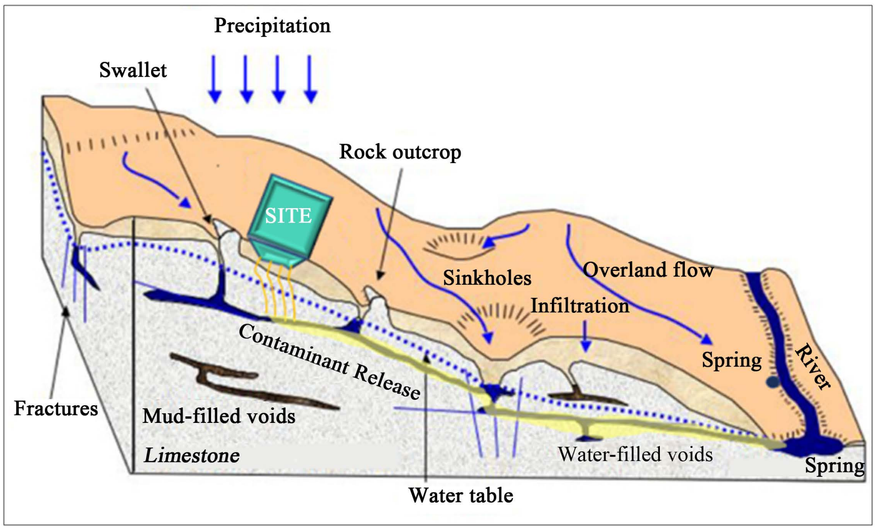
Karst terranes, covering approximately 12.5% of the world's ice-free land area and providing water to as much as 25% of the world's population (Ford & Williams, 2007; Hollingsworth, 2009), are susceptible to sinkholes, vulnerable to contamination, and unamenable to groundwater monitoring and remediation. These adverse consequences result from the peculiar characteristics of karst aquifers that consist of multiple porosity elements ranging from small pore spaces, solution-enlarged fractures/conduits to caves and a spectrum of flow regime from laminar flow to turbulent flow. While the small pores of the rock matrix function as storage, most karst groundwater and contaminants move through discrete conduits and discharge at springs. An effective monitoring program in a well-developed karst aquifer shall include not only monitoring wells but also springs that are hydraulically connected to the investigation site (Quinlan, 1989; Quinlan et al., 1991; Schindel et al., 1996; Ewers, 2016). In many karst aquifers, springs are an important component of conceptual site models, and identification of springs has been an essential part of site characterization. Because springs can provide data of aquifers in scales typically larger than monitoring wells, they have been considered as more effective monitoring points for detection of contaminant release (Zhou et al., 2002; Quinlan et al., 1991).

Construction of disposal units is not recommended in highly developed karst terrains. If a new solid waste disposal unit is proposed, the proponent must demonstrate that location in the karst terrain will not cause any significant degradation to the local groundwater resources. Meeting this requirement, however, requires groundwater monitoring. For any particular site, the monitoring strategy depends on the established conceptual site model and the project objective. Under U.S. EPA's Resource Conservation and Recovery Act, for example, a minimum of four wells, one upgradient from the unit and three downgradients from the source are required to monitor release of contaminants (EPA, 2004). The upgradient well is intended to sample background concentrations of the relevant constituents presumably unaffected by the contaminant source, while the downgradient wells represent points of compliance, where concentrations are established to determine whether contaminants are migrating from the regulated unit. While this design would typically be effective in porous media where contaminants tend to spread out in blob-like plumes, contaminants in well-developed karst aquifers can pass undetected by even closely spaced wells.

Figure 1(a) and Figure 1(b) show schematically a conceptual site model of a relatively isolated karst system in the plain view and vertical profile, which includes a hypothetical waste disposal facility labeled as SITE. The groundwater flow and associated contaminant transport are controlled by discrete conduits and dissolution-enlarged fractures. The path highlighted in yellow represents the likely migration route of contaminants if a release or leak occurs at SITE. When the probability of monitoring wells encountering the conduits is small the monitoring wells, designated by red circles in Figure 1(a), are not capable of detecting release of contaminants from the waste disposal facility or landfill. On the other hand, springs are preferred monitoring locations, and it is perceivable that any release of contaminants would move to and discharge at the springs. From a



(a)



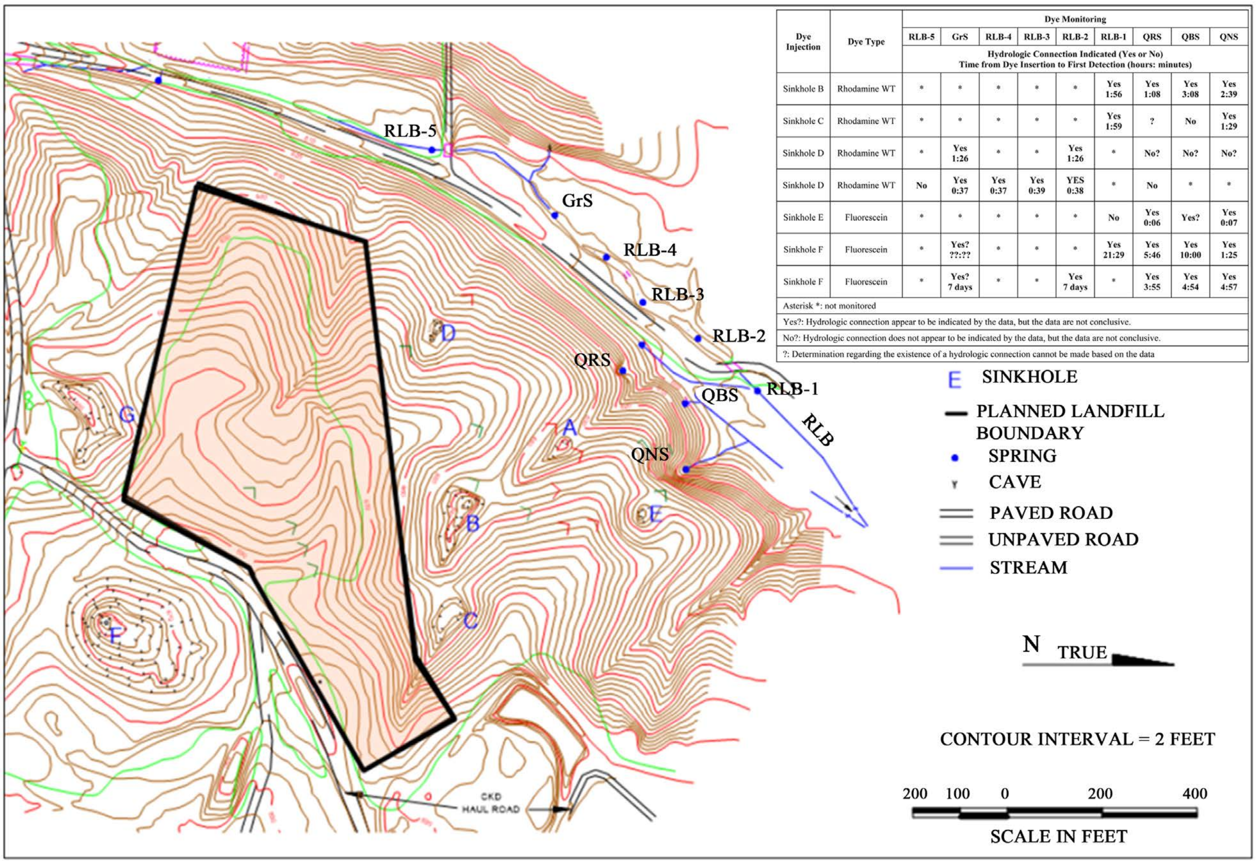
(b)

Figure 1. Schematic conceptual site model of a karst aquifer (red circles—monitoring wells; yellow line—likely migration pathway of contaminant released from the landfill site). (a) plain view; (b) vertical profile.

remediation perspective, springs are exposure points of contaminated groundwater to receptors such as human beings or plants. Therefore, the springs can be remedial action targets to eliminate the exposure pathway. However, use of springs as either monitoring locations or remedial targets shall be based on thorough understanding of the springs including their characteristics and relationship with the entire drainage basin. This paper presents a case study to demonstrate how springs helped accomplish project goals if used properly and the challenges of using springs as compliance monitoring points.

2. Geologic Setting of the Landfill

Figure 2 shows location of the landfill, which was constructed within the eastern slope of a small stream valley, which is entrenched into the Mitchell Plain of southern Indiana. The Mitchell Plain is a 2900-km^2 limestone plateau characterized by an abundance of underground drainage and a lack of streams on the land surface (Powell, 1973; McConnell & Horn, 1972). Physiographically, it is a subunit of the Highland Rim Section of the Interior Low Plateaus Province (Fenneman, 1938). It extends southward into Kentucky as the Pennyroyal Plateau; to the north, it is covered with a thick blanket of Pleistocene till (Palmer & Palmer, 1975). A sinkhole plain occupies the westernmost 30% of the Mitchell Plain (Palmer & Palmer, 1975).



Dye Injection	Dye Type	Dye Monitoring								
		RLB-5	GrS	RLB-4	RLB-3	RLB-2	RLB-1	QRS	QBS	QNS
		Hydrologic Connection Indicated (Yes or No) Time from Dye Insertion to First Detection (hours: minutes)								
Sinkhole B	Rhodamine WT	*	*	*	*	*	Yes 1:56	Yes 1:08	Yes 3:08	Yes 2:39
Sinkhole C	Rhodamine WT	*	*	*	*	*	Yes 1:59	?	No	Yes 1:29
Sinkhole D	Rhodamine WT	*	Yes 1:26	*	*	Yes 1:26	*	No?	No?	No?
Sinkhole D	Rhodamine WT	No	Yes 0:37	Yes 0:37	Yes 0:39	YES 0:38	*	No	*	*
Sinkhole E	Fluorescein	*	*	*	*	*	No	Yes 0:06	Yes?	Yes 0:07
Sinkhole F	Fluorescein	*	Yes? ??:??	*	*	*	Yes 21:29	Yes 5:46	Yes 10:00	Yes 1:25
Sinkhole F	Fluorescein	*	Yes? 7 days	*	*	Yes 7 days	*	Yes 3:55	Yes 4:54	Yes 4:57

Asterisk *: not monitored

Yes?: Hydrologic connection appear to be indicated by the data, but the data are not conclusive.

No?: Hydrologic connection does not appear to be indicated by the data, but the data are not conclusive.

?: Determination regarding the existence of a hydrologic connection cannot be made based on the data

Figure 2. Site location of the landfill.

Detailed geotechnical and geophysical investigations were conducted to evaluate risk of sinkhole occurrence, and the risk of structural collapse was factored into the landfill design (Zhou et al., 1999, 2000). Clayey overburden, up to 12 m thick overlies the St. Louis and Salem limestone bedrock of Mississippian Period. Seven sinkholes were identified in the vicinity of the study site, and they are labeled as A through G in **Figure 2**. A number of small springs, labeled as QRS (Quarry Road Spring), QNS (Quarry New Spring), and QBS (Quarry Base Spring), discharge groundwater to a local stream RLB along the base of the valley slope just west of the site. QNS is located at the head of a short, steep valley, whereas QRS and QBS emerge from small openings in the valley floor. GrS (Grissom Spring) is a submerged spring on the RLB riverbed and was discovered through the trace tests, as discussed below.

Permitting of the waste disposal facility required extensive hydrogeological and geophysical investigations, ecological evaluation, sinkhole risk assessment, and an effective groundwater monitoring program. Development of the groundwater monitoring program is discussed in this paper. First, one needs to demonstrate that the groundwater system at the study site can be monitored. The monitoring locations must be effectively connected to the groundwater system and are not impacted by any other disposal facilities. Secondly, the sampling and analysis plans should be designed to reflect the unique characteristics of the monitoring locations. Characterization of the natural variations in water quality requires sampling efforts under different flow conditions. Thirdly, evaluation of the potential impact of waste disposal units on the groundwater system requires an effective statistical evaluation plan. Due to heterogeneity of karst aquifers, intra-locational comparison is generally preferred to inter-locational comparison. The intra-locational statistical testing compares data collected prior to operation of the disposal facility versus data collected during operation of the disposal facility at the same sampling point. Because the comparison is made at the same sampling point, concentration differences between monitoring locations due to natural spatial factors do not affect the intra-locational tests. Concentration changes of the chemicals of concern over time cause an intra-locational test to be statistically significant and to show a change in groundwater quality (Interstate Technology & Regulatory Council, 2013). The out-of-compliance triggers and quality-control procedures should be developed based on site-specific conditions.

3. Dye Tracing to Select Springs for Early Detection Monitoring

A groundwater tracing study consisting of seven tracer tests was conducted to aid in the design of the karst groundwater monitoring program for the proposed landfill facility. Fluorescein and rhodamine WT dyes were introduced into five sinkholes. At sinkhole D and F, tracing tests were repeated under a different flow condition. On-site fluorometric analyses and concentration-dependent sampling were utilized at springs and the stream for dye monitoring. The table inserted in Figure 2 summarizes the dye tracing results. A dye trace breakthrough curve is shown in Figure 3.

The dye tracing results indicate that groundwater monitoring at the site can be conducted most appropriately at three natural discharge springs, QRS, QNS, and GrS. GrS is a submerged spring in the stream bed and not readily amenable for monitoring without a significant modification of the stream. Subsequently, springs QRS and QNS was established as the monitoring stations with approval of the relevant regulatory agency.

4. Instrumentation of Springs

Both QRS and QNS discharge water into irregular open channels and eventually flow into the local creek, RLB. Measuring the flow of either spring required construction of a structure to constrict the water flow in its open channel. Figure 4 shows the structure design that allowed discharge gauging, water-quality monitoring, and water sampling at QRS. Similar instrumentation structure was constructed at QNS. Every effort was made to minimize the modification of the springs. However, some improvements were necessary to install the instruments and calculate the discharge.

- Both flow measuring devices were to be installed with free fall, or no submergence whenever possible. This required enlargement and regrading of the outfall channel with 0.5 - 1-foot elevation difference between the weir and the outfall channel.
- Installation of these weirs included an approach section of 5 - 10 feet straight channel after the spring pools.
- The weir floor must be level. This required grading the channel section where the weir was to be installed.
- The weirs were designed to be freestanding and required no external support to maintain their dimensional integrity during operation.

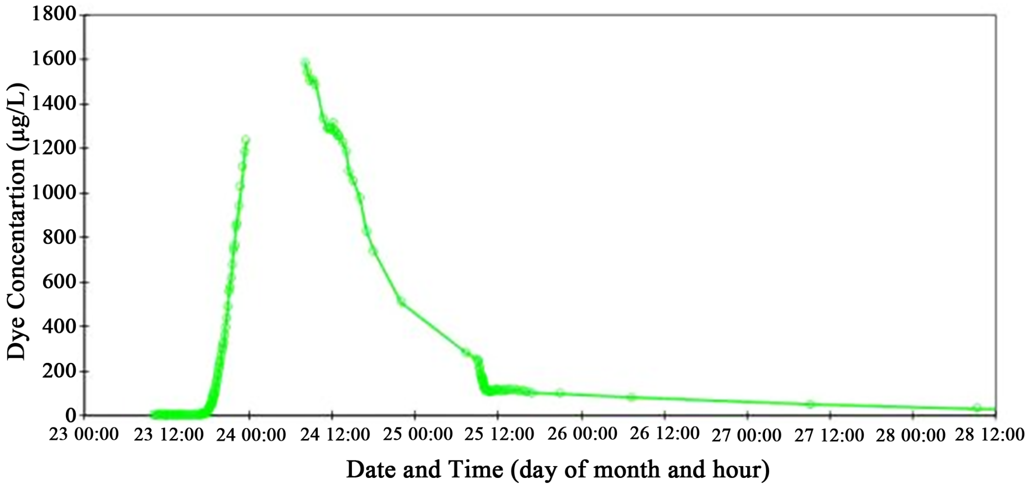
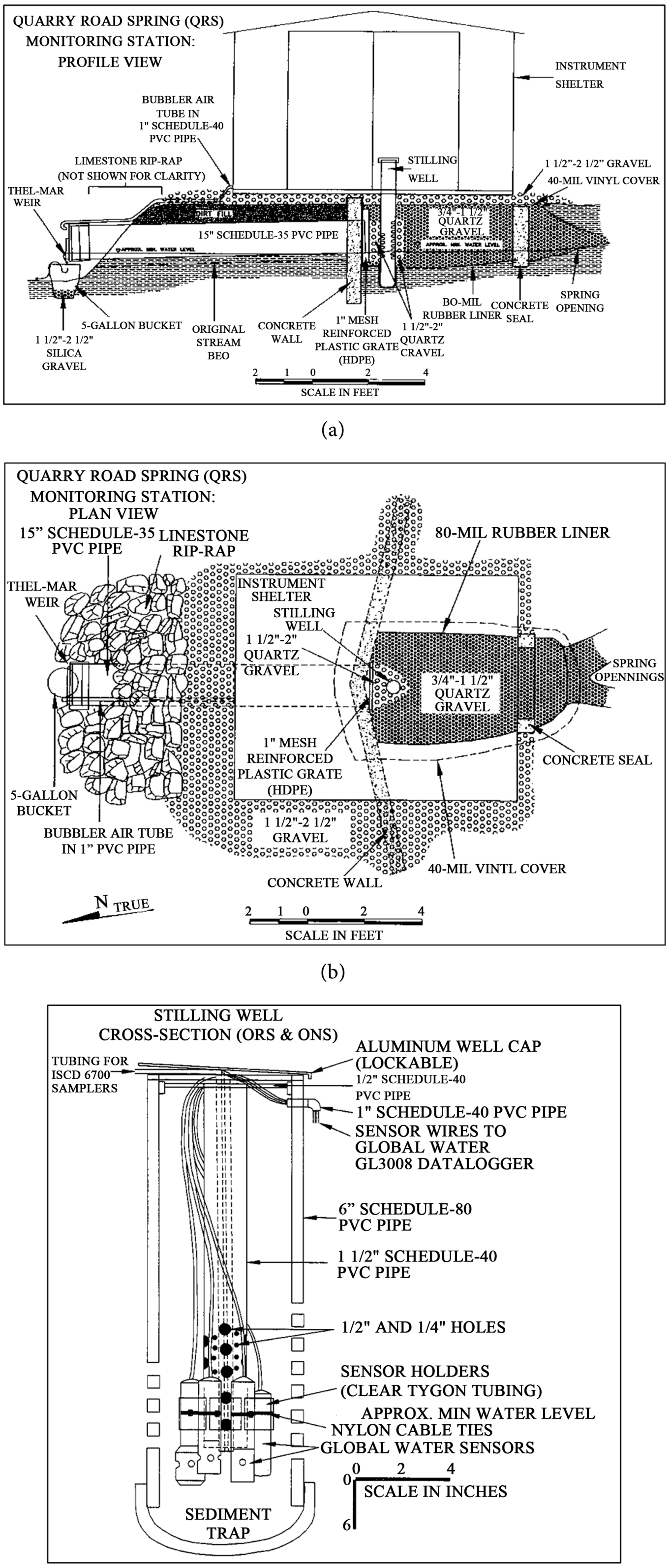


Figure 3. Fluorescein breakthrough curve at QRS in response to dye injection at sinkhole E.



(a)

(b)

(c)

Figure 4. Structural design for instrumentation at selected springs. (a) Vertical view of spring instrumentation design; (b) Plain view of spring instrumentation design; (c) Installation of multi-parameter sensors in still well.

- The PVC pipe connecting the weirs should be grouted into the open channel. Grouting the PVC in place lessens the chance of wall deflection and secures the weirs.
- A rock apron was placed beneath the flume outfall to protect against erosion.

The materials used for constructing the quasi-monitoring well and the installation of the well should not measurably alter the physical and chemical quality of the spring water. The packing gravel in the upstream should be grading in size toward the well. The inside packing material can be 2” stone and the outside may consist of large rubbles (>3”). These large diameter packing materials extend the spring orifice to the monitoring well.

A quasi-monitoring well of six-inch in diameter was installed to house the multi-parameter instruments. Two feet of the well casing was perforated, where the probes were located. The diameter of the slot openings should be in the range of 0.4” to 0.5”. The packing materials were quartz cobbles or sandstone fragments. The impermeable liner on top of the packing materials prevented rainwater infiltration. The surface sloped 15 degrees outward to avoid water ponding.

Karst springs have been known as having high-frequency, high-amplitude changes in water chemistry, especially in response to recharge events. The following parameters were monitored in real time at designated frequencies and stored in dataloggers for regular retrievals:

- Discharge;
- pH;
- Dissolved oxygen (DO);
- Oxidation and reduction potential (ORP);
- Temperature;
- Turbidity;
- Specific conductance (SC).

Figure 5 shows the installed devices for the spring monitoring. Figure 5(a) is the installed flume for discharge measurements, whereas Figure 5(b) illustrates

(a) (b)

Figure 5. Photos showing the installed instrumentation for spring monitoring. (a) Installed device for discharge measurement; (b) Installed instruments for water-quality parameter monitoring and sampling.

the water-quality monitoring devices and data logging system. The instrumentation is clearly site-specific. Monitorability of spring depends to a large extent on whether its discharge and water quality parameters can be measured. In this case study, for example, QrS was underwater and its monitorability requires a significant effort to modify the discharge point to install the instruments and a regulatory permit for such a modification on the surface creek. Because springs connect groundwater and surface water, it is common that springs are submerged in rivers, reservoirs, lakes, and oceans. The evidence that a spring is hydraulically connected to study site does not automatically mean that the spring can be used for compliance monitoring.

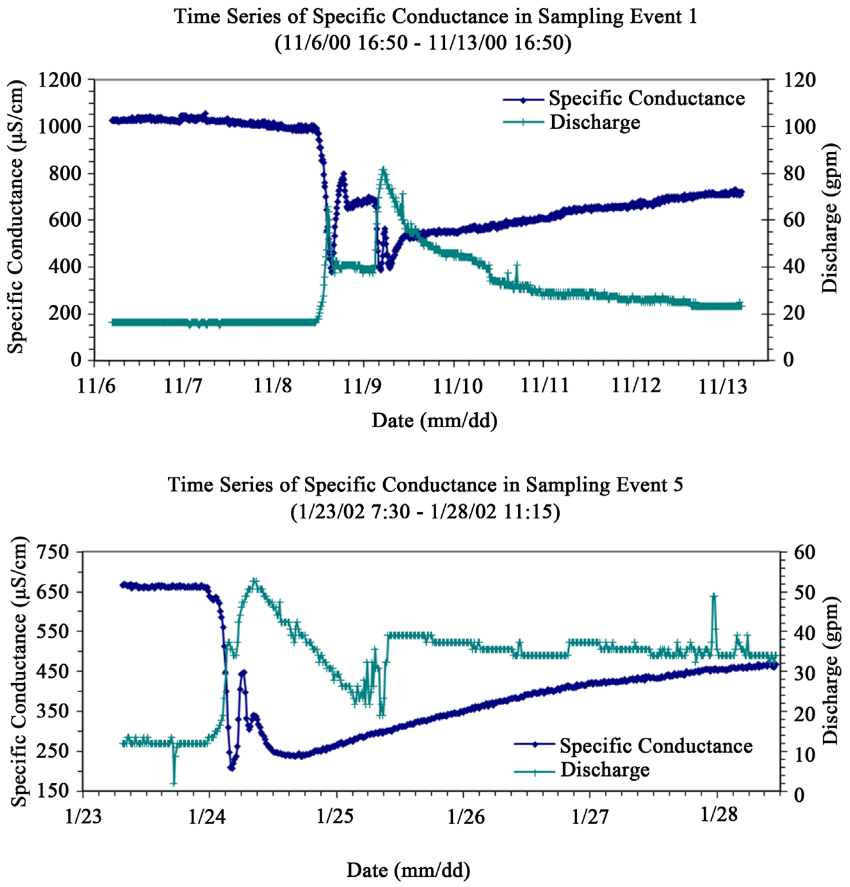
5. Storm-Driven Sampling and Analysis Program

Nine background sampling events were conducted at the two springs to characterize the background data population. Six of these background sampling events were high-frequency, storm-pulse type events in response to a variety of aquifer, flow, and precipitation conditions, while three were 24-hour base-flow events with no precipitation. Following each background sampling event, samples were judgmentally selected for laboratory analysis based on the spring discharge and field water-quality data (pH, DO, ORP, temperature, turbidity, and SC) collected during each event. Such a sampling approach characterized changes in natural ground water chemistry that occurred under different flow conditions. **Table 1** summarizes the natural variations of 11 water-quality parameters during the background sampling efforts at Spring QRS. Only data at QRS is presented in this paper because of the page limitation. **Figure 6** shows examples of water-quality change in response to recharge events in two background sampling events.

Table 1. Calculated FWCs of 11 water-quality parameters for nine sampling events (unit in mg/L).

Sampling Event	Alkalinity, Bicarbonate ($CaCO_3$)	Alkalinity, Carbonate ($CaCO_3$)	Alkalinity, Total ($CaCO_3$)	Magnesium	Potassium	Selenium	Sodium	Sulfate	Chloride	Solids, Dissolved	Calcium
1	258	0.6	258	20.9	71.8	0.003	22.6	131.1	53.6	772	143
2	195	1.0	195	18.5	81.7	0.005	22.2	211.7	65.7	727	121
3	212	0.4	212	20.2	53.5	0.05	17.9	149.1	55.5	698	130
4	256	0.5	256	23.0	34.0	0.003	17.6	93.0	56.1	676	134
5	242	0.4	242	20.4	33.5	0.010	15.1	107.4	46.1	620	132
6	274	0.3	274	22.7	65.8	0.008	20.4	205.5	64.5	748	141
7	255	1.0	255	22.2	59.5	0.010	19.9	188.9	62.9	684	129
8	203	1.0	203	21.9	85.0	0.005	24.1	180.0	68.9	749	138
9	232	0.8	232	22.5	60.6	0.004	21.9	177.8	71.0	761	138
FWC Mean or Mean Log	236	−0.5	236	21.3	60.6	−5.0	20.2	160.5	60.5	715	134
Standard Deviation	28	0.4	28	1.5	18.3	0.9	2.9	42.6	8.1	49	7
Distribution	N	Log-N	N	N	N	Log-N	N	N	N	N	N

N—Normality not rejected; Log-N—Log-normality not rejected.


Time Series of Specific Conductance in Sampling Event 1
(11/6/00 16:50 - 11/13/00 16:50)

Time Series of Specific Conductance in Sampling Event 5
(1/23/02 7:30 - 1/28/02 11:15)

Figure 6. Examples of water-quality variations in response to recharge events.

Clearly, these sampling approaches were non-conventional. To perform high-frequency, storm-induced sampling, accurate selection of the appropriate sampling events based on weather forecasts was important. This can be a major difficulty for any karst sampling program. Individual storm-induced sampling events that have been started may need to be discontinued because forecasted precipitation does not materialize, or a storm event may not produce a significant hydrographic or chemical response. Discontinuing a sampling event can cause significant unwanted expenses for clients, especially when significant mobilization times exist. Due to the complicated nature of the sampling, the fact that sampling could occur at any time of the day or night, and to facilitate smoother and more efficient handling of sampling related activities, a plan for monitoring the weather conditions and communication between all parties was developed (Lounsbury et al., 2003). When a weather condition was deemed to be favorable for sampling, the flow conditions at the springs and in the aquifer were immediately evaluated from the field data (groundwater level, discharge, and field water-quality parameters) to guide the sampling efforts.

As shown in **Figure 6**, concentrations of measured constituents varied with spring discharge and might be impacted by the antecedent soil moisture conditions, flow conditions, and other factors. Concentrations were correlated to discharge. Therefore, a flow-weighted concentrations (FWCs) was proposed and calculated for each individual sampling event for statistical evaluation. Although FWCs do not appear to have been used in regulatory-driven groundwater monitoring programs at karst springs, they have been accepted and widely used in storm water runoff evaluation. **Table 1** summarizes the calculated FWCs for 11 select chemical constituents.

6. Statistical Evaluation and Combined Shewhart-CUSUM Control Charts

When springs are used to monitor release of contaminants from waste disposal facilities, intra-locational statistical analysis is a better method than the inter-locational one (Zhou et al., 2007). Combined Shewhart-CUSUM control charts were used for this study.

Design of a combined control chart requires determination of the following five parameters:

- $\overline{X}$: Estimated mean of the FWC or adjusted FWC from the background samples.
- S: Estimated standard deviation of the FWC or adjusted FWC from the background samples.
- h: The value against which the CUSUM will be compared.
- k: A parameter related to the displacement that should be quickly detected.
- SCL: The upper Shewhart limits, which is the number of standard deviation units for an immediate release. In this application, the upper control limits are of interest.

$\overline{X}$ and S were computed from the nine sampling events. For any new water-quality parameter, the standardized difference z_i is calculated by:

$$z_i = \frac{(\text{FWC})_i - \overline{X}}{S}$$

And, the cumulative sum Y_i is calculated by:

$$Y_i = \max\left[0, (z_i - k) + Y_{i-1}\right]$$

In practice, $Y_0 = 0$ (Gibbons, 1994), which ensures that only cumulative increases over the background are considered. If a process is in control, such that all future observations come from a normal distribution with the fixed mean and standard deviation, the quantity z_i is approximately distributed as an $N(0,1)$ random variable and bounces around 0. The quantity z_i-k bounces around $-k$. As a result, the ith upper cumulative sum Y_i will tend to bounce around 0 (Millard & Neerchal, 2000). The procedures can be illustrated by plotting the values of Y_i and z_i against t_i. An out-of-control situation is declared on sampling event i if for the first time, $Y_i \geq h$ or $z_i \geq$ SCL.

The U.S. EPA (1989) and American Society for Testing and Materials (ASTM, 1998) recommend using combined Shewhart-CUSUM control charts for groundwater monitoring as an alternative to prediction or tolerance limits for intra-locational comparison of monitoring constituent concentrations. It takes advantages of good properties of both Shewhart and CUSUM control charts. The Shewhart control scheme is better than the CUSUM scheme in quickly detecting a large (>3 standard deviation) shift in the mean; whereas, the CUSUM scheme is usually faster in detecting a small change in the mean that persists (Lucas & Crosier, 1982). Because the integrity of the landfill liner is potentially threatened by sudden or catastrophic failure, in addition to more gradual and less severe types of failure, it is essential to account for both large and small changes in the water-quality data. Combined Shewhart-CUSUM control charts are sensitive to gradual and rapid releases. Using both charts can re-duce the false-negative rate and increase the overall correct-positive rate.

U.S. EPA (1989) recommends using SCL = 4.5, $k = 1$, and $h = 5$, based on the recommendations of Lucas & Crosier (1982) and Starks (1988). These values are suggested because they allow a displacement of two standard deviations to be detected quickly (EPA, 1992). For easy application, ASTM (1998) suggests the use of h = SCL = 4.5, which is slightly more robust in detecting leakage and thus reducing the rate of false negatives.

Unlike prediction limits, which provide a fixed confidence level (e.g., 95%) for a given number of future comparisons, control charts do not adjust for the number of future comparisons. The selection of $h = 5$, SCL = 4.5, and $k = 1$ was based on U.S. EPA's review of the literature and simulation (Lucas & Crosier, 1982; Starks, 1988). Since 1.96 standard deviation units correspond to 95% confidence on a normal distribution, there is approximately 95% confidence for this method as well for each comparison.

These recommendations for h, k, and SCL are based on analysis of a single statistical comparison. They do not account for adjusting the control chart parameters to account for the number of monitoring points and the number of constituents monitored during each sampling event (Gibbons, 1994; Davis, 1998). In practice, the statistical comparisons are often more than 1. For this study, twelve statistical comparisons need to be performed at the end of each sampling event. ASTM (1998) suggests several possible modifications to control charts by allowing re-sampling and updating background data to attempt to control the overall false-positive rate and keep the statistical power high on each monitoring occasion.

7. Discussions on Using Springs as Monitoring Points

Springs are one of the unique features in karst terranes and favored as monitoring locations for detection of contaminant release from waste disposal units by many researchers (Quinlan et al., 1991; Ewers, 2016). As demonstrated in this paper, use of springs as compliance monitoring points shall be based on the conceptual site model of the investigation site and characteristics of the springs. The following summarize the main characteristics of springs that shall be considered in their use as either monitoring locations or remedial targets:

- Response to recharge: Water quality changes with the increase of discharge at the spring. The lag time may vary, depending on the characteristics of the karst aquifer. Knowledge of within-event constituent concentration fluctuations provides limited information to decision makers regarding control measures that might be required. Sampling under various flow conditions and extensive data analyses are essential to provide interpretations for intelligent decisions. A one-time grab sampling is of little use for estimating the water quality, flow rate and mass loadings because one instantaneous value is not representative of the average conditions at the spring; even less, the variability of the concentration and mass changes cannot be described. Site-specific sampling and analysis plans may be needed to characterize the water quality of karst aquifers. Due to dynamic responses to recharge events, multiple-parameter, long-term, and high-frequency monitoring may be required. Sampling and analysis plans should be designed to reflect the unique characteristics of the monitoring locations. For example, in some cases light or dense non-aqueous phase liquids may be observed only during storm events, and other constituents might only be detected on sediment when mobilized. These types of temporal variations are in general not the case in porous media aquifers, and therefore traditional investigation techniques would often not be effective for sites in karst media. Characterization of the natural variations in water quality may require sampling efforts under different flow conditions.
- Non-repeatability: Measurements at the karst spring are observational, not experimental because of the continuous movement of groundwater, antecedent condition, rainfall intensity, and its constant reaction with the surrounding environment. Exactly recreating the many natural and anthropogenic influences that affect each measurement is impossible. This is especially true for the karst aquifer under study. The water flow and water quality have a dynamic response to the rainfall events. Ancillary and metadata (information about a given data set, including explanatory information and data-quality information) pertinent to the statistical characteristics of the sampled population are investigated using the data from nine sampling events. For the reason that statistical regularity cannot be demonstrated through controlled experiments at the site, ancillary data are important to quantify possibly confounding variables that may preclude meaningful interpretation of data. Any modifications on the land use upstream of the landfill site should be documented.
- Censored data: Negative values are not possible for the water quality data at the springs. Limits in methods for samples collection and analysis cause data to be reported as either above or (more typically) below one or more reporting limits, which produces a censored population of data. The effect of censored data can be especially problematic for interpretation of water-quality data (Gibbons & Coleman, 2001). Laboratory detection limits change with time and can be dramatically different from laboratory to laboratory and may even be different from method to method within a laboratory. Detection-limit

artifacts affect statistical properties of individual data sets. When a data set contains values reported as less than one or more detection limits an overestimation of central-tendency measures and an underestimation of dispersion measures will be caused by truncation of the lower tail of the true population. Because the relative uncertainty in the accuracy and precision of individual values tend to increase as reported concentrations approach the detection limit, the percent error expected for measurements near detection limits is much higher than for values well within the measurement range of the method of analysis.

- Meaningful statistical outliers: Valid measurements that are considerably higher or lower than most of the measured population are common among data sets at karst springs. Outliers can be extremely problematic in data interpretation. Outliers can arise from a variety of sources including but not limited to transcription errors, inconsistent sampling procedures, instrument failure, calibration or measurement errors, underestimation of spatial or temporal variability, and other factors. The presence of meaningful high-end outliers (actual but extreme values) contributes to the positive skew and is a factor producing non-standard distributions. High-end outliers represent times when, for example, regulatory criteria may be exceeded, and the health of the local ecosystems may be affected. Those outliers produce a host of potential problems for interpretation of data sets. If an outlier is discovered to have a strong influence on the slope of a regression line (the slope or the correlation coefficient changes significantly when the point is omitted), then it must be determined whether the outlier represents extreme values for a single process or if a secondary process is characterized by the outlier. Measurement and documentation of explanatory variables such as precipitation and flow; real-time measures of water-quality characteristics such as SC, pH, temperature, and turbidity, use of ratios between constituents of interest, and results from a comprehensive quality assurance/quality control (QA/QC) program can be used to identify and explain outliers in terms of the potential effect of real physicochemical processes as opposed to the effect of sampling artifacts. Because of the complexity in sampling and analysis at the spring, a strict QA/QC measure is taken to ensure the meaningful outliers not to be excluded in the statistical analyses. Elimination of outliers is considered a dangerous and unwarranted practice for the interpretation of water-quality data at the site, unless one has substantial objective evidence demonstrating that the outliers are not representative of the population under study. If outliers are not handled in an appropriate manner, unwanted, and potentially unnoticed bias in statistical calculations can occur, which could result in false-positive and/or false-negative detections.
- Positive skewness: Data sets that are not symmetrical around mean or median values are typical for spring water quality data sets because the combined effects of a lower bound of zero, censoring, and meaningful outliers tend to produce data sets in which the right tail of the distribution is ex-

tended and the left tail truncated.

- Autocorrelation and independence: An event is said to be independent of another event when the occurrence of one does not affect the occurrence of another. Spring peak flow-rates separated by a long period of time may be independent, but two peaks close to one another may not be independent. This is true when the recession limb of the first hydrograph at a spring becomes part of the rising limb of the next hydrograph. Natural and anthropogenic effects tend to cause conditions in which consecutive measurements are correlated. The natural and anthropogenic processes controlling groundwater quality and the methods for sampling, processing, and analysis often cause problems with autocorrelation. Autocorrelation is also referred to as serial correlation or correlation—the dependence of residuals in a time sequence because data reflect the effects of preceding conditions. Time-series effect may also occur between subsequent samples within individual sampling events. Autocorrelation can be important because it affects the optimization of regression coefficients, affects estimates of population variance, invalidates results of hypothesis tests, and produces confidence and prediction intervals that are too narrow for the real population being sampled.
- Interdependence: Changes in one characteristic of interest such as rainfall intensity, antecedent flow conditions, or temperature cause changes in other characteristics such as measured flows and concentrations. The interdependence makes it very challenging to characterize the natural variations of water quality at karst springs.
- Temporal variation: Temporal variation of water quality is a characteristic of many karst springs. Measured water-quality characteristics vary at time scales of hours, days, seasons, years, and even decades because of both natural and anthropogenic influence. Temporal variation may also increase variability in data and affect the comparability of data between sites.

Springs are not isolated hydrogeologic features; they are part of a drainage basin. Use of springs as either monitoring locations or remedial targets shall take their relationship with the entire drainage basin into consideration.

- One objective of a groundwater monitoring programs is to identify releases of contamination as soon as the releases occur. If the spring is too far away from the site, the contaminants may have migrated quite a distance by the time a spring is contaminated. Under such scenarios, monitoring of springs is still useful but needs to be supplemented with other monitoring efforts immediately downgradient of the disposal facility.
- Sufficient data are collected to prove that the springs to be monitored are hydraulically connected to the groundwater system of the investigation site. Some techniques to collect connection data include chemical fingerprinting, tracer testing, isotope analysis, or aquifer testing.
- Springs with large drainage basins may contain contamination sources in addition to the investigation site. The water quality at such springs is impacted by multiple potential contamination sources. An evaluation should be con-

ducted to determine if the chemical constituents can be differentiated from the different sources.

- Use of springs as monitoring points or remedial action targets shall consider practicability in implementing the program. For example, submerged springs are not readily accessible and use of the springs requires significant modifications of the discharge areas. Any changes in surface water bodies may require regulatory approval. There is also a possibility of modification of the discharge areas may result in adverse impacts on aquatic lives.
- Use of springs as monitoring points or remedial action targets shall consider feasibility of developing an effective statistical evaluation plan to evaluate the potential impact of waste disposal units on the groundwater system. Due to heterogeneity of karst aquifers, intra-locational comparison is generally preferred to inter-locational comparison. Some of the statistical methods typically employed for investigating groundwater in porous media systems are not readily applicable for statistical data analysis of the data collected at springs.
- A thorough background study is required if a spring is proposed as a remedial action target with an attempt to eliminate the exposure pathway.

8. Conclusion

Springs are favored as monitoring locations for early detection of contaminant release from waste disposal facilities constructed in karst terranes. However, their use faces several challenges and requires a systematic study of the spring characteristics. Figure 7 presents the general technical approach. Based on results from seven tracer tests, two springs were selected for compliance monitoring to support permit application of a waste disposal unit in a relatively isolated karst

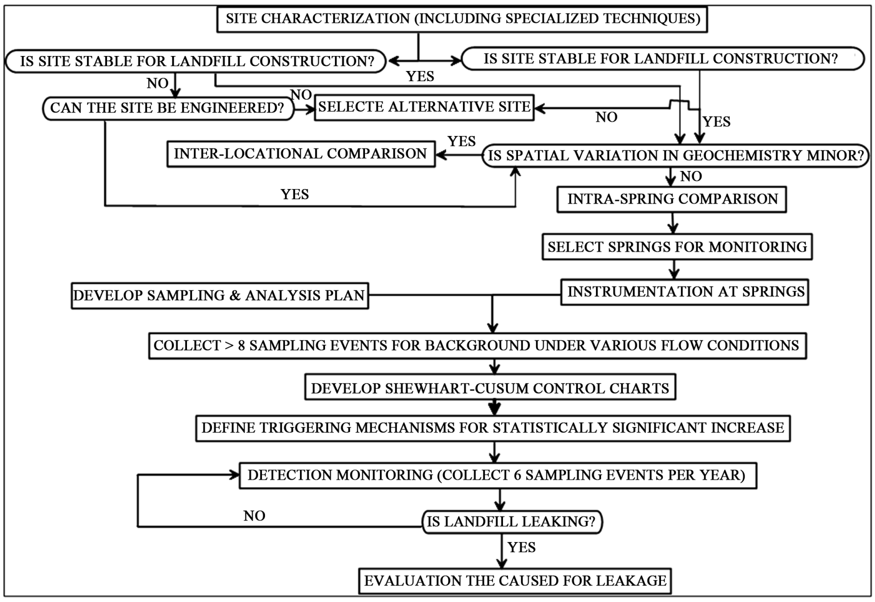


Figure 7. Technical approach of using springs as compliance monitoring locations.

area. Detailed engineering design and construction were conducted at these springs to allow for continuous monitoring of discharge, pH, DO, ORP, temperature, turbidity, and SC. Nine background sampling events consisting of six storm-pulse type events in response to a variety of aquifer, flow, and precipitation conditions and three 24-hour base-flow events with no precipitation were conducted at the two springs to characterize the background data population. Based on the spring characteristics, the FWC concept was proposed to represent the concentration of each sampling event for statistical evaluation. An inter-locational Shewhart-CUSUM control chart was developed to statistically evaluate potential impact of waste disposal units on the groundwater system. Although the specific procedures may not be duplicated, the overall technical approaches discussed in the paper may shed light on groundwater monitoring programs in other karst areas.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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