Mammoth Cave Research Symposia | 10th Research Symposium 2013

Feb 15th, 2:50 PM

An Alternative to the Advection Dispersion Model for Interpreting Dye Tracing Studies in Fractured-Rock and Karst Aquifers

Roger Painter
Tennessee State University

Irucka Embry
Tennessee State University

Victor Roland
Tennessee State University

Rick Toomey
MCICSL, Mammoth Cave National Park, Western Kentucky University, rick_toomey@nps.gov

An Alternative to the Advection Dispersion Model for Interpreting Dye Tracing Studies in Fractured-Rock and Karst Aquifers

Roger Painter[1], Irucka Embry[1], Victor Roland[1], Rick Toomey[2], Lonnie Sharpe[1], Acknowledgment - Tom D. Byl[1,3]

[1] Civil & Environmental Engineering, Tennessee State University
[2] Mammoth Cave International Center for Science and Learning, Mammoth Cave National Park, Western Kentucky University
[3] US Geological Survey (USGS)

Abstract

Due to the complexity of groundwater flow in fractured-rock and karst aquifers, solute transport models for these aquifers are typically stochastic models based on tracer transport studies. Water and tracers do not flow at one single advective velocity but experience a wide range of velocities, from rapid flow in conduits to near stagnant conditions in adjacent voids. This variance of velocities is referred to as dispersion and is traditionally described mathematically by the advection-dispersion equation (ADE). Analytical solutions to the ADE are available and are referred to as advection-dispersion models (ADM).The ADM is fitted to the tracer data by varying the parameters until a best-fit is achieved between the experimental residence time distribution (RTD) and the model RTD. The major shortcomings of this approach are due to the symmetry of the ADM and its associated prediction of finite concentrations at zero time and its inability to reflect the long upper tail typical in experimental RTD data. This paper presents an alternative conceptual approach to the ADM for modeling solute transport in fractured-rock and karst aquifers. In this approach the variance in flow velocities and flow path lengths are addressed directly by treating them as random, gamma distributed variables and deriving the RTD from a transformation of random variables based on the ratio of length to velocity and representing the RTD as a conditional probability distribution of time. The resulting four parameter (Gamma-RTD) model is relatively easily parameterized since the flow path length is tightly distributed about the known straight line distance between the injection point and the effluent. The model is demonstrated and contrasted to the ADM below by applying it to tracer data from a quantitative tracer study at Mammoth Cave National Park. The results indicate that the Gamma-RTD is superior to the ADM in modeling the shape as well as the area of the experimental RTD.

Introduction

A descriptive, probabilistic mathematical model was developed to model karst aquifers which is based on the gamma distribution. The gamma distribution is a function of random variables that are exponentially distributed and is frequently used as a probability model for waiting times studies. In hydrological karst studies, the gamma distribution can create an appropriate RTD as it is a two parameter model and allows for flexibility to account for nonlinearities. It is unclear which physical interpretation can be ascribed to the gamma distributions' two parameters (α, β). To address this, a gamma distribution for the residence time was derived by assuming that the velocity and travel distance of the karst system were gamma distributed random variables.

This gamma distribution RTD model was tested on a natural karst system at Mammoth Cave National Park. That model was compared to the results of the traditional Advection Dispersion Equation

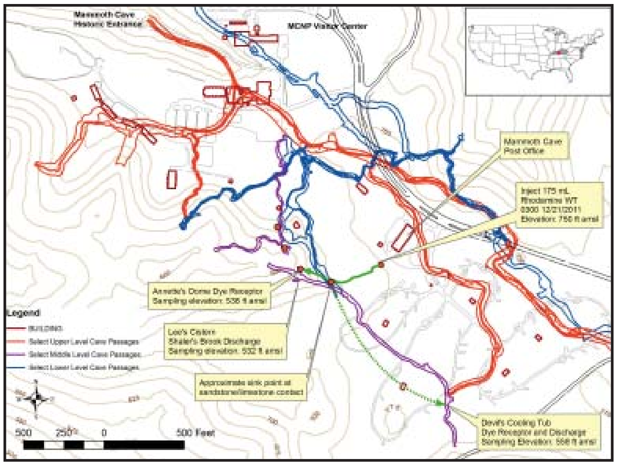

Figure 1: Topographical map of cave features with surface overlay. Injection point and tracer flow path indicated in green. Different levels in the cave are indicated by different colors.

(ADE) RTD model (see Painter, et. al. for a thorough discussion of the ADE RTD model). A quantitative rhodamine dye study was run to determine the travel time from the outlet of the Post Office filter which is indicated in Figure 2. The test was set up on the afternoon of December 20, 2011, because it was supposed to rain, but the rain came much later (around 3 A.M. on December 21). A tipping delivery system was triggered by the rain event and released both salt & rhodamine dye. (This set up is described more in the Materials and Methods section.)

At the outlet of the stormwater treatment system, which services the post office parking lot, a stream forms which empties into the cave approximately 875 feet downstream. Inside the cave as indicated in the Figure 2, the stream has been shown to empty into an area known as Annette's Dome and portions also enter into another area called the Devils Cooling Tub both located approximately 200 feet beneath the surface. Annette's Dome creates another feature known as Shaler's Brook, located approximately 60 feet beneath the ceiling. Shaler's Brook receives direct discharge from Annette's Dome, therefore it is used as an endpoint in the dye study along with Devil's Cooling Tub. These subsurface areas were selected because previous tracer data indicated relatively rapid rates of surface recharge at Devils Cooling Tub and Shaler's Brook. At Devils Cooling Tub discharge rates ranged from 0.5 L/min to 51.95 L/min. Discharge measurements for Shaler's Brook were taken at the formation known as Lee's Cistern, which receives direct discharge from Shaler's Brook approximately 50 yards downstream. Lee's Cistern discharge measurements ranged from 6.57 L/min to 176 L/min.

Materials and Methods

Discharge measurements were collected at Lee's Cistern and Devil's Cooling Tub at various dates preceding the quantitative dye tracer study. These discharge measurements were used to determine the amount of dye needed to avoid poor results from excessive dilution, but also remain within a safe range to preserve the karst ecosystem. At Lee's Cistern, discharge was measured using a plastic

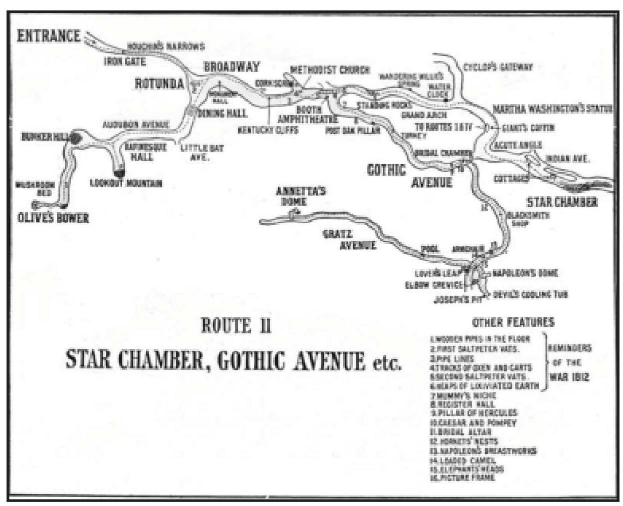

Figure 2: 1908 Tour Map showing the 200 feet level of the cave showing cave features by their colloquial names, which are used to this day. Annette's Dome and Devils Cooling Tub were referred to in this study (Hovey, 1909).

tarp to concentrate the stream, and then recording the amount of time needed to fill a container of known volume. This was done in triplicate. At Devil's Cooling Tub, a similar procedure was followed to measure discharge.

The quantitative dye study was conducted on December 20, 2011, beginning on the surface at the outlet of a stormwater filter, which services parking lots adjacent to the post office on the park grounds. Inside the cave, fluorometers with rhodamine sensors and first flush samplers were placed in two areas of the cave where they measured the amount of time taken by the dye to move through the karst system. The locations within the cave, Shaler's Brook and The Devil's Cooling Tub, were selected because they were suspected to interact with the surface relatively rapidly and provide surface recharge for two major karst springs in the formation, Echo River and River Styx. Dye selected for the study was Rhodamine WT-20. Concurrently, a salt tracer study was also conducted to gain additional hydrologic data. The tracers were set up on a release mechanism, see Figure 3 for the setup. The release mechanism consisted of a Styrofoam tray with approximately ¼ lb of table salt (114 g NaCl) laying flat on the tray and 175 mL of Rhodamine WT-20 in a plastic bottle standing upright on the tray. This mechanism was placed in the outlet of the storm filter system. Below, we placed a first flush sampler (white plastic container with the red lid) and a YSI datasonde (to measure the salt concentration) set to read every 5 minutes. [Additional first flush samplers and YSI datasondes with rhodamine sensors set to read at 20 minute intervals were placed in the cave. See Figure 4 to see the location of the datasondes and the first flush sampler in Shaler's Brook.] As the storm waters exited the filter, they reached a high enough velocity to flush the tray out and spill it. The tray was elevated approximately 0.5 inches in the discharge pipe to keep it from dumping on the very first trickle; rather, it needed enough flow to lift it and destabilize it. At 3:00 A.M. on December 21, 2011, both tracers were released.

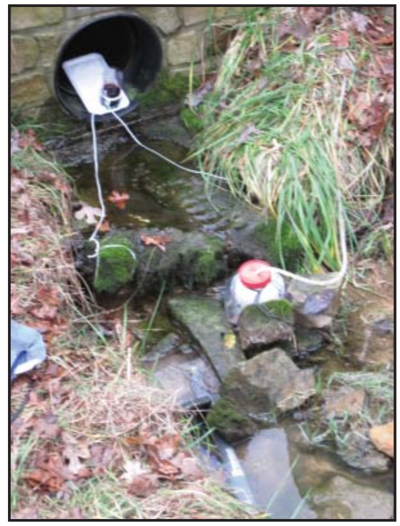

Figure 3: Photograph showing the dye and salt release mechanism. Also shown in the picture are the first flush sampler and the YSI datasonde.

Figure 4: Photograph showing the pool at the bottom of Annette's Dome and the beginning of Shaler's Brook. Also pictured is the YSI datasonde with the first flush sampler.

Results

The results of the Rhodamine WT-20 quantitative dye study at Mammoth Cave are shown in the following graphs and tables. We have only analyzed the results from Shaler's Brook thus far, we will describe the other results in a future journal article.

The results from numerical integration of the concentration versus time data for the tracer study conducted are shown in Table 1. Table 2 displays the numerical integration of the normalized gamma RTD versus the normalized time. Figure 5 shows the tracer breakthrough curve. The results of the dye study were then used to develop the residence time distribution (RTD) function. The RTD function (E(t)) for contaminant molecules in a single karst conduit or a complex system of conduits is a probability density function (PDF) which can be interpreted to define the probability that contaminant molecules present at the influent at time equals zero will arrive at the effluent after a particular amount of time. The RTD is depicted as a plot of E(t) versus time as time goes from zero to infinity.

E(t) was determined by injecting a pulse of a conservative tracer (Rhodamine WT-20) into the cave system by the mechanism shown in Figure 3 at time (t) = 0 and then measuring the tracer concentration in the effluent as a function of time.

The experimental normalized (dimensionless) RTD from the numerical integration of the tracer data is shown along with the normalized Advection Dispersion Equation (ADE) RTD and the normalized Gamma distribution RTD model in Figure 6.

Discussion and Conclusions

Based on the graphical evidence presented in Figure 6, the Gamma distribution RTD better resembles the experimental RTD for the Shaler's Brook area. Also, the area beneath the curve is a better fit for the Gamma model RTD rather than the ADE RTD model. In addition, it is possible to calculate the mean velocity and the mean distance traveled from the Gamma distribution RTD which is not possible with the ADE RTD. For those reasons, we conclude that the descriptive, probabilistic, Gamma RTD model better mathematical models this particular karst site at Mammoth Cave, Kentucky.

Acknowledgements

Bobby Carson, Mammoth Cave National Park – Division of Science & Resources Management

Shannon Trimboli, Mammoth Cave International Center for Science and Learning

References

Ryan, M., and J. Meiman. 1996. An examination of short-term variations in water quality at a karst spring in Kentucky. Ground Water 34, no. 1: 23-30.

Field, MS 2002. The QTRACER2 Program for Tracer Break-through Curve Analysis For Tracer Tests in Karst Aquifers and Other Hydrologic Systems. U.S. Environmental Protection Agency, Office of Research and Development, EPA/600/R-02/001, 194 p.

Danckwerts, P.V. Continuous Flow Systems. Distribution of Residence Times. Chemical Engineering Science 1952, 50, 3857-3866.

Fogler, H. Scott (1999). Elements of Chemical Reaction Engineering (3rd Edition). Upper Saddle River, New Jersey: Prentice Hall PRT.

Hovey, H.C. (1909). Mammoth Cave Kentucky Hovey's Practical Guide to the Regulation Routes. Louisville, KY: John P. Morton & Company, Inc.