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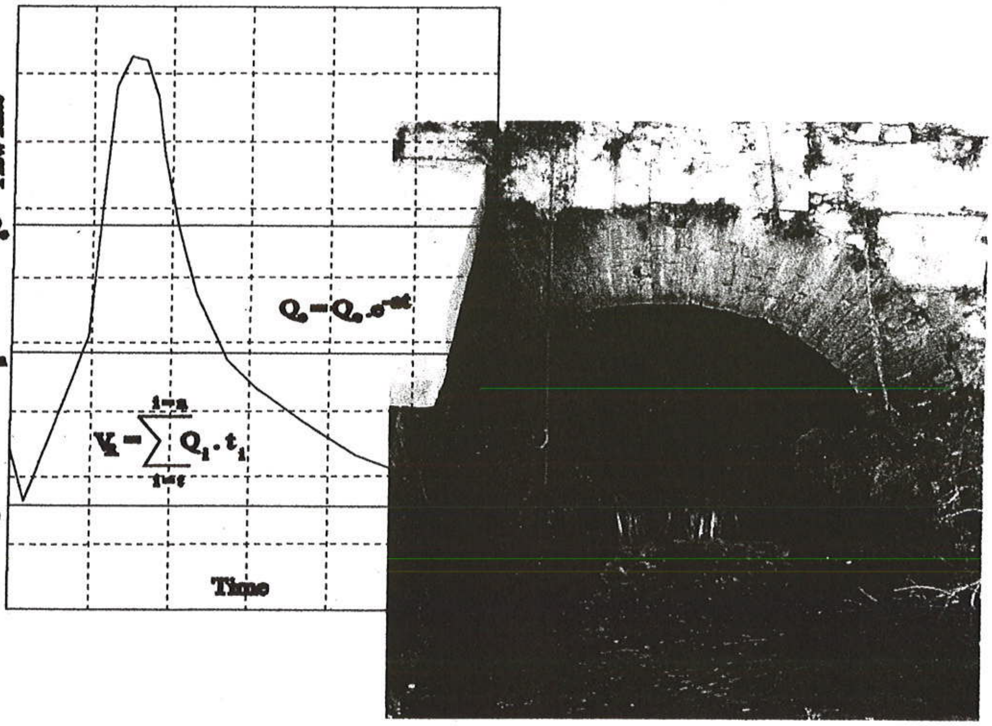
Groundwater Monitoring System Design for Landfills Sovjak and Visevac, Rijeka, Croatia

Phase I Report – Hydrogeological Study and Monitoring Concept Evaluation



prepared for: k.d. Cistoca d.o.o. Rijeka, Croatia

by: Center for Cave and Karst Studies, Western Kentucky University, Bowling Green, Kentucky, USA

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Groundwater Monitoring System Design for Landfills Sovjak and Visevac in Rijeka, Croatia

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by: Center for Cave and Karst Studies, Western Kentucky University, USA

Signed: Nicholas Crawford Date: 17-June-2002

Nicholas Crawford, Ph.D.

Director, Center for Cave and Karst Studies

Signed: Date: 17-June-2002

Stuart Edwards, P.E., BSc(Hons)

Consulting Environmental Engineer

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1. Introduction

This report presents the results of the first phase of a hydrogeological study of two contiguous landfill sites, Sovjak and Visevac, in Rijeka, Croatia. The purpose of the study is to develop the basis for design of an effective groundwater monitoring system that will be implemented following the planned closure of Visevac and the remediation of Sovjak.

Croatian environmental regulations require that groundwater beneath landfill sites be monitored by a minimum of two downgradient monitoring points during the post-closure period, to detect possible releases of contaminants. The complex karst hydrogeological environment in which Sovjak and Visevac are located is characterized by a considerable depth to groundwater. This, together with the inherent uncertainties of a karst flow regime, may preclude the use of a conventional well-based monitoring system. The sites are located approximately 4 kilometers (km) from the coast where several springs discharge, and which might prove to be useful monitoring points as part of an alternative approach to post closure monitoring.

The study was conducted in accordance with the proposal submitted by the Center for Cave and Karst Studies, dated September 26, 2001, and authorized by Cistoca December 6, 2001.

1.1. Background

The two landfills are located within 100 meters (m) of each other in an upland area approximately 10 km northwest of the sea port city of Rijeka. This is the largest port on the Adriatic coast, located in Kvarner Bay. The terrain rises steeply from the Adriatic coast, achieving elevations of more than 300 m within the 4 km that separates the landfill sites from the sea. The highly developed karst morphology of the area has produced rugged topography characterized by frequent deep depressions that may create in excess of 40 m of local relief. Two such features were developed as the waste disposal sites Visevac and Sovjak.

The municipal waste landfill Visevac is currently active and has been in use since 1964. It occupies a large sinkhole located about 100 m southwest of the hazardous waste landfill Sovjak, and presently has a surface area of about 74,000 square meters (sq m). The sinkhole depression has been filled, and the current operations involve filling at, or above, the surrounding natural elevations, which are on the order of 300 - 320 m. According to early topographic maps of the area, the base of the sinkhole was at elevation 266 m.

The hazardous waste landfill Sovjak was active from 1956 to the late 1980s and originally was used for the disposal of acid tar produced at the lube oil refinery located about 7 km to the southeast on the coast in Rijeka. Subsequently, during the 1970s, waste streams from other local industries and the shipyards in Rijeka were also brought to the site for disposal. These included waste coke plant tar, acetylenic sludge, tank bottoms and separator sludge, various petrochemical residues from the cleaning of marine tankers, waste solvents, cutting oil emulsions, motor oil, and occasional cargoes of spoilt produce or items confiscated by the customs authority at the port.

In 1997 a study of the size, properties and environmental impacts of both landfills was conducted (Dames & Moore and Ecoina, 1998). Detailed analysis of technical alternatives for their closure was made and preferred options selected. Municipal landfill Visevac is to be closed with a multilayer cap including a geomembrane, active extraction of gas and treatment for any recovered condensate. For hazardous waste landfill Sovjak, removal and treatment of wastewater, liquid and semi-liquid materials, followed by removal and stabilization of acid tar was selected as the remediation option. The empty sinkhole will be filled with inert construction material and capped in conjunction with Visevac.

By preventing rainwater infiltration into the body of the municipal landfill and by excavation and treatment followed by capping of the hazardous waste landfill, the environmental conditions will be dramatically changed, especially the potential for leachate seepage into the groundwater.

1.2. Approach

A three-step process has been initiated by Cistoca that will lead to the design of the most appropriate post-closure groundwater monitoring system for the sites. These steps are as follows:

- First phase – A desk study involving interpretation of existing data from the site and locale, development of leachate emission factors and theoretical dilution factors for the aquifer. General conclusions regarding the efficacy of alternative monitoring methods will be developed and preliminary recommendations for a groundwater monitoring system design will be made.
- Second phase – Field investigations will be conducted to determine the optimum location for monitoring points and/or leachate interception wells. Monitoring parameters will be listed and their selection justified. Interception or removal of leachate will be considered as a strategy to control discharge from the landfill if reliable monitoring systems appear to be infeasible.
- Third phase – Additional field investigations will be used as necessary to validate any of the models used in prior phases, so as to achieve better confidence in the results of long term monitoring.

This report addresses the first of the three phases.

1.3. Specific Project Requirements

In simple terms, the quality of groundwater in the aquifer between the landfills and the coast is controlled by three factors:

- leachate production and release rates at the landfills
- aquifer characteristics and hydraulics
- additional sources of pollution (upgradient and/or downgradient of the landfills)

The report examines each of these in turn. The results are integrated into a preliminary model of contaminant fate and transport. The most appropriate way to monitor possible releases from the landfills is then discussed and the scope of further studies defined.

In particular, Cistoca specified in its request for bid that this first phase of the project concentrate on three specific areas:

- Leachate emission factors to be developed for each landfill for both pre- and post-closure conditions.
- Leachate quality predictions to be made using site data together with literature derived chemical profiles.
- An analysis to be made of the site conditions with a view to determining the conceptual design for conventional downgradient monitoring wells. Cistoca recognizes that this type of monitoring system may not be satisfactory. Worldwide experience is to be examined to support the assessment.

Correspondent coastal springs are studied to determine whether they can be used for landfill monitoring. Careful consideration is given to the large variations in spring flow and the resulting impact on the reliability of monitoring at these points.

1.4. Project Team

The project was directed by Nicholas Crawford, Ph.D., the Director of the Center for Cave and Karst Studies at the University of Western Kentucky, United States where he also serves as a Professor in the Department of Geography and Geology.

Dr. Crawford was assisted by Stuart Edwards, P.E., an independent Consulting Environmental Engineer, who has studied landfill release mechanisms and monitoring systems extensively.

Curriculum Vita for both investigators is presented in the Appendix.

2. Groundwater Monitoring In Karst

Environmental monitoring at landfills has been an important aspect of their operation for more than two decades in many countries. While surface water and air quality are both of importance, by far the greatest monitoring effort and expense is for groundwater and the response to instances of contamination. The importance of a properly designed monitoring system that will function well during the operational life of the landfill, and then for post-closure periods of up to 30 years, is highlighted in the detailed specifications that are provided for such systems in regulatory programs around the world.

Many regulatory programs contain similar requirements. At the heart of these is a mandate <u>to determine whether there has been a release of contaminants to the groundwater</u> – sometimes known as 'detection monitoring' (U.S. EPA. 40 CFR Part 264.98). This asks the basic question 'Has there been a statistically significant change in the downgradient groundwater quality relative to the upgradient groundwater?' If the answer is 'Yes', then further investigations and, possibly, remediation will be required. If the answer is 'No', the detection monitoring program is repeated at its next scheduled interval.

It is the development of a 'detection' monitoring program that is now required for Sovjak and Visevac. The fundamental components of traditional detection monitoring systems do not differ significantly between the various national jurisdictions. For example, in the United States, most state programs require a minimum of one upgradient well and three downgradient wells. (Kentucky Legislature, 2001. 401 KAR 48:300). Alternatively, the specification may be for 'an appropriate number of wells ...(U.S. EPA. 40 CFR Part 264.97). In the European Union there is a requirement for 'at least one measuring point in the groundwater inflow region and two in the outflow region.' (EUR-Lex, 2002. Council Directive 1999/31/EC). In Croatia, the regulations require one upgradient and two downgradient monitoring wells.

In most cases, these regulatory requirements were developed with the somewhat simplistic expectation that aquifers are formed in unconsolidated materials that support porous media flow, that they are unconfined, and that the depth to groundwater is not excessive. In all fairness, these conditions are very common. But there are also extensive regions of the world where geological and hydrogeological regimes do not conform to this ideal. Noteworthy among them are karst regions such as the Dinaric coast where depth to groundwater is often in excess of 300 m and flow takes place through fractures and solution features, the locations of which are virtually impossible to predict.

The use of simple monitoring well-based systems in such terrain may be extremely problematic. The wells have to be drilled very deep at considerable cost, and with no guarantee of encountering water. In an exploration of karst hydrogeology in the southern Dinarides, 20 piezometers each were drilled to depths on the order of 300 m. In ten of them (50 percent), karst groundwater was not encountered (Bonacci and Bonacci, 2000). Where water is encountered, its source and flow regime are difficult to determine because of the complexities of karst drainage. For this reason, the representativeness of water samples collected from these wells can be called into question and monitoring results potentially discredited.

Regulators and standards setting bodies in the United States are attempting to address the problems of establishing reliable monitoring systems in karst (ASTM, 1995; Kentucky Legislature, 2001. 401 KAR 48:300). Their mandates typically include basin-wide hydrogeological studies, dye tracing and use of springs as alternative monitoring points. However, the underlying regulations that call for an initial program of well installation remain largely unchanged. In the United States, particularly in the east, groundwater typically is relatively shallow and the cost of initial drilling, even if ultimately of little value, is not prohibitive. Also, in that area there tends to be a well developed epikarst in which perched water may be found, and which is potentially important for initial monitoring purposes. Conditions in the Dinarides are markedly different, and so the installation of monitoring wells will inevitably be a costly and risky business.

Since there is no existing definitive guidance on the design of groundwater monitoring systems applicable to Visevac and Sovjak, this report examines the risks and benefits of alternative designs, recognizing of course the need for compliance with Croatian regulations. It is worth noting, however, that compliance with the letter of a law that results in an inadequate monitoring system may be less desirable than implementing an alternative system that, while violating the letter of the law, is effective in meeting its intent and spirit. In the United States, regulators are increasingly likely to allow waivers from the letter of the law where an appropriate, more scientifically sound monitoring system is proposed.

The monitoring system that is installed and operated must, to the extent possible, meet the following objectives:

- Allow for the collection of representative samples of groundwater from upgradient and downgradient locations relative to the landfills
- Specify appropriate chemical analyses based on the pollutants that are likely to be present in Sovjak and Visevac
- Provide a mechanism for evaluating and interpreting the data so that significant findings

3. Technical Approach

The design of a suitable groundwater monitoring system for Sovjak and Visevac will ultimately boil down to whether the system should be based on conventional drilled wells, or on alternative monitoring points such as springs, or on a combination of the two (Figure 1).

The technical approach to the project has been to assess both methods in detail and to then evaluate their relative merits separately and in combination. In the following sections of the report there is a logical development of the information needed to support this evaluation.

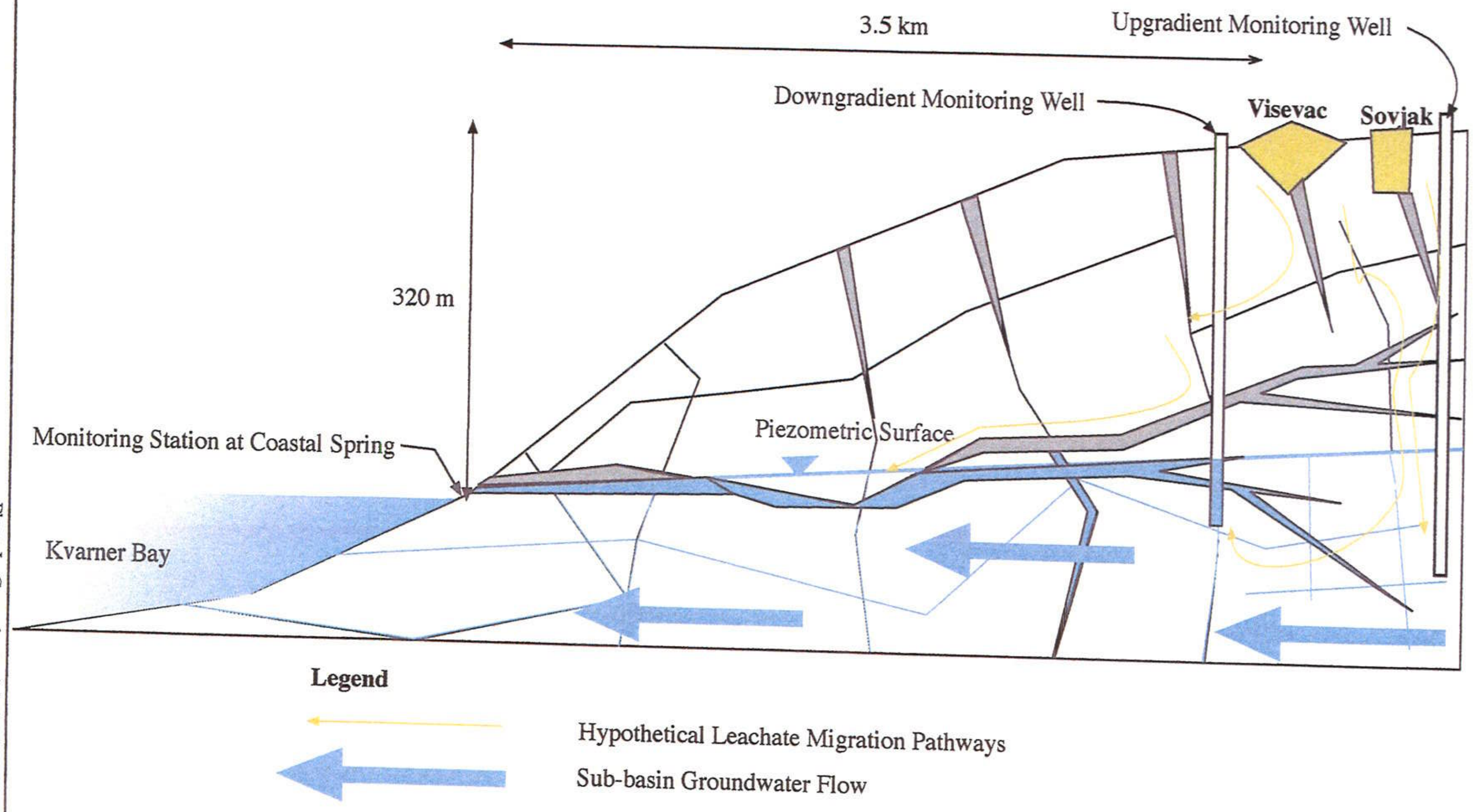
The use of conventional monitoring wells is a mature technology, and so the information presented in the report is relatively concise. The real issue for monitoring well design involves balancing high capital cost with the uncertainty of satisfactory performance. It is likely that a well in the near vicinity of the landfills that encounters karst groundwater would be in a good position to detect the presence of contamination emanating from the landfill. With unlimited resources, sufficient wells could probably be drilled to ensure success in locating karst groundwater. This requires only limited further technical elaboration.

On the other hand the concept of using coastal springs as alternative monitoring points, while initially attractive because of low cost and apparent simplicity, is actually fraught with considerable uncertainty and requires a very careful evaluation in order even to establish its technical feasibility.

Determining the value of monitoring at coastal springs requires that the likely detectability of landfill derived contaminants be established. In other words, if it is clear that the amount of leachate, its chemical quality, and the characteristics of the aquifer into which it discharges combine to create circumstances whereby there is a high probability that contaminants would be detected reliably at one or more coastal springs, then the method is technically feasible. Further, if there are expected to be relatively unique contaminants in the leachate that will distinguish it from the possible effects of other regional sources of contamination, the method becomes additionally attractive.

Figure 1. Schematic Groundwater Monitoring Alternatives for Sovjak / Visevac Landfills

(not to scale)



The first part of this evaluation is based on an understanding of four elements, which together dictate the contaminant levels in coastal springs:

- Leachate release rate
- Leachate chemical quality
- Aquifer flow characteristics
- Chemical fate of leachate when combined with groundwater flow

The first of these has been estimated using the Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al., 1994). The results generated by the model predict the leachate generation amounts and rates of release.

Chemical quality parameters for leachate were established using measurements taken at the landfill, and computed values based on the assumption of equilibrium between leachate and landfill gas.

Aquifer characteristics have been defined for purposes of the study based on evaluation of published regional hydrogeological information. Limited modeling was conducted to assess the likely relationship between spring flow and precipitation events since no measured data were available.

The chemical fate of the most important leachate contaminants has been reviewed based on the literature.

These results have been combined to generate dilution-attenuation-factors (DAF) for the pollutants under a variety of leachate release scenarios and groundwater flow regimes. This method is commonly used to relate the concentration of leachate leaving a source zone to its impact on downgradient water quality (Abrancovic, et al., 2001). The reliability of detection of the pollutants was then evaluated.

4. Landfill Release Mechanisms

4.1. Assessment Methodology

The release of leachate from a landfill occurs when water (usually rainfall or melted snow) enters it and percolates down through the waste, eventually exiting through the bottom liner as a chemically altered liquid with the potential to contaminate groundwater. Prediction of the amount, rate of release, and chemical quality of leachate from Sovjak and Visevac is required as input into the dilution-attenuation factor calculations. The amount and release rates have been evaluated using a model developed for the U.S. Environmental Protection Agency (EPA) known as the Hydrological Evaluation of Landfill Performance Version 3 (HELP) model (Schroeder, et al., 1994).

The model is used primarily by landfill designers and regulators to evaluate the likely performance of proposed landfill designs. However, it is equally useful to evaluate the performance of existing landfills as long as there is adequate data. It accepts weather, soil and design data and uses solution techniques that account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane or composite liners. Results are expressed as daily, monthly, annual and long-term average water budgets. These are presented in terms of the quantity of water moving through each component of the landfill, including lateral flow through drainage layers. For purposes of this study, interest lies primarily in the calculated flow through the bottom of the landfill – i.e. the leachate production.

Leachate production rates were calculated for the following scenarios:

- Visevac – open landfill, no cover
- Visevac – interim or daily cover present
- Visevac – closed landfill; final cover completed
- Sovjak – current conditions
- Sovjak – post remediation

4.2. *Input Parameters*

The model requires input data in two broad categories: local climate and engineering design of the landfill. The weather data are the same for each of the scenarios, but the engineering design details vary from one to the next.

4.2.1. Climatic Data

In order for the model to compute daily leachate production rates, detailed precipitation and temperature data are required over the period for which the simulation is to be carried out (30 years). To facilitate this, the model accepts monthly average measurements calculated from a recent period of record, and can then create its own synthetic daily values for the total length of the simulation. Solar radiation data are calculated based on the latitude of the site.

Rainfall in the area is strongly influenced by the presence of the Dinaride Mountains that rise steeply from the Adriatic Sea. Rijeka receives an average of about 1,500 millimeters (mm) of precipitation per year, whereas the mountains, just a few kilometers away, may receive in excess of 3,000 mm. Precipitation data for the community of Marcelji, which is approximately 3 km to the north of the landfills, was used in the simulation (Ekonerg Holding, 2001).

Temperature data for landfill sites were adapted from observations at Rijeka by reducing the monthly average values to account for the environmental lapse rate at the higher elevation (WorldClimate, 2002 and NASA, 2001).

4.2.2. Landfill Data

Visevac

For purposes of these simulations, Visevac is assumed to be 74,000 sq m in area and the depth of municipal waste to average 30 m. The cover conditions are varied from a worst case scenario with no surface protection at all, to an intermediate condition where there is a soil cover 30 centimeters (cm) in thickness (but no vegetation) and finally a simulation of hydrologic performance once the landfill has been completely closed with a multi-layer cap (Dames & Moore and Ecoina, 1998). The model accounts for each component in the landfill and containment system from the vegetated soil layer to the underlying soil layer individually. The layers used in the simulation are described in Table 1.

Sovjak

The chemical waste disposal site is formed in a 90-m diameter sinkhole with steep rocky sides and no cover or liner. The waste is tarry and is relatively impervious to infiltrating water; so much so that a layer of water on the order of a meter in depth has historically accumulated on its surface. A thick layer of floating oil may also be present on the water surface. The best hypothesis for movement of precipitation through this system is that the rain or snowmelt permeates through the floating oil layer where it is able to pick up contaminants. Then as part of the water layer, it comes in contact with the waste surface, again providing the opportunity to increase dissolved contaminant levels. The water (or leachate as it is by now) then seeps out laterally through the fractures and apertures in the exposed rock sidewalls. A nominal water layer may be preserved throughout most of the year. Some of the fractures immediately above the surface of the waste have become sealed by oil and tar during periods when the waste level was slightly higher.

To simulate this system using the HELP model requires some liberties to be taken with the input parameters, and the results should be viewed only as a good indication of the leachate generation pattern, but not a firm prediction. The model requires that all the layers are solid, and so it is necessary to assign solid material properties to the two liquid layers. For the floating oil layer, a sand was selected to simulate a material through which rainwater could penetrate without difficulty. The water layer is simulated by a layer of gravel, which readily transmits water vertically and horizontally. The gravel is identified as a lateral drainage layer since the predominant movement of water is out towards the rock walls. The tarry waste is modeled as low permeability liner soil. Details of the materials are presented in Table 1.

The post remediation simulation for Sovjak is more straightforward as remediation calls for the removal of the wastes and the backfilling of the cavity with building demolition debris or rock (Dames & Moore and Ecoina, 1998). The top of the filled area will be capped using a geomembrane to reduce seepage of precipitation through any residues that remain in the fissures and fractures of the rock.

Table 1. HELP Model Scenarios And Landfill Details

Landfill	Scenario	Layer	Material	Thick-ness (cm)	Permeability cm per second (cm/s)	Drainage-Horizontal (H)/ Vertical (V)	Slope (%)	Slope length (m)	Notes
Visevac	Scenario 1	1	Municipal Waste	3,000	1.00E-03	V	15	90	
	No Cover	2	Clayey Soil	30	1.20E-06	V	30	90	
	Scenario 2	1	Silty Soil	30	4.20E-05	V	15	90	
	Interim Cover	2	Municipal Waste	3,000	1.00E-03	V	30	90	
		3	Clayey Soil	30	1.20E-06	V	30	90	
	Scenario 3	1	Silty Soil	100	4.20E-05	V	15	90	Fair grass cover
	Final Cover	2	Sand	40	3.10E-03	H	15	90	
		3	HDPE	0.25	2.00E-13	V	15	90	Good quality material and installation
		4	Treated Waste	80	1.90E-06	V	30	90	
		5	HDPE	0.25	2.00E-13	V	30	90	Good quality material and installation
		6	Sand	30	1.00E-02	V	30	90	
		7	Municipal Waste	3,000	1.00E-03	V	30	90	
		8	Clayey Soil	30	1.20E-06	V	30	90	
Sovjak	Scenario 4	1	Sand	10	1.00E-02	V	1	45	Simulates floating oil layer
	Current	2	Gravel	150	3.00E-01	H	1	45	Simulates lateral drainage to rock
		3	Liner Soil	3,000	1.00E-07	V			Simulates dense tar waste
		4	Sand	30	1.00E-02	V			Simulates soil beneath waste
	Scenario 5	1	Silty Soil	100	4.20E-05	V	5	45	
	Post-remediation	2	Sand	40	1.00E-02	H	5	45	Simulates building rubble
		3	HDPE	0.25	2.00E-13	V			
		4	Sand	3,000	1.00E-02	V			

These materials are readily modeled as shown in Table 1.

4.3. Results

The model computes the flow of water through each layer on each day for the duration of the simulation, which was set to 30 years. Output reports are generated for each scenario, which may include daily, monthly or annual data depending on the needs of the user. Key output data are summarized in Table 2.

Table 2. Results Of Leachate Generation Simulations

Landfill	Scenario	Annual Average Leachate Discharge Cubic meters per year (cu m/yr)	Percentage of Total Precipitation (%)	Peak Daily Leachate Discharge (cu m/day)
Visevac	Scenario 1 No Cover	81,000	53.3	706
	Scenario 2 Interim Cover	30,000	19.4	262
	Scenario 3 Final Cover	40	0.03	0.16
Sovjak	Scenario 4 Current	9,400	71.7	2,277
	Scenario 5 Post-remediation	3	0.02	0.3

The three simulations for Visevac clearly show the benefits of capping as a means to reducing the quantity of leachate produced in a landfill. Without any cover, the landfill is projected to produce an average of 81,000 cubic meters of leachate per year. The simple use of an interim cover comprised of only 30 cm of soil effectively reduces this by about 60 percent (%). Installation of a complete layered cap incorporating two HDPE membranes reduces leachate production to a small fraction of one percent of the total precipitation.

Leachate production at Sovjak is projected to average about 9,400 cubic meters per year (cu m/yr) prior to remediation. This is a significantly higher percentage of the total precipitation than for Visevac because there is no surface run off possible in the steeply sided pit. It is also noteworthy that the maximum daily generation rate for Sovjak is almost 25% of the total annual average, whereas at Visevac the maximum daily rate is less than 1% of the average annual discharge.

This difference is characteristic of the quite independent leachate production mechanisms of the two landfills. At Visevac the landfill acts like a huge sponge that attenuates the fluctuations in rainfall to produce a relatively constant outflow of leachate of between 2.0 and 3.5 liters per second (L/s). The variability in production rate shows an inverse relationship with precipitation because of the time lag created by flow through the 'sponge'. This is illustrated in Figure 2.

In contrast, a review of daily production rates for Sovjak shows how variable they are. Figure 3 shows the daily discharge rates for year 10 of the simulation and the corresponding rainfall events. Clearly they are closely correlated, but erratic and virtually unpredictable on a day to day basis.

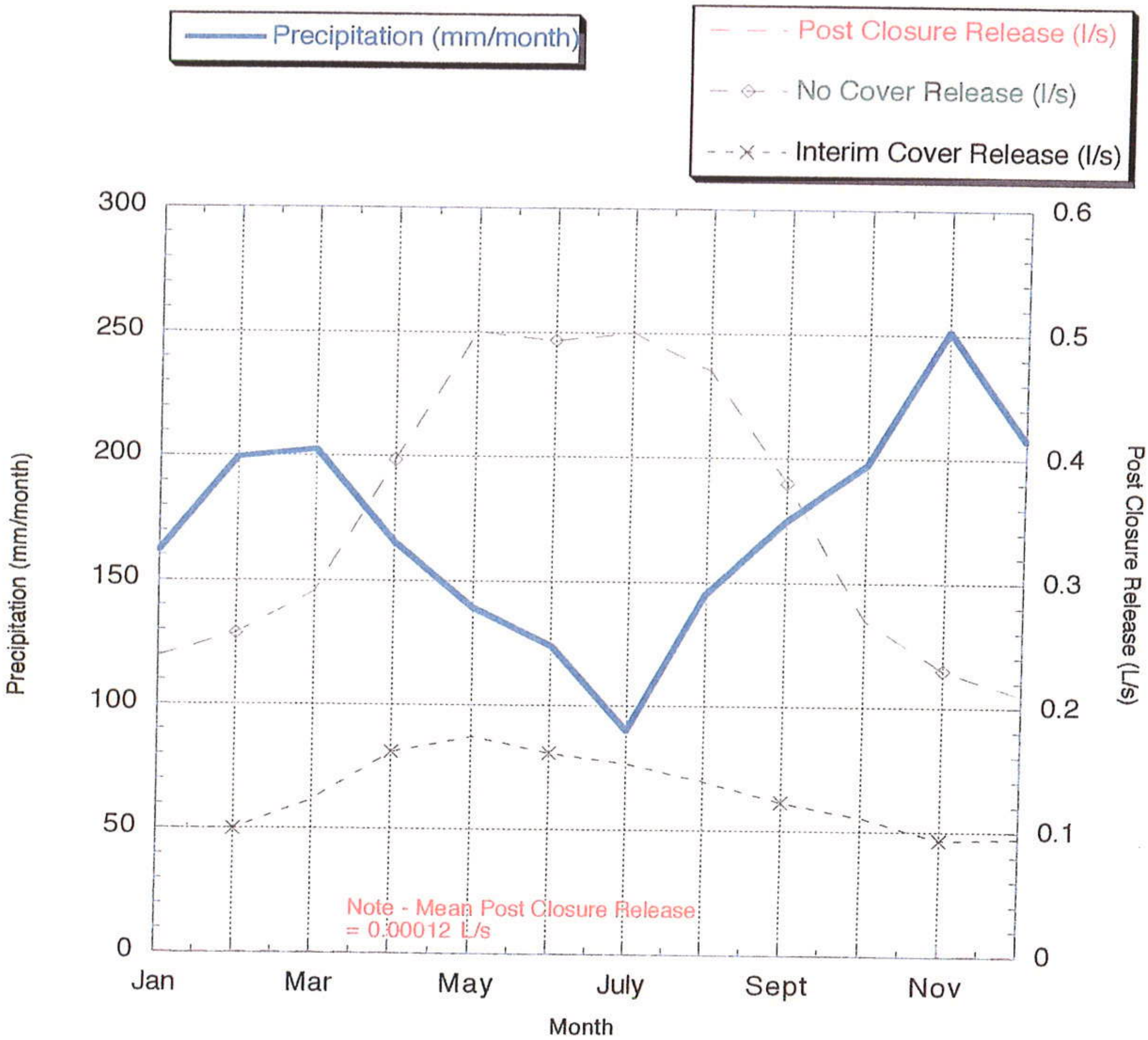


Figure 2. Average Visevac Leachate Release Rates

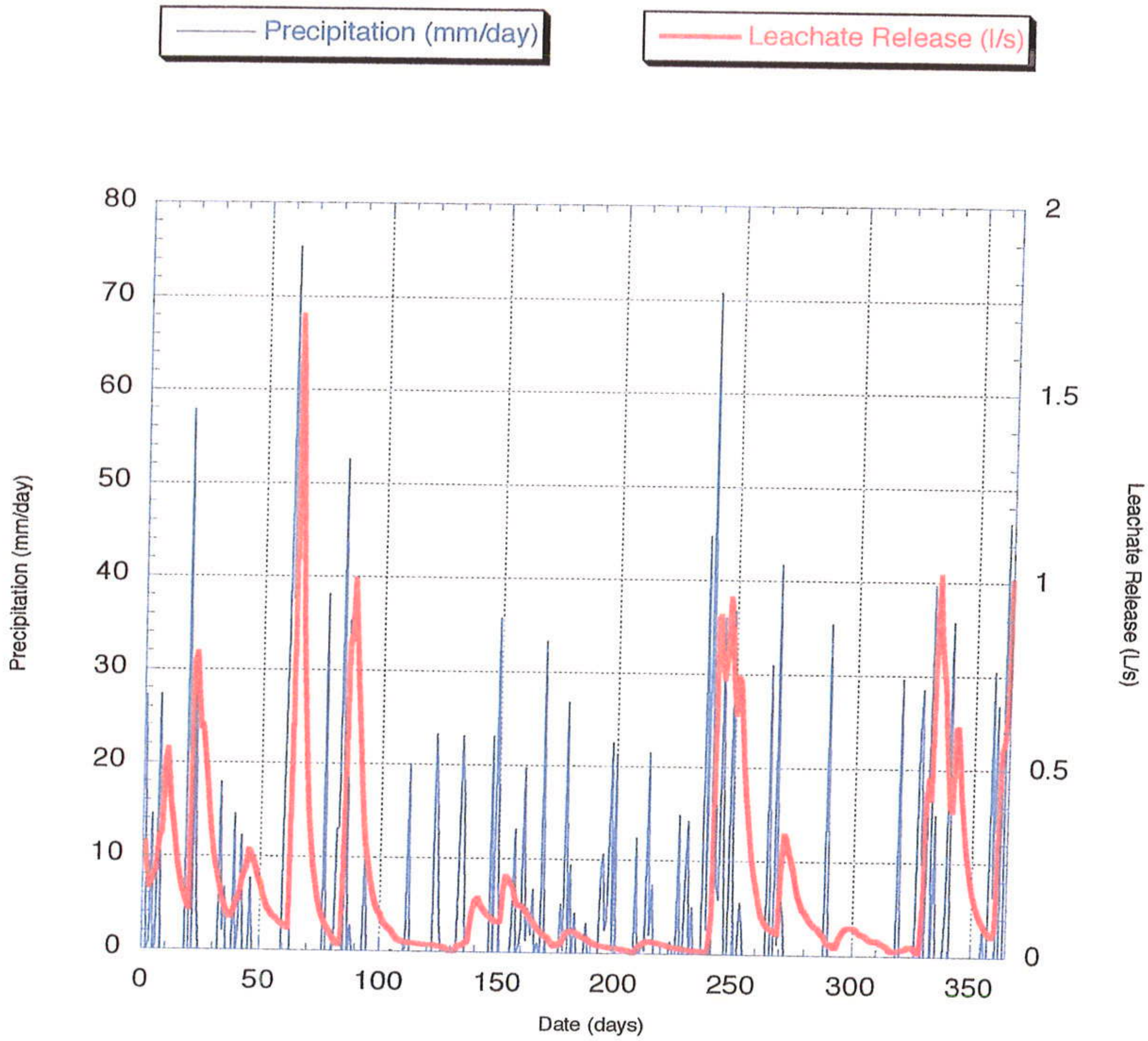


Figure 3 - Simulated Leachate Release from Sovjak Before Remediation

5. Leachate Chemical Characteristics

Leachate chemical characteristics for the two landfills are markedly different because of the distinct source materials that are present in each of them. Sovjak contains primarily tarry materials that are characterized by semi-volatile organic compounds and oils. Visevac is a municipal landfill, and the leachate will contain a variety of inorganic constituents, organic acids and trace volatile organic compounds. The quality of the leachate tends to vary with time depending on the age of the landfill and the state of waste decomposition (Reinhart and Al-Yousfi, 1995).

Leachate from Visevac has not been tested, but landfill gas samples provide a good indication of its volatile organic compound content. Based on this, together with literature values for other parameters, a likely chemical profile has been developed. Samples of Visevac landfill gas were collected and analyzed in 1998 (Dames & Moore and Ecoina, 1998). Results are shown in Table 3.

It is reasonable to assume that the non-methane hydrocarbons in the gas are in equilibrium with the leachate, and the aqueous concentrations can thus be back calculated based on knowledge of Henry's Law constant for each compound (Prosser 1995 and Sander, 1999). The results of this calculation are also shown in Table 3.

Conventional pollutants found in municipal waste landfills are frequently encountered at significantly higher concentrations than are volatile organics. However, these are often naturally occurring constituents that might be difficult to differentiate from ambient conditions. Typical values for these parameters are shown in Table 4.

Table 3. Volatile Organic Compound Concentrations In Visevac Landfill Leachate

	Measured Landfill Gas Concentration (mg/cu m)						Aqueous Concentrations (ug/L)	
	Vent 2	Vent 3	Vent 6	Vent 7	Vent 9	Average	Average	Maximum
Acetone	11.2	nd	nd	nd	nd	2.24	2,810.14	14,050.71
Hexane	2.7	nd	nd	nd	nd	0.54	0.02	0.11
Methyl ethyl ketone	12.8	1.5	nd	nd	nd	2.86	1,649.88	7,384.06
Ethyl acetate	0.5	1.3	nd	nd	nd	0.36	0.00	0.00
Cyclohexane	1.8	0.5	0.5	nd	0.5	0.66	0.23	0.63
Butilacetate	0.5	1.1	nd	nd	nd	0.32	0.00	0.00
Dimethylether	nd	0.5	nd	nd	nd	0.1	3.68	18.40
Methyl acetate	nd	1.6	nd	nd	nd	0.32	164.81	824.06
Heptane	1.8	0.5	nd	nd	0.5	0.56	0.05	0.17
Benzene	1.1	0.5	nd	nd	nd	0.32	3.60	12.37
Toluene	36	16	8.3	nd	1.2	12.3	145.07	424.58
Ethylbenzene	22	5.6	6.4	nd	2	7.2	73.38	224.23
Xylene	68	20	24	nd	11.6	24.72	356.94	981.86
Trimethylbenzene	3.7	0.5	1.3	nd	0.8	1.26	20.56	60.38
Methylene chloride (chloromethane)	2.1	2.2	2.6	nd	0.8	1.54	6.84	11.55
Tetrachloromethane	nd	0.5	nd	1.8	nd	0.46	2.04	7.98
1,1,2-Trichloroethylene	1.1	0.5	nd	nd	nd	0.32	40.98	140.88
Tetrachloroethylene	9.1	15.5	0.5	nd	nd	5.02	36.63	113.10
1,1,1-Trichloroethylene	nd	0.5	0.5	nd	nd	0.2	1.26	0.00
1,1-Dichloroethane	nd	0.5	nd	nd	nd	0.1	1.32	0.00

Table 4. Typical Concentrations Of Conventional Pollutants In Municipal Solid Waste Landfill Leachate (Reinhart, 1995)

Parameter	Concentration (mg/L)
Iron	20 – 2,100
BOD	20 – 40,000
COD	500 – 60,000
Ammonia	30 – 3,000
Chloride	100 – 5,000
Zinc	6 – 370

Literature derived values for metals concentrations in leachate are presented in Table 5.

Table 5. Typical Concentrations Of Metals In Municipal Solid Waste Landfill Leachate (USEPA, 1998)

Parameter	Concentration (mg/L)
Barium	1.4
Calcium	130
Magnesium	250
Manganese	21
Potassium	150
Sodium	710
Strontium	0.89

A water sample and six waste samples were collected from Sovjak in 1987 (Dames & Moore and Ecoina, 1998). Testing for metals revealed relatively low levels of contamination in the water sample, but no organic analysis was conducted (Table 6).

Table 6. Metals Content In Sovjak Leachate

Parameter	Concentration (mg/L)
Cadmium	0.008
Lead	0.26
Chromium	0.17
Mercury	0.006
Arsenic	0.02

Organic releases from the waste are likely to be occurring but have not been confirmed by testing. For purposes of this study, it is assumed that leachate (or 'squeezate') created by the consolidation of the waste results in the contamination of aqueous phase releases up to the solubility limit for the parameters that have been detected in the waste material. A variety of semi-volatile organic compounds were detected in the waste. These results are listed in Table 7 together with the maximum concentrations that can occur in leachate, based on solubility limits.

Table 7. Semi-Volatile Organic Compounds In Sovjak Waste And Maximum Leachate Concentration (Dames & Moore and Ecolna, 1998 and SRC, 2002)

	Average Concentration (mg/kg)	Maximum Concentration (mg/kg)	Aqueous solubility (mg/L) @25degC
Naphthalene	232	470	31.0
Acenaphthelene	39	110	16.1
Acenaphthene	13	20	3.57
Fluorene	98	200	1.98
Phenanthrene	390	840	1.15
Anthracene	63	180	0.043
Fluoranthene	213	470	0.206
Pyrene	103	300	1.35
Benzo (a) anthracene	58	150	Very low
Chrysene	70	150	0.006
Benzo (b) fluoranthene	52	140	0.002
Benzo (k) fluoranthene	48	120	0.001
Benzo (a) pyrene	60	170	0.002
Indo (1,2,3-CD)pyrene	47	130	0.001
Dibenzo (a,h) anthracene	12	30	Unknown, very low
Benzo (gh) perylene	45	110	Unknown, very low

6. Aquifer Characteristics

This section describes the body of groundwater that could be impacted by releases from Sovjak and Visevac. Unlike porous media flow where contaminants create a slowly expanding plume of impacted groundwater downgradient from the source, discharges to karst are more analogous to the addition of waste into a storm sewer pipe network through a single catch basin. The impact on the quality of water discharging from the final pipe in the network (coastal spring(s) in this analogy) is strongly influenced by the size of the drainage basin, the storm dynamics and the quantity and duration of the waste discharge.

First there is a brief description of the regional and local geology and hydrogeology, followed by an evaluation of conditions local to the landfills. This will support development of a reasonable model of groundwater flow in the vicinity of the two landfills, so that DAF's for the various contaminants can be developed.

6.1. Regional Geology

The regional geological conditions along the Adriatic coast have been studied in connection with evaluation of the area for possible hydrocarbon development (Grandic et al., 1997). These investigators place the Rijeka area in the Central Zone of the Dinarides where more than 8,000 m of carbonate and carbonate – anhydrite deposits formed during the Early Mesozoic (150 – 200 million years ago). This created what is known as the Dinarides Mesozoic Carbonate Platform upon which a variety of more recent deposits (primarily carbonate and/or dolomitic) developed during the later Mesozoic and Cenozoic.

The Rijeka area has been mapped geologically and described in some detail as part of both regional and local studies (Biondic et al., 1997). Some of this work has been conducted in support of groundwater development, or land use planning aimed at protecting groundwater resources. The area is characterized by the presence of Lower Cretaceous limestones and calcareous breccias, dolomitized breccias, and Upper Cretaceous deposits of alternating limestone and dolomite. Together these formations may be up to 1,000 m in thickness. More recent (Paleogene) deposits include limestone, clastic sediments and flysch deposits. The formations exhibit a wide range of hydrologic properties that, together with their geographic distribution, have a significant impact on groundwater flow in the area.

In an undisturbed or unaltered state, limestone is usually a low permeability rock. However, in the Dolomites, tectonic movement has created secondary permeability in the form of fractures and faults. These have been accentuated by extensive dissolution of the limestone by groundwater creating characteristic karst terrain and subsurface channeling that can lead to localized zones of very high permeability.

Table 8 presents a summary of the lithologic units and their generalized hydrologic properties (Biondic, et al., 1997). Figure 4 shows the generalized distribution of rock types throughout an area mapped as the groundwater basin in which Rijeka is located (Biondic 1996), and referred to in the Figure as the 'Rijeka Groundwater Basin'. For purposes of this illustration, the formations have been grouped into 'high permeability' ($E_{1,2}$, $K_2^{2,3}$, and K_1) and 'low and medium permeability' (E_3Ol_1, $E_{2,3}$, $K_{1,2}$ and $K_2^{1,2}$) rocks.

Physical properties of karst limestone are difficult to predict and may vary widely over just a few meters. Effective porosity is the porosity (volume of voids/volume of the total rock mass) that can support the flow of water and is important in the analysis of aquifer flow regimes. It contrasts with interstitial porosity, the property by which a rock may be capable of storage, but can not contribute to drainage and flow significantly. The effective porosity is attributable to the frequency and size of fractures and solution features. In karst, these may be virtually absent in some areas, and may dominate the rock mass in others. Investigations in the Dinaric karst (Komatina, 1984 and Bonacci, 1993) suggest that the effective porosity ranges within the limits of 0.1 – 1.5%. In a study of karst evolution (Gabrovsek, 2000) a seed value of 0.02% was inferred, that rose to about 0.5% at the end of the simulation.

Table 8. Lithologic And Hydrologic Properties Of Rock Formations In The Rijeka Area

Designation	Symbol	Lithologic Composition	Hydrologic Properties
Paleogene	E_3Ol_1	Limestone breccia. Rock fractures and fragments cemented by limestone and in places by marly binding material. JELAR DEPOSITS	Interstitial porosity. Poor permeability
	$E_{2,3}$	Clay siltstone, sandstone, marl and limestone marl alternately. FINE GRAINED CLASTIC SEDIMENTS (FLYSCH)	Interstitial or intergranular porosity. Impermeable complex.
	$E_{1,2}$	Fossiliferous limestone, crystalline, visibly fractured and fragmented	Interstitial – cavernous porosity. Good permeability.
Cretaceous	$K_2^{2,3}$	Limestone of organic origin, from lump shaped to thick beds. Intensively fractured and fragmented	
	$K_2^{1,2}$	Alternating limestone and dolomite, moderately fractured	Interstitial porosity. Moderate permeability
	$K_{1,2}$	Transitional dolomite breccia and porous limestone	Interstitial porosity. Poor permeability
	K_1	Limestone, breccia-shaped limestone with breccia lenses and dolomites, well layered, fractured and fragmented	Interstitial-cavernous porosity. Good permeability

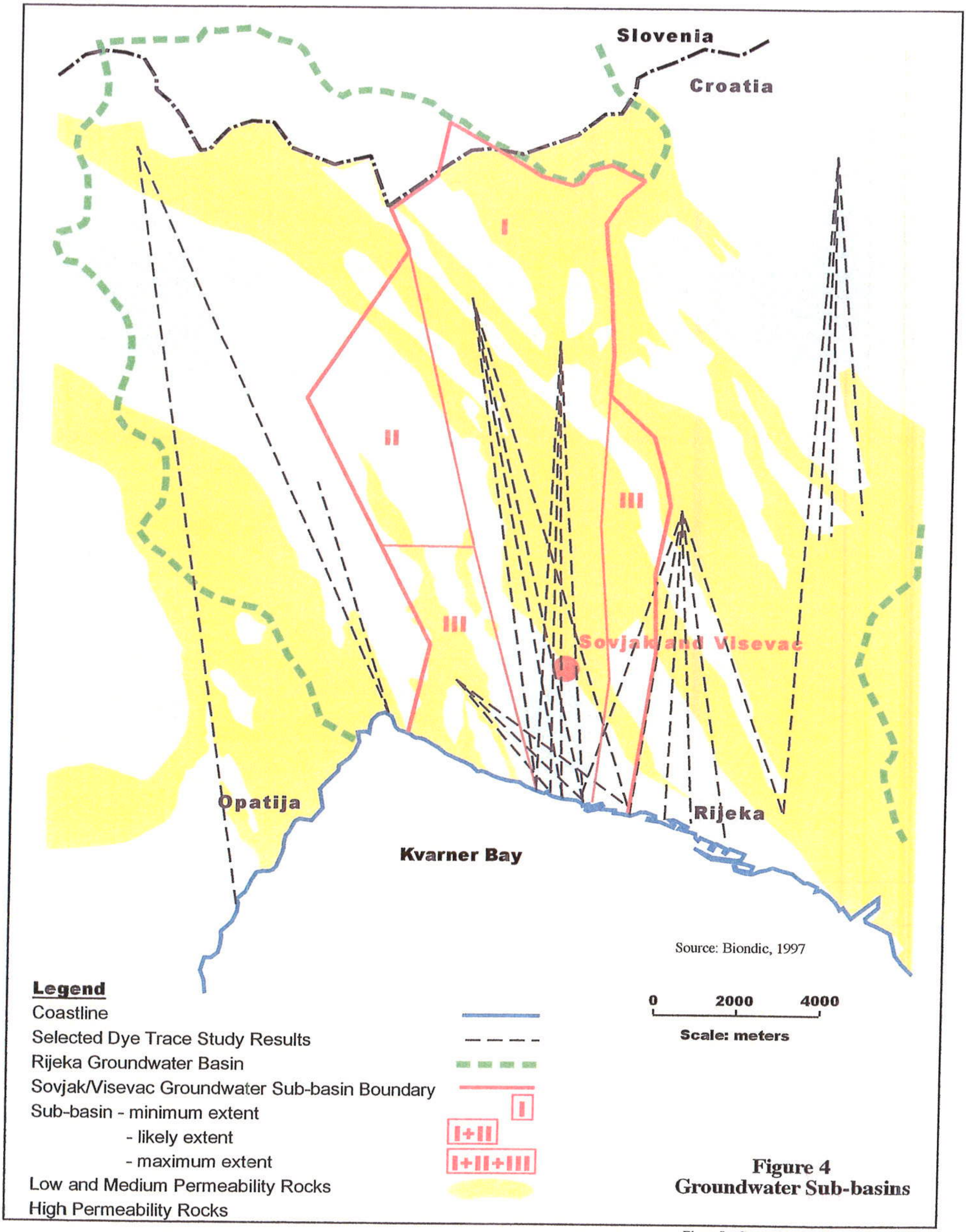


Figure 4
Groundwater Sub-basins

6.2. Local Geology

Geology in the vicinity of the landfills (Figure 5) is variable with at least three distinct rock units mapped within the boundary of the two sites ($K_{1,2}$, $K_2^{1,2}$, and K_2^2). Beds dip to the northeast at angles varying from 20 to 50 degrees. Geologic maps also show a large number of generally northwest – southeast trending faults in the area. Although there is some inconsistency between published sources on the exact location of the faults in the site vicinity, their density none the less indicates a high level of tectonic activity. It is noteworthy that the $K_{1,2}$ unit, a low permeability material, is shown occupying much of the sinkhole in which Visevac is formed. This suggests that the regional mapping may be insensitive to conditions at individual locations, and support the need for site specific mapping around the two landfills in order to establish material types, unit boundaries and geologic structure with greater certainty.

In addition to potentially complex lithology, the site is dominated by the two large karst features, which made it attractive for waste disposal. The municipal landfill Visevac is formed in a conical sinkhole approximately 300 m in diameter and on the order of 45 m deep. Less than 100 m away a 90-m diameter sinkhole with steep rock sidewalls and reportedly on the order of 50 m deep, was used to create the hazardous waste landfill Sovjak. Within 300 m there are more than a dozen sinkholes of various sizes, ranging in depth from 60 m to less than 10 m.

Geologic conditions in the 3.5 km between the landfills and the coast are relatively uniform, with the majority of the rock mapped as K_1 (high permeability limestone / porosity – cavernous). Structurally, there is a continuation of the northwest – southeast trending fault system.

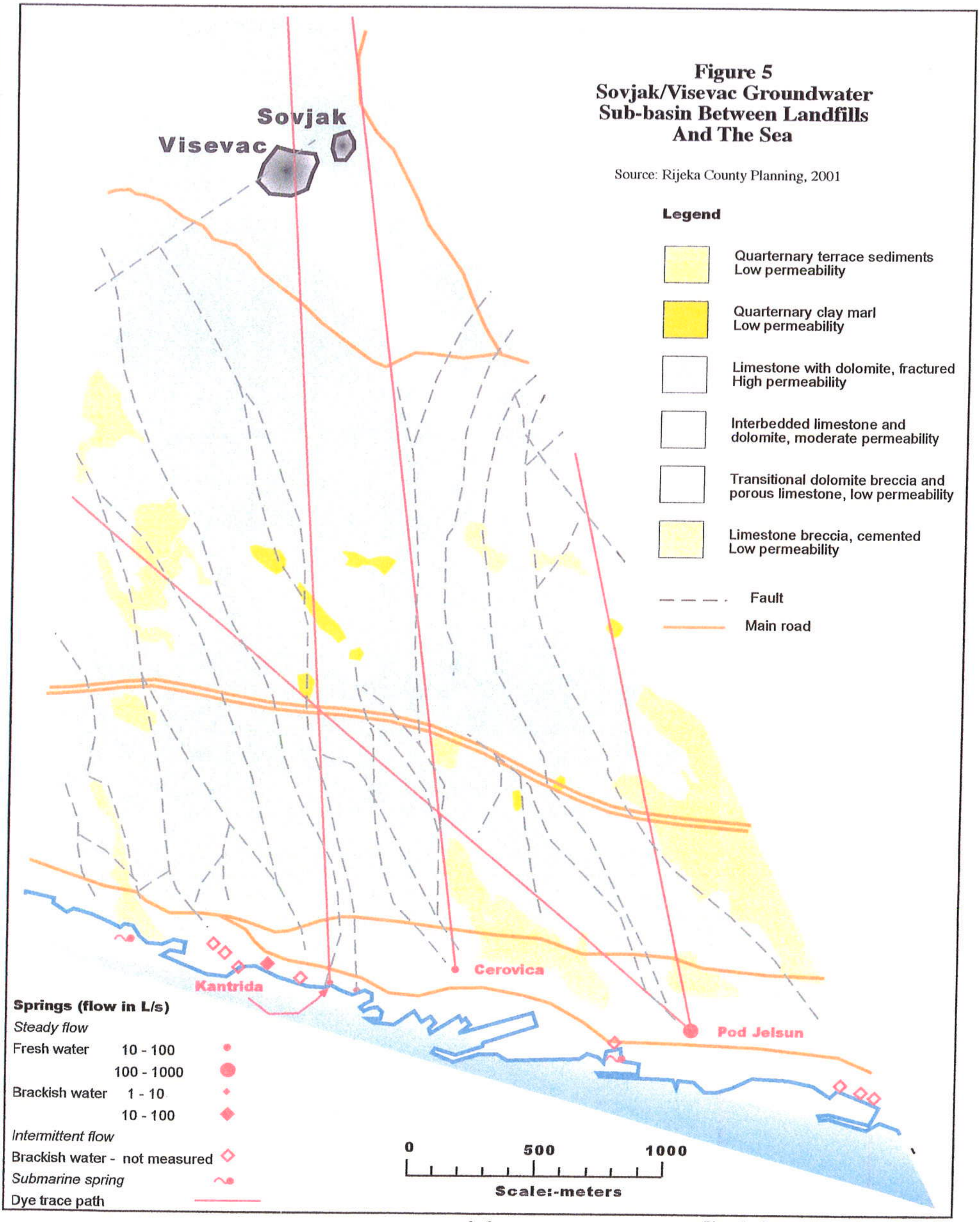


Figure 5
Sovjak/Visevac Groundwater
Sub-basin Between Landfills
And The Sea
Source: Rijeka County Planning, 2001
Sovjak
Visevac
Legend
Quarternary terrace sediments
Low permeability
Quarternary clay marl
Low permeability
Limestone with dolomite, fractured
High permeability
Interbedded limestone and
dolomite, moderate permeability
Transitional dolomite breccia and
porous limestone, low permeability
Limestone breccia, cemented
Low permeability
Fault
Main road
Kantrida
Cerovica
Pod Jelsun
Springs (flow in L/s)
Steady flow
Fresh water 10 - 100
100 - 1000
Brackish water 1 - 10
10 - 100
Intermittent flow
Brackish water - not measured
Submarine spring
Dye trace path
0
500
1000
Scale:-meters

6.3. Regional Hydrogeology

The Dinaric region receives high precipitation (1,500 – 5,000 mm/yr), most of which infiltrates rapidly into the karst systems and flows underground to the sea or other structurally controlled discharge points, where it emerges as springs. Groundwater discharge at these springs varies greatly in direct response to rainfall events because flow occurs primarily through fractures and solution features that permit high velocities. This is in marked contrast to porous media where the flow is interstitial and retarded by high friction losses.

The Ombla spring in Dubrovnic is the largest coastal spring in the Dinarides. It has a mean yield of 40 cu m/s, and a maximum of 160 cu m/s. In contrast, there are hundreds of intermittent and low flow springs where the discharge is less than 1 L/s. Coastal springs may have a maximum/minimum yield ratio as high as 100 (Komatina, 1984). The karst flow system in a particular area is relatively unique, and based on the structural weaknesses (fracture patterns, faulting etc.) that have allowed karstification to proceed, and the lithology which dictates the presence of impermeable layers or zones. While many coastal springs occur at or near sea level and are clearly visible, some discharge beneath the sea. More than 30 significant submerged springs are known to exist along the Dalmatian coast, nine of which are in the northern Adriatic (Alfirevic, 1979).

6.4. Local Hydrogeology

Rijeka is located in a groundwater basin that discharges to the Adriatic Sea. The boundaries of this basin (see Figure 4), which stretches along the coast of Kvarner Bay between Rijeka and Opatija, have been described in connection with establishing groundwater protection zones for the area (Biondic and Goatti, 1986). Examination of the basin geology, the distribution of springs and the results of dye tracing studies suggest that it is not homogeneous, and could reasonably be divided into 'sub-basins' for purposes of this analysis.

Proposed sub-basin boundaries for the area including Sovjak and Visevac are shown in Figure 4. To the east, the boundary conforms generally with the edge of a zone of low permeability rocks (mainly dolomite) and to the west, by the presence of a zone of rock of variable, but generally low permeability. These boundaries are imperfect because of the absence of detailed information. However, review of the results of numerous dye tracing studies suggests that they are reasonable estimates. As additional safeguard in the calculation of best and worst case DAF values, a postulated 'maximum' and 'minimum' extent of the basin, allows a range of possible groundwater flows to be established.

Based on these boundaries and the uncertainties discussed above, the area of the sub-drainage basin in which Sovjak and Visevac are located is calculated to be between 50 and 90 sq km, with a most likely value of 63 sq km. The quantity of water discharging from within the most likely sub-basin has been calculated using an adaptation of the HELP model. This computer code has a powerful ability to generate synthetic climatic data on a daily, monthly or annual basis, and to account for evapotranspiration. Based on this approach, the estimated annual average groundwater discharge is 100 million cubic meters (3,150 L/s). Annual variability was evaluated based on the individual outputs and the standard deviation of the average annual flow is estimated to be 700 L/s.

Using an alternative, more empirical method developed by Turc in 1954 (Bonacci and Magdalenic, 1993), a range of estimates from 2,721 – 3,325 L/s was calculated. Using another method quoted in the same reference and attributed to Srebrenovic, 1970, the predicted discharge rate is 3,460 L/s. These values appear to be reasonably consistent with each other and support the output produced by the HELP model. Conformity of these results should not be confused with uniformity of flow throughout each year. Figure 6 shows the results of year 26 of the 30-year HELP model simulation (selected because it was an average rainfall year) and the 'peaky' relationship between rainfall events and basin discharge is unmistakable. Thus, while the annual flows from the basin can be characterized with a fair degree of accuracy, the daily or monthly distribution can not. Daily flow varies from 400 - 10,700 L/s, with a standard deviation of 2,700 L/s. This is of great importance when considering the addition of pollutants to the groundwater system. DAFs are strongly dependent on the flow rate of the receiving water.

Depth to groundwater has not been measured at the landfill site. Based on the highly developed karst features and the lack of surface water or springs between the coast and the site, it is likely that groundwater is very deep. If a hydraulic gradient of 0.001 – 0.005 were maintained over the 3.5 km from the coast, the resulting water table would be only 3-17 m above sea level at Sovjak/Visevac resulting in a depth to groundwater of about 300 m.

Groundwater from the basin discharges along the coast through a series of springs that occur at or near sea level. In addition, a small number of submarine springs have been recorded. There is little available information regarding the quantity of flow at the springs or their response to rainfall events. Limited data are published on hydrologic maps maintained by the county. The location of springs that most likely support drainage from the Sovjak/Visevac sub-basin are shown in Figure 5 and classified by their strength (general range of flow rate), and whether the spring discharges fresh or brackish water. Several of the springs in the area are brackish. This is a phenomenon resulting from the cavernous nature of the aquifer that allows dispersive forces to create elevated salinity in groundwater near the salt water interface that may be significantly above sea level (Mijatovic, 1984). Several of the springs have, in the past been used for water supply and/or industrial purposes.

A crude inventory of the springs along the boundary of the sub-basin suggests that they could be discharging on the order of 1,000 – 1,500 L/s (average), which is considerably short of the 3,150 L/s that is calculated to flow from the sub-basin. The difference could be a result of inaccuracies in accounting for the unmeasured flows from brackish and submarine springs, fracture flow that may create a widespread discharge zone that is not reported, an over-statement of the sub-basin boundaries, or the possibility that a large amount of the sub-basin drainage is directed to discharge points outside the study area. The results of dye tracer studies over the past 25 years suggest that there is a low likelihood that the latter two possibilities are significant.

6.5. Groundwater Flow and Dye Trace Results

Dye trace tests have been conducted in the Rijeka basin since about 1974. As described above, the results were useful in assessing the likely boundaries of the Sovjak/Visevac groundwater sub-basin. There is little information available concerning the conduct of the tests or the hydrologic conditions that existed at the time, but there is some additional analysis that can support the development of DAFs.

At least three tests that have been conducted involved the injection of dye at locations generally upgradient from Sovjak and Visevac, and which resulted in theoretical flow paths passing beneath them, or nearby. Dye from these tests was detected at three coastal springs (see Figure 5) identified as Kantrida, Cerovica, and Pod Jelsun. Results from these tests as summarized in Ekonerg Holding, 2001, and in Biondic, 1996 are presented in Table 9 below.

Table 9. Selected Dye Trace Results

Date	Dye Injection Point	Dye Detection Point	Apparent Velocity (cm/s)
March 1974	Klana	Kantrida	3.24
		Cerovica	3.39
		Pod Jelsun	3.33
November 1988	Mariscina	Kantrida	0.66
		Cerovica	0.64
		Pod Jelsun	0.68
March 2000	Mariscina	Cerovica	4.71
		Pod Jelsun	4.86

As each of these traces appears to follow a similar path, it is interesting to note the variation in measured velocity. Historical climate data shows November 1988 to have been an unusually dry month whereas March 1974 appears to have been closer to normal, or average, conditions. The volume of groundwater flow therefore appears to have a significant impact on the flow velocity. The consistency between results for individual tests is also striking, indicating relatively uniform flow conditions even though the three springs are 400 – 700 m apart.

The most recent test was semi-quantitative, and dye breakthrough curves were developed (Ekonberg Holding, 2001), which provide some additional insight into the aquifer flow regime. Dye concentrations were measured regularly throughout the period that it was detected at the coastal springs, and the results were graphed. Quantitative tests (as compared to qualitative ones that merely make a detect/no detect determination) are particularly valuable as a source of data for evaluating solute transport parameters (U.S. EPA, 1999) and, consequently for estimating DAFs. The test at Mariscina is considered semi-quantitative because no information is presented regarding the prevalent hydrologic conditions at the time of the test (weather, spring flow rates etc), so limiting the extent of subsequent analysis that is possible.

Eighty kilograms of dye dissolved in 200 L of water was reportedly injected into the aquifer through a 30-m deep bore hole, and flushed with 105 cu m of water over a period of 12 hours. The resulting concentrations measured at the coastal springs Cerovica and Pod Jelsun are similar: first detection of dye after two days, a maximum concentration on the order of 0.04 mg/L after a further two days, and an average for the 19 days during which dye was detected of 0.01 mg/L. Based on this average value, it can be calculated that the dye was diluted into approximately 8 million cubic meters of groundwater. Movement of this 'slug' of impacted water from Marascina to the coast would require an average flow rate for the 19 days of 4,870 L/s. Figure 6 shows extended periods where the flow rate is in excess of this amount, thus lending general credibility to the result. The absence of flow data at the spring for the period of the test prevents any further analysis of these results.

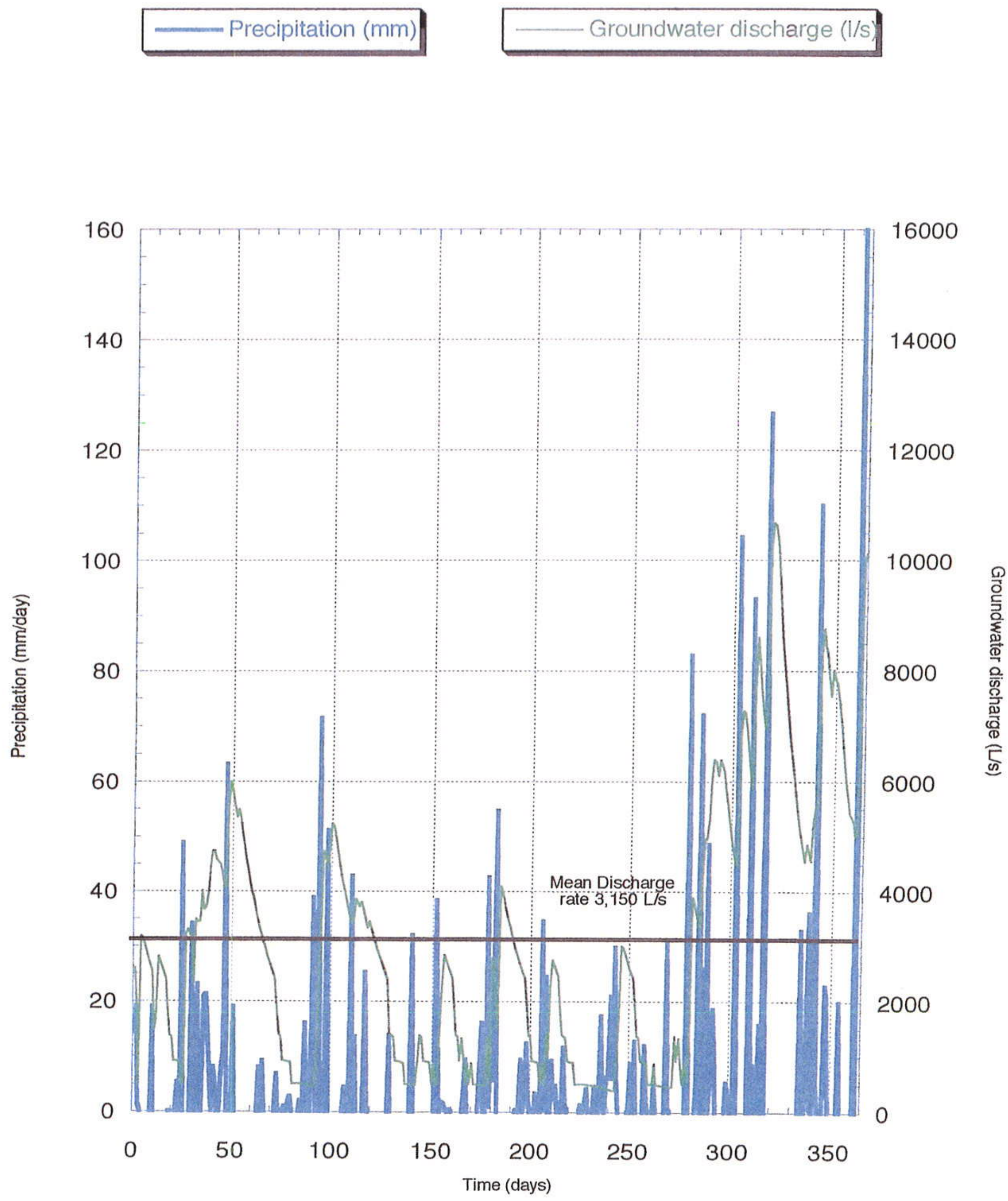


Figure 6. Simulated Groundwater Discharge/Precipitation for Sovjak/Visevac Karst Sub-basin

6.6. Groundwater Quality

The available data relating to chemical quality of groundwater in the sub-basin are limited to the subjective reports found on hydrologic maps that some of the springs discharge brackish water. If it is assumed that the term brackish refers to chloride levels that make the water undrinkable, a threshold in the range 250 mg/L – 3,000 mg/L is probably implied. It is reasonable to assume that the remaining springs contain less than 3,000 mg/L, but it is possible that they do contain low levels of sea water related constituents. Seawater is relatively rich in dissolved metals. Those present at levels typically greater than 1 ug/L (one part per billion) are shown in Table 10.

Table 10. Minerals In Sea Water

Element	Concentration (ugL)	Element	Concentration (ug/L)
Sodium	10,500,000	**Aluminum**	10
Magnesium	1,350,000	**Iron**	10
Calcium	400,000	**Indium**	10
Potassium	380,000	**Molybdenum**	10
Bromine	65,000	**Zinc**	10
Carbon	28,000	**Nickel**	5
Strontium	8,100	**Arsenic**	3
Boron	4,600	**Copper**	3
Silicon	3,000	**Tin**	3
Fluorine	1,300	**Uranium**	3
Lithium	180	**Krypton**	3
Rubidium	120	**Manganese**	2
Phosphorus	70	**Vanadium**	2
Iodine	60	**Titanium**	1
Barium	30		

These minerals may be present in brackish water at levels 10 – 50% of those shown in Table 10, while in coastal fresh water springs, the levels are likely to be 0.1 – 1.0%. In addition to a seawater derived mineral content, the groundwater is likely to be rich in dissolved solids because of the chemical characteristics of the limestones and dolomites that form the aquifer. These will include primarily, calcium, and magnesium, with smaller amounts of fluoride, sodium, potassium, silica and traces of many of the other constituents listed in Table 10.

The presence of naturally occurring minerals in groundwater and some spring water creates a potential complication in identifying suitable parameters for landfill monitoring purposes.

7. Monitoring Systems

This section presents an evaluation of the technical characteristics of the two candidate monitoring systems: conventional monitoring wells and the coastal karst springs. In addition to reviewing the general technical concepts, some possible solutions to operational problems are reviewed.

At the outset, the basic requirements for monitoring system design should be reiterated and used as a yard stick against which to compare the alternatives. To the extent possible, the system should be cost effective to install and to operate functionally, the system must be capable of accurately and reliably detecting a change to the quality of water in the aquifer resulting from a release from the landfill(s). This means that it must be designed to:

- detect one or more specific landfill derived constituents or chemical indicators in the groundwater
- distinguish a detected value from background or ambient conditions
- exhibit reliability under a range of hydrologic conditions

The general contaminant release-to-groundwater and environmental fate model is shown in Figure 1. The two monitoring concepts under consideration are also shown on the figure.

7.1. Wells

Conventional monitoring wells will play a role in the monitoring program for Sovjak and Visevac, as required by Croatian regulations. A conventional well is one that is drilled from the surface of the ground to a point below the water table to facilitate the collection of representative groundwater samples. Regulations require a minimum of two downgradient and one upgradient wells. At this site, there will be challenges to the successful design and implementation of a well-based monitoring system.

7.1.1. Well Depths

Wells should be drilled to the water table plus an additional 10 m to allow for variation in the level. This means that they will probably be at least 320 m deep. Wells of this depth must be drilled with heavy duty drilling equipment.

7.1.2. Well Locations

It is reasonable to assume that groundwater in the site vicinity is flowing towards the sea (almost due south). This suggests that wells drilled to the south of the landfills will be downgradient, while those drilled to the north will be upgradient. (see Figure 1). In addition to being upgradient from the landfills, the wells must also be unaffected by them. In a majority of applications, wells that are a few meters, or tens of meters upgradient will be unaffected by the landfill. However, because of the large depth to the groundwater table at this site, the upgradient area of impact can be quite significant. It is not unreasonable to assume an upgradient impact on the groundwater of 50 – 100% of the depth to the water table. For this reason, any upgradient well should be located at least 150 m north of the site. Downgradient wells should be located on the south side of the landfills, and as close as possible. Candidate well locations are shown on Figure 7.

The geology within the site boundary has not been well documented. Geologic maps of the area show a variety of formations dipping quite steeply to the northeast, with a spectrum of permeability characteristics, present at the surface. The geologic structure of the site may be important when locating wells so that they have the best chance of encountering groundwater. As indicated in an earlier section, five out of ten 300 m deep borings at a karst site in Croatia did not encounter groundwater. With more site specific mapping and interpretation, it should be possible to optimize the chance of successful drilling.

7.1.3. Well Construction

Well construction design details are important when considering the cost and reliability of the monitoring system, although they do not impact significantly on the technical feasibility of the installation. It is anticipated that steel will be used for the well casing and that it will be a minimum of 150 millimeters (mm) in diameter, requiring a hole of about 300 mm diameter. The bottom 10 m will be screened and a submersible positive displacement pump installed. The pump will be used for purging the well and for sampling. A power supply will be required to operate the pump.

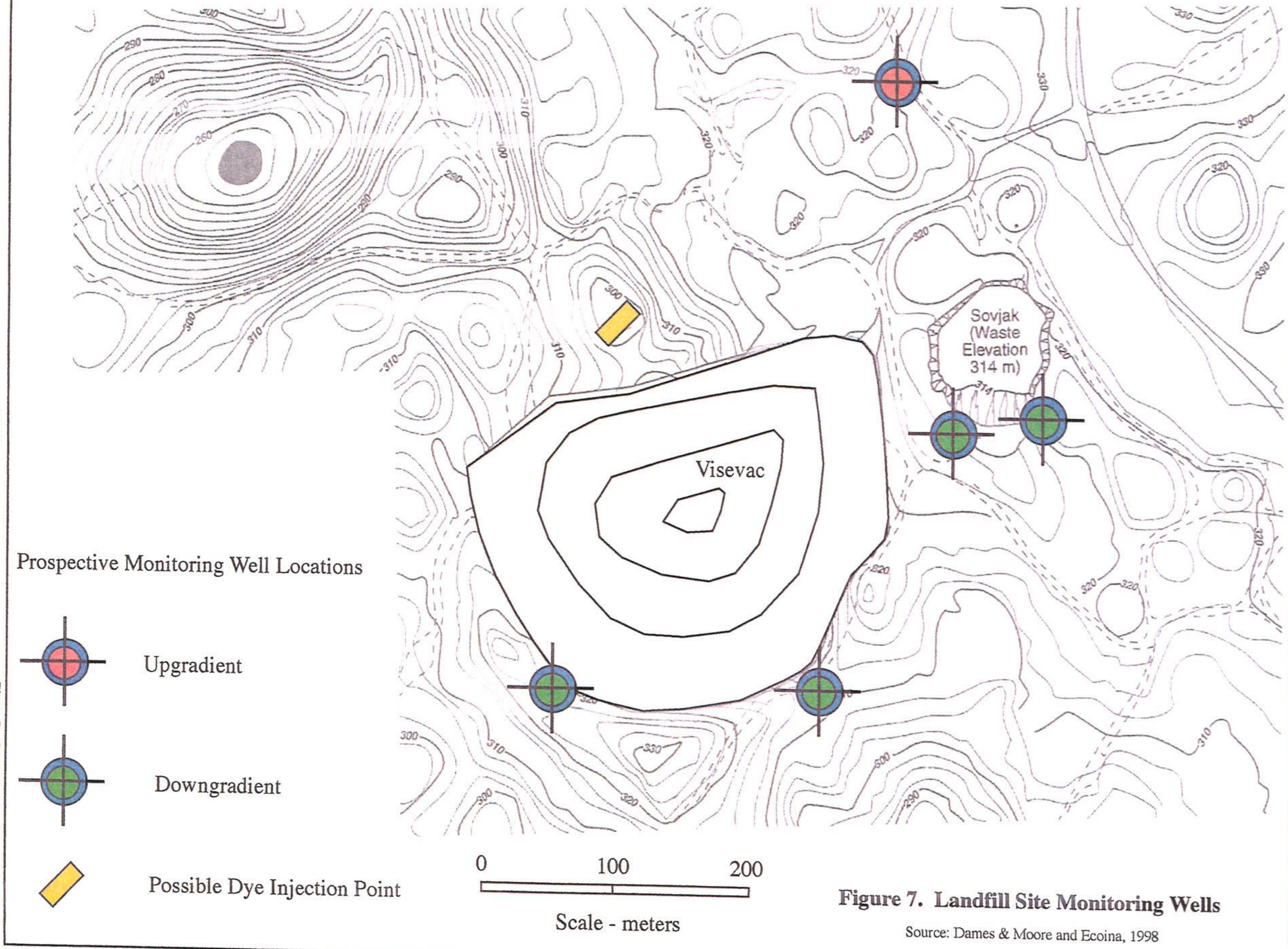


Figure 7. Landfill Site Monitoring Wells

Source: Dames & Moore and Ecoina, 1998

7.2. Springs

As indicated in earlier sections, the use of coastal springs for monitoring is an attractive proposition if its technical feasibility can be established. The approach is consistent with recognized good practice for monitoring groundwater in karst environments, and it is not capital intensive. Since dye tracing studies have been conducted successfully for many years in the area, there is strong precedent for the detection of contaminants that were introduced into the aquifer many kilometers away, at the coastal springs.

The controlling factor in the design of a spring based monitoring system will be to identify those leachate derived contaminants that can be reliably detected after dilution in the aquifer and possible attenuation on their journey from the landfills to the coast. The Dilution – Attenuation Factor (DAF) is a chemical specific measure of the overall reduction in concentration from leachate to spring water. The DAF for a constituent consists of two relatively independent parts. The first, a dilution factor (DF) is not chemical specific, and is based strictly on the quantity of sub-basin flow and the leachate production rate:

$$DF = Q_{\text{sub-basin}} / Q_{\text{leachate}}$$

The dilution factor is always greater than unity. The Attenuation Factor (AF) is chemical specific and is a measure of the reduction in concentration that can be expected due to natural attenuative mechanisms such as volatilization, biodegredation and adsorption (Xie and Zeiss, 1995). The AF is the ratio of the concentration of a constituent in leachate to its concentration in groundwater after several days:

$$AF = C_{\text{leachate}} / C_{\text{groundwater}}$$

Again, the AF is always greater than unity. The product of these two factors yields the DAF.

$$DAF = DF * AF$$

When the concentration of a constituent in leachate is divided by the DAF, the result is the predicted concentration in groundwater at the coastal spring.

$$C_{\text{coastal spring}} = C_{\text{leachate}} / DAF$$

7.2.1. Locations

There appear to be three candidate springs for monitoring purposes: Kantrida, Cerovica and Pod Jelsun. Of these, Kantrida should be excluded on the basis of its brackish production which could create possible confusion with leachate derived metals. Of the two remaining springs, Cerovica appears to be more directly on the flow path, although this would have to be confirmed through dye testing.

7.2.2. Dilution Factor

The sub-basin groundwater flow can vary significantly from day to day (Figure 6), and the potential for dilution therefore varies correspondingly. The leachate production rate also varies. At Visevac there is a seasonal fluctuation, and at Sovjak a rapid response to changes in precipitation. These factors combine to create a complex array of possible dilution factors. Dilution factors have been computed for a range of situations that most likely encompasses the extremes of conditions and look at both current and future (post-closure/remediation) landfill scenarios. The calculated values are presented in Table 11.

Table 11. Dilution Factors Between Landfills and Coastal Springs

			Visevac					
			Summer			Winter		
		Leachate Release Scenario	No Cover	Interim Cover	Post-Closure	No Cover	Interim Cover	Post-Closure
Groundwater Scenario		L/s	2.9	1.2	0.003	2.2	0.75	0.003
Sub-basin Flow	**Mean**	3,150	1,086	2,625	1,050,000	1,432	4,200	1,050,000
	Average Low	400	138	333	133,333	182	533	133,333
	Average High	10,700	3,690	3,917	3,566,667	4,864	14,267	3,566,667

Dilution Factors Less Than 10,000

Table 11. Continued

			Sovjak			
			Recent Storm		Low Flow	
		Leachate Release Scenario	Current	Post-Closure	Current	Post-Closure
Groundwater Scenario		L/s	0.5	0.00005	0.1	0.00001
Sub-basin Flow	**Mean**	3,150	6,300	63,000,000	31,500	315,000,000
	Average Low	400	800	8,000,000	4,000	40,000,000
	Average High	10,700	21,400	214,000,000	107,000	1,070,000,000

The results illustrate the wide variability in conditions, with DFs ranging from about 100 to more than 3 million for Visevac leachate, and from about 1,000 to more than a billion for Sovjak. Clearly, ignoring the additional complexity introduced by the attenuation factors, the timing of a spring water sample has a major impact on the results.

7.2.3. Attenuation Factor

There is well documented evidence demonstrating attenuation of some municipal wastewater organic constituents in karst environments (Masciopinto and Carrieri, 2002), but for many of the likely leachate parameters, data are sparce. Where testing has been conducted, there are frequent examples of significantly variable results based on differences in experimental procedure.

The dye testing results discussed above showed that, while the first arrival of dye at the coastal springs occurred in about two days, dye was present in the system for 19 days. This is a significant residence time and chemical changes should be expected. Sovjak and Visevac are closer to the coast than the dye injection point in the Marascina test (about half the distance), but the residence time is still expected to be a matter of several days, particularly during low flow conditions.

Attenuation factors have been assigned conservatively (showing minimum effect) in order not to screen out potentially useful monitoring parameters. The primary attenuative mechanisms are:

Biodegradation

Leachate is generally low in dissolved oxygen, low pH and eH, and only anaerobic activity is taking place in the bottom of the landfill. When released to the aquifer, the dissolved oxygen levels are likely to be higher (close to a normal value of about 5 mg/L) and this can trigger aerobic metabolization of some organics. BOD levels would be particularly affected, as would those of all readily degraded organics

Precipitation

The same dissolved oxygen increase can have a marked effect on the solubility of metals. Their behavior under varying redox conditions is unique to the species involved, but overall there is a clear tendency to oxidation and precipitation in the presence of additional dissolved oxygen.

Volatilization

The flow of groundwater through karst systems may become turbulent and passages may not always be filled with water creating conditions that allow transfer of volatile compounds such as toluene or xylene at the air/water interface.

Adsorption

Adsorption to soil and rock particles provides yet another attenuative mechanism. The processes are well known, but the extent to which they can take place in this system is not easily determined. It is likely that the effects are relatively minor since there is not much clayey soil through which the leachate passes. Parameters most affected are the semi-volatile compounds that make up the bulk of the likely Sovjak leachate profile.

A range of AFs has been assigned to each leachate parameter that is likely to be present at a level in excess of 100 ug/L. The values have been selected conservatively (showing lower levels of attenuation than may actually occur) as the processes are not easily predicted. These are shown in Table 12.

7.2.4. Dilution-Attenuation Factors

Tables 11 and 12 display an array of conditions that must be evaluated when considering the selection of monitoring parameters. For simplicity, DAFs and corresponding coastal spring concentrations have been calculated for the range of leachate parameters and for three DF scenarios – current conditions with mean groundwater flow, current conditions

Table 12. Chemical Specific Attentuation Factors For Landfill Leachate Parameters

Constituent Likely To Be Present In Leachate At More Than 100 ug/L	Land-fill	Considerations For Use In Monitoring	Considered Further	Attenuative Mechanisms	Assigned Attenuation Factor (Low)	Assigned Attenuation Factor (High)
Acetone	V	Biodegradable	Y	Biodegradation, volatilization	1.5	3
Methyl Ethyl Ketone	V	Biodegradable, common industrial solvent	Y	Biodegradation, volatilization	1.5	3
Toluene	V	Biodegradable, common pollutant resulting from gasoline releases	Y	Biodegradation, volatilization	1.5	3
Ethylbenzene	V	Biodegradable, common pollutant resulting from gasoline releases	Y	Biodegradation, volatilization	1.5	5
Xylene	V	Biodegradable, common pollutant resulting from gasoline releases	Y	Biodegradation, volatilization	1.5	3
Trichloro-ethylene	V	Relatively stable, common solvent	Y	Anaerobic decomposition, volatilization	1	1.1
Trichloro-ethylene	V	Relatively stable, common solvent	Y	Anaerobic decomposition, volatilization	1	1.1
Iron	V	Reactive underchanged ORP conditions	Y	Precipitation	1	3
Zinc	V	Reactive underchanged ORP conditions	Y	Precipitation	1	3

V-Visevac S-Sovjak Y-Yes N-No

Table 12. Continued

Constituent Likely To Be Present In Leachate At More Than 100 ug/L	Land-fill	Considerations For Use In Monitoring	Consid-ered Further	Attenuative Mechanisms	Assigned Attenuation Factor(Low)	Assigned Attenuation Factor (High)
Barium	V	Reactive under changed ORP conditions	Y	Precipitation	1	3
Calcium	V	Major constituent of limestone	N			
Magnesium	V	Major constituent of dolomite	N			
Potassium	V	Significant constituent in sea water	N			
Sodium	V	Major constituent in sea water	N			
Strontium	V	Significant constituent in sea water	N			
Lead	V	Reactive under changed ORP conditions	Y	Precipitation, adsorption	1	3
Chromium	V	Reactive under changed ORP conditions	Y	Precipitation, adsorption	1	3
BOD	V	Biodegradable	Y	Biodegradation	2	5
COD	V,S	Non specific, weak indicator	N			
Ammonia	V	Biodegradable	Y	Biodegradation	2	5
Chloride	V	Major constituent in sea water	N			
Naphthalene	S	Biodegradable, adsorptive	Y	Biodegradation, adsorption	1	5
Acenaphthelene	S	Adsorptive	Y	Biodegradation, adsorption	1	1.5
Acenaphthene	S	Adsorptive	Y	Biodegradation, adsorption	1	1.5
Fluorene	S	Adsorptive	Y	Biodegradation, adsorption	1	1.5
Phenanthrene	S	Adsorptive	Y	Biodegradation, adsorption	1.5	3
Fluoranthene	S	Adsorptive	Y	Biodegradation, adsorption	1	1.5
Pyrene	S	Adsorptive	Y	Biodegradation, adsorption	1	1.5

with low groundwater flow, and post- closure conditions at low flow. The first two investigate the 'best' opportunities to detect contaminants at the springs, while the third looks at a future post closure case. These results are shown in Tables 13, 14 and 15.

Table 13. **Predicted Coastal Spring Concentrations – Mean Sub-basin Groundwater Flow, Current Landfill Conditions**

Constituent Likely To Be Present In Leachate At More Than 100 ug/L	Landfill	Average Leachate Concentration (ug/L)	Dilution Factor - Current Conditions, Mean sub-basin Groundwater Flow	Assigned Attenuation Factor (Low)	Assigned Attenuation Factor (High)	DAF (low)	DAF (high)	High Concentration at Coastal Spring (ug/L)	Low Concentration at Coastal Spring (ug/L)
Acetone	V	2,810	1,086	1.5	3	1,629	3258	1.72	0.86
Methyl Ethyl Ketone	V	1,649	1,086	1.5	3	1,629	3,258	1.01	0.51
Toluene	V	145	1,086	1.5	3	1,629	3,258	0.09	0.04
Ethylbenzene	V	73	1,086	1.5	5	1,629	5,430	0.04	0.01
Xylene	V	357	1,086	1.5	3	1,629	3,258	0.22	0.11
Trichloro-ethylene	V	41	1,086	1	1.1	1,086	1,195	0.04	0.03
Tetrachloro-ethylene	V	37	1,086	1	1.1	1,086	1,195	0.03	0.03
Iron	V	500,000	1,086	1	3	1,086	3,258	460.41	153.47
Zinc	V	100,000	1,086	1	3	1,086	3,258	92.08	30.69
Barium	V	1,400	1,086	1	3	1,086	3,258	1.29	0.43
Lead	V	260	1,086	1	3	1,086	3,258	0.24	0.08
Chromium	V	170	1,086	1	3	1,086	3,258	0.16	0.05
BOD	V	200,000	1,086	2	5	2,172	5,430	92.08	36.83
Ammonia	V	100,000	1,086	2	5	2,172	5,430	46.04	18.42
Naphthalene	S	31,000	6,300	1	5	6,300	31,500	4.92	0.98
Acenaph-thelene	S	16,100	6,300	1	1.5	6,300	9,450	2.56	1.70
Acenaphthene	S	3,570	6,300	1	1.5	6,300	9,450	0.57	0.38
Fluorene	S	1,980	6,300	1	1.5	6,300	9,450	0.31	0.21
Phenan-threne	S	1,150	6,300	1.5	3	9,450	18,900	0.12	0.06
Fluoranthene	S	206	6,300	1	1.5	6,300	9,450	0.03	0.02
Pyrene	S	1,350	6,300	1	1.5	6,300	9,450	0.21	0.14

Potentially Detectable Levels With Conventional Sampling

Table 14. **Predicted Coastal Spring Concentrations – Low Sub-basin Groundwater Flow, Current Landfill Conditions**

Constituent Likely To Be Present In Leachate At More Than 100 ug/L	Land-fill	Average Leachate Concentra-tion (ug/L)	Dilution Factor - Current Conditions, Low sub-basin Groundwater Flow	Assigned Attenu-ation Factor (Low)	Assigned Attenu-ation Factor (High)	DAF (low)	DAF (high)	High Concentra-tion at Coastal Spring (ug/L)	Low Concentra-tion at Coastal Spring (ug/L)
Acetone	V	2,810	138	1.5	3	207	414	13.57	6.79
Methyl Ethyl Ketone	V	1,649	138	1.5	3	207	414	7.97	3.98
Toluene	V	145	138	1.5	3	207	414	0.70	0.35
Ethylben-zene	V	73	138	1.5	5	207	690	0.35	0.11
Xylene	V	357	138	1.5	3	207	414	1.72	0.86
Trichloro-ethylene	V	41	138	1	1.1	138	152	0.30	0.27
Tetrachloro-ethylene	V	37	138	1	1.1	138	152	0.27	0.24
Iron	V	500,000	138	1	3	138	414	3,623.19	1,207.73
Zinc	V	100,000	138	1	3	138	414	724.64	241.55
Barium	V	1,400	138	1	3	138	414	10.14	3.38
Lead	V	260	138	1	3	138	414	1.88	0.63
Chromium	V	170	138	1	3	138	414	1.23	0.41
BOD	V	200,000	138	2	5	276	690	724.64	289.86
Ammonia	V	100,000	138	2	5	276	690	362.32	144.93
Naphthalene	S	31,000	800	1	5	800	4,000	38.75	7.75
Acenaph-thelene	S	16,100	800	1	1.5	800	1,200	20.13	13.42
Acenaph-thene	S	3,570	800	1	1.5	800	1,200	4.46	2.98
Fluorene	S	1,980	800	1	1.5	800	1,200	2.48	1.65
Phenan-threne	S	1,150	800	1.5	3	1200	2,400	0.96	0.48
Fluoran-thene	S	206	800	1	1.5	800	1,200	0.26	0.17
Pyrene	S	1,350	800	1	1.5	800	1,200	1.69	1.13

Potentially Detectable Levels With Conventional Sampling

Table 15. Predicted Coastal Spring Concentrations – Low Sub-basin Groundwater Flow, Post-closure Landfill Conditions

Constituent Likely to be Present in Leachate at More than 100 ug/L	Landfill	Average Leachate Concentration (ug/L)	Dilution Factor – Post-Closure, low Sub-basin Groundwater Flow	Assigned Attenuation Factor (Low)	Assigned Attenuation Factor (High)	DAF (low)	DAF (high)	High Concentration at Coastal Spring (ug/L)	Low Concentration at Coastal Spring (ug/L)
Acetone	V	2,810	133,333	1.5	3	199,999.5	399,999	0.01	0.01
Methyl Ethyl Ketone	V	1,649	133,333	1.5	3	199,999.5	399,999	0.01	0.00
Toluene	V	145	133,333	1.5	3	199,999.5	399,999	0.00	0.00
Ethyl-benzene	V	73	133,333	1.5	5	199,999.5	666,665	0.00	0.00
Xylene	V	357	133,333	1.5	3	199,999.5	399,999	0.00	0.00
Trichloro-ethylene	V	41	133,333	1	1.1	133,333	146,666	0.00	0.00
Tetrachloro-ethylene	V	37	133,333	1	1.1	133,333	146,666	0.00	0.00
Iron	V	500,000	133,333	1	3	133,333	399,999	3.75	1.25
Zinc	V	100,000	133,333	1	3	133,333	399,999	0.75	0.25
Barium	V	1,400	133,333	1	3	133,333	399,999	0.01	0.00
Lead	V	260	133,333	1	3	133,333	399,999	0.00	0.00
Chromium	V	170	133,333	1	3	133,333	399,999	0.00	0.00
BOD	V	200,000	133,333	2	5	266,666	666,665	0.75	0.30
Ammonia	V	100,000	133,333	2	5	266,666	666,665	0.38	0.15
Naphtha-lene	S	31,000	8,000,000	1	5	8,000,000	4,000,0000	0.00	0.00
Acenaph-thelene	S	16,100	8,000,000	1	1.5	8,000,000	12,000,000	0.00	0.00
Acenaph-thene	S	3,570	8,000,000	1	1.5	8,000,000	12,000,000	0.00	0.00
Fluorene	S	1,980	8,000,000	1	1.5	8,000,000	12,000,000	0.00	0.00
Phenan-threne	S	1,150	8,000,000	1.5	3	12,000,000	24,000,000	0.00	0.00
Fluoran-thene	S	206	8,000,000	1	1.5	8,000,000	12,000,000	0.00	0.00
Pyrene	S	1,350	8,000,000	1	1.5	8,000,000	12,000,000	0.00	0.00

Under mean groundwater flow conditions, and current (pre-closure) conditions, the parameters that are potentially detectable are iron, zinc, naphthelene and acenaphthelene. During low groundwater flow conditions, these constituent levels increase, and barium, acetone and methyl ethyl ketone are added. However in no case are the levels likely to be above 40 ug/L for the organics or 4 mg/L for iron. In the post-closure scenarios, the results are reassuringly negative with no contaminants detectable under any flow conditions. To detect a failure of the closure (Visevac) or remediation (Sovjak), the release would have to be of the same general magnitude as the ongoing (current) releases.

7.2.5. Sampling Methods

The low levels of organic and inorganic contaminants that are anticipated to discharge at the springs are difficult to sample reliably by conventional grab sampling. Various methods have been developed that allow the concentration of constituents during the sampling process, in much the same way that air contaminants can be concentrated in a sorbent tube. The methods are not in widespread use and may be somewhat experimental for spring sampling. However, in light of the difficulties in monitoring the landfills, they are worth considering.

Activated Carbon

Activated carbon contained in mesh pouches is used extensively for sampling for dyes used in tracer testing in karst environments. The receptor packets are left suspended in the flowing spring water and recovered periodically for testing. Undoubtedly they have been used in tests that have been conducted historically in the Rijeka area. In that application the presence or absence of the dye is all that is required, and the lower the detection limit of the analytical equipment, the more sensitive the test.

A presence or absence test would be of value for monitoring releases from the landfill if there were no other better method. The suite of organic constituents that could be concentrated onto the activated carbon is fairly broad; most synthetic organic compounds adsorb on carbon to one degree or another. The primary disadvantage of the method is that quantification of contaminant levels is not practical.

Gore-Sorber

The Gore-Sorber is a sampling device used in soil for the detection of volatile organic compounds. It consists of an adsorption media contained in a Goretex pouch. Goretex is a fabric (used extensively in rainwear for campers and hikers) that allows the passage of vapor, but not water. The system is thus able to concentrate vapor phase organic compounds in the unsaturated part of the soil column without interference from groundwater. Recent experiments have been conducted into using Gore-Sorber modules for the detection of volatile organic constituents (VOCs) in spring water (Vesper et al., 1999). The modules are left in the spring, and adsorb vapor phase contaminants that diffuse from the groundwater through the fabric onto the media. The tests were generally successful, with several instances where VOCs were detected on the Gore-Sorber, but not on a corresponding grab sample. The use of this system for detection monitoring at Sovjak and Visevac should be considered further.

High Volume Water Sampling

High volume water sampling has been used to detect very low levels of organic pollutants in rivers and other surface water bodies (Dinkins and Heath, 2002). The method is often used where the regulatory standard for a constituent such as dioxin [0.013 parts per quadrillion (ppq)] is significantly below the conventional aqueous phase detection limit. One thousand liters of water is filtered and pumped through a resin column. The adsorbed contaminants are measured in the laboratory and the resulting equivalent detection limit for dioxin is 0.001 ppq. This is the equivalent of 10^{-12} mg/L. Clearly the scope for concentrating spring water contaminants is significant. The method has the advantage that the 1,000 L can be collected over an extended period of time using automatic pumping equipment, thus creating a time weighted average sample.

The suite of parameters that can be effectively sampled using this method is not known. The reported dioxin test indicated that the resin selected was strongly hydrophobic and that it therefore attracted hydrophobic molecules. A possible negative factor is the cost of the sampling equipment, which is on the order of $20,000. However, given the likely expense of monitoring well construction, this may be cost effective. Further evaluation of this technology should be conducted.

7.3. *Parameters*

Monitoring systems for the two landfills will be used to measure the levels of leachate constituents in groundwater. As shown in this study, the number of parameters that would be detected in springs may be significantly different from that measured in wells. Spring monitoring is likely to involve a small sub-set of parameters because of the high DAFs that will render many low level parameters undetectable. A period of testing will be required to determine the optimum analytical suite for long term monitoring.

Based on the current understanding of leachate production at the site, the parameters that will be most representative of Visevac are the conventional landfill leachate suite (Tables 3, 4 and 5) together with VOCs. For Sovjak the monitoring parameters will include metals and semi-volatile organic compounds (Tables 6 and 7).

These lists should be refined based on the results of further leachate testing and a preliminary monitoring phase prior to starting a long term program.

7.4 *Leachate Monitoring*

Evaluation of potential leakage from the landfills may be possible by intercepting and sampling leachate in the unsaturated zone between the base of the landfill and the water table. This approach would not meet a strict definition of 'groundwater' monitoring, but as a direct measurement of actual leachate presence and quality could be a useful addition to the program if found to be technically feasible.

Unsaturated zone monitoring is usually undertaken in studies relating to agricultural soil science. During the early phases of hazardous waste regulation in the United States it was required as part of the monitoring system at oily waste land farms. Monitoring is generally undertaken in soils (as opposed to rock) to depths generally less than 10 m, and often less than 3 m. The possible extrapolation for application at Sovjak and Visevac should therefor be viewed as experimental.

7.4.1 General Methodology

Unsaturated zone soil moisture sampling is accomplished using a vacuum lysimeter that is carefully installed in the soil at the depth to be monitored. Application of a vacuum causes water trapped in the soil due to surface tension to be drawn towards the sampler. Entry to the sampler takes place through a ceramic or stainless steel membrane, and once inside the leachate is stored until removed during a sampling event. Collection of a sample can require application of vacuum from an hour under ideal conditions (moist clayey soil) to several days under less ideal conditions.

7.4.2 Potential Application

Installation of lysimeters beneath Visevac would be accomplished by drilling angle holes up to 150 m in length, and at Sovjak up to 60 m in length. Completion depths would be selected based on the frequency of fractures encountered. Insertion of the lysimeters will require careful placement of the appropriate bedding and covering materials. Vacuum is applied using a portable vacuum pump. Samples are pumped to the surface through tubing under pressure.

8. Reliability Analysis

In the course of this study, calculations have been made to support a leachate fate and transport analysis. It is clear that in many instances the input data are less than perfect. There is generally a range of values that could be applied for any particular parameter. The combined effect of these uncertainties might cast doubt on the utility of the end result if no further evaluation of their impact was attempted. In this section, a statistical evaluation of the uncertainties is made, and their cumulative impact on the end result is described. The analysis serves two purposes: it provides an estimate of the confidence in the results, and it also points to those variables that are introducing the greatest uncertainty. When the parameters are prioritized in this way, it focuses attention on those that can benefit the most from additional study.

8.1. Modeling

Cumulative uncertainties are difficult to model using simple analytical methods. The combination of two normally distributed parameters by multiplication, for example, results in an unmanageable array of data. The problem is solved using a method known as a Monte Carlo Simulation. This method randomly samples each variable within its specified distribution, and computes a result. The process is repeated many times until a set of results is obtained that is large enough to support traditional statistical methods. Using this array of outcomes, the probability of a given result can be assessed.

The method is computationally intense, as a large number of results is generally required in order to define their statistical distribution accurately. For this evaluation, a commercially available computer model known as Crystal Ball was employed. The model is powerful and flexible, allowing for a variety of statistical distributions of individual parameters and a large number of simulations.

8.2. Uncertainties

Each of the variables used in the analysis to compute DAFs can be assigned a level of precision and its variability described in terms of standard statistical parameters (mean, standard deviation etc.):

8.2.1. Visevac

Time

The time at which the DAF is being calculated is considered randomly variable between one and 365 days, with a uniform distribution.

Leachate Generation

Leachate production varies throughout the year as shown in Figure 2. The distribution is approximately sinusoidal with a mean value of 2.68 L/s and amplitude of 0.83 L/s. The mean value varies from year to year depending on precipitation in the previous year, and the variability is assumed to be normally distributed. Using HELP model output data, the standard deviation of this variability is 0.53 L/s. Similarly, the amplitude of the curve varies from year to year and the standard distribution of this parameter is 0.23 L/s. By incorporating these variables into the analysis, the model effectively accounts for the leachate generation rate that may occur on any particular day throughout the period of interest.

Groundwater Flow

Groundwater flow from the Sovjak/Visevac sub-basin varies significantly not only from year to year, but also from day to day. Calculation of the flow rate depends on the size attributed to the sub-basin and to the HELP model results for the climatic and sub-surface flow simulation. The size of the basin is estimated to range from 50 to 90 sq km with a most likely value of 63 sq km. This distribution is assumed to be triangular.

HELP model results show a high level of variability in the sub-basin flow rates (Figure 6). There is a seasonal bias, but the short-term fluctuations are more dominant. This flow regime can be described statistically as being log-normally distributed with a mean of 3,150 L/s and a standard deviation of 2,700 L/s.

Leachate Characteristics

The characteristics of the leachate have been described largely on the basis of published data and through evaluation of secondary parameters (landfill gas, solubility limits etc.) There is, therefore, a high level of uncertainty as to the actual concentrations of the various constituents. The data are generally assumed to be log-normally distributed, with the maximum concentration (Table 3) assigned as the 95 percentile value.

The attenuation factors are another area of considerable uncertainty and a simple triangular distribution is used based on an assessment of literature derived low, high and most likely values.

8.2.2. Sovjak

The general methodology is similar to that employed for Visevac, and in fact, the treatment of groundwater is identical. Leachate production shows quite a different pattern, and leachate characteristics are considered in a slightly different way.

Leachate Generation

The pattern of leachate generation from Sovjak is more similar to the sub-basin groundwater flow variability (Figure 3) than to the Visevac sinusoidal pattern. It has similarly been assigned a lognormal distribution with a mean of 0.293 L/s and an upper 99th percentile value of 26.3 L/s based on HELP model results. This parameter is correlated to precipitation, which in turn is correlated to groundwater flow. The leachate production rate has been correlated moderately with groundwater flow for purposes of this analysis.

Leachate Characteristics

The leachate concentrations provided in Table 7 are based on maximum aqueous solubility levels and therefore represent theoretical maximum values. The distribution of actual values is assumed lognormal with a mean of one third the maximum.

8.3. Results

The DAF calculation process was conducted using Crystal Ball for several specific scenarios:

1. Visevac - Acetone – No restriction on groundwater flow. This simulates analysis for acetone in a sample collected at random from a coastal spring.

2. Visevac - Acetone – Groundwater flow restricted to less than the mean. This simulates the same sample, but assumes it is only taken when groundwater flow conditions are below the mean.

3. Visevac - Acetone – Low flow conditions (less than 1,500 L/s sub-basin flow). The sampling is biased to a narrow range of low flow conditions at the spring.

4. Sovjak - Naphthalene – No restriction on groundwater flow.

5. Sovjak - Naphthalene – Groundwater flow restricted to less than the mean.

6. Sovjak – Naphthalene – Low flow conditions.

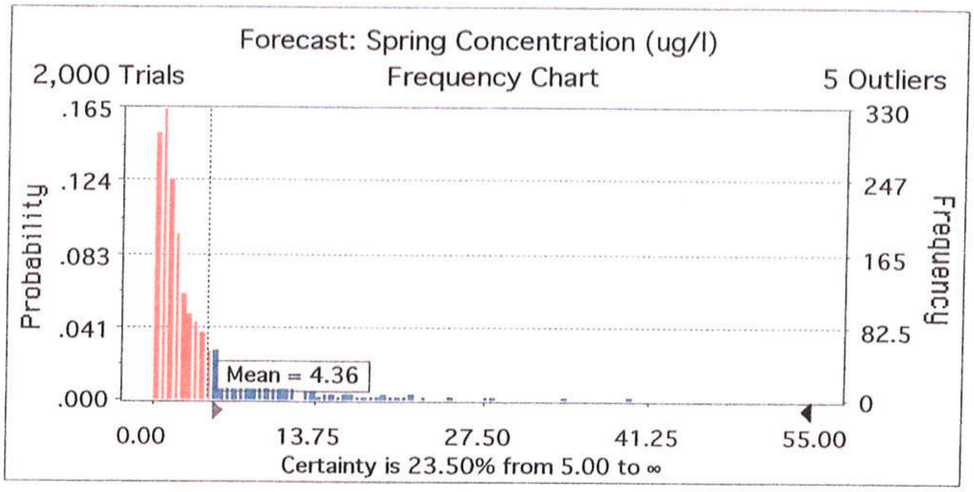
Output from the analysis shows the distribution of measured concentrations of the two parameters at the sampled spring (Figures 8 and 9). These charts indicate the mean of the anticipated results, and the likelihood of a detection in excess of 5 ug/L.

8.3.1. Visevac

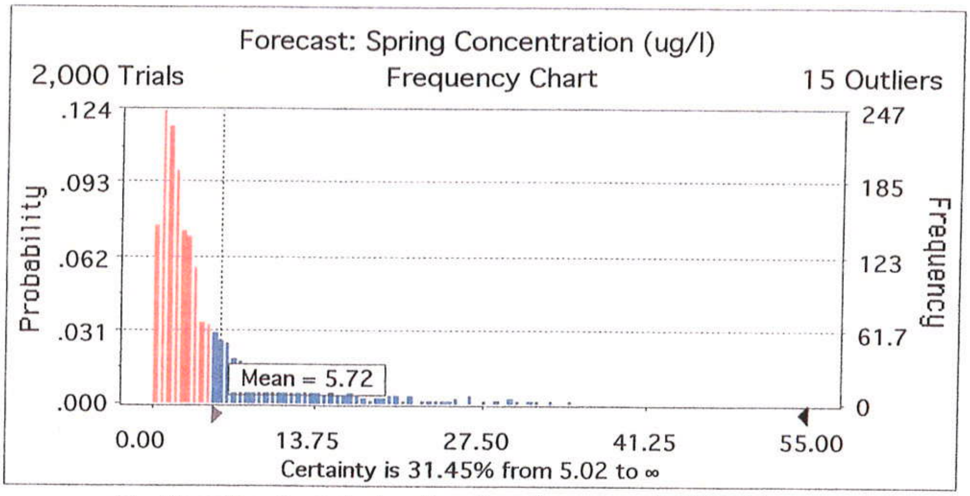
As would be expected, the measured concentrations are predicted to increase as the sub-basin groundwater flow at the time of sampling decreases. When a random sample is taken regardless of groundwater flow, the mean of the anticipated results is a little more than 4 ug/L. However there is less than a 25% chance that the result will be this high. Values less than 5 ug/L tend to be unreliable and the possibility of both false positives and false negatives rises steeply. It is noteworthy that some values as high as 30 or 40 ug/L may be measured, but these occurrences will be rare.

If the sample is taken when the flow in the sub-basin is less than the mean, the average result increases to about 6 ug/L. Not a significant increase from a detectability standpoint. The probability of a result in excess of 5 ug/L is about 31%.

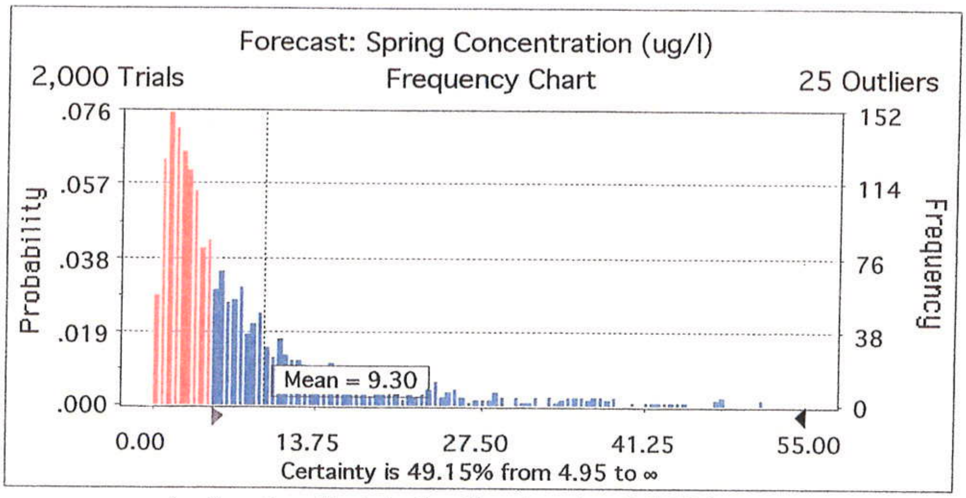
When the sampling is further restricted to low flow conditions (less than 1,500 L/s sub-basin flow) the mean result increases to 9 ug/L, and the probability of a value in excess of 5 ug/L rises to almost 50%. The number of results in the 15 to 40 ug/L range has increased significantly, and the likelihood of a reliable detection has increased significantly overall.



a) Sample not dependent on sub-basin groundwater flow

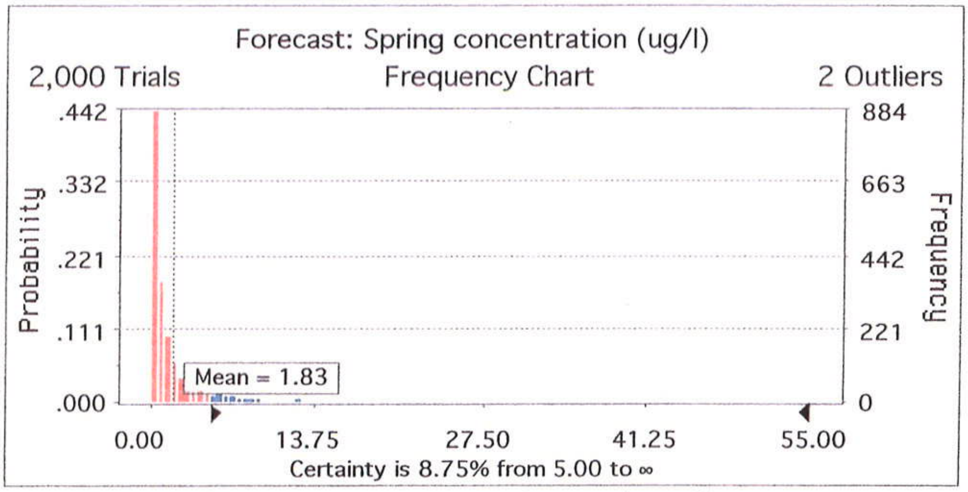


b) Sample collected when flow less than mean (3,150 L/s)

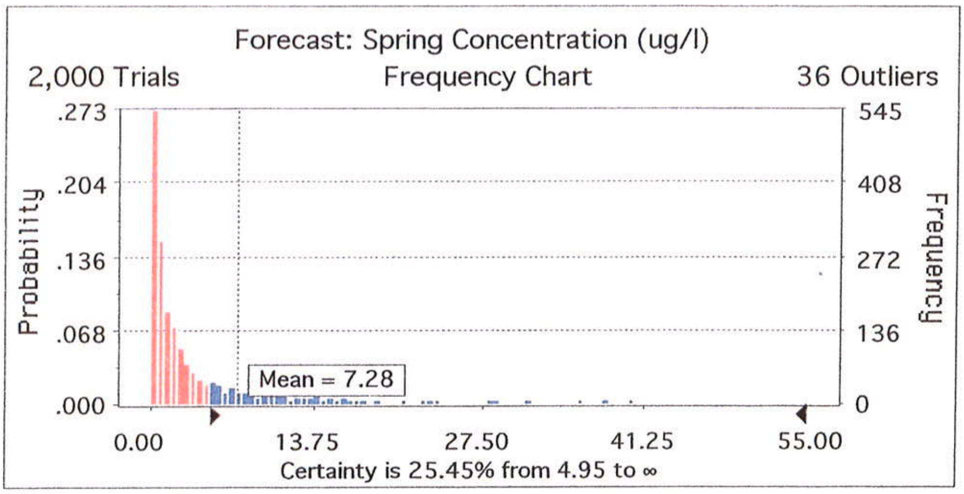


c) Sample collected when flow less than 1,500 L/s

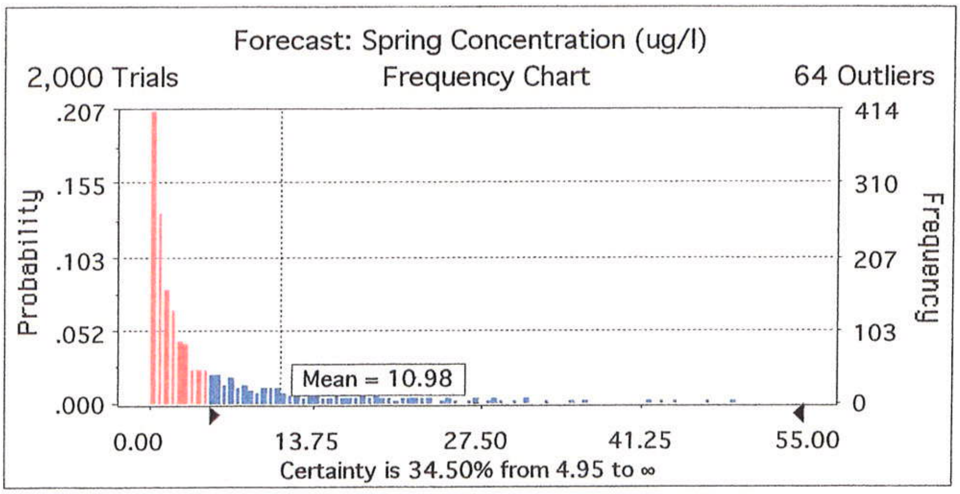
Figure 8. Visevac Sensitivity Analysis Results - Acetone



a) Sample not dependent on sub-basin groundwater flow



b) Sample collected when flow less than mean (3,150 L/s)



c) Sample collected when flow less than 1,500 L/s

Figure 9. Sovjak Sensitivity Analysis Results - Naphthalene

These results should be considered illustrative of the general trends that can be expected, and of the effects that widely variable and often unpredictable input variables can have. Acetone was selected as the test parameter because it appears to be present in the landfill gas at levels that support high leachate concentrations. Realistically, any one of several VOCs could become a strong indicator of a release.

8.3.2. Sovjak

The results parallel those from Visevac – as the sub-basin flow decreases, a sample taken at the coastal spring is more likely to detect a release.

The concentration in a random sample is likely to be less than 2 ug/L on average, which would not form the basis for a reliable detection system. The likelihood of a result in excess of 5 ug/L is less than 10%.

If the sample is taken at or below mean flow, the detectability increases markedly to an average of 7 ug/L. The probability of a detection greater than 5 ug/L rises to 25% and occasional values in the range 10 to 20 ug/L can be expected.

At low flow, the sample shows an average result of 11 ug/L and the likelihood of 5-ug/L detection rises to 34%.

Naphthalene was selected as the Sovjak indicator contaminant because it is the most soluble of the semi-volatile organic compounds (SVOCs) detected in the waste mass. Several of the other compounds are only slightly soluble and so the number of potential indicator chemicals is quite limited.

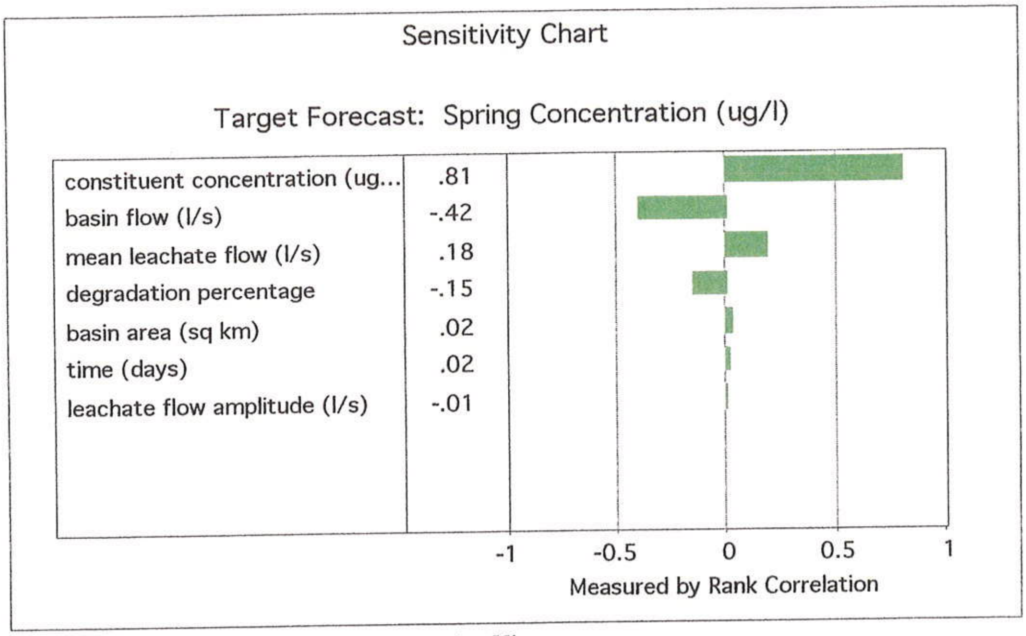
8.3.3. Sensitivity

Crystal Ball also provides information on the relative importance of each input parameter to the variability of the final result. Some inputs, because there is a high level of uncertainty, cause a wide array of possible outcomes. Others which may have the same uncertainty, but which have a subordinate role in the calculations, may be less important. Figure 10 shows the results of a sensitivity analysis for both landfills.

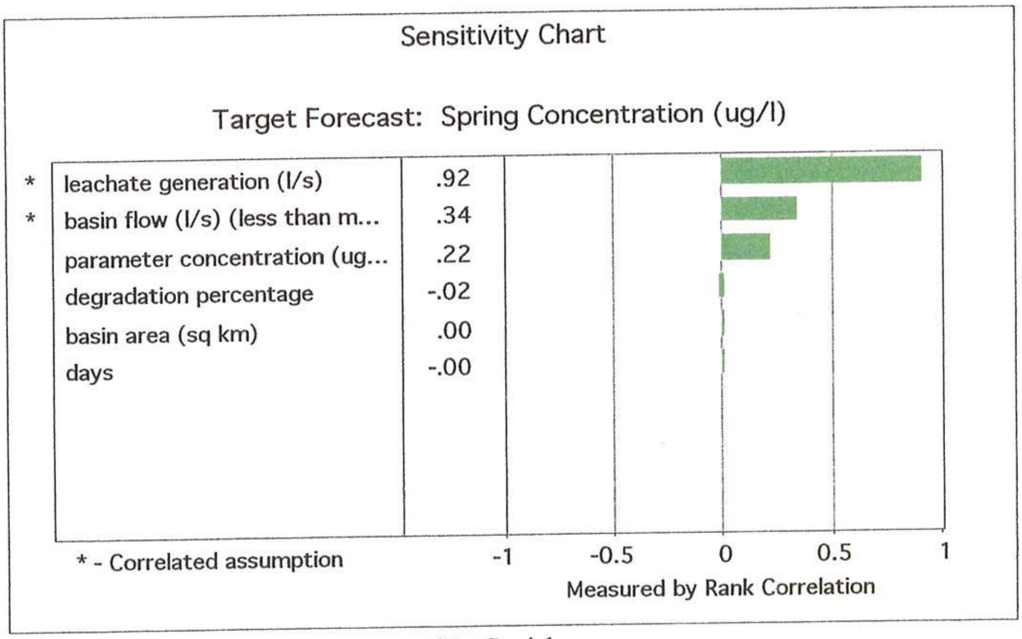
At Visevac, the variable with the greatest effect is the constituent concentration. This parameter has a high level of uncertainty, because there are no measured values, and no method to make more accurate predictions. Also, the concentration of acetone in the landfill leachate is probably quite variable. The next most important variable is the sub-basin groundwater flow. This is wildly variable, but relatively unpredictable on a day to day basis. The leachate generation flow rate and the degradability of the leachate parameter are about equal in importance, and other parameters are, by comparison, not defined satisfactorily.

For Sovjak, the situation is a little different; the leachate generation rate is the most influential parameter. Like the groundwater flow regime, it is unpredictable in the short term. Sub-basin flow and parameter concentration are roughly equal in importance, and others are of little consequence.

The results of the sensitivity analysis point to variables that must be refined if the precision of the overall results is to be improved. In this case, the opportunities for improving predictions are limited. The natural process driving leachate production – precipitation – will continue to be unpredictable in the short term regardless of additional study. The composition profile of the leachate could be refined with a modest effort and would improve the overall quality of the results significantly.



a) Visevac



b) Sovjak

Figure 10. Parameter Sensitivity Analysis Results

9. Conclusions And Recommendations

Based on the results of this study, neither conventional monitoring wells nor coastal springs can be ruled out as potentially feasible methods of monitoring the closed and remediated landfills Visevac and Sovjak. However, it is clear that both methods may be so seriously constrained that their technical feasibility would ultimately be rejected. In the following discussion, the positive and negative attributes of each system are summarized. Additional studies that are necessary before a final decision on monitoring system design can be made are then described.

9.1. Conventional Monitoring Wells

9.1.1. Advantages

- Wells may provide access to samples that are precisely located upgradient and downgradient of the landfills. Comparison of upgradient and downgradient sample results allows for the assessment of landfill derived impacts, without the potential for interference from other sources of pollution.

- Well samples taken near the landfills monitor worst case conditions in the aquifer with minimum downgradient dilution effects, and therefore provide the most sensitive monitoring locations.

- Technology for installation and monitoring groundwater using wells is mature, although the unique circumstances of depth and geology at the landfill site will present major challenges.

- Wells are required by Croatian regulations.

9.1.2. Weaknesses

- Geological conditions at the site create unique challenges for the installation of a high quality monitoring well based system. Karst geology introduces uncertainties in:

  - ability to encounter groundwater; dry holes are not uncommon in this geology
  - leachate migration patterns; migration to the north may confuse upgradient quality measurements, and southerly pathways could bypass downgradient wells leading to false negatives.

- Topographic conditions are such that the wells will inevitably be very deep; at 300 m, these will be some of the deepest groundwater monitoring wells in the world at a landfill site. This depth will result in unit installation costs that are much higher than those normally experienced at landfills.

- Well depth will complicate the collection of high quality groundwater samples and require the use of sophisticated and high cost sampling pumps. These pumps may have to be custom built for the site.

9.2. *Springs*

9.2.1. Advantages

- Springs may provide a valuable source of samples to monitor releases from the landfills. Groundwater impacts that are not detectable in conventional wells may be measured at springs.
- Capital costs for equipment are likely to be relatively low.
- Concentrating sampler technology may be available to improve detection limits.

9.2.2. Weaknesses

- Dilution and attenuation effects between the landfills and the coast create uncertainties as to whether pollutant releases will be detectable in spring water. Modeling results suggest that some pollutants will be detectable during low flow periods, but they may be so low as to be unreliable.
- There is no surface source of upgradient water quality against which to compare results. An upgradient monitoring well would be required to serve this purpose.
- Concentrating sampler technology is not mature.

- If releases from the landfills pre-closure (assumed worst case) can not be reliably detected, any smaller (anticipated) post closure releases will not be detectable.

9.3 *Leachate Monitoring*

9.3.1 Advantages

The advantages of such a system would be:

- Less drilling required than for the installation of monitoring wells
- Direct measurement of landfill leakage with reduced potential for false positives or negatives.
- Sampling equipment is relatively inexpensive.

9.3.2 Disadvantages

- Installation requires drilling fairly long (deep) angle holes
- Proper bedding and installation of the samplers may be difficult at these depths
- Equipment maintenance is difficult – samplers can not be removed easily once installed
- Unproven technology for unsaturated zone monitoring in fractured rock
- Unproven technology for unsaturated zone monitoring in fractured rock

9.4 *Recommendations*

Without further study it will not be possible to make an informed decision on the design of the monitoring system. Results of DAF modeling are too marginal for spring monitoring to be accepted or rejected at this time. Given the magnitude of the uncertainties in the analysis, actual field conditions could vary enough for there to be substantially higher results than the average levels predicted. Field testing will be required to reduce the uncertainty.

Installation of monitoring wells and pumping equipment can be attempted at any time. However, there are some preliminary field based activities that should be implemented before proceeding with full-scale installation.

Recommended additional testing consists of five main tasks:

Leachate Characterization

Leachate sampling at both Visevac and Sovjak will provide better information on both the type and concentration of contaminants in the leachates. Samples from Visevac may be collected from one of the several leachate breakouts that occur following rainfall. At a minimum, composite samples from several locations would give a reasonable picture. Sampling of the leachate from deep within the landfill using a boring into the waste would produce a more representative picture. A sample of water from Sovjak will be representative of most of the leachate. Releases caused by the consolidation of the sludge would be more difficult to sample, and are probably relatively small compared to the aqueous phase.

Geologic Mapping

An investigation of the site geology should be undertaken before final planning of the monitoring well system. Site mapping based on outcrops in the adjacent sinkholes should provide the information required to correlate the site conditions with regional structure. Cistoca will then be in a better position to anticipate the conditions that are likely to occur 250 – 350 m below the surface. Stratigraphic data from the pilot well will be valuable in interpreting subsurface conditions across the site.

Pilot Well Installation

A single, small-diameter core boring should be drilled to a depth of 320 m. This boring will be used to assess conditions at depth such as rock structure, lithology, depth to groundwater and possibly recovery of a groundwater sample for preliminary testing. The information from this boring should improve the design of the monitoring well system significantly. The borehole may also be used as a dye injection point for a tracer study.

Dye Tracer Study

In order to assign coastal springs for landfill monitoring, it will be necessary to establish a positive hydraulic connection between the site and the selected spring(s). Evidence to date based on nearby tracer studies strongly supports the notion that the landfills drain to springs Cerovica and Pod Jelsun, however the connections must be established positively prior to establishing them as monitoring locations.

Spring Sampling

The springs that are most likely to receive groundwater derived from the landfill sites should be tested for leachate constituents. Testing should be planned for the lowest practical sub-basin groundwater flow conditions so that the likelihood of detecting contaminants is maximized. If there is no evidence what so ever of landfill related constituents, it will be fair to conclude that the springs are extremely unlikely to have future role in the landfill monitoring system.

Once the results of these tests are known, it will be appropriate to proceed with the design of the monitoring system. Additional study of the possible use of concentrating samplers will be required if the springs are included in the system. Similarly, some ongoing flow monitoring will be required at the spring(s) to develop a protocol for scheduling samples.

References

Abrancovic D., P. C. Johnson, R. J. Charbeneau, and T. J. Hemstreet. 2001. A Graphical Approach for Determining Dilution-Attenuation Factors: Basic Theory and Approach for Submerged Sources. Ground Water Monitoring & Remediation. Volume 21. No. 1. pp. 115-124.

Alfirevic, S. 1979. Investigations of Underground Waters on the Sea Bed Along the Eastern Adriatic Coast. Selected Water Problems In Islands and Coastal Areas. Economic Commission for Europe.

American Society for Testing Materials. 1995. Standard Guide for Design of Ground-Water Monitoring Systems in Karst and Fractured-Rock Aquifers. Designation: D5717-95.

American Society of Testing and Materials. 1996. Provisional Standard Guide for Developing Appropriate Statistical Approaches for Ground-Water Detection Monitoring Programs. Designation: PS 64-96.

Biondic, B., F. Dukaric, M. Kuhta and R. Biondic. 1997. Hydrogeological Exploration of the Fjecina River Spring in the Dinaric Karst. Paper Presented at the Scientific Meeting Dedicated to the 80th Anniversary of the Life of Professor Milan Herak held on March 5th, 1997 in Zagreb. pp. 279-288.

Biondic. B. and V. Goatti. 1986. Protection of Ground Water in Karst Areas of Croatian Littoral. 19th Congress of The International Association of Hydrogeologists. Karlovy Vary 8.-15.9. 1986. Czechoslovakia.

Bonacci O. and T. R. Bonacci. 2000. Interpretation of groundwater level monitoring results in karst aquifers: examples from the Dinaric karst. Hydrological Processes. Voume 14. Issue No. 14. pp. 2423-2438.

Bonacci, O. 1993. Karst springs hydrographs as indicators of karst aquifers. Hydrological Sciences Journal. Vollume 38, Number 1. pp. 51-61.

Bonacci, Ognjen and A. Magdalenic. 1993. The Catchment Area of the Sv. Ivan Karst Spring in Istria (Croatia). Association of Ground Water Scientists & Engineers. Volume 31, Number 5, Pages 767-773.

Dames & Moore and Ecoina. 1998. Feasibility Study Remediation of Active Municipal Waste Landfill Visevac and Closed Hazardous Waste Landfill Sovjak.

Department of the Army, U.S. Army Corps of Engineers. 1995. Landfill Off-Gas Collection and Treatment Systems. 17 April 1995. Technical Letter No. 1110-1-160.

Dinkins, S. A. and J. P. Heath. Quantification of Dioxin Concentrations in the Ohio River Using High Volume Water Sampling. Ohio River Valley Water Sanitation Commission (ORSANCO). Online. 26 February 2002.

Ekonerg Holding. 2001. Konacna Studija O Utjecaju Na Okolis Gradevine Za Skladistenje, Obradu I Odlaganje Komunalnoga I Neopasnog Tehnoloskog Otpada S Podrucja Primorsko-Goranske Zupanije. Zagreb.

EUR-Lex. 2002. Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. The Council of the European Union. Official Journal of the European Communities L182. Online. http://europa.eu.int/eur-lex/en/index.html 18 March 2002.

Gabrovsek, F. 2000. Evolution of Early Karst Aquifers: From simple principles to complex models. Institut za raziskovanje drasa ZRC SAZU, Zalozba ZRC.

Grandic S., E. Boromisa-Balas and M. Sustercic. Exploration concept and characteristic of the Dinarides stratigraphic and structural model in the Croatian offshore area. Nafta. April 1997. Year 48. Volume 4.

Kentucky Legislature. 2001. Kentucky Adminstrative Regulations (KAR). Title 401 Natural Resources and Environmental Protection Cabninet Department of Environmental Protection Chapter 48:300 Surface and groundwater monitoring and corrective action. Online http://www.lrc.state.ky.us/regulations/401/048/3000.htm 7 December 2001.

Masciopinto, C. and C. Carrieri. 2002. Assessment of Water Quality After 10 Years of Reclaimed Water Injection: The Nardo Fractured Aquifer (Southern Italy). Ground Water Monitoring & Remediation. Volume 22. No. 1. pp. 88-97.

Mijatovic, B. F. 1984. Hydrogeology of the Dinaric Karst. International Contributions to Hydrogeology. Volume 4. pp. 55-73 and 115-142.

Prosser, R. and A. Janechek. 1995. Landfill Gas and Groundwater Contamination. Landfill Closures Environmental Protection and Land Recovery Proceedings of Sessions, October 23-27, 1995. American Society of Civil Engineers. Geotechnical Special Publication No. 53.

Reinhart D. R. and A. B. Al-Yousfi. 1995. The Impact of Full-Scale Leachate Recirculation on Leachate and Gas Characteristics. Innovative Technologies for Site

Remediation and Hazardous Waste Management. Proceedings of The National Conference. American Society of Civil Engineers. New York, New York.

Rochem Separation Systems, Inc., 1998. Disc Tube Model Technology. US EPA, EPA/54 0/R-96/507a. April 1998.

Sander, R. 1999. Compilation of Henry's Law Constants for Inorganic and Organic Species of Potential Importance in Environmental Chemistry. Version 3. Air Chemistry Department. Mainz, Germany.

Schroeder, P. R., T. S. Dozier, P. A. Zappi, B. M. McEnroe, J. W. Sjostrom and R. L. Peyton, 1994. The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3. EPA/600/R-94/168b, September 1994. U.S. Environmental Protection Agency Office of Research and Development, Washington, D.C.

SRC, 2001. CHEMFATE Search Results. Syracuse Research Corporation (SRC). Online. http://esc.syrres.com/scripts/CHFcgi.exe. March 23, 2002.

Stojic P., M. Milicevic, and P. Milanovic. 1976. Use of Piezometers Boreholes For Karst Investigations. Karst Hydrology and Water Resources. Volume 1. Karst Hydrology. Water Resouces Publications. Ann Arbor, Michigan. pp. 19-1-19-10.

U.S. Environmental Protection Agency. February 1999. The QTRACER Program for Tracer-Breakthrough Curve Analysis for Karst and Fractured-Rock Aquifers. National Center for Environmental Assessment -Washington. EPA/600/R-98/156a.

U.S. Environmental Protection Agency. Part 40 of the Code of Regulations. 264.97 General ground-water monitoring requirements. 264.98 Detection monitoring program.

Vesper D. J., J. E. Rice, and R. Efenstermacher. 1999. Use of GORE-SORBER® modules to screen for organic contaminants in karst springs. Hydrogeology and Engineering Geology of Sinkholes and Karst. Pettit & Herring, Balkema, Rotterdam. ISBN 90 5809 046 9. pp. 351-355.

WorldClimate. 2002. Average Maximum and Mimimum Temperature Rijeka/Omisalj. Online. http://www.worldclimate.com 18 March 2002.

Xie, F. and C. Zeiss. 1995. Assessing Mobility of Household Organic Hazardous Chemicals in Landfill. Innovative Technologies For Site Remediation and Hazardous Waste Management. Proceedings of the National Conference. American Society of Engineers. New York, New York.

APPENDIX

VITA

NICHOLAS C. CRAWFORD

POSITIONS:

President of Crawford and Associates, Inc.
480 Peachtree Lane
Bowling Green, KY 42103
Office phone 270-745-9224
Email: canda@premiernet.net
World Wide Web: http://www.dyetracing.com

Professor and Director of the Center for Cave and Karst Studies
Department of Geography and Geology
Western Kentucky University
Bowling Green, Kentucky 42101
Office phone 270-745-9224
Home phone 270-843-4979

SPECIALTY:

Hydrology, Karst Hydrogeology, Groundwater

DATE OF BIRTH:

June 2, 1942

EDUCATION:

Tennessee Technological University	B.S. 1965
East Tennessee State University	M.A. 1967
Clark University, Worcester, MA	Ph.D. 1978

Dissertation: Subterranean Stream Invasion, Conduit Cavern Development and Slope Retreat: A Surface-Subsurface Erosion Model for Areas of Carbonate Rock Overlain by Less Soluble and Less Permeable Caprock.

ACADEMIC EXPERIENCE:

1967-68 Austin Peay State University (Instructor)
1968-70 Peabody College (Instructor)
1972-76 Peabody College (Assistant Professor)
1972-76 Vanderbilt University (Assistant Professor)
1976-79 Western Kentucky University (Assistant Professor)
1979-82 Western Kentucky University (Associate Professor)
1982-present Western Kentucky University (Professor)

REGISTRATION:

- Certified Professional Geologist KY-1564
  TN-3780

RESEARCH INTERESTS:

Groundwater Hydrology
Karst Hydrogeology
Karst Hydrologic Problems
Groundwater Pollution
Sinkhole Flooding
Sinkhole Collapse

PROFESSIONAL AFFILIATIONS:

Member, Cave Research Foundation
Honorary Life Member, National Speleological Society
Member, Geological Society of America
Member, Association of American Geographers
Member, Sigma Xi, The Scientific Research Society
Member, Phi Kappa Phi, National Honor Society
Member, International Association of Hydrogeologists
Member, Kentucky Water Well Association
Member, Kentucky Academy of Science
Member, Association of Ground Water Scientists and Engineers,
National Water Well Association
Member, Kentucky Society of Professional Geologist

HONORS AND AWARDS:

1982 Elected to Membership in Cave Research Foundation for contributions in karst education and research.

1982 One of thirteen speakers selected to present a paper at a national conference on Groundwater as a Geomorphic Agent, Thirteenth Annual Geomorphology Symposium, Troy, New York.

1984 Associate Editor of Stygologia: international journal of basic and applied groundwater research

1984 Certificate Merit in the National Speleological Society.

1984 Recognized for Public Service by the Faculty Senate of Western Kentucky University as follows:
The Western Kentucky University Faculty Senate recognizes Dr. Nick Crawford from the Department of Geography and Geology for exemplary public service. Without his persistent and selfless efforts, a potentially toxic and explosive situation in the Forest Park neighborhood likely would have been ignored by the appropriate government agencies, with possibly tragic consequences. His actions represent the highest standards of professional responsibility and concern for the public welfare.

1984 Paper entitled "Toxic and explosive *fumes rising* from carbonate aquifers: *a hazard for residents of* sinkhole plains" was selected as one of the six best papers presented at the First Multidisciplinary Conference on Sinkholes, Orlando, Florida.

1985 Received the Western Kentucky University Faculty Excellence Award for Outstanding Achievement in Research.

1985 *Elected Fellow of the National Speleological Society.*

1986 Elected to Faculty Membership in Phi Kappa Phi, National Honor Society.

1986 One of five speakers selected to present a paper at a session on Groundwater Pollution in Karst Terrain at the American Association for the Advancement of Science annual meeting, Philadelphia, Pennsylvania.

1988 Selected by *Garden Clubs of Kentucky as their nominee for the Gold Seal Award of the National* Council of State Garden Clubs. The emphasis of the National Council of State Garden Clubs for this year was the environment, with a particular focus on groundwater protection. Only one Gold Seal Award is awarded each year from the state nominees. 1989 Awarded the Environmental Enrichment Award for efforts to protect groundwater by the Garden Clubs of Kentucky at annual meeting at Cumberland Falls State Park, April 12, 1989.

1989 Recognized for academic accomplishments by an introduction by President Meredith to Western Kentucky University Board Regents, April 27, 1989.

1990 Received the Silver Seal Award for work in protecting groundwater by the National Council of State Garden Clubs. One of four national medal recipients honored at an Awards Banquet in Seattle, Washington, May 18, 1990.

1990 One of three scientists invited to present his research at the New Concepts in Geology Conference, sponsored by the Kentucky Geological Survey and the University of Kentucky Geology Department, Lexington, Kentucky, April 21, 1990.

1992 Quoted in an article on caves, "Subterranean Secrets," in *Time* Magazine, November 30, 1992, about groundwater contamination potential of karst aquifers.

1994 Honorary Life Membership Award, awarded by the National Speleological Society at the National Convention in Brackettsville, Texas, June 24, 1994. This is the highest award given by the NSS with only one awarded each year.

1994 Certificate of Merit awarded by the National Speleological Society at the National Convention in Brackettsville, Texas, June 24, 1994.

1995 Keynote Speaker at Site Investigations: Geotechnical and Environmental, Twenty-Sixth Ohio River Valley Soils Seminar, Clarksville, Indiana, October 20, 1995.

1996 Quoted with photograph in an article, "Our Polluted Runoff," in National Geographic Magazine, February, 1996.

1997 Featured with Photograph in an article about Dr. Crawford and the Center for Cave and Karst Studies, which he founded, in The Chronicle of Higher Education, February 14, 1997

1998 *Outstanding Kentucky Geologist Award for 1998 presented by American Institute of Professional* Geologist, Kentucky Chapter at Annual Banquet in Owensboro, Kentucky May 20, 1998.

PUBLICATIONS AND PROFESSIONAL REPORTS:

1975 Investigation of precipitation and drainage conditions at Tennessee Valley Authority Gas Turbine Generating Facility, Gallatin Site, September, 1974, through March, 1975, for Westinghouse Electric Corporation Gas Turbine Systems Division, 54 p.

1975 Investigation of the hydrogeology of Lost Cove, Franklin County, Tennessee, for J.R. Wauford and Company Consulting Engineers, 37 p.

1977 Participated in preparing a report: Community flood damage abatement program study for the Barren River Area Development District: for BRADD, 120 p.

1978 The Mill Cave Drainage System: Speleonews, (December), p. 72-86.

1978 Doctoral dissertation: Subterranean stream invasion, conduit cavern development and slope retreat: a surface-subsurface erosion model for areas of carbonate rock overlain by less soluble and less permeable caprock, 451 p.

1979 Karst hydrogeology of the Cumberland Plateau Escarpment in the Lost Creek Cove and Grassy Cove areas of Tennessee: Safford Centennial Society (Tennessee Professional Geologists) Field Trip Guidebook, 49 p.

1979 Grider Pond - Cave Mill Road interceptor project phase II: dye tracing of septic tanks be believed to be contributing to the impairment in water quality of the Lost River in Bowling Green, Kentucky: for G. Reynolds Watkins Consulting Engineers, 19 p.

1979 The Karst Hydrogeology of the Cumberland Plateau Escarpment of Tennessee, Part I: Subterranean Stream Invasion, Conduit Cavern Development and Slope Retreat in the Lost Creek Cove Area, White County, Tennessee, Cave and Karst Studies, Series No. 1, Center for Cave and Karst Studies for Department of Geography and Geology, Western Kentucky University, Bowling Green, Kentucky, 75 p.

1979 The Karst Hydrogeology of the Cumberland Plateau Escarpment of Tennessee Part II: Karst Valley Development and the Headward Advance of the Sequatchie Valley in the Grassy Cave Area, Cumberland County, Tennessee, Cave and Karst Studies Series No. 2, Center for Cave and Karst Studies, Department of Geography and Geology, Western Kentucky University, Bowling Green, Kentucky, 50 p.

1996 The Karst Hydrogeology of the Cumberland Plateau Escarpment of Tennessee: Erosional Processes Associated with Subterranean Stream Invasion and Conduit Cavern Development in White, Cumberland, and Franklin Counties. Tennessee Division of geology Report of Investigations, No.44, Part IV, 142p.

1996 *Crawford, N. C. and S. Capps, "Groundwater Flow in the Vicinity of Country Crossroads Store,* Franklin Crossroads, Hardin County, Kentucky", prepared for Protec Environmental Management, Inc., July 2, 1996.

1996 "Laboratory Report for Texas-Eastern Gladeville, Tennessee Dye Tracer Study", Vols. 1-2, prepared for S. S. Papadopulos and Associates, Inc., July 7, 1996.

1996 "Microgravity Subsurface Investigation, RAD Chemical Site, Bowling Green, Kentucky", prepared for Fuller, Mossbarger, Scott, and May Engineers, August 9, 1996.

1996 "Tracer Study Data Analysis: Mealer's Phillips 66, Lweisburg, Tennessee", prepared for Petrotec, Inc., August 23, 1996.

1997 "Dye Tracer Investigation of Groundwater Flow in the Vicinity of the Bill Branch Coal Company Maine Number 3, McDowell, Floyd County, Kentucky", prepared for PRC Environment Management, November, 1997.

1997 "Karst Investigation Technical Report, Stauffer Chemical Company Complex, Maury County, Tennessee, TDSF #60-501", prepared for Zeneca, Inc., August 1997.

1997 "Dye Trace Study of Mystery Falls Cave, Chattanooga, Tennessee", prepared for Colonial Pipeline, October 1997.

1997 "Groundwater Flow in the vicinity of the Former Langley Quarry Site, Near Elizabethtown, Kentucky", prepared for Environmental Resources Management", August 21, 1997.

1997 "Dye Trace Study of Groundwater Flow in the Vicinity of an Oil Pipeline Leak near Murfreesboro, Tennessee", prepared for Colonial Pipeline, September 1997.

1997 Dye Tracer Study Report of Veliscol Chemical Company, Chattanooga, Tennessee", prepared for Veliscol Chemical Company, April 20, 1997.

1997 "Dye Tracer Investigation of Groundwater Flow at Vulcan Materials Quarry, Chattanooga Tennessee", prepared for Hardin, Lawson and Associates, Inc., October 1997.

1998 (with Clauson, Will) "Dye Tracer Study of underfloor sewer system, at Raytheon Company, Bristol, TN." Prepared for Conestoga-Ratheon Company, May, 1998.

1998 (With Clauson, Will) "Dye Tracer Study of the Mallory Capacitor Company Site, Waynesboro, Tn., prepared for Conestoga-Rovers Associates, Inc., September, 1998.

1998 (with Tucker, Richard B.) "Groundwater Flow in the Vicinity of the Fastway # 7 Gas Station, Leitchfield, KY, " prepared for ECM, Inc. January 26, 1998.

1998 `(with Clauson, Will) "Dye tracer study of groundwater flow in the vicinity of an oil Pipeline leak near Murfreesboro, TN," prepared for Colonial Pipeline Company, March, 1998.

1998 "Surface and Subsurface Flow of the Overall Creek Karst Drainage Basin, Rutherford County, Tennessee: Hydrogeologic investigation of Tennessee's proposed site for the Superconducting Supercollider, Guidebook prepared for Karst hydrogeology Workshop, Murfreesboro, Tennessee. Sponsored by Center for Cave and Karst Studies, U.S. Environmental Protection Agency and Tennessee Department of Environment and Conservation, March 18-19, 1998.

1998 "Southern Kentucky Regional Airpark, Site evaluation and marketing strategy study," contributing author on *Potential Environmental Impacts*, prepared for HNTB, Inc., August, 1998.

1998 "Leakage and Sinkhole collapse under Hog Waste Lagoons in Kentucky," prepared for Sierra Club, Hank Graddy, September, 1998.

1998 "Karst Environmental Problems and Solutions, Southcentral Kentucky," Guidebook for Joint Meeting of Friends of Karst and the International Geological Correlation Program, Project #379: Karst Processes and the Global Carbon Cycle, sponsored by Center for Cave and Karst Studies, and *Mammoth Cave National Park, Bowling Green, KY., September 23-25, 1998.*

1998 (with Kerpan, Andrei) "Phase I Karst Groundwater Investigation of the Glasgow Regional Landfill, Glasgow, KY," prepared for Rhodes, Inc., May, 1998.

1998 (with Kerpan, Andrei) "Dye trace investigation of Groundwater flow in the vicinity of the Outokumpu Copper Facility, Simpson County, KY," prepared for Camp, Dresser and McKee, Inc. August, 1998.

1998 (with Kerpan, Andrei) "Dye tracer Study of Groundwater flow in the Vicinity of the Glasgow Regional Landfill, Phase II Expansion, Glasgow, Barren County, Kentucky," prepared for Rhodes, Inc., September, 1998.

1998 (with Lewis, Michael) "Microgravity Subsurface Investigation at Flying J Truck Stop, July 28, 1998.

1999 Crawford, N.C. (1999) Lost River Cave and Valley Tour; Field Trip to Observe Onsite Wastewater Treatment and other Groundwater Contamination Problems Associated with Karst Aquifers, guidebook for National Environmental Health Association Onsite Wastewater System Conference, Nashville, Tennessee, July 6-7, 1999.

1999 Crawford, N.C., (1999) Groundwater Basin Delineation and Site Conceptual Hydrogeologic Model for Sadd-Trousdale Superfund Site, CSX-Radnor Yard Site and General Electric Service Facility Site in Nashville, Tennessee, April 12-14, 1999.

1999 Crawford, N.C., Lewis, M.A., Winter, S.A. and J.A. Webster (1999) Microgravity Techniques for Subsurface Investigation of Sinkhole Collapses and for Detection of Groundwater Flow Paths Through Karst Aquifers; in Beck, Pettit and Herring (eds) Hydrology and Engineering Geology of Sinkholes and Karst, Balkema, Rotterdam, ISBN 9058090469, pp 203.

1999 Crawford, N.C., (ed) Karst Environmental Issues Manual, prepared for Karst Environmental Issues *Seminar, sponsored by Science Applications International Corporation,* Oak Ridge, Tennessee, March 15, 1999.

1999 Tucker R.B. and N.C. Crawford (1999) Non-linear Curve Fitting Analysis as a Tool for Identifying and Quantifying Multiple Fluorescence Tracer Dyes Present in Samples Analyzed with a Spectrofluorophotometer and Collected as Part of a Dye Tracer Study of Groundwater Flow; in Beck, *Pettit and Herring (eds) Hydrogeology and Engineering Geology of sinkholes and Karst,* Balkema, Rotterdam, ISBN 9058090469, pp 307.

1999 Crawford, N.C. (1999), Phase I Karst Groundwater Investigation of the Proposed Florida Rock Quarry, Floyd County, Georgia, prepared for the County Manager, Floyd County and Florida Rock Industries, Inc., June, 1999.

1999 Lewis, M.A., Clauson, W. and N.C. Crawford (1999) Microgravity Subsurface Investigation, Lone Star Gas Pipeline Segments B and C, Austin, Texas, prepared for PBS & J, Dallas, Texas, July 28, 1999.

1999 Clauson, W. and N.C. Crawford (1999), Groundwater Basin Delineation of White Mills Spring, Hardin County, Kentucky, prepared for Hardin County Water District #2, April, 1999.

1999 Kerpan, A. and N.C. Crawford (1999) Dye Tracer Study of Groundwater Flow in the Vicinity of the Glasgow Regional Landfill, Barren County, Kentucky, prepared for Rhodes Incorporated, December, 1999.

1999 Lewis, M.A. and N.C. Crawford (1999) Microgravity Subsurface Investigation, Lone Star Gas Pipeline, Austin, Texas, January 13, 1999.

1999 Lewis, M.A. and N.C. Crawford (1999) Microgravity Subsurface Investigation: George C. Marshall Space Flight Center, Building 4663, Huntsville, Alabama, prepared for QORE Property Sciences, April 13, 1999.

1999 "Groundwater Basin Delineation and Site Conceptual Hydrogeologic Model for Sadd-Trousdale Superfund Site, CSX Radnor Yard Site and General Electric Service Facility Site in Nashville, Tennessee", Tennessee Water Resources Symposium, Nashville, Tennessee, April 12-14, 1999.

1999 "Microgravity Techniques for Subsurface Investigations of Sinkhole Collapses and for Detection of Groundwater Flow Paths Through Karst Aquifers" (with M.A. Lewis, S.A Winter and J.A. Webster), Seventh Multidisciplinary Conference on Sinkholes and he Engineering and Environmental Impacts of Karst, Harrisburg-Hershey, Pennsylvania, April 10-14, 1999.

1999 "Non-linear Curve Fitting Analysis as a Tool for Identifying and Quantifying Multiple Flourescence Tracer Dyes Present in Samples Analyzed with a Spectrofluorophotometer and collected as Part of a Dye Tracer Study of Groundwater Flow" (with R.B. Tucker), Seventh Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Harrisburg – Hershey, Pennsylvania, April 10-14, 1999.

1999 "Environmental Problems in Karst" (banquet speaker), Minnesota Karst Workshop, presented by the Minnesota Pollution Control agency and the Minnesota Department of Natural Resources, Rochester, Minnesota, May 11, 1999

CORPORATE EXPERIENCE

Crawford and Associates (1975-2001) and the new Crawford Hydrology Laboratory have probably had more experience in dye-tracing groundwater flow at industrial sites than any other organizations in the world. Many of the karst hydrology investigations performed by Crawford and Associates and by the Crawford Hydrology Laboratory have been for clients under legal orders with strict regulatory scrutiny by a state environmental agency or the US EPA. Increased demands by the state environmental agencies and US EPA in terms of work plans, QA/QC, Health and Safety training, permits, matrix interference analysis, lower detection limits, etc. were the primary motivational factors in the establishment of Crawford and Associates, Inc. The newly renovated Crawford Hydrology Laboratory is a 550 square foot well-equipped laboratory for fluorescence dye analysis. The following are examples of large dye tracer studies, performed within the last three years, under strict regulatory scrutiny, by a state or US EPA:

1. Saad Superfund Site, Nashville, TN for Roy F. Weston (US EPA)
2. Velsicol Chemical, Chattanooga, TN for Velsicol Chemical (US EPA)
3. Zeneca Chemical, Mt. Pleasant, TN for Camp, Dresser and McKee (Tennessee Division of Superfund)
4. Kentucky Industrial Haulers Landfill Site, Elizabethtown, KY for Shield Environmental (Kentucky Division of Superfund)
5. K-1070-A Burial Ground Dye Tracer Investigation, K-25 Gaseous Diffusion Plant, Oak Ridge, TN for SAIC Oak Ridge, TN (Tennessee Division of Superfund)
6. Century Electric Site, McMinnville, TN for EMPE Environmental (Tennessee Division of Superfund)
7. CSX Train Wreck Site, Lewisburg, TN for Ogden Environmental, CSX Railroad (US EPA)
8. Fort Knox, KY for Dames and Moore (Kentucky Division of Superfund)
9. Rad Chemical Site, Bowling Green, KY for Fuller, Mossbarger, Scott and May (Kentucky Division of Superfund)
10. Texas Eastern Pipeline Site, Lebanon, TN for S.S. Papadopoulas and Associates, Inc. (Tennessee Division of Superfund/US EPA)
11. Kendall Site, Franklin, KY for Kendall Company (Kentucky Division of Superfund)
12. Colonial Pipeline Spill Site, Chattanooga, TN for Colonial Pipeline (Tennessee Division of Superfund, National Park Service, US EPA)
13. Anniston Army Depot, Anniston, AL for SAIC.

CRAWFORD AND ASSOCIATES
REFERENCES

<u>Industrial</u>

1. Bill Stilson
   Zeneca, Inc.
   1391 S. 49th Street
   Richmond, CA 94804
   (510) 231-1249

2. Nancy Van Eman
   Velsicol Chemical Company
   4902 Central Street
   Chattanooga, TN 37409
   (423) 825-8226

3. Jim Mesereau-Kempf
   Dow Corning Corporation
   3901 South Saginaw Road
   Midland, MI 48686-0995
   (517) 496-5813

<u>Environmental Consulting Firms</u>

1. Brian Murray
   Science Applications Intl. Corp.
   800 Oak Ridge Turnpike
   Oak Ridge, TN 37831
   (423) 481-4748

2. Dennis Connair
   Dames and Moore, Inc.
   644 Linn Street, Suite 501
   Cincinnati, Ohio 45203
   (513) 651-3440

3. Tom Duffey
   Camp, Dresser, and McKee
   2100 River Edge Parkway
   Suite 500
   Atlanta, GA 30328
   (770) 952-8643

<u>Government Agencies</u>

1. Greg Powell
   US EPA ERT
   B-05 26 MLK Bldg.
   Cincinnati, OH 45268
   (513) 569-7931

2. James Smith
   USEPA, Region IV
   c/o RCRA Permitting Section
   100 Alabama Street
   Atlanta, GA 30303
   (404) 562-8502

3. Fred Stroud
   USEPA, Region IV
   CERCLA
   100 Alabama Street
   Atlanta, GA 30303
   (404) 562-8751

4. Linda Locke
   Tennessee Division of Env. Conservation
   Columbia Env. Assistance Center
   2484 Park Plus Drive
   Columbia, TN 38401
   (931) 380-3371

EXAMPLES OF DYE TRACES

1. Performed a karst hydrology investigation in the vicinity of the Campus-Injector Complex for the proposed Middle Tennessee Site for the Superconducting Super Collider. Identified the major flow routes of the Snail Shell Karst - Overall Creek Drainage Basin. This involved over 14 dye traces using four different dyes simultaneously. Recommended and designed a continuous monitoring, total recovery, and total containment system for an underground stream to prevent groundwater contamination downgradient from the site.
2. Emergency response to a train wreck where 15,000 gallons of chloroform (a DNAPL) and 4,000 gallons of styrene (a LNAPL) were spilled into a karst aquifer. Performed 21 dye traces to establish groundwater flow to springs, prepared a potentiometric map of the karst aquifers, used microgravity to locate sites for exploratory wells, excavations into caves, and installation of product recovery wells.
3. Performed a karst hydrologic investigation at a large limestone mine being used to store aluminum salt cake fines. Water was entering the mine at places were the roof had collapsed and from sinkholes in the limestone above the mine. Over forty surface springs and water intrusion sites within the mine were found and monitored with passive dye receptors and 18 dye traces were performed. Surface water sources found to be sinking into the mine were diverted into nearby surface streams.
4. PCBs were detected on the filters at a municipal water treatment plant. It was hypothesized that the PCBs had been carried by groundwater from a nearby dump site, where transformers had been burned, to Blue Lake. Blue Lake, located in an abandoned rock quarry, was used as a supplemental water supply by the municipality. The first dye trace from the site did not go to the lake, but instead to a spring on a nearby river. Then 40 million gallons were pumped from the lake and the trace was repeated. As hypothesized, with the lake pumped down, the dye trace from the site was positive at springs flowing into the lake
5. Performed a series of dye traces to find the source of TCE contamination in water wells. Three wells were pumped continuously over a period of two months and samples were collected by automatic water samplers.
6. Investigation of PCBs resurging from a karst spring. Measured discharge, PCBs in bedload and PCBs in suspended load. Fourteen dye traces were performed to determine karst groundwater flow routes and drainage basin divides.
7. Hydrogeologic investigation to select a suitable site for a 70-acre wetland waste treatment facility for a large factory. Project included several dye traces to determine groundwater flow under a 1,000 acre site.
8. Toxic and explosive vapors were rising from a karst aquifer under a city into homes, buildings and two elementary schools. A series of dye traces were performed to identify the sources of the contamination. Microgravity was used to located caves so that observation wells could be drilled into cave streams.

CRAWFORD AND ASSOCIATES, INC.

Proudly announces its consolidation with the

Center for Cave and Karst Studies

Now the Crawford Hydrology Laboratory

WESTERN KENTUCKY UNIVERSITY

Center for Cave and Karst Studies
Applied Research and Technology Program of Distinction
Department of Geography and Geology – EST 403
Western Kentucky University
Bowling Green, Kentucky 42101
Office: (270) 745-3252 ♦ Lab: (270) 745-9224
Email: nicholas.crawford@wku.edu ♦ caveandkarst@wku.edu
Or View Us At: http://caveandkarst.wku.edu/ ♦ www.dyetracing.com

Our primary objective continues to be assistance to consulting firms with their karst subsurface investigations

❖ Same Quality Investigations

- Karst Groundwater
- Dye Tracing
- Sinkhole Collapse & Sinkhole Flooding
- Improved Karst Geophysical Subsurface Investigations using the Center's Swift Sting Resistivity Meter and Scintrex Microgravity Meter

❖ Same Quality Personnel

- Dr. Nicholas Crawford - Senior Hydrogeologist on all projects
- Scott Roach, Chemist, full-time Laboratory Manager in newly renovated Crawford Dye Analysis Laboratory
- Leigh Ann Croft, Hydrogeologist - full-time karst hydrogeologic investigations
- Rita Collins - full-time Administrative Assistant

❖ Same Quality Fluorescent Dye Trace Lab and Products...

- The same excellent **QA/QC** will be maintained.
- Although graduate students will assist with the Center's research, full-time professional employees will perform all dye analyses and make all interpretations.

❖ *Please examine the enclosed brochure for the Applied Research and Technology Program of Distinction at Western Kentucky University. The Program boasts ten Centers of Excellence, including the Center for Cave and Karst Studies, and offers state-of-the-art assistance in all areas.*

STUART EDWARDS, P.E.
Consulting Environmental Engineer

Expertise

Environmental Engineering, Civil Engineering, Geotechnical Engineering, Project and General Management

Academic Background

B.Sc. (Hons.), Civil Engineering, Portsmouth College of Technology, United Kingdom, 1969

Registrations

Professional Engineer--Ohio, Kentucky, Texas, Missouri, Indiana, Delaware, Connecticut, Pennsylvania, and Michigan

Experience

More than 30 years of engineering experience of which 20 have concentrated on the technical direction and management of environmental projects involving complex issues of strategic and financial planning, and risk management. Consults on environmental projects involving regulations promulgated under CAA, CWA, RCRA, TSCA, and CERCLA.

Site Remediation
- Director/manager for remedial investigation/feasibility study and remedial design / implementation projects at six US Superfund sites including Powell Road Landfill, OH; BOC/Airco, KY; Bowers Landfill, OH; and City of Coshocton Landfill, OH; NSA, KY, Ohio River Site, PA.
- Director for remedial feasibility studies and cost allocation analysis for large hazardous waste disposal site in Croatia.
- Director/manager of major environmental projects for large multi-national clients involving strategic planning, hydrogeologic investigations, regulatory compliance consulting, risk assessment, corrective action, RFI/CMS.
- Engineer of Record for numerous hazardous waste management facility closures under RCRA, with particular expertise in surface impoundments.
- Design and installation of ground water monitoring systems in complex geological environments including karst and fractured limestone.

Due Diligence
- Project director for environmental site assessments (Phase I and Phase II) of industrial and commercial properties worldwide.

- Consultant on industrial portfolios involving complex ownership, remediation issues and risk management

- Specialist in transactions involving waste treatment/disposal facilities including portfolio of incinerator and landfill assets, worldwide portfolio of solvent management facilities, multiple portfolios of ferrous recycling operations.
- Environmental due diligence of large integrated US utility including coal burning generating stations, hydroelectric facilities, transmission and distribution system and historical liabilities.

Environmental Engineering

- Design of solid waste landfills, ground water extraction and treatment facilities, sheet pile bulkhead and storm protection measures
- Design of above-grade lined earthen containment structures for hazardous waste storage and disposal at industrial facilities.
- Conceptual design, siting and licensing studies for hazardous waste treatment and disposal facilities.

Professional History

Independent Consultant (2000 – present)
Partner/Vice President - Dames & Moore, Cincinnati, OH and Manchester, England (1982 - 2000)
Senior Project Engineer - Fugro Gulf, Inc., Houston, TX (1980-1982)
Project Engineer - Dames & Moore, Jakarta, Indonesia, Tehran, Iran, Anchorage AK (1973-1980)
Staff Engineer - Gallaher & Bovey/Pioneer Consultants, Riverside, CA (1971-1973)

Countries Worked In

United States, United Kingdom, Indonesia, Iran, Saudi Arabia, Croatia, Slovenia

Professional Affiliations

American Society of Civil Engineers, Institution of Civil Engineers (United Kingdom)

Publications

Yang, J.Y., Edwards, S., Nicholas, J., and Armstrong, G.I., (2000) "Quantifying Company-Wide Environmental Risk and Liability" ChemExpo 2000.

Edwards, S., Hauer, K.L., and Kreuger, J.J., (1999) "Monitored Natural Attenuation of Coking Waste Contaminants in Groundwater." 5th International Symposium, In Situ and On-Site Bioremediation.

Yang, J.Y., Gates, T.M., and Edwards, S., (1999) "SVE Design: Mass Transfer Limitations Due To Molecular Diffusion." J. Env. Eng. A.S.C.E. 125 (9), (Winner, Greeley Award 2000)

Edwards, S., Mikulic, J. and Burela, S. (1998) " Natural Attenuation as a Tool for Remediation of Contaminated Ground Water Beneath Municipal Landfills" 5th International Symposium, Waste Management-Zagreb '98