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**Physical and Numerical Modelling of a Dual Porosity
Fractured Rock Surrounding an In-Pit Uranium Tailings
Management Facility**

by

Karina Lange

B. Eng., Carleton University

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

Master of Applied Science
Environmental Engineering

Department of Civil and Environmental Engineering
Carleton University, Ottawa

June 2003

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Department of Civil and Environmental Engineering

The undersigned recommend to the Faculty of Graduate Studies and Research
acceptance of the thesis

**Physical and Numerical Modelling of a
Dual Porosity Fractured
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Tailings Management Facility**

Submitted by

Karina Lange

in partial fulfillment of the requirements for the degree of Master of Applied Science

Professor Paul Van Geel (Supervisor)

Abd El Halim, Acting Chair
Civil and Environmental Engineering
Carleton University

Abstract

In-Pit Tailings Management Facilities (TMFs) have been used to dispose of uranium mine tailings in Saskatchewan. These TMFs are located within fractured rock and their design includes a pervious surround or natural surround concept to limit the rate of release of compounds of concern to the surrounding environment. A previous study evaluated the impact of the pervious surround concept, where the fractured rock was represented using an equivalent porous medium approach and a discrete fracture approach. The research outlined herein represented the host rock as a dual porosity medium. The objective was to determine the impact of a dual porosity representation of the fractured rock on the downgradient concentrations and flux to a downgradient receptor. A dual porosity physical model was simulated using concrete blocks separated by sand filled fractures. The experiments were numerically simulated using SWIFT II. The actual and simulated mass fluxes and downgradient concentrations are presented.

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CHAPTER 1

1.0 Introduction

Canada is a world leader in uranium production, largely because of the extraordinarily rich uranium deposits found in Northern Saskatchewan. Uranium mining activity in this region has rapidly escalated over the past few decades and is continuing to expand. In 2001, Canada was responsible for 35% of the world's total uranium production [Figure 1.0]. Although uranium is a valuable commodity, large amounts of waste are generated through the actions of mining and chemical treatment processes. The waste from uranium mining contains radioactive material and elements such as arsenic and nickel, which require additional consideration during disposal to reduce any long term impacts on the environment. Since the operation of the first uranium mill, management practices of mine tailings have evolved from lake disposal to more current in-pit Tailings Management Facilities (TMFs). An in-pit TMF is an excavated pit in which tailings are placed while the pit is continuously dewatered, to limit transport and consolidate the tailings. At decommissioning, the pit is capped, the water table is allowed to recover, and the tailings are left submerged. This type of placement limits radioactive exposure, and provides for a stable anaerobic environment; however a long-term source of groundwater contamination is created. The most recent TMFs have proposed a pervious surround concept to direct flow around the compressed low permeability tailings through a higher permeability material such as sand or crushed rock. Previous and ongoing studies are attempting to quantify the impact that the pervious surround has on minimizing the flux of contaminants from the containment pit and hence reducing the impact on downstream

groundwater systems. Groundwater modelling of the host rock surrounding the Saskatchewan TMFs provides for additional challenges due to the fractured nature of the sandstone deposits. The movement of the contaminant through the fractures is more difficult to predict than typical homogeneous aquifers. The fractures can provide a fast path for contaminant distribution, but can also act to retard the plume through processes such as matrix diffusion.

Figure 1.0 Annual Uranium Production, 2001

[Source: WISE Uranium Project, 2001]

1.1 Background: Uranium Mining in Northern Saskatchewan

The first documented discovery in Saskatchewan of uranium occurred in 1936. At this time uranium was used mainly for color addition to glass and ceramics. It wasn't until 1939 that uranium was discovered to produce significant amounts of energy. The creation of the atomic bomb in World War II peaked a world wide interest in the uranium deposits found in Saskatchewan, which helped to establish Uranium City [Figure 1.1] where uranium mining was prominent. During the 1970's, as Uranium City was closing, the richest uranium deposits in the world were discovered in the Athabasca Basin, a geological formation located 700 km north of Saskatoon. About 1.8 billion years ago, metamorphic rocks of the Canadian Shield were eroded into a surface known as an unconformity. Sandy sediments were later deposited on top of this unconformity, then consolidated into the relatively flat lying sandstones of the Athabasca Group. Uranium has since been mobilized and re-deposited around the unconformity, especially along fault zones. Uranium production from the high grade deposits of the Athabasca Basin began in 1975 at Rabbit Lake, and the opening of subsequent mines followed [Cameco Corp., 2003]. Current mining operations in northern Saskatchewan are occurring at McClean Lake, McArthur River, Key Lake, Rabbit Lake, and Cluff Lake [Figure 1.1]. Table 1.0 shows values of uranium production per year at each aforementioned site. Saskatchewan is presently the largest uranium producing region in the world. Ore reserves at McArthur River are estimated to be 200 million kilograms, with an average grade of 17% U_3O_8 . This is an extremely high-grade ore; the ores found at Key Lake, for instance, are on average of 2% U_3O_8 [UEX, 2002]. Uranium is sold by the mining companies to electric power utilities in Canada, the United States of America, Europe and

the Far East. Saskatchewan's uranium mining industry is expected to remain competitive well into the future due to its substantial, lower-cost and high-grade uranium resources.

Figure 1.1 Map of Saskatchewan

[Source: Government of Saskatchewan, 2000]

Table 1.0: Canadian Uranium Mine Production (metric tonnes Uranium)**[Source: Uranium Information Centre Ltd., 2002]**

	1994	1995	1996	1997	1998	1999	2000	2001	2002
McArthur River							3739	6640	7199
Key Lake	5074	5464	5429	5434	5386	3731	402	299	*
McClellan Lake						560	2308	2539	2342
Rabbit Lake	2868	3148	3973	4663	4502	2693	2790	1755	440
Cluff Lake	1065	1214	1926	1964	1039	1234	1443	1269	1626

* = small, included with McArthur River figure.

1.1.1 Mining and Milling Waste

Uranium mining, like most mining activities, produces waste rock, tailings from the milling process, industrial waste and waste water. In nature, uranium atoms exist in several isotopes, primarily uranium-238 (U-238) and uranium-235 (U-235). In a typical sample of natural uranium, most of the mass (99.3%) would consist of atoms of U-238, and a very small portion of the total mass (0.7%) would consist of U-235 atoms [UEX, 2002]. The uranium ores are predominantly pitchblende, a sooty black mineral. The pitchblende ore in Saskatchewan is mined by both underground and open pit methods. In the case of an open pit mine, the amount of waste rock which must be mined in order to get at the ore may be larger than the actual volume of ore. The waste rock does not

contain uranium, and it typically does not contain large amounts of minerals to recover for economic purposes. These low concentrations of minerals may not be economically valuable for extraction, but could affect surrounding environmental conditions. The uranium host rock at Key Lake for example contains arsenic and nickel. Pyrite and chalcopyrite minerals also exist at several sites which can lead to the oxidation of sulphur and the generation of sulphuric acid. Acidic waters can be very harmful to surrounding lakes and rivers, and the acids could also dissolve heavy metals found in the waste rock which increases the toxicity of any water seepage.

After the waste rock is removed, the ore is processed to extract the uranium. The first step in processing involves grinding the rock into a sandy material. The resulting material is leached using sulphuric acid and washed to ultimately separate the uranium solution from the crushed rock. Solvent extraction is performed to purify and concentrate the uranium solution, and the uranium is typically dried so it can be shipped in a crystal form. The impurities left after the solution is removed are neutralized with lime and blended with the crushed rock to form the tailings slurry; therefore, the tailings contain crushed rock, chemical precipitates, non-targeted metals, and trace amounts of uranium.

1.1.2 Cumulative Impacts

The disposal of wastes from mining and milling operations will have a major effect on Saskatchewan's surrounding environment. The treatment of wastewater and industrial waste will add to existing pollution processes, contaminating nearby surface water.

Waste rocks as mentioned earlier will be a source of nickel, arsenic, and radioactive contamination. Finally, the major concern is the long term source of surface and ground water contamination posed by the tailings. Ongoing research focuses on designing containment facilities to minimize the flux of contaminants of concern from the tailings. Other researchers continue to assess and predict the possible impacts on nearby groundwater systems.

1.1.3 Concept for Tailings Disposal

In the past, typical disposal practices included natural geographical depressions, tailings ponds, and surface impoundments. Difficulties like seepage from unlined surface impoundments impacted local groundwater and excess ice build-up caused liner systems to fail. As a result, the in-pit Tailings Management Facility concept was implemented at three sites in Northern Saskatchewan (Rabbit Lake Pit/Rabbit Lake, Deilman Pit/ Key Lake, JEB Pit/McClean Lake). The TMF facilities used existing mined-out pits and newly excavated pits, and have liner and pump systems to minimize pore water build-up during tailings disposal. The in-pit facilities exist either above or below the water table depending on the pumping rate. The ability to use underwater disposal (subaqueous) deposition was important for tailings produced from high grade ore because it provides for greater worker protection. As described by the Canadian Environmental Assessment Agency [2001], “deposition of the tailings under a few meters of water protects the people working around the pit from exposure to radiation”. In addition to limiting exposure, subaqueous disposal limits the segregation of fines, reduces acid generation,

minimizes gradients across the pit, increases consolidation and limits weather access (thereby reducing frozen ice layers within the tailings body). The JEB pit facility at McClean Lake uses this 'subaqueous' tailings deposition method. The Rabbit Lake and Key Lake mine uranium deposits are typically low grade and therefore exposed radioactivity is not a serious problem, making above the water table (sub-aerial) disposal acceptable.

A new concept used at these TMF sites in Saskatchewan, called the 'pervious surround' method, attempts to reduce ground water flow through the tailings, and thereby moderate the rate of flux of radioactive and metal contamination that could enter the local groundwater via advection. A more permeable lining layer of crushed rock and sand is placed in the pit around the tailings. This permits ground water to flow around, rather than through the tailings. The filter (rock) is drained of all contaminated water via pumps, dewatering shafts, and wells. Ideally, at the time of decommissioning, excess contaminated pore water will have already been released from the tailings during their consolidation, and pumped away for treatment.

1.2 Application of the Pervious Surround Concept

The primary purpose of the pervious surround is to minimize the hydraulic gradient across the tailings in order to prevent ground water from flowing through them and carrying away contaminants via advection. Secondly, the pervious surround is used as a bottom and side drain to collect pore water and aid in the consolidation of the tailings.

With time, the tailings themselves upon consolidation become denser and less permeable than the surrounding rock. The pervious surround concept is used for the Rabbit Lake pit and a partial pervious surround is used at Key Lake. It was decided not to use a pervious surround at the JEB pit for the McClean Lake tailings. Brief descriptions of the three aforementioned TMF sites follow. For a more thorough review of diagrams and schematics for each site, consult West [2001].

1.2.1 Rabbit Lake Mill and Rabbit Lake Tailings Pit

The Rabbit Lake mine site began operating in 1975. Tailings were deposited at a surface tailings management area until 1985 when deposition of tailings into the Rabbit Lake in-pit TMF began [Figure 1.2]. The Rabbit Lake TMF pit was lined on the bottom and sides by crushed rock. Collection pipe systems were set-up to withdraw contaminated pore water released during consolidation and to pump that water to a nearby treatment plant. Some layers in the tailings' body consist of ice and frozen tailings due to the deposition of tailings during wintertime [Landine et al., 2001].

Figure 1.2: Rabbit Lake pit, mined from 1975 to 1984, now used as a TMF

[Source: UEX Corporation, 2002]

1.2.2 Key Lake Mill and Dielmann Tailings Pit

The subsurface geology surrounding the Dielmann tailings pit varies from the Rabbit Lake pit, requiring a slightly different containment design. For the disposal of the Key Lake mill tailings, a pervious surround design similar to Rabbit Lake was implemented.

Wells were then located within and surrounding the pit to optimize dewatering during disposal. Crushed rock and sand were placed into the bottom and part way up the sidewalls. The consolidation of the tailings together with the crushed rock and sand lining were expected to direct the majority of flow around the tailings. Once the top of the pervious surround is reached, pumping will be reduced to allow for partial flooding of the pit. At this time, higher grade blended McArthur River Mill tailings will subsequently be disposed of underwater into the flooded pit, as illustrated in Figure 1.3.

A movable discharge device capable of placing partially consolidated slurry materials is used.

Figure 1.3: Dielmann TMF [UIC, 2002]

1.2.3 McClean Lake Tailings and JEB In-Pit TMF

The JEB pit has favorable site geology to permit the use of a system without a pervious surround [Canadian Environmental Assessment Agency, 2001]. The surround concept was initially proposed, however disposal of higher ore grades would result in workers being exposed to unacceptable levels of radiation, as extra work would be required to

raise the surround as the tailings rise. Therefore a subaqueous TMF with a natural surround concept was chosen as the preferred disposal method.

1.3 Standards for Uranium Tailings Management

The Canadian Nuclear Safety Commission (CNSC) and subsequent provincial authorities are responsible for the management of uranium mine and mill tailings. The regulations require the design, construction, maintenance and monitoring of an engineered facility for storing tailings as long as the mine/mill complex is operational. The CNSC is also responsible for assuring that the decommissioning stage abides by certain prerequisites. The in-pit TMFs in Northern Saskatchewan (Rabbit Lake, Deilmann, JEB) have not yet reached the decommissioning phase, and have had to rely on modelling efforts to predict the performance of in-pit disposal methods.

1.4 Previous Work

Among several reports related to tailings disposal in Northern Saskatchewan, West conducted a study entitled, "Physical and Numerical Modelling of an In-Pit Tailings Management Facility" [West, 2001], for his Master's research at Carleton University, in conjunction with the CNSC. The fundamental processes that affect the performance of an in-pit TMF were reviewed by reproducing laboratory scale versions of the containment pit scenarios found in the Athabasca region via numerical and physical modelling.

The report judged the capability of numerical models to predict actual physical TMF situations through a comparison of computer model simulations and experimental data collected from laboratory scale physical models. The report focused on the use of the pervious surround method, and evaluated its significance in the overall design of the in-pit TMF.

The physical experiments were intended to simulate the naturally fractured rock in the Athabasca region using the equivalent porous media approach, and the discrete fracture approach. Through his numerical and physical models, he was able to clarify the impact that the pervious surround had in reducing contaminant flux and the downstream plume concentrations, and suggested that other mechanisms involved with the host rock may facilitate the further retardation of the plume. The study recommended modelling the fractured rock as a dual porosity medium in order to gain a better understanding of the impact of the host rock porosity on the migration of contaminants within the fractured rock system.

1.5 Thesis Objectives and Scope

The intent of this study was to model an in-pit TMF which utilizes a pervious surround and deals with the host rock as a dual porosity system.

As mentioned in Section 1.4, a modelling exercise performed by West [2001] assessed the performance of an in-pit TMF and the application of the pervious surround concept for the CNSC. This study attempted to take his modelling efforts a step further by

replicating his physical and numerical models and representing the host rock as a dual porosity system. The representation of the host rock as a dual porosity system took into account important factors such as matrix diffusion, which may have had a significant impact on the predicted contaminant plume.

There were four main objectives associated with this thesis. They were to:

- (1) introduce the reader to the notion of fractured flow and elaborate on the fundamentals of the dual porosity concept;
- (2) describe the results of a physical model attempting to represent a dual porosity reservoir surrounding an in-pit TMF with a pervious surround design;
- (3) identify the ability of a dual porosity numerical model to quantify the physical results obtained in (2); and
- (4) provide a comparison between the results of current and previous representations of the fractured rock reservoir representations, and comment on the overall concept of the pervious surround method.

Chapters 2 and 3 of this thesis address objective (1). It is only in recent decades that modern theories of conceptualizing fracture flow have been developed. Various fracture flow models have been tested and are continuing to improve. The most common representations of fracture flow include but are not limited to: the discrete fracture approach, the equivalent porous media approach, different stochastic approaches and more recently, the dual porosity approach. The theory of dual porosity has many

applications, and is valuable due to the incorporation of factors such as matrix diffusion and block to fissure flow. Conceptually, a dual porosity medium is generally assumed to involve two overlapping pore domains having different hydraulic and transport properties [Gerke and vanGenuchten, 1996].

Based on this theory, the relevant research tools are identified and an experimental model is described in Chapter 4. The physical model consists of a simulated in-pit TMF surrounded by low permeability, highly porous blocks thus simulating a dual porosity host rock. Chapter 4 also presents the results to several ancillary tests that were performed on the material used in the physical model. Chapter 5 introduces the numerical model (SWIFT) used to describe the physical system, and presents a sensitivity analysis and model calibration using the ancillary test results and tracer test results presented in Chapter 4. The numerical model, SWIFT [Sandia National Laboratories, 1982], is a fully transient three dimensional dual porosity model which is typically used to model the flow and transport at subsurface radioactive waste facilities. The SWIFT program allows for the input of many variables, and boundary conditions to allow for close representation to the physical model, with minimal assumptions and limitations. A series of tests were conducted using the physical model and are presented and discussed in Chapter 6, thus addressing objective (2).

Chapter 7 compares the SWIFT simulations with the results obtained from the physical representation (objective 3).

Chapter 8 addresses objective (4) by comparing current and previous results obtained using different representations of the fractured host rock. It also describes the role of the pervious surround within the entire in-pit TMF system.

Chapter 9 summarizes the overall study, states final conclusions and gives recommendations for further study.

CHAPTER 2

2.0 Contaminant Transport in Fractured Porous Media

Contaminant migration and fluid flow in fractured porous media is an important recurring geological issue. Freshwater aquifers and petroleum reservoirs are known to be composed of fractured rock. Harmful underground waste disposal facilities, especially those involving nuclear waste or mine tailings, are often situated in fractured igneous or sedimentary rock, and hence have dictated the need for research on solute transport in fractured porous media.

The occurrence of fractures creates a fast channel for widely distributing contaminants throughout an aquifer and it also creates an uncertain path for the migration of contaminants making fractured aquifers more vulnerable to multifaceted pollution processes. The most common conceptual picture of flow and contaminant transport in a fractured porous medium is that of advective flow of water and transport of pollutants are largely or entirely through the fractures. In comparison to the rapid flow rates in the fractures, the surrounding rock matrix typically provides for very little advection due to its low permeability, but it does carry a high porosity and a subsequent large storage capacity to the entire fracture-rock system. This storage capacity allows for potential contaminant retention by diffusion, adsorption and other processes.

Fluid migration and contaminant transport in this situation require modifications to the traditional methods used to investigate flow and transport in porous media due to the heterogenic nature of the fractures and other factors such as matrix diffusion. Previous

research regarding fracture flow and solute transport has principally focused on the development of conceptual models with both analytical and numerical solutions, fracture hydraulics, and laboratory and field-scale testing.

2.1 Fractured Rock Systems

Fractured rock can be created naturally through geologic stress or through anthropogenic means such as mining or drilling. In either case, fractures provide a pathway for groundwater flow in an otherwise impermeable rock mass. For example, the flow through a 100-m-thick cross-section of a porous medium with a hydraulic conductivity of 10^{-9} m/s might also come from one single fracture with an opening not wider than 0.1 mm in a fractured medium with an impervious rock matrix.

Most fractured rock systems consist of rock blocks (matrix blocks) bounded by fractures, discontinuities and shear zones usually occurring in sets with similar geometries. Fractures can be open, deformed, or filled with material such as mineral deposits. Depending on the type of rock, groundwater flow can occur both in the rock matrix and in the fractures. Which part dominates depends on the porosity and properties of the fractures and surrounding matrix. Metamorphic and igneous rocks generally have low porosity and permeability, whereas sedimentary rocks have higher porosity and varying permeability.

Flow through fractured rock depends on various fracture characteristics such as spacing, density, orientation, fracture area, effective aperture width, and the nature of the rock

matrix. Fracture spacing, density, and orientation determine the interconnectivity of the fracture sets which affect the overall hydraulic conductivity of the system. Orientation plays a key role as fractures oriented parallel to the hydraulic gradient will be more effective in carrying a contaminant further distances than those perpendicular to the gradient. The fracture area and effective aperture width will dictate the amount of flux through the system. Factors affecting fracture apertures (eg. stress) become important when they impact the sizing of the opening. Fracture apertures are typically up to a few millimetres in width, and typical fracture spacings are in the centimetre to metre range. The nature of the rock matrix refers to properties such as diffusivity, porosity, and permeability, which can all have a direct impact on a contaminant plume. Several reports outline informative approaches to interpreting fracture systems from actual geologic field data: Gale and Rouleau [1983]; Wealthall et al. [2001].

2.1.1 Flow Conditions

Virtually all models describing flow in fractured formations assume that water flows primarily along the fractures in a laminar regime, and that matrix flow is small or negligible. If flow is exchanged between the matrix and fractures, it is typically assumed to occur under a smooth pressure gradient. Flow into and out of the matrix becomes important under situations involving wells and transient flow [Esposito and Thomson, 1999].

Darcy's law and most flow models experience limitations when faced with fractured flow settings. In some regions, the concept of equivalent porous media (discussed further in Section 2.2.1) may be applied in order to use the Darcy concept. Alternative approaches to Darcy's law are described in Choi et al. [1997] for faster flow regimes in fractures.

Whether Darcy's law or other flow equations are applied to analyze fractured rock aquifers, a representative elementary volume (REV) of field conditions is often selected to represent the region under study. The concept of an REV has been well established in groundwater literature. In fractured regions, a small increase in REV can provide for a very large increase in flow results, therefore it is necessary to ensure proper assumptions are made when representing a fractured region as an REV.

Previous studies on fracture systems were often performed under saturated conditions, due to the complexities that arise when dealing with the unsaturated zone (variable water content, etc.). Many studies have adequately described the dynamics that are introduced when fracture flow occurs in the unsaturated zone [Zimmerman et al., 1996; Doughty, 1999]. These models have been extended to multiphase flow systems, adding viscous, capillary and gravity forces to the fracture system [Gilman and Kazemi, 1983; Slough et al., 1999].

2.1.1.1 Flow in a Single Fracture

Prior research has provided useful information regarding fracture flow by examining transport conditions through a single fracture. Through these studies, the importance of

factors such as fracture aperture, fracture skins, and flow profiles have been described. For example, discharge through a given fracture was shown to be proportional to the cube of the fracture aperture. Dispersion and porosity are often determined through single fracture tests. Studies that reflect this concept include: Neuzil and Tracy [1981]; Pyrak et al. [1988]; Witherspoon et al. [1980].

2.1.2 Dispersion and Diffusion

Mechanical dispersion describes the spreading of a tracer pulse due to local variations in velocity. In fractures, these variations might be caused by fracture skins, orientation and aperture deviations. Generally in fracture models, longitudinal dispersion is more pronounced than transverse dispersion. The dispersion may be expressed as a function of the standard deviation of the residence time distribution [Bedient et al., 1999]. Laboratory column studies indicate dispersion is a function of average linear velocity and a factor called dispersivity, α .

For non-interacting solutes the water flow rate and flow porosity determine the residence time. The dispersion of these solutes will, therefore, be a function of the spatial distribution of water flow rate and flow porosity. For solutes that interact with the matrix (e.g. diffuse, precipitate), the dispersion is determined by the water flow rate and the flow-wetted surface in addition to the diffusion/precipitation properties of the rock. This implies that a dispersion coefficient determined by one tracer experiment with a non-interacting tracer cannot be used for another study where solutes interact differently with

the rock matrix. In assessing the solute transport through dual porosity soils, Hoag and Price [1997], showed that as the solute interacted with the matrix, more spreading of the solute occurred, thus creating a greater overall dispersion.

Channelling dispersion can affect solute transport in fracture flow under certain conditions. When there is no mixing of the fluid flowing in different channels, the velocity differences in the channels will have carried a tracer different distances at a given time [Neretnieks et al., 1982]. A tracer will arrive at the end of the fractures in different channels at different times, making the plume dispersed.

In the fracture, diffusion of the contaminant has little effect in comparison to mechanical dispersion. Molecular diffusion is less important in the fracture and more important in the matrix. The majority of rocks have microscopic fissures that exist naturally between adjacent crystals which tend to create a pore system within the rock matrix. The molecules of a solute are much smaller than these fissures and can thus diffuse into and out of this pore system. The matrix blocks act as a dynamic storage mechanism for the mass in the system. Matrix diffusion constitutes a process that can be effective in transferring mass from and/or to the moving subsystem into and/or from the matrix and thus can retard transport processes through the system.

2.2 Models for Fracture Flow

All groundwater models are simplified in some form to represent biological, chemical or natural physical processes. Fractured rock models, for obvious reasons, are simplified

sometimes to great extents. As in any model design, it is important to be aware of the assumptions and simplifications that were used to obtain the most suitable results. Analytical models exist for more simple fracture representations that typically involve one fracture and one phase flow. These models are a good basis for understanding how parameters such as diffusion, aperture width and velocity affect fracture flow.

Fractured rock systems could be modeled explicitly by accounting for flow in each fracture and every matrix block through a detailed computational mesh. In reality, this would be complex, introducing a large number of grid blocks and the need for various aperture and orientation distributions. To simplify matters, several models have been developed that describe fluid flow and solute transport in fractured rock systems. These models were created through the modification of existing contaminant transport science, and in the process have uncovered new concepts.

Four principal conceptual models are discussed here that are based largely on the idea that advective transport occurs mainly through the fractures, if not entirely through the fractures. These models are: (1) discrete fracture, (2) equivalent continuum or equivalent porous medium, (3) dual porosity, and (4) stochastic distribution fracture model.

Fundamentally, each method can be distinguished on the basis of the storage and flow capabilities of the porous medium and the fracture. The storage characteristics are associated with porosity, and the flow characteristics are associated with permeability. Further distinctions can be drawn on the basis of the spatial and temporal scales of integration or averaging of the flow regime. Bear and Berkowitz [1987] describe four scales of concern in fracture flow: (1) the very near field, where flow occurs in a single

fracture and porous medium exchange is possible; (2) the near field, where flow occurs in a fractured porous medium and each fracture is described in detail; (3) the far field, where flow occurs in two overlapping continua with mass exchanged through coupling parameters; and (4) the very far field, where fracture flow occurs, on average, in an equivalent porous medium. For additional review of conceptual and mathematical groundwater models, see Bear et al. [1993].

The selection of the modelling approach is affected by the type of results aimed for, the data available, the scale of the modeled domain and some practical limitations like computational resources. Furthermore, the applicability of alternative methods for modelling various physical processes in fracture systems is different. Each type of model has particular advantages and disadvantages for modelling of fractured rock masses.

2.2.1 Equivalent Continuum

The Equivalent Continuum or Equivalent Porous Media (EPM) approach defines a fractured system as a single continuum, where the parameter values are affected by the presence of fractures, but the fractures are not modeled explicitly. The continuum theory itself is very broad and has been applied to many branches of science.

In basic terms, the real porous medium domain is replaced by a model in which each phase is assumed to be present at every point [Bear, 1969]. An equivalent porous medium method is most appropriate when the media of interest has a high number of fractures that are all similar in size [Figure 2.0]. In such a system the REV

(Representative Elementary Volume) has a major impact on parameter estimates such as porosity and conductivity. This approach is advantageous since only a few parameters such as conductivity, dispersivity and effective porosity need to be known for a simulation. Endo et al. [1984], present a technique for determining when fracture networks can be modeled as equivalent porous media in transport scenarios. This approach does however introduce a high level of uncertainty since these parameters are usually obtained through “fitting” simulations and may vary in space and time. Examples of EPM models include: Pankow et al. [1986]; Peters and Klavetter [1988]; Berkowitz et al. [1998].

Figure 2.0: Transfer from a Complex Fracture System to a Homogenized System

2.2.2 Discrete Fracture

To conceptualize a discrete fracture network (DFN), parameters regarding the actual fractures of interest, as well as the surrounding rock or matrix are required. The most important advantage of the DFN model is the possibility to incorporate fracture geometry data in the model and explicitly represent properties of fractures and fracture zones [Figure 2.1]. One apparent problem with this approach is the level of detail required for this model and one's ability to collect this data in the field.

Figure 2.1: Transfer from a Complex Fracture System to a DF Network

2.2.3 Stochastic Continuum (SC)

It is often difficult to identify deterministically all the fractures contained within a defined section of rock, therefore, some models use a stochastic approach to represent the spatial variability of the fracture system [Figure 2.2].

Figure 2.2: Transfer from a Complex Fracture System to a SC

The geometrical and physical properties for these stochastic fractures are often assigned through Monte Carlo sampling of relevant distributions. Sampling of relevant distributions may include characteristics such as fracture conductivity, frequency, and orientation. Synthetic networks are generated in simple rectangular forms, but with properties based on statistical distributions of the measured characteristics. Selroos et al.

[2002], treat the hydraulic conductivity of the equivalent system as a random spatial distribution of block/element hydraulic conductivities that represent the spatially averaged fracture properties. One challenge with this method lies in the ability to obtain proper representative data. A potential verification can be performed by comparing the output values (e.g. conductivities) to further site measurements.

2.2.4 Dual Porosity Approach

In the dual-porosity (DP) model, the bedrock is assumed to consist of two homogeneous and overlapping continua: the fractures and the matrix blocks [Figure 2.3]. The fractures are characterized by very high permeability and very low storage, while the porous blocks are characterized by low permeability and high storage. Water containing solute flows through the interconnected fractures, and becomes dispersed. The solute is also diffused into the surrounding rock matrix.

Separate equations are applied for the fractures and the matrix blocks, and are coupled using a mass transfer term. The mass transfer term represents the amount of fluid/mass exchanged between the pore water in the matrix (host rock continuum) and the moving water in the fractures (fracture continuum). The following chapter describes the conceptual and mathematical models relating to the dual porosity concept for fractured flow.

Figure 2.3: Transfer from a Complex Fracture System to a Dual Porosity Medium

CHAPTER 3

3.0 Dual Porosity Model

Under the dual porosity (DP) approach, the combination of fractures and blocks is substituted by two overlapping continua, where a pair of average properties is defined over the entire system at each spatial point. The fractures can be thought of as a continuum (early models dubbed fractures as a “series of connected pipes”) and the matrix perceived as the adjacent sources or sinks. The DP approach thus defines two porosities and two permeabilities to account for each medium. The porosity associated with the fractures is low, but the permeability is high. The opposite is true for the surrounding matrix.

Dual porosity models have expanded to accommodate other situations such as the dual permeability model in which flow is significant in the matrix blocks as well as the fractures [Moench, 1984], and the triple porosity model that represents more complex fracture domains [Lagendijk et al., 2000]. In any case, the element that distinguishes this type of model from any other is the fracture-matrix interaction term. This term has been studied extensively and solved in a number of ways using parameters such as geometry and diffusion coefficients.

The approach has been widely used to represent groundwater flow and contaminant transport in fractured porous media. It has also been invoked to explain phenomena of fluid and solute transport in aggregated soils [Brusseau et al., 1994; Hoag and Price, 1997; Saxena et al., 1994; Schwartz et al., 2000], petroleum recovery [Kazemi et al.,

1976; Esposito and Thomson, 1999], and transport in variably saturated structured media [Gerke and vanGenuchten, 1993; Larsson and Jarvis, 1999; Tseng et al., 1995; Ray et al., 1997; Katterer et al., 2001; Yeh, 2000].

The contaminant, in addition to being advected and dispersed in the fractures, can also be diffused into the matrix, which retards the front's motion. Typical dual porosity models employ repeating blocks of the same simple geometrical shape with consistent fracture spacing. While no aquifer exhibits such an ideal setup, the model itself can be applied as a practical tool for modelling flow and contaminant transport in a fractured medium through addressing important issues such as matrix diffusion.

3.1 Theoretical Development

The concept of a double-continua approach was first conceptualized by Barenblett et al. [1960] to describe flow in fissured groundwater systems. The authors introduced “two liquid pressures at each point in space; the liquid pressure in the pores and pressure of the liquid in the fissures”. Equations which govern water flow and/or solute transport are described separately for each subsystem, and suitably coupled to account for the exchange of fluid and/or contaminants between the two interacting continua [Tseng et al., 1995]. The primary porosity and permeability are those of the porous but low permeability blocks that are separated by the fractures. The secondary permeability and porosity are associated with the fractures. This secondary porosity refers to a ratio of the cavity space occupied by the fissures to the total volume of the rock [Barenblett et al.,

1960], and is considerably smaller than the porosity of the individual matrix blocks (primary porosity). It is also assumed that the porous matrix blocks act as sinks (or sources) that drain (or feed) the fractures with fluid or solute mass [Zhang et al., 2000]. The source or sink term needs to capture the local scale microscopic processes with a relatively simple term for use in a macroscopic dual porosity medium.

Therefore, in order to use the dual porosity approach, two sets of properties must be known for fracture and matrix zones. The properties are “averaged” using different methods, in order to homogenize the medium which acts to simplify the mathematical model. The most important factors, as far as solute transport is concerned, are the fracture and matrix porosity and conductivity, the spacing between the fractures (connectivity), and the diffusion coefficient of the matrix blocks.

Warren and Root [1963] outlined three elemental assumptions which form the basis of the most common dual porosity model applied to fractured flow and is the basis for the mathematical model described later in Section 3.2:

- (1) The material containing the primary porosity is homogeneous and isotropic, and is contained within a systematic array of identical rectangular parallel-pipeds.
- (2) All of the secondary porosity is contained within an orthogonal system of continuous, uniform fractures which are oriented so that each fracture is parallel to one of the principal axes of permeability; the fractures normal to each of the principal axes are uniformly spaced and are of constant width.

- (3) Flow can occur between the primary and secondary porosities, but flow through the primary-porosity elements cannot occur (i.e. no flow within matrix blocks, only a decrease/increase in storage).

3.2 Mathematical Model

The dual porosity mathematical model is represented by two sets of equations: one for the fractures and the other for the matrix. The equations describing flow and transport for the fractured regions are the same as the equations for a typical EPM, except for source/sink terms depicting exchange with the matrix. The equations describing flow and transport in the fractures, developed as the secondary equations, are termed the “fracture” or “global” equations. The matrix equations differ from the fracture equations, so processes that occur in the matrix are called the primary or “local” equations. Here, the fracture or global porosity is often represented as a fraction over the entire domain. The other porosity (local) simply acts as a source or sink to the global equations.

A number of mathematical models describing dual porosity flow have been developed. The differences between each model is a function of the conceptual model upon which they are based, and the methods used to solve the governing equations.

Two idealizations of the porous block geometry are considered here for the dual porosity model: parallel fractures/slabs [Figure 3.0 a,b] and intersecting sets of parallel fractures [Figure 3.1]. Intersecting fractures can be further represented by prismatic or spherical blocks [Figure 3.2], where matrix blocks are imbedded in a network of inter-connected

fractures. Slabs are suitable for predominantly parallel fractures and spheres are suitable for networks composed of orthogonal fracture sets or randomly oriented fractures.

Figure 3.0(a): Dual porosity concept model, parallel fractures

[Source: Huyakorn et al. 1983 b]

Figure 3.0(b): Dual porosity concept model, parallel fractures

Figure 3.1: Dual porosity concept model, parallel intersecting fractures

[Source: Xu and Pruess 2001]

Figure 3.2: Dual porosity concept model, Spherical [Source: Huyakorn et al. 1983 b]

3.2.1 Global Equations for Flow and Transport

The equation of continuity from fluid mechanics is combined with Darcy's law to yield the following equation for flow in porous media (one dimensional, x direction),

$$\frac{\partial}{\partial x_i} \left[K \frac{\partial h}{\partial x_i} \right] = S_s \frac{\partial h}{\partial t} \quad (3-1)$$

where K is the hydraulic conductivity tensor [L/T], h defines hydraulic head [L], and S_s represents the specific storage of the medium [L⁻¹] [e.g. Van Geel, 1999]. This equation can be applied to the DP model by considering a representative elementary volume (REV) consisting of a sufficiently large number of matrix blocks and fractures:

$$\frac{\partial}{\partial x_i} \left[K_g \frac{\partial h}{\partial x_i} \right] = S_s \frac{\partial h}{\partial t} \pm \Gamma_w \quad (3-2)$$

K_g and S_s are now continuum parameters, representing either the fracture or the global system.

A new term is introduced here called the fluid mass transfer term (Γ_w), and refers to the amount of fluid exchanged with the fracture at a given length over time. This term is positive or negative depending on whether fluid is gained or lost from the matrix. This exchange term has been dealt with in different ways, and is of importance primarily under transient flow situations [Zhang et al., 2000; Alboin, 2000; Ray et al., 1997; Bai et al., 1994]. Warren and Root [1963] derived a mass transfer term based on the hypothesis that the flow of fluid from blocks to fractures occurs in response to the difference in the average hydraulic head in the fractures and the average hydraulic head in the blocks.

Zhang et al. [2000] provide a good review for determining the fluid mass transfer term in transient systems. Huyakorn et al. [1983a], review three mathematical models for describing Γ_w (quasi-steady, unsteady parallel fracture and unsteady block fracture flow models). Γ_w has also been treated as a simple adjustment factor used to produce a desired result [Robinson et al., 1998].

Frequently, the immobile-mobile model [e.g. Wallach and Parlange, 1998], under a fully saturated system, is used to describe transport in a dual porosity model. The immobile-mobile model assumes that only the water in the fractures moves and the matrix water remains stagnant. This assures that the matrix has no influence on groundwater flow, only on contaminant transport. The matrix-exchange term is therefore set to zero since it is assumed that no fluid mass is transferred between the matrix and the fractures. This model also assumes that fluid mass accumulation/storage in the fractures is negligible, making the first term on the right hand side of equation (3-2) zero. Since these assumptions suggest steady state flow and a consistent saturation of the matrix, the immobile-mobile model is not typically used in variably saturated situations, where the water content in the matrix would be changing over time.

The classical groundwater advection-dispersion equation can be applied to the global system, which describes the amount of mass transported with the flowing water in the fracture domain (one-dimensional):

$$\frac{\partial}{\partial x_i} \left[D \frac{\partial C}{\partial x_i} \right] - \left[u \frac{\partial C}{\partial x_i} \right] - \Gamma_c = \phi_s \frac{\partial C}{\partial t} \quad (3-3a)$$

where u is the Darcy flux, thus defining the seepage velocity (v) as:

$$v = \frac{u}{\phi_g} \quad (3-3b),$$

C represents the contaminant concentration $[M/L^3]$ at distance $x[L]$, and time $t[T]$, D refers to the dispersion in the fractures $[L^2/T]$ and is described as:

$$D = \alpha_L u + \tau D_m \quad (3-4)$$

where α_L is the longitudinal dispersivity $[L]$, τ is the tortuosity $[L/L]$, and D_m is the diffusivity in the fractures $[L^2/T]$ and is equal to

$$D_m = \phi_g D^* \quad (3-5)$$

The diffusion coefficient in water is denoted as $D^* [L^2/T]$, and I_c denotes the amount of contaminant mass exchanged between the fractures and the matrix (discussed later). Moreno et al. [1997] examined the use of a retardation factor in order to “replace” the mass transfer term which acts to retard the front. Their study found that a retardation factor only accounts for a specific case, and that it has no practical, general utility.

Finally, ϕ_g is the porosity for the fracture or global system. The global system porosity depends solely on the fracture network geometry and can be directly calculated as the volume of the available flow in the fractures divided by the volume of the entire system $[L^3/L^3]$.

Equation (3-3a) assumes that the solute is non-reactive. For reactive (precipitating/adsorbing) solutes, an additional expression would be incorporated into equation (3-3a) to represent the amount of pollutant lost due to sorption at the surface of

the matrix or via other processes. This equation could be expressed as a first-order exchange rate, or it could incorporate a sorption coefficient. Surface sorption in fractured reservoir models is described in various papers [e.g. Moreno et al., 1997].

Ostensen [1998] divides transport in a Cartesian dual porosity system into three time regimes: 1) fracture transport, 2) dual-porosity transport, and 3) total porosity transport. The fracture transport describes a time where the contaminants have not yet commenced significant diffusion into the matrix and advection dominates the contaminant migration. The second phase (dual porosity transport) occurs when most of the contaminant has diffused into the matrix, but has not yet penetrated that deeply into the matrix. The last stage of transport occurs when the contaminant has substantially equilibrated throughout the matrix porosity. Ostensen [1998] further hypothesizes that the early and final stages (except dual porosity) can be represented by the classic single porosity system where the fracture porosity is used primarily (fracture only) and for total transport, the total porosity (fracture and matrix) is used.

3.2.2 Matrix (Local) Equations for Flow and Transport

The movement of solute particles between fractures and the rock matrix includes both an advective component due to fluid flow between the two media, and a diffusive component related to differences in concentration. The model described here includes only diffusive transport between the fractures and the matrix blocks, as indicated earlier through the immobile-mobile model. Mass transport in the matrix blocks is dominated

by molecular diffusion and it can be described with a one-dimensional diffusion equation written for the solute concentration in the matrix blocks.

$$\frac{\partial}{\partial s'} \left[D' \frac{\partial C'}{\partial s'} \right] = \phi' \frac{\partial C'}{\partial t} \quad (3-6)$$

where C' is the concentration in the matrix $[M/L^3]$ at distance $s[L]$, and time $t[T]$, ϕ' is the matrix/primary porosity $[-]$, s' is the space dimension in the matrix blocks $[L]$, and D' is the effective diffusion coefficient of the matrix material $[L^2/T]$. Other than directly measuring the diffusion coefficient, there are several ways to calculate D' . It is typically based on the free water diffusivity of the solute, and it may consider effects of tortuosity, permeability, or geometry. It often depends on the type of rock under consideration and the available parameters. An example of an equation for D' is

$$D' = D^* G \phi' \quad (3-7)$$

where G is a geometric factor derived by Neretnieks [1980], and it is related to the constrictivity and tortuosity of the medium. Quantity D^* is the aqueous (free water) diffusion coefficient. ϕ' was defined earlier as the matrix porosity, and has a direct relation with the effective diffusivity as shown in Figure 3.3, with the matrix porosity equivalent to the volumetric water content under saturated conditions. The numerical model described in Chapter 7 (SWIFT) incorporates tortuosity into the equation for D' .

Figure 3.3: 300 Diffusion Coefficients for Various Geologic Media as a Function of Volumetric Water Content [Source: UFA Ventures © 1996]

Equations (3-3) and (3-6) are coupled by the continuity of the diffusive mass flux at the interface of the fracture and the matrix block. The rate of solute transfer between the matrix block and the fracture can be expressed by applying Fick's law. The mass transfer term for a matrix block unit is [Figure 3.0(b)]:

$$\Gamma_c = -AD' \frac{\partial C'}{\partial s'} \quad (3-8)$$

where $A [L^2]$ represents the area of the interface between the fracture and the matrix. The matrix system is one-dimensional and perpendicular to the fractures (s direction in the equations 3-4 to 3-6).

For a rectangular prismatic matrix block as shown in Figure 3.0 (a, b), where l is the length of the block $[L]$, d is the width $[L]$ and a is half of the block width $[L]$, and Γ_c is given by Huyakorn et al. [1983b] as:

$$\Gamma_c = -(D \left. \frac{\partial c'}{\partial s'} \right|_{s'=a}) * \left(\frac{2ld}{2ald} \right) \quad (3-9a)$$

$$\Gamma_c = -\frac{1}{a} (D \left. \frac{\partial c'}{\partial s'} \right|_{s'=a}) \quad (3-9b)$$

Similarly, for a spherical matrix block [Figure 3.2] with radius $a [L]$, the mass transfer term was given by Huyakorn et al. [1983b] as:

$$\Gamma_c = -\frac{3D}{a} \left. \frac{\partial c'}{\partial r'} \right|_{r'=a} \quad (3-9c)$$

Transport of solute particles in the matrix parallel to the fractures is assumed to be negligible.

3.3 Matrix Diffusion

As mentioned earlier, during contaminant transport through fractured rock, contaminant species may interact with the rock, and may be chemically adsorbed on the fracture

surfaces. They may also diffuse into the stagnant water in the pores of the rock and be sorbed onto the inner pore surfaces. Matrix diffusion has been studied extensively for various purposes. Surface adsorption typically occurs on the surface of the matrix and is represented by various equations. However diffusion can potentially carry contaminants into the entire pore network and hitherto the entire volume of the matrix can provide for a larger retardation than for surface adsorption alone.

Rasmuson and Neretnieks [1981] described diffusion into the rock matrix as occurring in three stages: (1) diffusion of the component from the water in the fracture zones to the external surface of the blocks (external or film diffusion), (2) diffusion through the porous network of the blocks (internal diffusion), and (3) the sorption process, when the component is bound to some sorption site in the pores or microfissures.

The amount of diffusion will depend upon the porosity and diffusive properties of the matrix and solute, as well as the surface area of the matrix. Ahn et al. [1984] defined two porosities associated with the matrix: a diffusion porosity and a residual porosity. The diffusion pores are interconnected with fractures and affect the transport of solutes. The residual pores are not connected to the fractures and do not affect solute migration. This is the reason that the total porosity is not a good approximation of "diffusion porosity", and specific diffusion tests should be used to verify the diffusion porosity. Consideration has also been drawn to cases where changes in matrix porosity would reflect on changes in diffusion. For example, Skagius and Neretnieks [1986b] demonstrated how rock samples existing at repository depths are exposed to rather high stress, and when removed

for sampling, the porosity of the rock samples increased causing an increase in effective diffusivity.

Matrix diffusion is a slow and transient process, which can rarely be assumed to have reached a steady state, and therefore it may have a long term effect on the transport phenomenon of the modeled domain. Diffusion into the rock is not important if the contact time between rock and contaminants is too short or if the diffusion coefficients are too small [Moreno et al., 1997]. Diffusion into the matrix is only relevant when the velocity of the groundwater flow is slow, i.e. slow enough to allow for sufficient time for the solute to diffuse into the rock matrix. For example, Hoag and Price [1997] showed additional delays for initial breakthrough in dual media material for low flow velocities in comparison to higher flows since there was more time for the solute at the front to diffuse into the matrix pores. Grisak and Pickens [1980] found in their modelling study that fracture velocities needed to be higher than “most conceivable hydrogeological conditions” before the effects of matrix diffusion could be eliminated.

More complex matrix diffusion processes may consider multiple-species transport, radioactive contaminants, fracture skins or matrix replenishment.

Huyakorn et al. [1983c] described the transport of multiple species into a matrix where calculations become very complicated as multiple interactions and decay processes are occurring within one section of rock.

In the case of radioactive contaminants, the migration distance is finite because of decay [Tang et al., 1981]. The porous matrix in this case may be viewed as a reservoir which holds the contaminant until it decays.

The deposition of a thin layer of low permeability material, referred to as a fracture skin, may disrupt the free exchange of fluids between the rock matrix and the fracture [Moench, 1984; Robinson et al., 1998]. Fracture skins may be created through chemical precipitation reactions or through simple material deposition at the surface of the matrix. As fracture skins might develop or increase, the diffusion coefficient may change significantly with time.

The influence of matrix replenishment (diffusion out of matrix block) deserves attention because the solute is stored in the matrix temporarily and can be rendered gradually to the fracture system when the contaminant front has passed. After the source has been removed, these low permeability zones will serve as low concentration sources for ongoing contamination. The removal of contaminant from these lower porosity zones may be rate limited, such as diffusion out of the low porosity material.

3.3.1 Mass Transfer Term

Mass transfer in dual-porosity models is frequently approximated using a first-order differential equation. More sophisticated formulations that consider analytical solutions of flow and transport into or out of porous matrix blocks of known size and shape are generally limited to relatively simple situations, such as for well defined matrix or block

geometries. Gerke and van Genuchten [1996] derive expressions that appropriately describe the structural geometry of a dual-porosity medium using parameters that can be related to measurable properties. Lim and Aziz [1995] provide a good discussion of shape factors used to determine diffusivity. Dershowitz and Miller [1995] present a dual porosity/matrix diffusion model based on realistic fracture geometries. Gilman [1986] presented a 1-d fully implicit two phase numerical simulator in which matrix blocks are represented by several subdomains in a given gridlock. A study by Zimmerman and Bodvarsson [1995] provides a good discussion of matrix size and shapes, and their relevance in the matrix diffusion equation and hence the mass transfer term.

3.4 Summary

Solute transport through fractured media is often described by the immobile-mobile model as a combined process of advective-dispersive transport in the fractures, and diffusive (Fickian) transport into the surrounding matrix blocks.

The dual porosity concept considers the fractures and the matrix as two separate but overlapping continua, coupled through a mass transfer term. The dual porosity model is a powerful method that can be made very complex, involving multi-species transport and/or transient flow. The immobile-mobile model is typically applied to the DP model where fluid flow is not affected by the matrix blocks, but the blocks have an effect on plume retention through matrix diffusion. Although matrix diffusion has been the core of many studies, it continues to be a challenge to fully understand its behaviour when

analyzing a full fractured rock system. There is no single correct way to model the diffusive interaction term in a DP system, as the assumptions and conceptual model set up by the investigator will dictate the outcome.

CHAPTER 4

4.0 Experimental Program

An experimental program was undertaken to construct a physical model to simulate an in-pit TMF with a pervious surround in a dual porosity zone. The three primary objectives of the physical model were:

- (1) Quantify the effect of matrix diffusion on slowing down the movement of the contaminant front;
- (2) Assess the impacts that the pervious surround and the dual porosity rock have on reducing the net mass flux down gradient of the tailings facility; and
- (3) Make observations and measurements against which a numerical model could be compared, in order to validate its ability to model the in-pit TMF system with the surrounding host rock represented as a DP medium.

The test system attempted to use the same dimensions that were used in a previous physical model constructed by West [2001] at Carleton University, to permit the comparison of test results. A number of ancillary tests and tracer tests were conducted to obtain all of the necessary parameter estimates required as input for the numerical model.

The following chapter is divided into two principal sections. Section 4.1 describes past relevant experimentation, the current dual porosity TMF physical model including design, construction, testing and preliminary tracer tests. Section 4.2 describes ancillary tests that were made in order to establish values for the numerical model input. In

addition, the range of values obtained from the ancillary tests were used for a sensitivity analysis (Chapter 5) of the model's response to changes in dual porosity input parameters.

4.1 Overview of Physical Model

The idealized laboratory scale in-pit TMF was created within a 2.7 (length) x 1.45 (width) x 1.0 (height) m steel casement. The steel casement contained a 2.3 (length) x 1.35 (width) x 0.72 (height) m physical model with a 0.2 m wide reservoir at each end. The dual porosity host rock was represented by a layered concrete block system, with sand filled fractures between the blocks. The pit was 0.91 m in diameter, and 0.48 m in depth. The pit was lined with a 0.025 m thick pervious surround. Tailings were placed adjacent to the pervious surround. Since transport within the tailings is diffusion dominated (i.e. negligible advection), and to aid in constructing the model, the centre of the pit was filled with a 0.76 m steel drum, and a tailings layer of 0.05 m was placed between the drum and the surround. An idealized schematic plan layout of the system is presented in Figure 4.0. Assembled and exploded diagrams of the model are shown in Figures 4.1(a) and 4.1(b) respectively. Corresponding isometric top view photographs are shown in Figure 4.2 (a, b).

Units=mm

Figure 4.0: Overview of Dual Porosity TMF Physical Model

Figure 4.1(a): Dual Porosity TMF Physical Model

Figure 4.1(b): Exploded View of Dual Porosity TMF Physical Model

Figure 4.2: (a) Actual Physical Model, Upgradient Top View

Figure 4.2: (b) Actual Physical Model, Downgradient Top View

4.1.2 Previous Apparatus

Two physical models were constructed at Carleton University prior to this work, each representing a different conceptualisation of the host rock surrounding an in-pit TMF with a pervious surround design.

In one model, the host rock was conceptualised as an equivalent porous medium (EPM). The EPM host rock consisted of screened, washed mortar sand from a local pit. The sand had a mean grain size of 0.3 mm, and a packed hydraulic conductivity of 6×10^{-5} m/s. For a complete review of the sand properties and methods of EPM placement, see West [2001].

The other model represented the host rock as a basic network of discrete fractures. Five slabs of Indiana limestone were lain one on top of another inside the box, exposing four gaps as conduits for groundwater flow between the two end reservoirs. Two fractures intersected a 0.9 m diameter, and 0.45 m deep tailings pit lined with a pervious surround design. Two materials were used in the surround design: the mortar sand that had been used as the EPM material and a 3-6mm diameter filter gravel with a hydraulic conductivity of 0.06 m/s. For a complete review of the gravel properties and discrete fracture placement, see West [2001].

The procedure used to fill the pit involved the placement of a 20 mm lift of pervious surround material into the bottom of the containment pit. In order to line the perimeter of the pit with the surround, an 860 mm diameter geotextile-lined steel mesh drum was placed on top of the compacted material, leaving a 20 mm gap from the pit wall. The

mesh drum also had the dual purpose of preventing the tailings from mixing with the surround material. The 20 mm gap was filled with the surround material in lifts to ensure even compaction.

The tailings were represented by ground silica the size of medium-grained silt [West, 2001]. The measured hydraulic conductivity of the tailings ranged from approximately 1×10^{-6} m/s for a loosely compacted material to 1×10^{-7} m/s for tightly compacted material. A known mass of silica was partially saturated with a solution containing a known mass of sodium fluorescein dye (trade name Uranine), to achieve a final design source concentration. The tailings (silica) were compacted into a 50 mm lift in the bottom of the pit. Ideally the rest of the pit would have been filled with silica; however this would require extensive labour and extra cost, which lead to the decision of using a steel drum lined on its bottom and sides by the tailings. Therefore a 760 mm steel drum was placed on top of the tailings, which left a 50 mm gap between the drum and the mesh. The tailings were then placed in the 50 mm gap surrounding the steel drum in shallow lifts, which were carefully compacted. The measured porosity for the moderately packed silica was 0.4 (vol/vol).

Piezometers were installed in both models, however due to the nature of the set-up, more piezometeres could be placed in the EPM model. Sample ports for dye concentration measurement were installed throughout both models, primarily down gradient and along the centreline downstream of the pit.

4.1.2.1 Previous Experimental Testing

The EPM gravel-surround and sand-surround experiments were each repeated once, for a total of four EPM experiments. The DF gravel-surround experiment was repeated once, but the DF sand-surround experiment was not repeated, for a total of three DF experiments [West, 2001].

At the outset of an experiment, the reservoir levels were raised to the top of the system to allow for complete saturation, and then the down-gradient reservoir overflow was lowered to achieve the desired gradient. The difference in upstream and downstream reservoir water levels ranged from 5 to 50 mm for all experiments. Estimation of heads and discharge were accomplished through measurement of piezometric head and downstream overflow. The estimate of the tailing's concentration was determined both at the beginning and at the end of the experiment. The sampling times and locations were performed according to the progression of the plume. The gradient across the model was adjusted after a specific time to make observations regarding flow and solute transport. Sampling of the ports and piezometer measurements continued after this change until the end of the experiment.

4.1.3 Building the Dual Porosity Physical Model

The current model was built in four main stages. The first stage involved the preparation of the casement, and the construction of a device to constrain the blocks at each end of the model, and sealing the blocks along the sides of the casement with bentonite. The

second stage consisted of placing the blocks in the casement, and cutting the blocks to form a circular pit in the 7 upper layers (400 mm). The third stage involved the placement of the surround material and the steel filter fabric faced mesh drum. The final and fourth stage involved making and placing the tailings to surround the steel drum. Measuring instrumentation was placed during the first two stages. Figures 4.3(a) and 4.3(b) present scaled top and side views of the physical model, respectively.

In addition to the pictures found in this Chapter, a full set of construction photos are found in Appendix E.

Figure 4.3 (a): Side view of Physical Model

Units=mm

Figure 4.3 (b): Plan Top View of Physical Model

4.1.3.1 Casement

One layer of limestone, remaining from the previous project by West [2001], was used as a base for the dual porosity model. The limestone measured 2.3 x 1.35 x 0.17 m in size. The limestone was left in place to provide a well defined seal and lower boundary, and also to reduce the work required to construct the dual porosity model. A 1.45 m x 0.9 m steel grating lined with a filter fabric was used to constrain the blocks at each reservoir. The grating (2.5 cm thick), provided for a rigid end constraint while allowing for unimpeded water flow from the blocks. The grating was cut to size using a circular saw with an abrasive metal cut-off disc. The grating was then scraped, sanded, and painted with a rust inhibiting primer, and two top coats of epoxy paint. The grating was covered with a filter fabric and placed at each end of the limestone slab. The fabric prevented sand from being washed out of the fractures, into the adjacent reservoirs. Figure 4.4 shows a section of the steel grating. Four 5 mm thick steel plates were cut from one large plate using a torch to a width of 0.2 m and a height of 0.9 m. Two steel plates were placed vertically at each end of the reservoir to ensure that the steel grating would not move once the blocks were placed inside the casing.

Figure 4.4: Casement, Steel Grating

A 5 cm gap at each lateral side of the limestone was filled with bentonite to provide for a no flow boundary condition. A device was placed at each end of the bentonite seal against the grating to prevent the bentonite from entering the end reservoirs. The device consisted of two steel angles combined to form a channel section. The steel angles were fastened together using self tapping metal screws. The resulting channels were then fastened to the grating using toggle bolts. Once this channel was placed in all four corners of the container, the toggle bolts were tightened. Figure 4.5 shows one of the channel devices fastened to the grating using a toggle bolt.

Figure 4.5: Channel Shape Angle Attachment to Steel Grating

4.1.3.2 Host Rock

The matrix was represented by concrete rectangular-prism blocks. The block dimensions were 190 (length), by 90 (width), by 58 (height) mm.

Figure 4.6: Matrix, Concrete Block (units=mm)

The first layer of blocks were placed one next to another, to allow for the smallest possible gap (2mm) until the entire surface of the limestone was covered. In order to achieve exact coverage of the limestone, the blocks at one side of the model were cut on a bench standing “quick cut” tool using a diamond tipped cut off blade (typically used for concrete and blocks). Sand (EPM sand, porosity of 0.4) was spread over the block surfaces and the system was compacted with a hand tamper to allow the sand to fill the block interstices. This step was repeated at least four times, or more until the sand filled all fractures. A small amount of sand was then placed on top of the first completed layer of blocks (2mm). The sand helped to smooth over any irregularities in the blocks.

Bentonite was placed loosely on the sides of the outer blocks to laterally constrain them and provide a seal between the outer block and casement. A second, third and fourth layer of blocks were placed in the same manner. Then a 900 mm diameter steel drum cylinder, was placed on the completed fourth layer (height = 240 mm), to indicate the required hole size for the tailings pit. This allowed for the secure and exact placement of blocks to form the proper shaped pit. The fifth layer of blocks was placed in the same manner, except next to the steel drum cylinder, where the blocks had to be measured and cut to conform to the circular shape. The remaining 7 layers of blocks were placed in similar fashion thus completing a 12 block high overall system (final height = 720 mm).

4.1.3.3 Surround

The steel cylinder was carefully removed, leaving a carved out circular pit. The pit was then measured and found to have an average diameter of 910 mm (slightly larger than 900 mm due to gaps when cutting the blocks). A 25 mm lift of the surround material (gravel, sand) was placed in the bottom of the pit. A filter fabric lined steel mesh cylinder (diameter=860 mm) was then placed on top of the 25 mm lift, centered in the circular pit leaving a 25 mm gap all around. This gap was filled with the surround material in compacted lifts. Figure 4.7 depicts the placement of the surround and filter fabric lined steel mesh cylinder.

Figure 4.7: Stage 3, Pervious Surround and Mesh Cylinder (units=mm)

4.1.3.4 Tailings

The silica was mixed in a concrete rotating drum mixer with a known mass of dye dissolved in water. The ratio of water to silica was chosen to maximize the water content to improve compaction without any water leaving the material during compaction [West,

2001]. 320 mg of fluorescein dye were mixed with 26 litres of water and added to 126 kg of silica. Based on a tailings porosity of 0.4, this would create a design source concentration of approximately 10,000 ppb in the tailings pit, once fully saturated. Two or three equal size batches (differed for each experiment) were needed to create the tailings mix. Once the tailings were mixed, they were placed in a 50 mm thick lift in the bottom of the pit. A 760 mm steel drum was then placed on top of the tailings, leaving a 50 mm gap between the drum and the wire mesh cylinder. The steel drum was used by West [2001], and during this study to save time and resources in completely filling the pit. West [2001] performed several preliminary numerical model simulations to show that advection through the tailings was negligible for the gradients and time frames used for the physical modelling. Tailings were placed in the gap in 5 cm, well-compacted lifts. Several samples of tailings were collected and analyzed to ensure the design source concentration had been achieved. Figure 4.8 shows an actual picture of the compacted tailings held in place by the mesh drum on one side and the steel drum on the other.

Figure 4.8: Tailings and Steel Drum

4.1.3.5 Flow

Overflow pipes in the up-gradient and down-gradient reservoirs controlled the water levels in the respective reservoirs and thus the hydraulic gradient across the physical model could be controlled. The height of the water was measured against a specified datum level. Flow was measured by noting the volume of water being received by the down-gradient overflow pipe over a specified time. A limited number of piezometers were installed to assess the hydraulic head and flow characteristics, since it was thought that locating additional tubing along the fractures would disrupt the overall dual porosity representation significantly. The water used for the experiment was first directed through the existing EPM sand model adjacent to the current model, to allow the water to reach ambient temperature and to de-air. The water from this EPM sand model was used to fill a container that drained into the current model under gravity through a control valve. It did not matter if the inflow varied, as the overflow device located at the upgradient reservoir maintained the desired up gradient reservoir level.

4.1.3.6 Instrumentation and Measurement

A limited number of sample ports were installed within the model in order to minimally disrupt the finite fracture-matrix system. Sample ports were installed at the bottom and sides of the surround, and at different depths throughout the matrix-fracture (block-sand) system [Figure 4.9 (a)]. Each port consisted of a length of 0.5 mm ID plastic tubing, attached to a 23 gauge needle at the sampling end. For the ports located within the block-

sand system, solution was drawn into the tube directly. The ports located within the surround material drew water in through the opposite end of a needle covered by a piece of filter fabric to ensure that sand would not enter the tube [Figure 4.9 (b)]. The needle was attached to a PVC sample panel [Figure 4.9 (c), and Figure 4.10]. A 1 ml syringe was attached to the needle to allow for sample collection. The purge volume was approximately 0.2 to 0.5 ml for plastic tube lengths ranging from 0.5 to 2 m.

Figure 4.9 (a) Tube collecting water from block-sand section (b) filter fabric/needle system used to collect water from surround (c) typical sampling panel

Figure 4.10: Sampling device

A TD-700 fluorometer analyzed the samples for fluorescence. The TD-700 calibration procedure sets the instrument's range and sensitivity based on a fluorescent sample or a set of standards [Turner Designs, 2000]. The instrument can be calibrated using single or multi-point calibration. For direct concentration readout and highly accurate measurement, the multi-point calibration procedure was used. The fluorometer was re-calibrated between each successive experiment.

The fluorometer was calibrated to display the concentration of tracer in units of parts per billion (ppb), or micrograms per litre ($\mu\text{g/l}$). Calibration standards were prepared by serial dilutions from a standard stock solution of 1 g/l and ranged from 1 ppb to 500 ppb. The same stock solution was used for the tailings source mix.

Once a sample was collected, approximately 0.2 mls of the sample was injected into a small glass tube and inserted into the fluorometer. The “discrete sample averaging

method” was used for sample analysis. This process took 24 seconds in total during three stages of operation: 1) a 7 second delay for the signal to stabilize, 2) a 12 second averaging period, and 3) a 5 second display of read out [Turner Designs, 2002]. When time permitted, duplicate samples were taken.

4.1.4 Physical Model Test Procedure

The laboratory test procedure of the physical model consisted of four principal experiments. After the completion of the first four block layers of the dual porosity model, a hydraulic conductivity and instantaneous point source tracer test were performed. These tests were useful in determining the parameters needed for computer modelling.

The full physical TMF dual porosity model was tested three times. The gravel surround configuration was completed twice, and the sand surround configuration was performed once. Measurements for each experiment were taken for approximately one month.

4.1.4.1 Initial Flow and Tracer Test of Four Block Layers

After the completion of the bottom four layers of block (depth = 0.24 m), a flow and tracer test were performed. Flow and tracer tests were used to establish an overall conductivity of the block-fracture system, and to attempt to determine transport parameters (dispersivity, porosity) required for the numerical model. A 0.5 mm ID tube

was placed under a block located at the top layer at the up gradient end of the model to allow for the injection of a predetermined source. A known volume and concentration of dye solution was injected into the physical model over a short period of time. Once all of the dye was injected, readings were taken at hourly intervals, or according to the progression of the plume. A few days after the test ended, the system was washed out with hot water, for several days. This test was repeated three times. The mass of dye injected was increased each time, as better results were noticed as the concentration and volume of dye solution injected increased. Of the three tests completed, only the experiment with the largest mass released (injection of 3 mls of a 1 g/l solution of dye) results in measurable concentrations at the downgradient sample locations. Figure 4.11 provides a schematic cross section of the four layer block system and Figure 4.12 shows the locations and coordinates of the sample ports. All ports except for port 8 were located at the top fracture plane (height=18 cm). Port 8 was located at the top of the second layer of bricks (height=12 cm).

Figure 4.11: Four Layer Block-Sand System (y-z plane)

Port No.	1	2	3	4	5	6	7	8
x coord m	1.538	1.538	1.538	1.919	1.919	2.109	2.109	1.919
y coord m	0.548	0	0.125	0	0.194	0.319	-0.32	0.125
z coord m	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.12

Figure 4.12: Top View (x-y plane) of Sample Points, and Corresponding Table of Coordinates

4.1.4.2 Testing of Full Scale Physical Model

Once the full scale physical model was constructed and the compaction of the tailings was completed, each reservoir was slowly filled to allow for full saturation of the system; both the rock matrix and the fractures. This was accomplished by raising the water level to the midpoint of each block layer and allowing the block to saturate due to capillary forces. An experiment was conducted to determine that it took approximately 7 minutes for a block to fully saturate by capillary forces. Once a block layer reached saturation, the water level in each reservoir was again raised by one block thickness allowing the next block layer to saturate. This process was repeated until the entire system was saturated, which took approximately one hour. Immediately after saturation, the experiment was initiated and the downgradient overflow was lowered by 1 cm to create a hydraulic gradient across the system of 0.004 m/m. Port sampling and flow measurement began immediately at this point. Measurements were taken aggressively at the beginning, within minutes of each other, and then tapered off as the plume migrated through the system. Figure 4.13 (a,b) shows the port locations, and the corresponding coordinates are found in Table 4.0. West [2001] adjusted the gradient across his experimental system after the mass flux to the downgradient reservoir approached a steady state condition. The gradient was adjusted to evaluate the impact of flow in the pervious surround on the downgradient concentrations and net mass flux to the downgradient receptor. Similarly, during each experiment conducted for this study [typically after 16 to 20 days], the gradient was increased at a certain time by lowering the overflow in the downgradient reservoir. This increased the gradient across the model by a factor of two]. At the completion of an experiment, the tailings concentration was measured at several locations

selected along the top tailings layer (accessible), the tailings and surround were removed, and warm water was passed through the system for five to seven days. Sampling was performed periodically throughout this “flushing” period to ensure that no dye remained in the system. The top few layers of blocks were often rebuilt due to the bentonite penetrating into the top few fracture planes which pushed the blocks at the sides up slightly. Experiments 1, 2 and 3 were conducted for 18, 50 and 30 days respectively.

(a) Sample Points (x-y plane)

(b) Sample Points (x-z plane)

Units = meters

Figure 4.13(a, b): Sample Points (Dual Porosity, TMF Physical Model)

Table 4.0: Coordinates of Individual Sample Points

X,y,z(m)	1a	1b	1c	1d	2	3	4	5a	5b	6	7	8
X	2.11	2.11	2.11	2.11	1.92	1.92	1.92	1.73	1.73	1.73	1.73	1.73
Y	0.00	0.00	0.00	0.00	0.00	0.13	-0.07	0.00	0.00	0.62	-0.26	-0.37
Z	0.60	0.48	0.30	0.12	0.24	0.60	0.60	0.48	0.12	0.54	0.54	0.48
10b	12	14	15	16	17a	17b	17c	18b	18a	19a	19b	20a
1.54	1.34	1.15	0.77	0.68	1.13	1.13	1.13	0.68	0.68	0.98	0.98	0.98
0.00	0.00	0.00	0.54	0.00	0.00	0.00	0.00	0.44	0.44	0.35	0.35	-0.35
0.48	0.30	0.30	0.54	0.24	0.60	0.48	0.30	0.24	0.48	0.48	0.24	0.48

4.2 Ancillary Tests

A series of preliminary tests were conducted to estimate the necessary input parameters for the dual porosity model. The resulting parameters or parameter ranges are indicated in the following section and encompass:

- Matrix Porosity
- Hydraulic Conductivity
- Fracture Porosity
- Matrix Diffusivity

The ranges for these parameters were determined experimentally. However to further calibrate the model, the parameters were adjusted within the acceptable ranges to fit the experimental tracer test data (Chapter 5) and full pit simulation data (Chapter 7).

4.2.1 Material Discussion

As previously noted, the matrix material is represented by concrete blocks. Several materials were tested before this selection was made, and the concrete blocks proved to be the most suitable choice primarily due to their high porosity, geometry, and cost. It was noted that the nature of the concrete introduced a level of uncertainty in measuring certain parameters. For example, the porosity of each block sample was expected to differ slightly, since each sample may not consist of the same amount of aggregates, cement air voids, etc. When assessing the diffusion and hydration properties of a concrete material, another important issue to consider is the difference in volume proportions of the surface layer of the concrete. Because of the fabrication and finishing, the outer surface of the concrete will most likely contain a higher volume of cement paste and less coarse aggregate than the bulk of the concrete.

4.2.2 Water Content

Water content can be evaluated by several different methods. The simplest method is the water loss method, where a sample of saturated rock of known volume is weighed, dried

at 100°C, and reweighed. This procedure was used to measure the water content for the concrete blocks. This procedure is outlined in ASTM Annual Book of Standards [1984].

The block was placed in a glass container, filled with a small volume of water (depth=1 cm), in order to saturate the brick by capillary forces. The container was slowly filled with water until the depth of water exceeded the depth of the brick by 5 cm. The container was vacuum sealed to promote removal of excess air in the water and block. The block remained in the water for one day, and then was removed, residual water was wiped off, and the wet weight of the block was measured using a scale. The block was placed into an oven at 100°C for 2 days, or until the weight did not fluctuate by more than 1 milligram. The volume of water was determined by subtracting the dry mass from the wet mass. The water content was set equal to the volume of water divided by the volume of the brick. The average water content was 0.08 (vol/vol), and ranged from 0.05 to 0.11 (vol/vol).

4.2.3 Leaching

Leach tests were conducted to ensure that no chemical/additive in the concrete would impact the measurement of the fluorescent dye. Two leach tests were conducted. First, a block was placed in clear water and observations of the water were noted. Since no cloudiness or change in water color were noticed it was assumed that the blocks were not leaching any additives into solution. Second, the block was placed into a container of dye and water solution (pre-measured), and the solution was sampled using the

fluorometer over a period of a few days. It was assumed that the measurement of fluorescence would decline slightly due to diffusion, however no significant change in measurement occurred, since the volume of water was significant in comparison to the volume of the brick. The consistent fluorescence measurements ensured that the nature of the material would not impact the measurement of the dye concentrations.

4.2.4 Diffusivity Tests

The primary mechanism considered for transport of compounds within the chosen concrete is through Fickian diffusion. The effective diffusivity (D_e) is the coefficient that determines the extent to which a soluble component is transported by diffusion in a solid [Kyi and Batchelor, 1994]. The term “effective diffusivity” is reserved to describe transport in accordance with Fick’s law that is solely due to physical diffusion and not a chemical or adsorption derived reaction [Kyi and Batchelor, 1994].

4.2.4.1 Measuring Effective Diffusivity

Measurements of effective diffusivity typically involve measuring the flux of the contaminant through the solid matrix, and by measurements of the concentration profile at select distances along the solid. These methods are often time consuming, but relatively easy to perform. Common tracers used for these tests include uranine, tritium and iodide. Other methods may use electrical conductivity tests [Kyi and Batchelor,

1994; Skagius and Neretnieks, 1986b], which measure the movement of ions through the material.

If properties such as water content, air content, and aggregate size are known for the concrete batch, there are several available equations that can be used to estimate diffusivity. Sharif et al. [1999] developed a new technique for determining effective chloride ion diffusion in concrete that takes only 3 to 4 hours to complete.

4.2.4.2 Method

Five rectangular test specimens were cut from several block samples to a uniform size of 7.5 (height) x 8.5 (length) x 1.1 (width) cm. The water content of the specimens were determined using the water saturation method (section 4.2.2). The average porosity was 0.07 (n=5).

The apparatus selected to measure diffusion has been previously used by many researchers including Dykhuizen and Casey [1989], and Skagius and Neretnieks [1986a]. The apparatus used to measure diffusivity consisted of two Plexiglas reservoirs separated by the block specimen. The edges of the rock specimen in contact with the Plexiglas reservoir were sealed with silicone to prevent any leakage from occurring. The integrity of the seal was tested by inducing a pressure gradient across the rock slab, to ensure no flow due to leakage [Dykhuizen and Casey, 1989]. Each side of the cell was slowly filled up with water to allow sufficient time for proper saturation of the block. The reservoir on each side of the block specimen had a volume of approximately 1.5 litres. Once the

block was saturated, a known mass of fluorescein dye (uranine) was mixed into one side of the container to create a solution of 10,000 ppb [Figure 4.14]. 0.2 millilitre triplicate samples were collected periodically from each reservoir using a 1 millilitre syringe, and the concentration was measured using the fluorometer (Section 4.1.3.6). Concentrations were recorded once a day for at least 30 days.

Figure 4.14: Plexiglas Cell, Rock Specimen Separating Two Chambers

4.2.4.3 Solute Transport Equation

The equations that quantify diffusive transport through the block specimen are described in several articles [Dykhuisen and Casey, 1989; Skaigius and Neretnieks, 1986a]. The transport rate from the reservoir with a high concentration (C_0) of tracer through the rock sample of thickness d and cross sectional area A , to the adjacent reservoir of volume (V),

with an initial concentration of zero can be described by Fick's first law, whereas the concentration change $C(t)$, at the outer boundary of the specimen is described by Fick's second law. The following analytical solution for Fick's 2nd law can be used to fit the breakthrough curves obtained by measuring the concentration change in the receiving cell:

$$C(t) = \frac{AdC_o}{V} \left(\frac{D_e t}{d^2} - \frac{\alpha}{6} - \frac{2\alpha}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} \exp \left[-\frac{D_e n^2 \pi^2 t}{\alpha d^2} \right] \right) \quad (4-1)$$

where D_e is the effective diffusion coefficient [L^2/T] and α is the rock capacity factor [-]. As time becomes large, the higher-order exponential terms become progressively smaller and one may estimate the exponential terms as dominated by the first-order term of a series expansion. In the limit as t goes to infinity, the concentration time dependence becomes [Skaigius and Neretnieks, 1986a]:

$$C(t) = \frac{AdC_o}{V} \left(\frac{D_e t}{d^2} - \frac{\alpha}{6} \right) \quad (4-2)$$

The assumptions relevant to equation 4-2 are that D_e is constant, the concentration in the first cell, C_o is constant with time and much greater than C and all times ($t \geq 0$). The slab is considered homogeneous in thickness and quasi-steady state is reached. These assumptions were assumed to be reasonable for the laboratory experiments performed.

The two fitting parameters (effective diffusivity, D_e and rock capacity factor, α), were changed to best fit the slope of the linear part of breakthrough curve (i.e. lowest R^2 value

for slope). The measured value of water content was used as an initial value for the rock capacity factor [Skagius and Neretnieks, 1986a].

Concentration versus time data for all five diffusivity tests are presented in Appendix B, and their graphical relations are shown in Figures 4.15 (a, b, c, d, e). The fitted diffusivity and porosity values are shown in Table 4.1. Most curves experience a short lag time, followed by a steady linear increase in concentration over time, as suggested in literature. Figure 4.15 (b) shows the trend exhibited by one of the five tests performed, test 2. In test 2 (highlighted in Table 4.1), the initial readings rapidly increased from a very low concentration to a higher concentration in a short amount of time. The data was treated by subtracting an average base value from all data points. It was postulated that a certain mass of dye was released into the downgradient reservoir due to sampling or slight overflow from the upgradient reservoir.

Table 4.1: Parameters for Diffusivity Tests

Test	Fitted Porosity (vol/vol)	Effective Diffusivity (D_e) m ² /s	Measured Porosity (vol/vol)
Test 1	0.04	3*10 ⁻¹²	0.076
Test 2	0.04	3.1*10 ⁻¹²	0.078
Test 3	0.07	3.8*10 ⁻¹²	0.065
Test 4	0.06	2.9*10 ⁻¹²	0.080
Test 5	0.02	4.2*10 ⁻¹²	0.068

The values for effective diffusivities were very similar and all of the same order of magnitude. The fitted porosities were much lower than the actual measured porosities (obtained by water saturated method). This trend was also observed in Skagius and Neretnieks [1986a]. They hypothesized that a smaller amount of pores could have been available for diffusion to explain the lower porosity, but indicate that this method of determining porosity is not completely accurate.

Figure 4.15(a): Diffusivity Test 1

Figure 4.15(b): Diffusivity Test 2

Figure 4.15(c): Diffusivity Test 3

Figure 4.15(d): Diffusivity Test 4

Figure 4.15(e): Diffusivity Test 5

4.2.5 Geometry

The geometry of the dual porosity system was examined to estimate a fracture porosity. The fracture porosity, as discussed in Chapter 3, in general terms is the volume or area of fractures divided by the entire modelled volume or area (fractures and matrix). The fracture aperture of the modelled system was approximately 2mm. The spacing between fractures was 19.2 cm in the x direction, 9.2 cm in the y direction and 6.0 cm in the z direction. The fracture porosity based on surface area ratio (i.e. surface area of voids in fractures in y-z plane divided by total surface area of system in y-z plane) is 0.022, and based on a total volume ratio (i.e. volume of void space in fractures divided by total volume of system) is 0.026. Since flow is predominantly horizontal and the fracture porosity is used to calculate the effective seepage velocity, the effective porosity of the surface area perpendicular to flow was used in the numerical model to correctly simulate the transport.

4.2.6 Hydraulic Conductivity

4.2.6.1 Matrix

The apparatus used to measure diffusivity [4.2.4.2], was useful in determining whether advective flow would occur through the block. To get an indication of the potential advective flow, only one reservoir was filled with water and the flow across the test specimen evaluated. Careful visual inspection of the monitored pores revealed that no holes existed where water was moving out at a fast rate and only a few drops of water

appeared on the downgradient face of the test specimen over an extended period of time. Hence it was assumed that advection in the blocks can be neglected and the immobile-mobile model was used.

4.2.6.2 Fractures

Hydraulic conductivity tests were performed by measuring the flow through the four layer block system using an overflow device located at the down gradient reservoir. The flow was measured over a short period of time. The estimated seepage rate of the fractures was calculated based on the calculated area of the fractures perpendicular to flow (y-z plane), the sand porosity of 0.4, under the imposed gradient. Interference effects at fracture intersections (head loss) were considered as negligible according to Wilson and Witherspoon [1976]. The estimated average seepage velocity within the horizontal fracture planes was 6.0×10^{-5} m/sec. The corresponding seepage flow rate through the entire system (global) was found based on the total flow area in the horizontal plane (fractures and block) and the estimated fracture porosity ($v=6.67 \times 10^{-5}$). The hydraulic conductivity of the fractures ranged from 0.0127 m/sec to 0.0154 m/sec. The hydraulic conductivity for the total system (global) ranged from 0.00028 m/sec to 0.00034 m/sec.

CHAPTER 5

5.0 Computer Modelling and Dual Porosity Sensitivity Analysis of Tracer Tests

SWIFT is a fully-transient, three-dimensional model used to simulate groundwater flow, heat (energy), brine and radionuclide transport in porous and fractured geologic media [Geotrans, 2000]. SWIFT can be applied to a variety of groundwater problems, ranging from simple well flow to complex transport analysis. The SWIFT model has been applied to many fields such as nuclear waste isolation in fractured media and migration of contaminants from landfills. SWIFT is ideally suited to handle the dual porosity representations along with the rock matrix interactions experienced in this project. A wide range of boundary conditions can be treated including those involving confined or unconfined water table conditions, infiltration, general head boundary conditions, and pumping and injection wells. The contaminant transport module may account for advection, dispersion, sorption, and decay. The equations are solved using forward, central or backward spatial and time weighting approximations by the finite-difference method. The method of analysis, simulation options and code discussion are discussed in further detail in this chapter.

Generally, certain parameters such as matrix porosity, fracture spacing and hydraulic conductivity are readily measured experimentally and are easily incorporated into the SWIFT model. Parameters such as fracture dispersivity can be estimated based on experimental work, but are typically calibrated using a numerical model.

In a first attempt to assess the impact of the dual porosity host rock on reducing the mobile contaminant mass through matrix diffusion, a sensitivity analysis was carried out based on the initial tracer test scenario. The initial tracer test [Section 4.1] scenario was modelled using SWIFT, and compared to the corresponding experimental results, followed by a sensitivity analysis of relevant transport parameters. The purpose of this sensitivity analysis was two-fold. First it attempted to compare the SWIFT model results to the experimental tracer test results, and calibrate undetermined parameters such as dispersivity. Second, it helped to demonstrate the sensitivity of the important parameters that are known to impact the simulation of transport in a dual porosity medium. This demonstration helped when modelling the full physical model of the TMF system, since the user understood in advance how the input parameters affected the model predictions.

Sensitivity analysis of the model's responses to changes in matrix porosity, matrix diffusivity, fracture dispersivity, and fracture porosity were carried out for each set of experimental data. This chapter provides a complement to chapter 4, by examining the sensitivity of various dual porosity parameters.

5.1 SWIFT Computer Model

SWIFT can model flow and transport using an EPM, dual porosity and discrete-fracture approach. For the EPM approach only the global (three-dimensional) process simulator is used. For DP and DF media, the global process simulator is used for the fracture network, and the local (one-dimensional) process simulator is used for the rock matrix.

5.1.1 Dual Porosity Method of Analysis

The dual porosity formulation allows for fluid interactions between the fractures and the matrix blocks, advective-dispersive transport within the fractures, and matrix diffusion.

When the dual porosity option is used in SWIFT, the modelled system is described in two parts: the fractures and the matrix (porous blocks). These are called “global” and “local” systems respectively. Both systems have certain properties that must be defined at each point over the entire model domain. Using these properties the model solves for two sets of equations.

Discretization is performed by the finite-difference method using centered or backward weighting in the time and space domains. Matrix solution is performed either by Gaussian elimination or by two-line successive overrelaxation.

5.1.2 Model Simulation

Input to the SWIFT model for dual porosity media include grid sizing (global and local), material properties, boundary conditions and time specifications.

5.1.2.1 Grids

Flow and transport in the global system are defined through cylindrical coordinates and/or three dimensional Cartesian coordinates. The ratio of fractures to the matrix system is defined as the fracture porosity.

The rock matrix can be represented as either one dimensional prisms or spheres to simulate matrix diffusion within the local system. If a local unit is discretized, concentrations can be obtained at specific points within the matrix. The prisms are given a cross-section of unity and a depth of “a” (half of block thickness, refer to Figure 3.0). Similarly, the spheres are taken to have a radius of “a” [Figure 3.2]. All matrix units are assumed to be homogeneous, but can differ from block to block if specified by the user. Since the blocks are one-dimensional only, it should be noted that no block to block flow is possible.

5.1.2.2 Material Properties

The majority of the input material properties and parameters are required to define the global system. The input parameters for the local system are fewer in number due to the one-dimensional nature and no advective flow in the matrix.

Heterogeneous and anisotropic material properties related to flow such as hydraulic conductivity and dispersivity may be included in the global flow and transport analyses.

Other properties related to flow and transport in the global system include fracture porosity and density. Matrix properties consist of diffusivity and porosity.

5.1.2.3 Boundary Conditions

Boundary conditions for groundwater flow simulations may be prescribed by nodal values of hydraulic head or prescribed integrated nodal values of fluid flux. A steady state option is provided for the global flow equations. The matrix processes (local) can only operate under transient conditions, as it is assumed that matrix processes are negligible at steady state.

SWIFT contaminant transport boundary conditions can be specified as Type I Dirichlet (Fixed/Specified Concentration Boundary), Type II (Fixed Flux Boundary) and Type II (Variable Flux Boundary). Zones of initial concentrations can be assigned to grid cells to represent instantaneous point sources, line sources and planar sources in units of mass per volume.

5.1.2.4 Simulation Outputs

Output may be printed at selected time steps. Windowing routines are available to view selected sections of output.

Postprocessor interface (UNSWIFT) contour maps of pressure or concentration in any window in any plane can be quickly processed directly into uniformly-spaced grid files for the SURFER contouring software. STLINE Particle Tracking allows for transient flowpath evaluation of streamlines.

5.1.2.5 Model Verification

The SWIFT code has been verified against available analytical or semi-analytical solutions [Geotrans, 2000].

5.1.2.6 Summary of Key Assumptions

- Three-dimensional transport via advection and dispersion in the global system, and one-dimensional transport via diffusion in the local rock-matrix subsystem
- Local rock matrix may be characterized by either prisms or spheres
- Confined or unconfined aquifer (transient or steady-state free water surface)
- Hydraulic conductivities may be heterogeneous and/or anisotropic
- Longitudinal and transverse dispersivities may vary throughout the model

5.2 Modelling the Laboratory Fractured Rock Model

Prior to modelling the full laboratory scale TMF, a sensitivity analysis was carried out with the SWIFT model based on the ancillary test results and the initial contaminant transport results [Chapter 4] for the initial four layer dual porosity model. Several model simulations were conducted using SWIFT based on the range of parameters obtained experimentally in Chapter 4 and the model predictions were compared to the results obtained from the initial tracer test. It was noted that the SWIFT model was able to simulate the tracer test results adequately, using the range of parameters estimated in separate experiments. The sensitivity of the model predictions was observed as the value for each parameter was varied.

5.2.1 Tracer Test

The experimental tracer test consisted of releasing a small slug of dye into the top fracture of the four layer brick model discussed earlier [Chapter 4]. The location of the release and the location of the sampling ports were presented in Figure 4.12. This transport boundary condition was set by releasing the equivalent mass as an instantaneous point source into the model scenario. The conditions and parameters that governed the model input are presented in Table 5.0.

Table 5.0: SWIFT parameters

Property	Value	Units
Discretization for Cartesian Geometry		
Total Distance (x)	2.3	m
Cell Length (x)	0.0115	m
Number of Cells (x)	200	-
Total Distance (y)	0.675	m
Cell Length (y)	0.01	m
Number of Cells (y)	66	-
Total Distance (z)	0.24	m
Cell Length (z)	0.03 to 0.07	m
Number of Cells (z)	6	-
Total Number of Cells	79200	-
Boundary Conditions		
Boundary Concentration Condition	Instantaneous Source	-
Initial Mass	3 mls of 1g/l uranine	ppb
Time Stepping	1000 (min) – 1200 (max)	s
Flow Conditions: Steady State	Pressure Gradient	Pa
Free Water Surface	Inactive, confined g/w flow	-
Global System Properties (fracture)		
Number of global rock types	1	-
Hydraulic Conductivity (x)	0.00028	m/s
Hydraulic Conductivity (y and z)	0.00018	m/s
Fracture Porosity	0.022	-
Longitudinal dispersivity	0.07	m
Transverse dispersivity	0.007	m
Effective Diffusivity	4.1E-12	m ² /s
Local System Properties (matrix)		
Number of local rock types	1	-
Matrix Porosity	0.08	-
Geometry	Spherical Units	-
Matrix Diffusivity	3x10E-12	m ² /s
Local grid control	Single mesh generation	-
Characteristic Length (a)	0.029	m

5.2.2 Sensitivity Analysis

The key parameters of matrix porosity, fracture porosity, matrix diffusivity and fracture dispersivity were varied as part of the sensitivity analysis. The input parameters for the base case scenario were selected from the centre of the range determined experimentally. The matrix porosity, fracture porosity and matrix diffusivity were varied over the range determined experimentally. The range of fracture dispersivities were estimated based on literature values and basic groundwater principles. Table 5.1 shows the parameters, corresponding range estimates, and values used for the base case scenario.

Table 5.1: Estimated Ranges for Modelled Parameters

Parameter	Range	Base case
Matrix Porosity (vol/vol)	0.05-0.11	0.08
Fracture Porosity (vol/vol)	0.013-0.05	0.022
Matrix Diffusivity (m ² /s)	1*10 ⁻¹² to 7*10 ⁻¹²	3*10 ⁻¹²
Fracture Dispersivity x axis (m)	0.01 to 0.10	0.07
Fracture Dispersivity y+z axis (m)	0.001 to 0.020	0.007

5.2.2.1 Results

The results are displayed in both graphical and numerical format, and consist of concentration (ppb) versus time (days) at the sampling locations. A full set of tracer test data is found in Appendix C. Table 5.2 recounts the coordinates for the locations of all 8

sample ports. The results presented include the experimental data and SWIFT model results for several selected points downstream from the point source. The set of selected sample locations consist of two points along the centerline at the same elevation of the source (2, 4), while 2 other points are located at distances laterally and vertically from the centerline (6, 8). Figures 5.0 to Figure 5.6 display experimental and model results for the set of selected sample ports for each parameter varied. The results are interpreted based on the theory described in chapter 2 and 3. It should be noted that variability from fracture to fracture is expected due to local heterogeneity and preferential flow paths. It is recognized that the port data values can be highly variable, therefore the port data is used as an indicator regarding the general progression of the plume.

Table 5.2: Coordinates of Tracer Test Ports (units = m)

[illegible]

5.2.1.2 Sensitivity Interpretation

The uncalibrated SWIFT results based on the parameter values determined in the ancillary tests were similar to the results obtained from the experimental tracer test. For example, in Figure 5.0(a), it can be seen that the non-dual porosity simulated results (matrix porosity = 0%) are very different from the simulated dual porosity results (matrix porosity > 0%), demonstrating how the matrix porosity acts as a dynamic storage mechanism. The process of matrix diffusion is sufficient enough to retard the overall migration rate of the plume as compared to advective transport in the fractures. The dual porosity predictions also simulate the predominant trailing tails characteristic to dual porosity situations [Flach, 2002] following the bulk of the plume that was measured by the tracer test. Neunhauserer et al. [1999], further indicate how mass exchange between fractures and the matrix will show a pronounced tailing while the concentration peak diminishes rapidly. Overall the dual porosity scenarios were able to more accurately represent the tracer test results. However, the simulated time for peak concentration to reach each port does not agree well with the measured data, as tracer test data showed longer delays in time to peak concentration than predicted. It was suspected that an additional retardation mechanism other than diffusion acted to retard the plume in addition to the dual porosity mechanism. This will be discussed later in this chapter in further detail. It should be noted that the terms, 'peak concentration' and 'time to peak' refer loosely to the maximum concentration reached and the time at which that maximum value was reached. Arrival time refers to the arrival of the first solute particles, i.e. approximately $1/10^{\text{th}}$ of the maximum concentration.

The sensitivity of the model predictions to the input matrix porosity can be seen in Figures 5.0 (a, b, c, d). As the matrix porosity increased, the concentration profile approached the experimental curve, causing the peak concentration to be lower and have a later arrival time. As expected, the higher matrix porosity increased the solute transfer to the host rock and increased the retardation effect of the matrix diffusion. The highest matrix porosity of 11% provided the closest peak arrival time to the measured data for all ports.

Figure 5.0 (a): Sensitivity of Matrix Porosity at Port 2 (Range = 0% to 11%)

Figure 5.0 (b): Sensitivity of Matrix Porosity at Port 4 (Range = 0% to 11%)

Figure 5.0 (c): Sensitivity of Matrix Porosity at Port 6 (Range = 0% to 11%)

Figure 5.0 (d): Sensitivity of Matrix Porosity at Port 8 (Range = 0% to 11%)

Figures 5.1 (a, b, c, d) illustrate the model's sensitivity to the input fracture porosity. An increase in the fracture porosity corresponded to a decrease in the seepage velocity causing the predicted peak concentration to arrive at a later time. Additional modeling showed that when the fracture porosity was increased beyond the specified range (5%), the peak arrival time was significantly increased, and equal to the peak arrival times of ports 2, 4, and 6.

Figure 5.1 (a): Sensitivity of Fracture Porosity at Port 2 (Range = 1.3% to 5%)

Figure 5.1 (b): Sensitivity of Fracture Porosity at Port 4 (Range = 1.3% to 5%)

Figure 5.1 (c): Sensitivity of Fracture Porosity at Port 6 (Range = 1.3% to 5%)

Figure 5.1 (d): Sensitivity of Fracture Porosity at Port 8 (Range = 1.3% to 5%)

The sensitivity of the model predictions to the input matrix diffusivity is shown in Figures 5.2 (a, b, c, d). The experimental range for matrix diffusivity did not have much impact on the contaminant plume. Although the peak arrival times did not change significantly, the maximum peak concentration became smaller for larger diffusivities.

Figure 5.2 (a): Sensitivity of Matrix Diffusivity at Port 2

Figure 5.2 (b): Sensitivity of Matrix Diffusivity at Port 4

Figure 5.2 (c): Sensitivity of Matrix Diffusivity at Port 6

Figure 5.2 (d): Sensitivity of Matrix Diffusivity at Port 8

Figures 5.3 (a, b, c, d) show the model prediction's sensitivity to longitudinal dispersivity. The shape of the curve, peak arrival time and maximum concentration were all influenced by dispersivity. As expected a large dispersivity had the effect of reducing the arrival time, and decreasing the peak concentration. For the higher longitudinal dispersion value modelled for ports 2 and 4 in Figure 5.3, the larger dispersivity matches the spread of the experimental curve better, however the peak concentration is reduced to a value much lower than the measured value. Port 8 shows a very similar concentration profile to the lowest dispersivity, however the arrival times are significantly different.

Figure 5.3 (a): Sensitivity of Fracture Dispersivity (Longitudinal, x) at Port 2

Figure 5.3 (b): Sensitivity of Fracture Dispersivity (Longitudinal, x) at Port 4

Figure 5.3 (c): Sensitivity of Fracture Dispersivity (Longitudinal, x) at Port 6

Figure 5.3 (d): Sensitivity of Fracture Dispersivity (Longitudinal, x) at Port 8

Similarly when the transverse dispersion is varied in Figure 5.4 (a, b, c, d) from 0.005 to 0.02, the peak concentration and peak arrival times are impacted. Ports 2, 4 and 8, are represented best by a transverse dispersivity of 0.007 m. Port 6 is best described with a dispersivity much lower than 0.007 m. The contrast in peak concentrations between ports 6 and 8, illustrates that channeling did occur within the current simulated fractured rock system and that the estimated transverse dispersivity is approximate and can not be calibrated to match the data collected at every port.

Figure 5.4 (a): Sensitivity of Fracture Dispersivity (Transverse, y) at Port 2

Figure 5.4 (b): Sensitivity of Fracture Dispersivity (Transverse, y) at Port 4

(note: values for port 6, fracdispy=0.001 m are close to zero)

Figure 5.4 (c): Sensitivity of Fracture Dispersivity (Transverse, y) at Port 6

Figure 5.4 (d): Sensitivity of Fracture Dispersivity (Transverse, y) at Port 8

5.3 Summary

The simulated results using the estimated parameter ranges adequately represented the concentration profiles of the tracer test data, with the exception of the time to peak concentration. All tracer test data showed a longer delay in reaching peak concentration than the simulated results. It was shown that increases in matrix porosity or global porosity, beyond that measured in the lab, could increase the arrival time of peak concentration to better represent the experimental data. The higher matrix porosity provides for more fluid volume into which the contaminant can diffuse from the fracture, thus reducing the mass of the contaminant within the fracture system. The global

porosity assigned to the model could have been lower than the actual experimental global porosity, or an additional retardation mechanism could have been present to explain the time delay. Figure 5.5 introduces the concept of sorption delaying a concentration profile in addition to diffusion. Figure 5.5 shows profiles of a relative concentration of a contaminant within a fracture over a certain distance. The adsorption in addition to diffusion is shown to significantly delay the solute arrival time [Figure 5.5 (c)].

Figure 5.5: Effect of diffusion on contaminant migration in porous fractured medium: (a) Unidirectional hydraulic transport in a fracture in a nonporous medium, (b) Hydraulic transport with migration into matrix through diffusion, (c) Transport with diffusion and adsorption [Source: Bear et al., 1993]

The effect of matrix diffusivity did not result in a significant change in arrival time but did affect the peak concentration values. The diffusivity is the rate at which the solute enters the matrix, and is dependent on the time required for the pore water in the matrix to become saturated by the solute [Rowe et al., 1995]. As discussed in Chapter 3, the diffusive flux into the matrix is directly proportional to the matrix porosity, the diffusivity and the concentration gradient across the fracture-matrix system. An increase in any of these variables can act to increase the diffusive flux into the matrix. Since the rate at which the diffusivity enters the matrix is dependent on the amount of storage available, the peak concentration is reduced in the fracture, however a significant retardation in peak arrival is not observed. However if the matrix porosity is increased, the resulting storage is increased causing the gradient to become larger, thus showing a more pronounced effect on plume migration. With the exception of port 6, the smallest value of diffusivity ($1.0\text{E-}12 \text{ m}^2/\text{s}$) best represented the measured peak concentrations.

Overall the base case dispersivities provided for a good fit to the experimental data.

The tracer test results demonstrated the variability experienced when measuring data using ports. Due to channelling effects, REV concepts etc., the port data can only be an indicator of the overall plume development in the system, and the data can not be considered accurate. However, in general, the time to peak at each location was consistent in that the peak reached the closest locations first followed by the points located at distances further downgradient from the source. For this reason Chapter 6 and 7 focus primarily on the solute flux into the downgradient reservoir as the primary output parameter for model comparison and calibration of contaminant transport.

CHAPTER 6

6.0 Physical Model Results and Discussion

Testing of the in-pit TMF physical model was performed using both the sand and gravel pervious surround materials, as discussed in Chapter 4. The concentrations and mass flux entering the downgradient reservoir under steady state flow conditions were observed over time and are the primary focus of this chapter. The main goal of the physical testing was to (1) observe how the solute moved through the simulated dual porosity medium; and (2) quantify the impact that the pervious surround had on reducing contaminant flux out of the TMF system.

6.1 Experimental Data

Three experiments were performed; two with a gravel surround and one with a sand surround. In the first experiment using the gravel surround, the silica (tailings) was not properly compacted, causing the silica to settle 10 cm below the top surface of the model. As a result, the water levels were lowered in each reservoir to the elevation of the top of the collapsed tailings and then the gradient was applied across the system. This effectively reduced the flow domain, however, the experiment was allowed to proceed to see what data could be collected and used to support the following experiments. A second gravel surround experiment was repeated and those results are presented throughout this chapter, unless otherwise indicated. The results from the first gravel surround experiment are still used for comparison but were not considered as reliable.

6.1.1 Flow Regime

As previously mentioned, piezometer devices were not installed throughout the physical model in order to minimize the disruption to the finite fractures created between adjacent blocks, thereby limiting the characterization of the flow regime to measurement of the flow to the downgradient reservoir. The average flow rate was determined by measurement of the overflow rate at the downstream end of the model at selected times throughout the experiment. For all experiments, the initial pressure drop across the physical model was 98.1 Pa (0.01 m), producing a gradient of 4.35×10^{-3} m/m across the model. During each experiment, the gradient was increased after 15 to 26 days by lowering the water elevation in the downgradient reservoir by an additional 0.01 m, producing a gradient across the model of 8.69×10^{-3} m/m. The full set of flow data, including flow data after the gradient change, can be found in Appendix D-I. The data measured after the gradient change only displayed a small increase in flow and became relatively unstable. It was later recognized that the experimentation did not allow for an accurate increase in gradient.

The variance of the measured flow rates was smaller for the gravel experiments (prior to gradient change) than for the sand experiment indicating that the gravel flow rates were more consistent. The average flow rate for the sand surround was found to be less than the gravel surround as expected. Observation of the flow data from all three experiments shows a small but steady increase in flow measurements over time.

6.1.2 Concentrations

The concentrations at selected times were measured and recorded at each port for all experiments and are reported in full in Appendix D-II. The concentrations were measured in parts per billion ($\mu\text{g/l}$) and time was measured in days. Most ports tended to be located along the lateral centreline of the model ($y=0$), and within the middle layers of the system. Graphical representation of the port locations for the full physical model are found in Chapter 4.

A typical concentration profile with time at a downgradient port is shown in Figure 6.0(a). Generally, the concentration profiles for all experiments exhibited rapid increases in concentration, only reaching a peak concentration for a short time and then proceeded to have long descending extended tails. Previous experimentation conducted by West [2001] exhibited very similar curves, although the current trailing edges of the curves appeared longer. Dual porosity models are often invoked to explain such a phenomenon [Flach, 2002] however considering the nature of the source term, it is difficult to establish whether the extended tails were in fact a function of matrix replenishment.

Figure 6.0(a): Gravel concentration profile for a port (1c) located 0.525 m downgradient of tailings pit along the lateral centreline($y=0$, $z=0.3$ m)

The arrival times for the ports located along the lateral centerline axis were generally consistent from port to port, for the same flow rate. Ports located at different lateral distances from the centreline of the model experienced significant variation, indicating that the plume was likely travelling down preferential pathways (channelling). As mentioned in Chapter 5, due to the variability of the port results, the port data was only used as an indicator of plume development and provided a guide for numerical model calibration of parameters such as transverse dispersivity. An example of such variability is shown in Figure 6.0(b). Figure 6.0(b) shows the data measured at 5.9 days for the

gravel surround experiment. The numbers appear relatively consistent however one port located far from the centreline measures a value of 178.4 ppb, which is much higher than any other measured value for that time, demonstrating the short circuiting effects and data variability.

Figure 6.0(b): Gravel concentration profile for ports located downgradient of tailings pit ($z=0.48\text{m}$)

6.1.2.3 Gravel Surround

Figure 6.1(a) shows data measured along the centreline ($y=0$) of the gravel surround physical model at various distances down gradient from the pit, and at the same height as the bottom silica layer ($z=0.3\text{ m}$). The pit ends at a distance of $x= 1.105\text{ m}$.

Figure 6.1(a): Gravel concentration profile for ports (17c, 14, 12, 1c) located at various distances downgradient from the tailings pit along the centreline ($x=n$, $y=0$, $z=0.3$ m)

The gravel surround models tended to reach peak concentrations at very early times. Port 17c was located on the outer boundary of the gravel surround and reached a peak concentration of 560 ppb at 0.02 days. Similarly the other three ports (14, 12, 1c) reached their peak concentrations at 0.04, 0.08 and 1.83 days respectively. The peaks exhibited a high initial concentration for a short time followed by a steady decrease in concentration. The port located within the pervious surround (17c) remained at an

average value of 150 ppb for the remainder of the experiment. The other ports maintained lower values (below 100 ppb) for the remainder of the experiment.

Figure 6.1 (b) shows concentration profiles for several ports located at the height of the bottom layer of pervious surround material ($z=0.24$ m). Ports 16 and 18b are located within the gravel material, while port 2 is located in the host rock downgradient of the pit. Port 16 exhibited a peak concentration of 247 ppb at 0.04 days and maintained a constant concentration around 200 ppb for the remainder of the experiment. Port 18 b experienced its highest concentration at the beginning of the experiment and decreased rapidly during the experiment. The peak concentrations for port 2 occurred at 0.21 and 1.83 days, and decreased to a value of 20 ppb after 15 days.

Figure 6.1(b): Gravel concentration profile for ports 2 ($x=1.92$, $y=0$), 16 ($x=0.675$, $y=0$) and 18b ($x=0.68$, $y=0.44$), all located at a vertical height of $z=0.24$ m

The ports located at distances laterally away from the centerline ($y=\pm$) and at different depths still measured concentrations above 100 ppb. Figure 6.1(c) is an example of such ports, showing two ports located approximately 0.26 m away from the centreline, at vertical distances of 0.54 m and 0.48 m. These ports exhibited wider peaks than most ports located along the centreline of the model, and decreased to values of less than 100 ppb at 12 days.

Figure 6.1(c): Gravel concentration profile for port 7 located 0.26 m away from the centreline ($z=0.54\text{m}$); port 8 located 0.37 m away from the centreline ($z=0.48\text{m}$)

Figure 6.1(d) shows a graph of concentration versus time for several ports located at a distance of $x=2.11\text{ m}$ along the centerline of the model at various depths. Port 1c is located at a vertical distance of $z=0.30\text{ m}$, in line with the bottom silica layer. Ports 1a and 1b are located at vertical distances above the bottom of the silica (1a, $z=0.60$ and 1b, $z=0.48\text{ m}$), and port 1d is located below the bottom of the pit ($z=0.12\text{ m}$). The port located at 0.48 m experiences the earliest arrival time and highest peak concentration. This observation is important as all data collected from the gravel surround experiment

exhibited the highest concentrations along this layer (including the pervious surround points). Theoretically it was expected that the $z=0.24$ m location would experience higher values of concentration and earlier peak arrival times since it is in line with the bottom layer of surround material.

Figure 6.1(d): Gravel concentration profile for ports (1a, b, c, d) located at $x=2.11$, $y=0.0$ m and $z=0.60, 0.48, 0.30, 0.12$ respectively

The first gravel experiment [Figure 6.1(e)] showed port 1b ($z=0.48$ m) reaching the highest concentration however it did not experience the earliest arrival time.

Figure 6.1(e): Gravel (1st experiment) concentration profile for ports (1a, b, c, d) located at $x=2.11$, $y=0.0$ m and $z=0.60$, 0.48 , 0.30 , 0.12 respectively

6.1.2.4 Sand Surround

Figure 6.2(a) is analogous to Figure 6.1(a), showing concentration profiles at various distances located down gradient from the pit. Ports 17c and 14 located 1.13 and 1.15 m along the x axis, reach peak concentrations of 1050 and 1126 ppb at 1.28 and 0.82 days respectively. Ports 12 and 1c reach their peak value at 1.99 days. In the sand surround, the ports located at distances far from the centerline experienced relatively small concentrations. All curves showed a steady decline to values below 200 ppb, including 17c located in the surround material.

Figure 6.2(a): Sand concentration profile for ports (17c, 14, 12, 1c) located at various distances downstream from the tailings pit along the centreline ($z=0.3$ m)

Figure 6.2 (b) is analogous to Figure 6.1 (b), showing concentration profiles for several ports located at the height of the bottom layer of pervious surround material ($z=0.24$ m). Ports 16 and 18b reach peak concentrations at 1.99 days, and port 2 reaches a peak concentration at 2.65 days.

Figure 6.2(b): Sand concentration profile for ports 2 ($x=1.92$, $y=0$), 16 ($x=0.675$, $y=0$) and 18b ($x=0.68$, $y=0.44$), all located at a vertical height of 0.24 m

Figure 6.2 (c) is analogous to Figure 6.1(c) and shows the concentration profiles for two ports located at distances 0.26 and 0.27 m laterally from the centreline. Port 7 reaches a peak value of 102 ppb at 4.5 days and port 8 reaches a peak value of 72 ppb at 7 days. It

is noted that port 7 ($z=0.54$ m) reaches a much higher concentration and has a sharper peak than port 8 ($z=0.48$ m).

Figure 6.2(c): Sand concentration profiles for port 7 located 0.26 m away from the centreline ($z=0.54$ m); port 8 located 0.37 m away from the centreline ($z=0.48$ m)

Figure 6.2(d) can be compared to Figure 6.1(d). Ports located at different depths along the centreline ($y=0$ m), and at a distance downstream of the source ($x=2.11$ m) are shown. Port 1c reaches a peak concentration of 278 ppb at 2.6 days while port 1b reaches a peak

concentration of 222 ppb at 4.5 days. Port 1d reaches a small peak concentration of 22 ppb at 12 days. Some of the data was missing for port 1a as shown in the graph, due to clogging of the sampling device, and therefore a peak concentration could not be determined. The sand surround experiments experienced highest concentrations at points located along the $z=0.30$ m level where the bottom layer of silica was located.

Figure 6.2(d): Sand concentration profile for ports (1a, b, c, d) located at $x=2.11$, $y=0.0$ m and $z=0.60, 0.48, 0.30, 0.12$ respectively

6.2 Calculated Mass Flux Out of the System

Mass flux was calculated based on the measured flow rate out and the concentration measurements obtained from the downstream reservoir (Appendix D-II). Equation 6-1 was used to calculate mass flux out of the system assuming that the downgradient reservoir was acting like a completely mixed reactor:

$$M = \frac{(C_2 - C_1)V + \left(\frac{C_1 + C_2}{2}\right)Q\Delta t}{\Delta t} \quad (6-1)$$

where C_1 and C_2 [M³/T] are the first and second of a pair of solute concentrations measured in the downgradient reservoir over a time period of Δt . V [L³] is the volume of the down gradient reservoir, and Q is the outflow rate [L³/T]. This equation assumes a linear change in concentration occurred in the reservoir during the specific time interval, and that the calculated solute mass flux represents an average rate for the time period [West, 2001]. Figures 6.3 and 6.4 present the mass flux out of the system (boundary efflux) with time for the gravel and sand surround models. The peak mass efflux for the gravel surround was much higher and sharper than for the sand surround, and was reached at a much earlier time. The gravel experiment reached a peak value of 19 mg/day at 0.68 days and the sand experiment reached a peak value of 7.9 mg/day at 2.6 days. The later arrival time of the peak mass flux in the sand surround experiment was expected since the total fluid flow through the experiment is less for the sand surround. These trends were also compatible with the trends seen by West [2001].

Figure 6.3: Mass Flux from Down-Gradient Boundary-Gravel Surround

Figure 6.4: Mass Flux from Down-Gradient Boundary-Sand Surround

6.3 Mass Balance

As discussed in Chapter 4, the concentration of the solute in the silica was measured at the beginning and at the end of each experiment. These silica samples were averaged, and multiplied by the volume occupied by the silica (0.078 m^3) and the silica porosity (0.4) to obtain a mass. The results of these measurements are presented in Appendix D-III. The cumulative mass out of the system was calculated by summing the mass flux out of the system over time calculated by equation 6-1. This mass was compared to the initial and final solute concentrations to achieve a mass balance. The comparison is shown in Table 6.0.

Table 6.0: Mass Balance

	Gravel (2)	Sand (1)	Units
Duration of Experiment	35	51	days
Initial Solute Mass in Tailings	314.8	320.1	mg
Final Solute Mass in Tailings	187.4	144.7	mg
Initial – Final	127.4	175.4	mg
Total Measured Mass Out	74.1	85.7	mg
Mass Remaining in System	53.3	89.7	mg
Percent Retained in System	41.9	51.1	%

The mass balance demonstrates that more solute was drawn out from the sand experiment than for the gravel experiment, which is expected due to the time difference. Both experiments began with an average solute concentration of approximately 10,000 ppb. The final average concentrations along the top of the tailings were determined for the gravel and sand experiments were 6005 and 4637 ppb respectively. The mass remaining in the system for the sand was 91.5 mg, and the gravel was 53.5 mg.

6.4 Discussion

The primary goal of the physical model was to create a fractured environment where matrix diffusion would occur and act to retard a contaminant plume. The key design

features were to create a steady and slow flow, providing enough time for the solute to diffuse into the matrix material; to ensure proper spacing of fractures and even sand compaction in order to minimize channelling effects; and finally to measure solute plumes in an appropriate time interval, to examine concentrations with times at the ports and downgradient reservoir.

The very long tails and delayed arrival times exhibited by most measured data show evidence of dual porosity effects. For the most part, the key design features have been met: the observed flow rates were very low and corresponded well to predicted values based on ancillary tests; although variability was observed from the sampling port measurements, all sample ports were able to measure significant concentrations, indicating that the contaminant's pathway was not limited to only a few fractures; the experiment timing was able to capture entire concentration profiles with time. The solute concentrations at the beginning of the gravel experiment peaked almost immediately making it difficult to capture the initial increase in concentrations at ports close to the surround. The concentrations in the sand experiment were slower to rise and therefore were easier to measure, however the measurement of full concentration profiles at some ports took extended time.

6.4.1 Gravel and Sand Surround Comparison

Previous experimentation/modelling conducted by West [2001], demonstrated that the gravel surround typically has the effect of drawing water into and around the tailings, in

comparison to the sand surround. The result was a greater total flow through the experimental domain. A similar trend was noted here (Appendix DI, Flow Data).

West [2001] observed that the greater flow in the gravel surround tended to draw water towards the pit upgradient of the pit and tended to divert water away from the pit downgradient of the pit. This tended to create a wider plume downgradient of the pit. The sand surround (natural surround) diverted water around the TMF upgradient of the pit and caused the water to converge downgradient of the pit. This resulted in a narrower plume downgradient of the pit. Figures 6.5 and 6.6 show the equipotential lines illustrating the flow regime experienced by the gravel and sand experiments respectively for West's [2001] equivalent porous media (EPM) host rock representation.

a) Plan view at 600mm elevation

b) Centerline section view

Figure 6.5: EPM Gravel Surround Experiment Equipotential and Flow Lines [West, 2001]

Figure 6.6: EPM Sand Surround Experiment Equipotential and Flow Lines [West, 2001]

Since the gravel surround generated a large flow, the residence time in the surround adjacent to the tailings source was less and hence the peak concentration at the downgradient edge of the tailings was less. In comparison, the travel time in the sand surround was greater and hence the peak concentration at downgradient edge was greater. The data observed for the gravel and sand surround for this research closely followed this pattern. In Figures 6.1 (a) and 6.2 (a), ports 17c and 14, indicated that the concentration of solute leaving the sand surround was much higher than the concentration leaving the gravel surround. Concentrations at ports 1 and 12, located further downgradient, were lower for the sand surround, most likely due to channelling effects. Figures 6.1 (c) and 6.2 (c) showed that ports located far from the source centerline (ports 7, 8) exhibited higher concentrations in the gravel experiment than in the sand experiment. This observation and values from other remote data points (Appendix D-II) support previous analyses that the sand surround forms a narrow plume in comparison to the gravel surround which acts to spread the solute out.

The gravel scenario showed a higher initial mass efflux at an early time with a fast decline. Conversely the sand experiment reached a low peak mass flux value at a later time. Similar curves were seen by West [2001], where the solute release rate from the tailings was seen to decline asymptotically with time, as a result of the outwards-directed diffusion from within the tailings. Peak mass boundary efflux values measured by West [2001] were higher for both sand and gravel surrounds for EPM experiments than for the current dual porosity experiments. However, it is difficult to compare early time boundary efflux values between past and present experiments due to variations in diffusive tailings mass efflux resulting from variations in initial concentrations and

compaction density. West [2001] also noted this problem when comparing duplicate experiments.

A large percentage of the data indicated that the gravel experiment concentration values were highest at a height of 0.48 m, corresponding to a value in line with the middle of the pit, and the sand experimental values were highest at a height of 0.30 m, corresponding to a value in line with the bottom silica layer. Due to the heavy steel drum that was set on top of the bottom layer of silica and surround, the hydraulic conductivities of these materials likely decreased causing flow to be diverted around the tailings. In the case of the gravel surround, the flow would have been diverted around the tailings pit more than through the bottom layer of gravel and therefore caused solute concentrations to be higher at the middle of the pit. This would not impact the sand surround as much since the flow would not necessarily have as much of a preferential pathway, thus resulting in high solute concentrations at the silica level.

6.4.2 Impact of Dual Porosity Media

The experimental results in this chapter illustrate that matrix diffusion could have been responsible for the significant retention in solute mass. A mass balance performed on the sand and gravel experiments showed that in both events, over 40% of solute mass was retained within the system after most port values decreased to small values. The mass balance is in error due to limited sampling of the final tailings mass (discussed in following section). However the occurrence of such a large consistent discrepancy in

mass does imply that some mass was stored within the rock matrix. Although a higher concentration was measured during the sand experiment, a smaller amount of mass was observed at several downgradient locations in comparison to the gravel. For example, when comparing Figure 6.1 (a) and Figure 6.2 (a), the ports located at distances of 1.34 m and 2.11 m exhibited much higher concentrations for the gravel than for the sand surround, even though the other ports closer to the source show much higher concentrations for the sand surround. From an initial review of such data, it was postulated that the slower flow rate occurring in the sand experiment provided for a longer contact time for diffusion to occur. Also the higher concentrations experienced by the sand experiment could have created a greater gradient between the fracture mobile water and the immobile matrix water increasing the mass diffusing into the rock matrix. However examination of the mass flux showed that the delay and peak reduction was not as high as shown by the ports. Since the mass flux represented the primary indicator of the system's transport behaviour, the trend observed in the ports was attributed to channelling effects.

Although the peak arrival times of the sand and gravel were compared, it is much harder to determine whether the peak arrival times were impacted by matrix diffusion without comparison to a numerical model. Chapter 7 provides more detail regarding breakthrough times since a dual and no dual porosity case can be modelled and compared more easily.

6.4.3 Experimental Discussion

There are several instances where the construction and testing of the physical model could explain some of the variable results obtained. The upper portion of the model was reassembled and disassembled approximately 4 or 5 times. This could have resulted in some ports moving from their original position, thus providing improper concentration-time measurement information. As previously mentioned in Chapter 4, preferential flow paths were expected and the sample ports demonstrated this. The flux to the downstream reservoir gave a good measure of the flux leaving the TMF and the overall transport.

A pump was placed in the downstream reservoir to ensure complete mixing, although periodic clogging caused the reservoir to go “un-mixed” for short periods of time. This would have lead to inaccurate measurements in the downstream reservoir.

In reviewing the flow data, it is important to note how the experiment was initiated; the water level was kept at a height just below the pit while silica compaction occurred. Initially, only the bottom four layers were fully saturated. Once the silica compaction was finished, the water levels in both reservoirs were slowly raised at the same rate until the top brick was reached. It was possible that during this filling period one reservoir could have been higher/lower causing a small gradient to occur before the timing commenced. This was seen in the data for the gravel surround as the concentrations had already reached certain ports before the start of the experiment. After full saturation, the down gradient reservoir water level was then lowered to generate the desired gradient for the experiment. The model was assumed to be saturated at this time, but could have possibly been under saturated, causing unsteady flow to occur for the first period of the

experiment. The flow rates increased steadily throughout the course of each experiment, indicating that steady state flow was not reached or that sand was washing out of the cracks, possibly acting to increase flow rates.

The measurement of the tailings concentration helped to ensure that the initial concentration was obtained. However final sampling of the tailings could only be taken from the top five to ten centimetres of material without significant disruption. It is obvious that this concentration could not be considered consistent throughout the entire tailings domain. West [2001] also found large discrepancies in the mass balance and attributed it primarily to the limited sampling of the final tailings concentration.

CHAPTER 7

7.0 SWIFT Dual Porosity Numerical Model of In-Pit TMF Experiment

The SWIFT model was used to obtain contaminant transport results for the in-pit TMF scenarios described in Chapter 4. The basic objective was to closely represent the experimental model and assess the adequacy of the numerical model in predicting dual porosity transport by comparison with experimental data.

Chapter 5 established the importance of several parameters involved with dual porosity flow that are typically difficult to determine for a field TMF pit scenario. The parameter ranges established through ancillary tests, and tracer tests evaluated in Chapter 5 were used as input for the SWIFT model.

7.1 Model Description

The in-pit TMF scenario was modelled to closely represent the physical experiments performed for both a sand surround and a gravel surround material (Chapter 4). Due to the symmetry of the physical experiment it was possible to model only half of the actual domain which allowed for a finer grid, given the significant memory constraints imposed when three dimensional models are invoked. To simulate the source term in SWIFT, an initial concentration corresponding to the desired mass of dye (160 mg) was applied to the medium representing the tailings to achieve a design source concentration of 10,000 ppb. Additional modelling applied a source term of 10,000 ppb to the entire tailings pit

(including steel drum) in order to ensure the steel drum had minimal effect on the solute transport output data.

SWIFT assumes that the solute is subject to advection and dispersion which includes diffusion in the fractures and diffusion into the rock matrix. The transport within the dual porosity system in SWIFT is governed by equations 3-3a to 3-7 in Chapter 3. At the fracture matrix interface the flux was shown to be continuous:

$$\Gamma_c = -A_v D' \frac{\partial C'}{\partial s'}, \text{ where } A_v \text{ represented the area at the interface between the matrix [L}^2\text{]}$$

and fracture, and D' was the effective diffusion coefficient [L^2/T].

7.2 SWIFT Input Specifications

The base case parameters established in Chapter 5, were used to model the TMF pit scenario. The input parameters were then adjusted within the ranges given to further calibrate the model. The parameters that provided the best fit are presented in Table 7.1. A complete listing of the input data is given in Table 7.2.

Table 7.1: SWIFT Input Parameters

Global Properties (Fractures)		
Hydraulic Conductivity	0.00048	m/s
Fracture Porosity	0.022	-
Longitudinal Dispersivity	0.1	m
Transverse Dispersivity	0.005	m
Fracture Diffusivity	4.095E-12	m ² /s
Local Properties (Matrix)		
Matrix Porosity	0.08	-
Matrix Diffusivity	3.00E-12	m ² /s

The fracture porosity, matrix porosity and matrix diffusivity were taken from the experimental ranges. The longitudinal dispersivity was calibrated to fit the model's mass flux (downgradient) results, and the transverse dispersivity was calibrated to best illustrate the port concentration profiles. All parameters used to fit the experimental data were contained within the ranges provided by Chapter 4, with the exception of hydraulic conductivity. The initial hydraulic conductivity of 0.00024 m/s was input into SWIFT, however SWIFT did not return the same flow rates as measured experimentally. The SWIFT flow rates were much lower than measured experimentally. Due to the nature of the pit construction, the blocks were not cut into a perfect circle, therefore leaving extra space for the water to flow through and possibly increase the flow. It is also likely that

the top layers were not as tightly compacted as the bottom four layers (used to establish the initial conductivity) thereby also acting to increase the flow. Since SWIFT could not incorporate such effects, the hydraulic conductivity was increased to 0.00048 m/s to reach the flow measured experimentally. This conductivity produced proper flow values for both the sand and gravel surround scenarios.

Table 7.2: Input Specifications

Property	Value	Units
Total Number of Cells	133,000	-
Boundary Conditions		
Boundary Concentration Condition	Instantaneous Source	-
Initial Concentration	1.0×10^{-5}	ppb
Time Stepping	1500 (min) – 2500 (max)	s
Flow Conditions: Steady State	Pressure Gradient	Pa
Free Water Surface	Inactive, confined g/w flow	-
Global System Properties (fracture)		
Number of global rock types	4	-
Hydraulic Conductivity (x)	0.00048	m/s
Hydraulic Conductivity (y and z)	0.00028	m/s
Fracture Porosity	0.022	-
Longitudinal dispersivity	0.1	m
Transverse dispersivity	0.005	m
Diffusivity	4.09×10^{-12}	m^2/s
Local System Properties (matrix)		
Number of local rock types	1	-
Matrix Porosity	0.08	-
Geometry	Spherical Units	-
Matrix Diffusivity	3×10^{-12}	m^2/s
Local grid control	Single mesh generation	-
Dispersivity	0.0	m
Surround Material Properties		
Porosity Gravel	0.35	-
Porosity Sand	0.35	-
Dispersivity (long. and transverse)	0.1 (for both gravel and sand)	m
Hydraulic Conductivity Gravel	6.0×10^{-2}	m/s
Hydraulic Conductivity Sand	1.0×10^{-4}	m/s
Tailings Properties		
Porosity	0.4	-
Tailings Dispersivity (long. and transverse)	0.001	m
Hydraulic Conductivity	6×10^{-7}	m/s

Figure 7.0 is a representation of the grid used to simulate the physical model. The physical model was represented by 133,000 grid cells. The lengths and number of cells for each axis are given in Table 7.3.

The system was modelled as a confined aquifer unit with single phase flow. The bottom surface, outer sides (lateral) and top surface, were considered no-flow boundaries. The fluid pressures at each end of the domain were set as fixed-heads with values equivalent to the actual physical model, thereby recreating the same flow regime. The initial concentration in all global and local blocks was set equal to zero.

Table 7.3: Discretization for Cartesian Geometry

Axis	Discretization (m)	Total Number of Cells	Total Length (m)
x	1@0.030, 5@0.020, 9@0.010, 120@0.00755, 20@0.010, 35@0.028	190	2.30
y	1@0.035, 2@0.050, 2@0.020, 5@0.010, 60@0.00755	70	0.675
z	1@0.18, 1@0.16, 1@.06, 1@.025, 2@.0125, 1@.00755, 1@0.0151, 1@.122, 1@.12	10	0.71

(a)

(b)

Figure 7.0: Numerical (SWIFT) Discretization of In-Pit TMF Design with Surround

(a) x-y plane (b) x-z plane

7.3 Numerical Solution

A centered finite difference approximation in time was chosen for solution and the spatial and time increments were chosen to be consistent with the criteria suggested by the Courant and Peclet numbers. The Peclet numbers were violated for two of the z spatial increments (top of model), as the characteristic lengths were much larger than the corresponding dispersivity. This was unavoidable due to memory constraints that severely limited proper discretization of the z axis. The simulations were performed on an Intel Pentium 4, 2.6 GHz computer with 1 GIG of DDR RAM.

7.4 Simulation Output

SWIFT model output includes velocity data, mass balance information for both the local and global systems, and concentration data for both space and time. When possible, the numerical results were displayed against experimental results for comparison purposes.

In order to examine the influence of matrix diffusion on performance, two simulations are compared; the no dual porosity case in which the matrix porosity was set equal to zero, and the dual porosity case in which the matrix porosity is considered.

7.4.1 Flow Regime

As noted earlier, the SWIFT model was recalibrated to match the experimental flow data. The fluid flux was identical in both the non dual and dual porosity models, assuring that the immobile-mobile model was established, meaning that the addition of a secondary porosity did not influence the overall flux through the system. The SWIFT model velocity results verified previous theory that the gravel surround would act as a short circuit, directing flow into the surround and around the tailings layer. Conversely the sand surround had only minimal impact on directing flow around the tailings. It should be noted that the modeled permeability of the sand was very close to that of the fractured rock, almost implying a natural surround situation. Figure 7.1 (a) shows a profile of flow vectors for the gravel surround scenario taken at a height of $z=0.30$ m of the x-y plane. The surround material begins at approximately 0.23 m (x) and ends at 1.11 m (x). The flow experienced by the gravel reached a value that was ten times higher than the flow in the sand. Figure 7.1 (b) shows a similar flow vector profile for the sand scenario.

Figure 7.1(a): Flow Vectors for Gravel Scenario (x-y plane in meters at $z=0.30$ m)

Figure 7.1(b): Flow Vectors for Sand Scenario (x-y plane in meters at $z=0.30$ m)

The highest flows occurred in line with the bottom surround layer as expected due to the amount of flow drawn into the pervious surround. The gravel surround also experienced relatively high flows at heights above the pervious surround layer. The sand surround conversely experienced a more even distribution of flow illustrating that the flow is diverted around the TMF and converges downgradient of the pit.

7.4.2 Concentration Data

Figures 7.2 (a) and 7.2 (b) show model results at selected experimental locations for the gravel surround model. Figure 7.2 (a) shows modelled and experimental peak arrival times for port (17c), located within the gravel surround along the centreline of the model at the same height as the bottom silica layer ($z=0.30$ m). The effect of dual porosity is limited since the port is located within the surround, in which there is no matrix diffusion. However the concentration in the adjacent fractured rock does include matrix diffusion

which can impact the contaminant concentration and flux from the surround. The experimental data is much higher initially, and does not decrease as quickly as predicted by SWIFT, yet experiences a relatively long tail. SWIFT was not able to simulate the experimental source term which maintained a higher concentration at a later time. It was realized that if the model was unable to simulate the higher concentrations at the source, this would also impact the model predictions at the downgradient locations.

Figure 7.2 (b) compares modelled versus experimental results for a port located much further from the source ($x=2.11$ m), at a height in line with the bottom tailings layer ($z=0.30$ m).

Figure 7.2(a): Comparison of concentration profiles at the 1.13 m location (port 17c) along the centerline for DP, non DP and experimental curves ($z=0.30$ m)

Figure 7.2(b): Comparison of concentration profiles at the 2.11 m location (port 1c) along the centerline for DP, non DP and experimental curves ($z=0.30$ m)

The difference between the non dual and dual porosity considerations is more evident due to the port being located further from the source, thus having time to diffuse into the matrix material. The initial shape of the predicted curve and the experimental curve are very close, however the peak arrival time of the experimental data was longer than predicted. Finally, the tail of the experimental data remains very high in concentration, in comparison to the modelled curve, likely attributed to results of 17c (next to the source) discussed earlier.

Figures 7.2 (c, d) are analogous to Figures 7.2 (a, b), showing ports 17c and 1c at $z=0.30$ m for the sand surround model. The peak arrival time experienced by port 17c in the sand experiment is much longer than predicted by the model. The peak is also higher and

remains at a very high value until approximately 20 days. The measured data at port 1c experiences a lower peak and larger corresponding arrival time than predicted.

Figure 7.2(c): Comparison of concentration profiles at the 1.13 m location (port17c) along the centerline for DP, non DP and experimental curves ($z=0.30$ m)

Figure 7.2(d): Comparison of concentration profiles at the 2.11 m location (port 1c) along the centerline for DP, non DP and experimental curves ($z=0.30$ m)

Figures 7.3 (a, b, c, d) show concentration data for an x-y plane cross section at a height of $z=0.30$ m (bottom tailings layer) for the gravel surround scenario. The corresponding Figures 7.3 (e, f, g, h), show data for the same locations for the sand surround scenario.

Figures 7.3(a, b) show concentrations measured at 0.18 days and 0.647 days for a non-dual porosity host rock. The 250 ppb concentration contour has already migrated a significant distance after 0.18 days and has reached the down-gradient reservoir after 0.647 days.

Figure 7.3(a): Gravel Surround with no Dual Porosity

x-z section ($z=0.30$ m) at 0.18 days (top)

x-y section ($z=0.30$ m) at 0.18 days (bottom)

Figure 7.3(b): Gravel Surround with no Dual Porosity

Cross section ($z=0.30$ m) at 0.647 days

Figures 7.3 (c, d) illustrate the concentrations at the same times with the inclusion of dual porosity. At an early time of 0.18 days, the dual porosity shows an impact of retarding the solute plume. This is more evident at 0.647 days where the 250 ppb concentration contour has already reached the down gradient reservoir in the non DP model; conversely the 250 ppb concentration contour has not reached the reservoir for the DP model.

Figure 7.3(c): Gravel Surround with Dual Porosity

Cross section ($z=0.30$ m) at 0.18 days

Figure 7.3(d): Gravel Surround with Dual Porosity

Cross section of layer 4 ($z=0.30$ m) at 0.647 days

Figure 7.3 (e, f) show concentrations measured at 0.18 days and 0.647 days for a non-dual porosity host rock for the sand scenario. The plume shows very high concentrations occurring adjacent to the solute source, (e.g. 750 ppb at 0.647 days).

Figure 7.3(e) Sand Surround with No Dual Porosity

Cross section of layer 4 ($z=0.30$ m) at 0.18 days

Figure 7.3(f) Sand Surround with No Dual Porosity

Cross section of layer 4 ($z=0.30$ m) at 0.647 days

Figures 7.3 (g, h) are analogous to Figures (e, f) however include dual porosity. Both figures capture an almost immediate retardation of plume development. In Figure 7.3 (f), the 500 ppb concentration contour had reached 1.9 m, however with the introduction of dual porosity the 500 ppb concentration contour was retained to 1.5m.

Figure 7.3(g) Sand Surround with Dual Porosity

Cross section of layer 4 ($z=0.30$ m) at 0.18 days

Figure 7.3(h): Sand Surround with Dual Porosity

Cross section of layer 4 ($z=0.30$ m) at 0.647 days

A few apparent conclusions can be made by comparing the DP gravel and DP sand plumes directly. The sand plumes appear much narrower and more defined than the gravel plumes. At 0.18 days, the 50 ppb concentration contour is almost at the end of the domain for the dual porosity gravel model, however has only reached the 1.8 m mark in the dual porosity sand model, illustrating the slower flow for the sand scenario.

7.4.2.1 Full Pit Simulation

Additional modelling applied a source term of 10,000 ppb to the entire pit to observe any change in concentration-time data. Figures 7.3(i, j) shows the results for the non-dual porosity scenario with a gravel surround with the source term applied to the full pit at 0.18 and 0.647 days. The 150 ppb concentration contour in Figure 7.3(i) has progressed slightly further than the same contour in Figure 7.3(a). Similarly, observation of Figure 7.3(j) shows that the 75 and 100 ppb contours have spread out slightly more than the same contours in Figure 7.3(b). Overall there is very little difference in the spatial and temporal concentrations simulated for the full pit simulation in comparison to concentrations simulated with the solid core (steel drum) in the pit. This confirms the earlier assumption that advection through the tailings is negligible for this research.

Figure 7.3(i): Gravel Surround with no Dual Porosity

Cross section of layer 4 ($z=0.30$ m) at 0.18 days

Figure 7.3(j): Gravel Surround with no Dual Porosity

Cross section of layer 4 ($z=0.30$ m) at 0.647 days

7.4.3 Mass Flux

Figures 7.4 (a, b) show the modelled and experimental mass flux leaving the downgradient model boundary over time for the gravel and sand scenarios. The mass efflux of the gravel reaches a higher peak mass flux relative to the sand. The

experimental efflux profile for both sand and gravel systems are similar to the DP physical models. The gravel experimental curve is higher than predicted by the numerical model, where as the sand experimental curve is lower than predicted. The trailing tail values following the peak concentration of the DP and non DP models reach similar values, however the experimental curves reach an even lower value.

Figure 7.4(a) Modelled and Experimental Mass Flux Leaving the System for Gravel

Figure 7.4(b) Modelled and Experimental Mass Flux Leaving the System for Sand

7.4.4 Mass Balance

The mass balances were determined for the dual porosity cases for the sand and gravel surround and compared to the actual mass balance. Table 7.6 summarizes the mass balance information. The total mass out of the system was calculated by multiplying the mass efflux (mg/day) by the related time step, and summing all values. In both cases the amount of cumulative mass predicted by the model was much higher than corresponding measured values.

Table 7.4: Mass Balance Information

	Experiment	SWIFT DP model
	Mass Out of System	Mass Out of System
Gravel	74.1 mg at 35 days	93.4 mg at 35 days
Sand	83.15 at 51 days	119.2 mg at 50 days

Throughout this research, it has been noted that the sand surround experiments contributed to an increased mass diffused into the matrix due to the higher concentrations relative to the gravel surround and slower flow rates. Figure 7.5 shows a typical curve for mass diffusing into the total matrix material for the first 5 days of the simulated experiments. Although the mass reaches its peak value first in the gravel scenario, the mass diffused proves to be higher over time for the sand scenario. It is interesting to note how the mass values quickly reach a peak and then slowly decline, as the mass re-enters the fracture system due to a reversal concentration gradient.

Figure 7.5: Mass Entering the Total Matrix Material over Time

7.5 Discussion

The results from the numerical model produce reasonable values in comparison to the experimental data. Overall, the model predictions of concentration-time data were appropriate for peak arrival times and initial concentration profiles with time. The major difference noted between model predictions and experimental data, was the model's underestimation of high concentrations following the curve peaks [Section 7.4.1]. West [2001] experienced a similar problem in modelling the results adjacent to the surround in the numerical model FRAC3D.

Figures 7.1 (a, b) demonstrated the flow regime for the gravel and sand scenarios. This supports previous theory that the water is drawn upwards and into the gravel surround creating a higher specific discharge in the gravel relative to the sand surround. The visible narrow plumes of the sand surround in comparison to the dispersed plumes of the gravel surround viewed in Figures 7.3 (a to h) corresponds to previous experimental results in Chapter 6, where the gravel surround caused the solute to migrate outwards in comparison to the sand surround plume.

Figures 7.2 (a, b, c, d) all show that the numerical model predicted shorter peak arrival times compared to the experimental results. This was more evident in the sand surround than in the gravel surround. Most ports exhibited very long extended tails of high concentration following peak concentration in comparison to the numerical results, indicating that the source was still releasing solute, even though the model predicted a lower decline.

Figures 7.4 (a, b, c) show the modelled and experimental mass flux leaving the system boundary over time for the gravel and sand scenarios. The mass efflux of the gravel reached a higher peak concentration relative to the sand, and also higher than predicted by the model. This could be explained by the initial high flux that left the surround found by experimentation. The experimental mass flux curve for sand was again lower than predicted by the model. In a typical sand concentration profile shown by the model [e.g. Figure 7.2 (d)], the concentration reached a peak value and declined slowly.

Prior to the peak concentration, considerable mass diffused into the rock matrix. After the peak, the concentration gradient is reversed and matrix acts as a source to the fracture network [Figure 7.5]. The mass boundary efflux performed by the model also indicated that dual porosity acted to slow down the contaminant front and reduce the maximum solute loading, but in a given amount of time, the mass would leave the system once the diffusion was reversed.

The impact of dual porosity on plume retardation is visible in Figures 7.3 (a to h). The concentration plumes are delayed as DP is introduced into both the sand and gravel scenarios.

The impact of modelling the source term across the entire pit was shown in Figures 7.3(i, j). There is only a slight increase in plume arrival when the entire pit is modelled versus only the volume surrounding the solid steel drum.

CHAPTER 8

8.0 Comparison to Previous Experimentation and Discussion of Dual Porosity Approach as a Representation for Fractured Rock Reservoirs

Chapter 1 discussed previous experimentation that studied the processes affecting an in-pit TMF with a pervious surround design, with the host rock represented using both the EPM and DF approach [West, 2001]. The experimentation used for this research attempted to duplicate the physical design but represented the host rock as dual porosity medium, to assess the impact of matrix diffusion on solute transport. The completion of these three main experiments, allowed for a unique comparison of the different possible representations of fractured media.

This chapter introduces a brief discussion and comparison of flow and transport patterns observed in both projects primarily with regard to the overall performance of the pervious surround concept. A discussion and comparison of the different conceptualizations of the host rock follows.

8.1 Flow Regime

The study performed by West [2001], focused largely on the flow patterns imposed by the pervious surround. West indicated, "...the pervious surround caused a drop in specific discharge through the tailings, an increase in specific discharge adjacent to the tailings, and an increase in specific discharge down-gradient of the pit, relative to the

sand surround.” As the current study did not have any piezometric devices located throughout the model, the flow patterns observed by West could only be verified through downstream flow measurement and concentration data. High concentrations at early arrival times experienced adjacent to the tailings, as well as the higher flow rate relative to the sand experiment, verified the increase in specific discharge through the pervious surround (gravel). The high concentrations typically experienced at heights located at the centreline of the pit ($z=0.48$) indicate preferential flow at this height. This was explained by West [2001] in that compaction of the bottom gravel layer might have reduced the permeability of the surround below the pit causing the groundwater to flow around the pit rather than taking the shorter travel path below the pit.

West also stated, “The water flowed inwards into the up-gradient half of the pit and downwards and outwards in the down-gradient half of the pit.” This statement is analogous to the higher concentrations observed at points located far from the centreline in the gravel surround scenario for this research. Additionally, the sand plumes were shown to be narrower both in the physical and numerical modelling efforts.

8.2 Solute Concentrations

The solute concentrations observed by West reached as high as 10 times higher in the sand experiments than in the gravel experiments. Initially, in the DP model, the concentrations were higher in the sand surround experiment than in the gravel by a factor of 2 to 4, however as the plume travelled along the host rock, the concentrations were no

longer distinguishable (matrix diffusion was attributed to this, and is discussed later). Mass flux curves produced by West's experimentation were very similar to the mass flux curves shown in Chapter 6, where the gravel produces a larger initial efflux (mg/day) than the sand surround.

8.3 Equivalent Porous Media, Discrete Fracture and Dual Porosity Approaches

Fractures play a significant role in transporting contaminants through the subsurface by providing preferential pathways. It is important to consider the presence of fractures when considering a contaminant source. The fractures could act to increase or decrease the travel time. Chapter 2 discussed the different representations of fractured rock. Equivalent porous media are often assigned to represent a host rock with a high number of fractures, where a single hydraulic conductivity is assigned to represent the combination of all fractures. Discrete fracture models attempt to represent each fracture that occurs in the field, and often requires extensive data. Dual porosity models incorporate both EPM and DF approaches by overlapping two media: one representing the fractures and the other representing the matrix. The two media interact through an exchange term, which is usually the most difficult parameter to estimate. An important factor considered in dual porosity models is matrix diffusion, which can act to significantly retard contaminant movement.

The study conducted by West [2001], represented the host rock surrounding the in-pit TMF as EPM and DF media. The DF experiment demonstrated how quickly fractures

can act to carry a contaminant down to the receptor point. The DF plumes were less dispersed, and more difficult to measure. Conversely, the EPM experiment used sand as the representative material, which allowed for slower breakthrough curves, and more dispersed plumes in comparison to the DF model.

The current study was found to include characteristics from both DF and EPM experiments. Certain ports exhibited early, sharp breakthrough curves, much like the DF network results. This was likely an effect due to channelling, where certain paths acted to move the contaminant rapidly.

The dual porosity study demonstrated that the presence of matrix diffusion can reduce initial peak concentration, reduce peak mass flux to a downgradient receptor/reservoir and delay the breakthrough time of concentration curves.

The current experimental set up of blocks divided by finite fractures filled with sand could possibly be represented by an EPM, with the effect of matrix diffusion represented through terms such as fracture porosity, dispersion and sorption. It is possible that by increasing the fracture porosity, a later peak arrival time could have been achieved however this would not affect the peak concentration. Dispersion would have to be changed in order to match the spread of the concentration profile. Sorption could be used to provide for retardation of the peak concentration.

8.4 Engineering Applicability

Examination of data from this study may only demonstrate minimal decreases in concentration and arrival times. However when considering larger time frames such as those considered in long term radioactive waste disposal (e.g. 10,000 years), any delay in solute arrival at the receptor location would cause a significant increase in disposal facility life. In addition any temporary decrease in concentration would also reduce the peak mass loading on a downgradient receptor, could possibly reduce some hazardous constituents below detection limits.

CHAPTER 9

9.0 Conclusions and Recommendations

The research has modelled an in-pit TMF which utilizes a pervious surround and deals with the host rock as a dual porosity system. The main objectives of the thesis were successfully met and are briefly outlined below.

9.1 Conclusions of Research

Reservoir simulation using a dual porosity approach to represent the fractured reservoir can be more challenging than it is for more simplified approaches such as the EPM approach. In the dual porosity approach, advective-dispersive transport occurs within the fractures and diffusive transport moves the solute into and out of the adjacent porous matrix. This thesis illustrated through numerical and physical modeling how matrix diffusion can act to retard a contaminant plume by reducing peak concentrations and by delaying arrival times.

The physical model successfully represented a dual porosity system surrounding an in-pit TMF. This was accomplished by ensuring that characteristic features of a DP system were met such as low velocities, small fractures, and sufficient matrix porosity and diffusivity.

Numerical modeling was able to simulate the experimental results reasonably well. The model tended to overestimate the decline in concentrations after the peak concentration at

sampling locations close to the TMF. The model also tended to overestimate the mass flux reaching the downgradient reservoir, indicating that the transport mechanisms close to the source were not represented well in the numerical model.

As noted in this report, West [2001] represented the same host rock as EPM and DF media. The DP model was compared to the results obtained by West [2001]. The concentration profiles and mass flux curves were similar to West's [2001] work. It was found that West's [2001] numerical model was also unable to accurately represent the transport mechanisms in the vicinity of the surround.

As demonstrated in this thesis, it is important to consider the effects of dual porosity in fractured rock contaminant transport. If the dual porosity effects could be observed on such a small spatial and temporal scale, application to actual field conditions may prove to provide for significant reductions in mass loading and arrival times at downgradient receptors.

9.2 Future Recommendations

Future recommendations would include:

- (i) Numerical model recommendations would include:
 - simulating the DP system to represent the full site model;
 - examine the inability of the numerical model in representing the transport mechanisms in the vicinity of the surround

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Appendix A															
Coordinate Locations for Physical Model (m)															
Experiment #2: sand and Experiment #3: gravel															
	1a	1b	1c	1d	2	3	4	5a	5b	6	7	8	10b	12	14
x	2.11	2.11	2.11	2.11	1.92	1.92	1.92	1.73	1.73	1.73	1.73	1.73	1.54	1.34	1.15
y	0.00	0.00	0.00	0.00	0.00	0.13	-0.07	0.00	0.00	0.62	-0.26	-0.37	0.00	0.00	0.00
z	0.60	0.48	0.30	0.12	0.42	0.60	0.60	0.48	0.12	0.54	0.54	0.48	0.48	0.30	0.30
Experiment #1: gravel															
	1a	1b	1c	1d	2	3	4	5a	5b	6	7	8	10b	12	14
x	2.11	2.11	2.11	2.11	1.92	1.92	1.92	1.73	1.73	1.73	1.73	1.73	1.54	1.343	1.151
y	0.00	0.00	0.00	0.00	0.00	0.13	-0.07	0.00	0.00	0.62	-0.26	-0.37	0.00	0.00	0.00
z	0.6	0.48	0.30	0.12	0.42	0.60	0.60	0.48	0.12	0.54	0.54	0.48	0.48	0.30	0.30

	15	16	17a	17b	17c	18b	18a	19a	19b	20a	
x	0.77	0.68	1.13	1.13	1.13	0.68	0.68	0.98	0.98	0.98	
y	0.54	0.00	0.00	0.00	0.00	0.44	0.44	0.35	0.35	-0.35	
z	0.54	0.24	0.60	0.48	0.30	0.24	0.48	0.48	0.24	0.48	
	15	16	17a	17b	18b	19a					
x	0.77	0.68	1.13	1.13	0.68	0.98					
y	0.54	0.00	0.00	0.00	0.00	0.35					
z	0.54	0.24	0.60	0.48	0.24	0.24					

Appendix B
Diffusivity Tests

Diffusivity Test 1		eff porosity	0.04	diffusivity	3E-12	m ² /sec	
length (m) =	0.011						
Co (ppb) =	10,000						
time	Concentration			1st term	2nd term	Mass/area	Conc
days	Sample 1	Sample 2	Average			micro/m ²	ppb
0	0	0	0	0	733.3333	-733.333	-3.12889
1	0	0	0	235.6364	733.3333	-497.697	-2.12351
2	0.3	0.2	0.25	471.2727	733.3333	-262.061	-1.11813
3	4	3.9	3.95	706.9091	733.3333	-26.4242	-0.11274
4	5.1	5	5.05	942.5455	733.3333	209.2121	0.892638
7	5.8	5.6	5.7	1649.455	733.3333	916.1212	3.908784
8	4.5	4.6	4.55	1885.091	733.3333	1151.758	4.914166
9	6.9	6.7	6.8	2120.727	733.3333	1387.394	5.919547
10	8.1	9.6	8.85	2356.364	733.3333	1623.03	6.924929
11	13.2	10.4	11.8	2592	733.3333	1858.667	7.930311
12	11.9	12.4	12.15	2827.636	733.3333	2094.303	8.935693
14	11.2	13.2	12.2	3298.909	733.3333	2565.576	10.94646
15	14	14	14	3534.545	733.3333	2801.212	11.95184
16	15	14.3	14.65	3770.182	733.3333	3036.848	12.95722
17	16.1	16.4	16.25	4005.818	733.3333	3272.485	13.9626
18	17.3	17	17.15	4241.455	733.3333	3508.121	14.96798
20	18.6	18.4	18.5	4712.727	733.3333	3979.394	16.97875
21	18.4	18.1	18.25	4948.364	733.3333	4215.03	17.98413
22	19.3	18.8	19.05	5184	733.3333	4450.667	18.98951
23	20.4	19.7	20.05	5419.636	733.3333	4686.303	19.99489
24	21.2	21.1	21.15	5655.273	733.3333	4921.939	21.00027
28	23.3	23	23.15	6597.818	733.3333	5864.485	25.0218
29	23.5	23.4	23.45	6833.455	733.3333	6100.121	26.02718
30	25.4	25.5	25.45	7069.091	733.3333	6335.758	27.03257
32	27.8	27.5	27.65	7540.364	733.3333	6807.03	29.04333
35	29.7	29.3	29.5	8247.273	733.3333	7513.939	32.05947
36	30.6	30.4	30.5	8482.909	733.3333	7749.576	33.06486
39	28.8	30.2	29.5	9189.818	733.3333	8456.485	36.081
43	31.1	31.4	31.25	10132.36	733.3333	9399.03	40.10253
44	32	32.1	32.05	10368	733.3333	9634.667	41.10791
46	32.2	32.7	32.45	10839.27	733.3333	10105.94	43.11867
49	32.3	32.3	32.3	11546.18	733.3333	10812.85	46.13482
50	34.1	35.6	34.85	11781.82	733.3333	11048.48	47.1402
51	32.4	32.4	32.4	12017.45	733.3333	11284.12	48.14558

Appendix B
Diffusivity Tests

Diffusivity Test 2		eff poros=	0.04		diffusiv=	3.1E-12	m ² /sec	
length (m)	0.011							
Co (ppb) =	10,000							
time	Concentration				1st term	2nd term	Mass/area	Conc
days	Sample 1	Sample 2	Average	Sub Base			micro/m ²	ppb
0	0	0	0		0	733.3333	-733.3333	-3.128889
1	1.2	1.5	1.35		243.4909	733.3333	-489.8424	-2.089994
2	29.3	27.2	28.25		486.9818	733.3333	-246.3515	-1.0511
3	51.8	49.6	50.7		730.4727	733.3333	-2.860606	-0.012205
4	58.6	58.1	58.35		973.9636	733.3333	240.6303	1.026689
7	62.6	61	61.8	1.8	1704.436	733.3333	971.103	4.143373
8	66.4	66.3	66.35	6.35	1947.927	733.3333	1214.594	5.182267
9	69	69.7	69.35	9.35	2191.418	733.3333	1458.085	6.221162
10	71.5	73	72.25	12.25	2434.909	733.3333	1701.576	7.260057
11	74.9	73.3	74.1	14.1	2678.4	733.3333	1945.067	8.298951
12	74.7	72.1	73.4	13.4	2921.891	733.3333	2188.558	9.337846
14	71.9	74.9	73.4	13.4	3408.873	733.3333	2675.539	11.41563
15	74.4	74.3	74.35	14.35	3652.364	733.3333	2919.03	12.45453
16	75	71.4	73.2	13.2	3895.855	733.3333	3162.521	13.49342
17	73.3	76.8	75.05	15.05	4139.345	733.3333	3406.012	14.53232
18	78.5	78	78.25	18.25	4382.836	733.3333	3649.503	15.57121
20	73.1	73.4	73.25	13.25	4869.818	733.3333	4136.485	17.649
21	73.4	75.1	74.25	14.25	5113.309	733.3333	4379.976	18.6879
22	79.3	77.5	78.4	18.4	5356.8	733.3333	4623.467	19.72679
23	80.5	77.5	79	19	5600.291	733.3333	4866.958	20.76569
24	82.7	80.8	81.75	21.75	5843.782	733.3333	5110.448	21.80458
28	85.3	86.6	85.95	25.95	6817.745	733.3333	6084.412	25.96016
29	86.9	86.7	86.8	26.8	7061.236	733.3333	6327.903	26.99905
30	88.8	89.5	89.15	29.15	7304.727	733.3333	6571.394	28.03795
32	90	91	90.5	30.5	7791.709	733.3333	7058.376	30.11574
35	94.9	95.5	95.2	35.2	8522.182	733.3333	7788.848	33.23242
36	91.8	95.5	93.65	33.65	8765.673	733.3333	8032.339	34.27131
39	91.8	92.3	92.05	32.05	9496.145	733.3333	8762.812	37.388
43	91.3	91.3	91.3	31.3	10470.11	733.3333	9736.776	41.54358
44	91.7	91.7	91.7	31.7	10713.6	733.3333	9980.267	42.58247
46	91.4	91.6	91.5	31.5	11200.58	733.3333	10467.25	44.66026
49	90	90	90	30	11931.05	733.3333	11197.72	47.77694
50	91.8	90.5	91.15	31.15	12174.55	733.3333	11441.21	48.81584
51	91	91.2	91.1	31.1	12418.04	733.3333	11684.7	49.85473

Appendix B
Diffusivity Tests

Diffusivity Test 3		eff poros=	0.07	diffusiv=	3.8E-12	m ² /sec	
length (m) =	0.011						
Co (ppb) =	10,000						
time	Concentration			1st term	2nd term	Mass/area	Conc
days	Sample 1	Sample 2	Average			micro/m ²	ppb
0	0	0	0	0	1283.33	-1283.33	-5.47556
1	0	0.1	0.05	298.4727	1283.33	-984.861	-4.20207
2	0.1	0.6	0.35	596.9455	1283.33	-686.388	-2.92859
5	0.5	0.6	0.55	1492.364	1283.33	209.0303	0.891863
6	3.5	3.5	3.5	1790.836	1283.33	507.503	2.165346
8	4.5	4	4.25	2387.782	1283.33	1104.448	4.712314
9	5.5	5.6	5.55	2686.255	1283.33	1402.921	5.985797
10	7.8	7.7	9.8	2984.727	1283.33	1701.394	7.259281
11	7.7	7.8	10.2	3283.2	1283.33	1999.867	8.532764
12	7.8	7.8	14.1	3581.673	1283.33	2298.339	9.806248
13	8.9	8.8	14.65	3880.145	1283.33	2596.812	11.07973
14	9.9	9.7	15.55	4178.618	1283.33	2895.285	12.35322
15	10.2	10.2	17.55	4477.091	1283.33	3193.758	13.6267
16	14.1	14.1	18.5	4775.564	1283.33	3492.23	14.90018
17	15	14.3	18.1	5074.036	1283.33	3790.703	16.17367
18	15.6	15.5	19.4	5372.509	1283.33	4089.176	17.44715
20	17.5	17.6	20.3	5969.455	1283.33	4686.121	19.99412
21	18.6	18.4	21.3	6267.927	1283.33	4984.594	21.2676
22	18.1	18.1	23.15	6566.4	1283.33	5283.067	22.54108
23	19.2	19.6	22.15	6864.873	1283.33	5581.539	23.81457
24	20.3	20.3	25.5	7163.345	1283.33	5880.012	25.08805
28	21.3	21.3	27.8	8357.236	1283.33	7073.903	30.18199
29	23.3	23	29.9	8655.709	1283.33	7372.376	31.45547
31	22.4	21.9	31.85	9252.655	1283.33	7969.321	34.00244
32	25.5	25.5	31.2	9551.127	1283.33	8267.794	35.27592
35	27.8	27.8	36.75	10446.55	1283.33	9163.212	39.09637
36	29.9	29.9	32	10745.02	1283.33	9461.685	40.36986
39	33.6	30.1	32.85	11640.44	1283.33	10357.1	44.19031
43	31.2	31.2	32.3	12834.33	1283.33	11550.99	49.28424
44	36.8	36.7	34.85	13132.8	1283.33	11849.47	50.55772
46	32	32	34.2	13729.75	1283.33	12446.41	53.10469
47	32.8	32.9	33	14028.22	1283.33	12744.88	54.37818
48	32.3	32.3	34.6	14326.69	1283.33	13043.36	55.65166
49	34.1	35.6	36.9	14625.16	1283.33	13341.83	56.92514
50	33.6	34.8	32.4	14923.64	1283.33	13640.3	58.19863

Appendix B
Diffusivity Tests

Diffusivity Test 4		eff poros=	0.06	diffusiv=	2.9E-12	m ² /sec	
length (m)	0.011						
Co (ppb) =	10,000						
time	Concentration			1st term	2nd term	Mass/area	Conc
days	Sample 1	Sample 2	Average			micro/m ²	ppb
0	0	0	0	0	1100	-1100	-4.69333
1	0	0	0	227.7818	1100	-872.218	-3.72146
2	0.1	0.5	0.3	455.5636	1100	-644.436	-2.7496
3	0.6	0.7	0.65	683.3455	1100	-416.655	-1.77773
4	1.6	1.2	1.4	911.1273	1100	-188.873	-0.80586
5	1.8	2	1.9	1138.909	1100	38.90909	0.166012
6	3.8	3.9	3.85	1366.691	1100	266.6909	1.137881
9	4	4.5	4.25	2050.036	1100	950.0364	4.053488
10	5.6	6.5	6.05	2277.818	1100	1177.818	5.025358
11	6.7	6.9	6.8	2505.6	1100	1405.6	5.997227
12	8	8	8	2733.382	1100	1633.382	6.969096
13	8.1	8.2	8.15	2961.164	1100	1861.164	7.940965
14	9.6	9.7	9.65	3188.945	1100	2088.945	8.912834
15	10.2	9.8	10	3416.727	1100	2316.727	9.884703
16	11.5	11.5	11.5	3644.509	1100	2544.509	10.85657
17	14.2	14.1	14.15	3872.291	1100	2772.291	11.82844
19	17.8	17.5	17.65	4327.855	1100	3227.855	13.77218
21	17.9	17	17.45	4783.418	1100	3683.418	15.71592
22	16.9	16.8	16.85	5011.2	1100	3911.2	16.68779
24	20.4	19.7	20.05	5466.764	1100	4366.764	18.63152
26	21.6	21.5	21.55	5922.327	1100	4822.327	20.57526
28	23.3	23	23.15	6377.891	1100	5277.891	22.519
29	24.1	24.1	24.1	6605.673	1100	5505.673	23.49087
30	25.4	25.5	25.45	6833.455	1100	5733.455	24.46274
32	27.8	27.5	27.65	7289.018	1100	6189.018	26.40648
35	29.7	29.3	29.5	7972.364	1100	6872.364	29.32208
36	30.6	30.4	30.5	8200.145	1100	7100.145	30.29395
37	30.8	30.2	30.5	8427.927	1100	7327.927	31.26582

Appendix B Diffusivity Tests							
Diffusivity Test 5		eff poros=	0.02	diffusiv=	4.2E-12	m ² /sec	
length (m)	0.011						
Co (ppb) =	10,000						
time	Concentration			1st term	2nd term	Mass/area	Conc
days	Sample 1	Sample 2	Average			micro/m ²	ppb
0	0	0	0	0	366.6667	-366.667	-1.56444
1	0.7	1.1	0	329.8909	366.6667	-36.7758	-0.15691
2	2.5	2.6	2.55	659.7818	366.6667	293.1152	1.250625
3	5.5	5.9	5.7	989.6727	366.6667	623.0061	2.658159
5	6.9	6.7	6.8	1649.455	366.6667	1282.788	5.473228
6	7	7.1	7.05	1979.345	366.6667	1612.679	6.880763
7	8.9	9.6	9.25	2309.236	366.6667	1942.57	8.288297
8	11.6	11.9	11.75	2639.127	366.6667	2272.461	9.695832
9	12.6	12.9	12.75	2969.018	366.6667	2602.352	11.10337
11	14.5	14.6	14.55	3628.8	366.6667	3262.133	13.91844
12	19.1	19.5	19.3	3958.691	366.6667	3592.024	15.32597
14	20.6	20.6	20.6	4618.473	366.6667	4251.806	18.14104
16	20.6	20.5	20.55	5278.255	366.6667	4911.588	20.95611
17	20.9	20.9	20.9	5608.145	366.6667	5241.479	22.36364
18	25.6	25.7	25.65	5938.036	366.6667	5571.37	23.77118
19	26.9	27	26.95	6267.927	366.6667	5901.261	25.17871
22	27.5	27.8	27.65	7257.6	366.6667	6890.933	29.40132
24	31.1	32.1	31.6	7917.382	366.6667	7550.715	32.21638
25	36.6	37.5	37.05	8247.273	366.6667	7880.606	33.62392
26	38.5	38.5	38.5	8577.164	366.6667	8210.497	35.03145
27	41	41	41	8907.055	366.6667	8540.388	36.43899
28	43.6	43.9	43.75	9236.945	366.6667	8870.279	37.84652
29	44.5	42.1	43.3	9566.836	366.6667	9200.17	39.25406
32	51.1	51.1	51.1	10556.51	366.6667	10189.84	43.47666
36	51.6	51.6	51.6	11876.07	366.6667	11509.41	49.1068
37	52.9	25.3	39.1	12205.96	366.6667	11839.3	50.51433
38	55.6	55.9	55.75	12535.85	366.6667	12169.19	51.92187
39	52.6	52.3	52.45	12865.75	366.6667	12499.08	53.3294
43	53.6	53.9	53.75	14185.31	366.6667	13818.64	58.95954
45	54.8	54.9	54.85	14845.09	366.6667	14478.42	61.77461

Concentrations (ppb)								
	d/s	1	2	3	4	5	6	8
x coord	2.3	1.538	1.538	1.538	1.919	1.919	2.109	1.919
y coord	0	0.548	0	0.125	0	0.194	0.319	0.125
z coord	0	0.18	0.18	0.18	0.18	0.18	0.18	0.12
time (d)								
0.041667	0.2	0	9.2	6.6	7.6	1.4	0.7	1.1
0.25	0.3	0.2	23.6	7.4	7.2	2	0.8	2.1
0.35625	0.2	0.5	25.8	7.2	6.1	1.7	0.7	4.2
0.461111	0.2	0.2	72.9	9.9	15.4	3.7	0.7	3.9
0.51	0.2	1.1	125.6	92.2	25.6	4.1	0.8	5.1
0.849306	0.2	1.1	298.6	246.3	62.8	9.1	0.7	11.6
0.945833	0.1	1.9	356.8	239.8	120.1	10.7	0.7	11.7
1.111111	0	2.6	348.1	259.9	194.4	6.6	0.7	12.9
1.285417	0.1	9.1	262.3	280.7	255.9	5.7	0.8	16.7
1.453472	0.1	9.5	170.2	200.1	256.6	107	3.6	145
1.916667	0.1	3.6	60.8	120.5	161.5	53.7	3.4	127.5
2.121528	0.1	3.2	55.6	58.9	152.9	15.7	3.2	55.9
2.152083	0.1	8.1	45.9	39.5	117	8.5	0.6	48.8
2.484722	0.2	1.2	30	37.6	90.8	46.4	0.7	50
2.988194	0.2	1.1	31.2	46.4	71.9	36.4	0.7	59.8
3.958333	0.2	0.9	30.5	57	57.6	50	0.7	45.8
6.958333	0.2	0.9	19.6	52.6	50.5	24.5	1.2	35.4
15.95833	0.2	0.9	11.2	13.8	17.3	2.5	1	15.8
18.95833	0	0.9	6.9	19.2	10.4	1.8	0.3	10.9

Appendix D-1 Flow Data
Experiment 1: Gravel Surround

Flow Measurements		
	Time	Flow
	Days	mL/min
start	0	52
	0.0625	49
	0.270833	44
	0.5625	45
	0.729167	48
	1.020833	49
	1.520833	52
	1.854167	45
	2.854167	60
	3.5625	53
	4.645833	55
	10.72917	60
grad chan	13.47917	60
	14.5625	61
end	17.0625	57

Flow Statistics(0-10.7 days)

Mean	51
Standard Error	1.561856
Median	50.5
Mode	52
Standard Deviation	5.410428
Sample Variance	29.27273
Kurtosis	-0.63096
Skewness	0.491804
Range	16
Minimum	44
Maximum	60
Sum	612
Count	12
Largest(1)	60
Smallest(1)	44
Confidence Level(95.0%)	3.437623

Flow Statistics(13-17 days)

Mean	59.33333
Standard Error	1.20185
Median	60
Mode	#N/A
Standard Deviation	2.081666
Sample Variance	4.333333
Kurtosis	#DIV/0!
Skewness	-1.29334
Range	4
Minimum	57
Maximum	61
Sum	178
Count	3
Largest(1)	61
Smallest(1)	57
Confidence Level(95.0%)	5.171149

Appendix D-1 Flow Data
Experiment 2: Sand Surround

Flow Measurements		
	Time	Flow
	Days	mL/min
start	0.00	39
	0.03	42
	0.53	47
	0.82	52
	1.28	53
	1.99	48
	2.65	48
	3.57	49
	4.57	55
	6.90	39
	9.57	45
	11.94	58
	12.61	55
	13.78	59
	18.30	46
	19.20	49
	23.10	48
grad chan	24.53	51
	29.78	55
	30.65	56
	32.65	60
	34.65	51
	40.65	52
end		

Flow Statistics (0-23 days)

Mean	48.94118
Standard Error	1.433503
Median	48
Mode	48
Standard Deviation	5.910484
Sample Variance	34.93382
Kurtosis	-0.50694
Skewness	-0.03237
Range	20
Minimum	39
Maximum	59
Sum	832
Count	17
Largest(1)	59
Smallest(1)	39
Confidence Level(95.0%)	3.03889

Flow Statistics (24-40 days)

Mean	54.16667
Standard Error	1.44722
Median	53.5
Mode	51
Standard Deviation	3.544949
Sample Variance	12.56667
Kurtosis	-0.0762
Skewness	0.885932
Range	9
Minimum	51
Maximum	60
Sum	325
Count	6
Largest(1)	60
Smallest(1)	51
Confidence Level(95.0%)	3.72019

Appendix D-1 Flow Data
Experiment 3: Gravel Surround

Flow Measurements		
	Time	Flow
	Days	mL/min
start	0.00	60
	0.02	62
	0.04	65
	0.08	66
	0.21	65
	1.08	66
	1.83	69
	2.13	72
	3.04	71
	5.92	72
	6.79	68
	8.79	67
	7.10	71
	9.92	75
	13.92	71
	14.83	68
grad chan	16.63	80
	17.50	81
	18.60	79
	18.90	78
	25.60	90
end	27.63	85

Flow Statistics(0-15 days)

Mean	68
Standard Error	0.991632
Median	68
Mode	71
Standard Deviation	3.966527
Sample Variance	15.73333
Kurtosis	-0.18934
Skewness	-0.30033
Range	15
Minimum	60
Maximum	75
Sum	1088
Count	16
Largest(1)	75
Smallest(1)	60
Confidence Level(95.0%)	2.113614

Flow Statistics(16-28 days)

Mean	82.16667
Standard Error	1.851426
Median	80.5
Mode	#N/A
Standard Deviation	4.535049
Sample Variance	20.56667
Kurtosis	0.792379
Skewness	1.246549
Range	12
Minimum	78
Maximum	90
Sum	493
Count	6
Largest(1)	90
Smallest(1)	78
Confidence Level(95.0%)	4.759234

appendix d-II
Gravel Experiment 3
bold=peak conc
blank=no measured value

Concentrations ppb

198

	1a	1b	1c	1d	2.00	3.00	5a
x coord	2.11	2.11	2.11	2.11	1.92	1.92	1.73
y coord	0.00	0.00	0.00	0.00	0.00	0.13	0.00
z coord	0.60	0.48	0.30	0.12	0.24	0.60	0.48
time (d)							
0.00	0.90	1.10	7.20	5.20	8.40	2.50	747.60
0.02	3.00	6.50	6.50	6.60	51.20	6.90	632.10
0.04	21.90	16.40	17.30	12.10	167.00	1.50	521.80
0.08	70.20	100.20	26.10	13.20	196.50	142.30	520.30
0.21	84.90	201.50	41.20	16.30	431.30	198.20	484.20
0.83	76.85	215.60	153.20	23.90	106.30	199.60	400.20
1.08	111.50	298.70	239.50	121.00	188.80	201.20	352.20
1.83	104.70	185.20	209.00	123.80	466.80	256.40	485.30
2.13	33.90	165.40	195.60	139.00	239.70	158.30	326.10
3.04	35.60	187.50	189.10	110.10	230.70	147.50	169.10
5.04	55.60	145.00	152.30	111.00	135.00	162.30	177.00
5.92	62.50	43.30	120.10	33.90	106.20	59.80	77.80
6.79	59.80	21.90	121.20	71.70	76.40	29.60	53.00
8.79	56.10	16.70	108.50	41.30	42.40	25.60	38.60
9.92	16.30	15.10	106.10	40.50	35.50	20.10	34.80
10.60	15.60	19.60	98.50			18.40	
11.10	19.60	7.20	91.60	51.20		19.60	
13.92	14.80	5.60	92.60	29.60		18.90	
14.83	17.90	8.10	88.40	30.60	27.00	17.40	24.10
16.63	10.30	6.50	81.20	19.10	20.20	21.00	22.10
18.60	9.80	4.60	76.20	14.10	13.20	19.50	12.30
25.60	4.10	3.60	75.20	5.20		25.60	
27.63	6.90	6.80	71.20	6.50		11.80	

appendix d-II
Gravel Experiment 3
bold=peak conc
blank=no measured value

Concentrations ppb

199

5b	6.00	7.00	8.00	10b	12.00	14.00	15.00
1.73	1.73	1.73	1.73	1.54	1.34	1.15	0.77
0.00	0.62	-0.28	-0.37	0.00	0.00	0.00	0.54
0.12	0.54	0.54	0.48	0.48	0.30	0.30	0.54
34.80	7.40	23.00	3.50	500.20	45.20	458.90	
86.00	16.50	31.70	32.60	596.60	125.60	479.80	
38.20	17.90	37.10	39.60	701.20	225.40	498.60	
38.70	68.90	45.90		648.20	300.10	475.60	
36.20	82.30	42.90	46.40	736.50	289.50	448.80	
55.90	116.00	78.90	167.80	489.60	278.40	398.20	
97.40	47.30	106.90	180.80	377.30	241.50	351.10	
92.50	51.60	170.30	213.40	149.80	182.30	325.60	
102.80	42.40	162.00	220.60	119.70	176.60	201.60	
80.80	26.70	155.20	232.00	134.00	189.60	189.60	
49.30	23.10	135.40	201.20	83.40	126.60	192.60	
94.10	19.00	133.60	178.40	89.60	123.60	178.50	
35.40	18.50	127.20	148.90	53.90	114.60	155.40	
25.90	15.70	105.60	111.20	45.00	98.60	108.50	
21.50	14.20	121.30	107.00	36.10	89.50	101.20	
		87.20	100.10		76.10	98.60	
		80.30	98.50		65.10	115.50	
13.20		61.00	83.20		46.50	104.20	
11.40	18.70	50.30	84.80	25.40	51.40	94.50	
23.20	10.00	17.20	51.50	18.10	69.60	89.80	
6.50	6.20	15.10	17.50	16.10	55.40	78.60	
5.40	5.40	7.80	6.30	11.20	48.90	56.20	
2.30	1.20	2.60	11.40		59.80	55.20	

appendix d-II
 Gravel Experiment 3
 bold=peak conc
 blank=no measured value

Concentrations ppb

200

16.00	17a	17b	17c	18b	18a	19a	19b
0.68	1.13	1.13	1.13	0.68	0.68	0.98	0.98
0.00	0.00	0.00	0.00	0.44	0.44	0.35	0.35
0.24	0.60	0.48	0.90	0.24	0.48	0.48	0.24
214.10	1537.20	2413.00	500.20	307.90	155.00	758.70	
238.80	1852.20	872.10	560.90	227.50	314.40	885.70	
247.40	998.60	1979.60	459.60	228.60	240.70	751.80	
236.50	968.10	767.60	381.50	225.90	224.80	693.40	
226.70	604.20	484.80	365.20	211.80	207.70	696.90	
244.50	1095.10	636.30	300.20	224.20	159.10	779.30	
220.90	716.90	479.40	280.60	222.00	134.70	250.60	
189.50	411.60	515.10	278.90	228.30	134.10	228.10	
216.10	322.40	191.90	259.80	183.90	100.30	132.20	
180.90	151.00	75.00	200.50	103.30	97.40	136.90	
200.40	223.10	41.20	205.60	163.20	61.80	98.20	
189.80	137.20	188.20	251.20	164.50	57.30	87.20	
169.50	154.00	101.40	200.10	21.30	63.70	77.50	
162.00	151.00	88.70	195.60	23.00	86.00	77.00	
170.40	138.20	108.00	189.90	14.60	55.70	62.30	
175.40	122.60		156.60	13.60	61.20	75.60	
165.30	120.10		165.20	14.50	56.40	65.90	
189.00	124.10		152.40	12.90	50.20	51.90	
194.00	118.90	68.60	159.60	11.50	45.40	44.30	
166.00	107.70	46.20	142.00	4.80	36.00	43.70	
96.00	39.40	29.10	130.20	4.60	18.00	24.50	
87.90	35.20		132.30	2.10	14.20		
	26.90		125.40	1.10	12.60	7.80	

appendix d-ii
Experiment #2 Sand
Bold=peak conc
Blank=no measured data

Concentration ppb

201

	1a	1b	1c	1d	2.00	3.00	5a
x coord	2.11	2.11	2.11	2.11	1.92	1.92	1.73
y coord	0.00	0.00	0.00	0.00	0.00	0.13	0.00
z coord	0.60	0.48	0.30	0.12	0.24	0.60	0.48
time in d							
0.00	2.7	5.5	2.2	4.1	1.3	0.2	1.2
0.03	1.3	2.9	3.6	3.4	3.2	0.4	2.6
0.53	14.3	16.3	16.5	7.9	118.4	1.2	9.8
0.82	36.8	26.3	52.6	12.6	152.2	3.6	11.2
1.28	77.6	111.1	78.9	9.6	429.7	17.5	12.4
1.99	37.2	112.2	101.2	8.2	450.1	18.6	16.7
2.65	78.4	156.2	98.8	6.7	524.7	26.5	61.3
3.57		200.2	61.2	7.9	294.1	52.4	
4.57		222.2	58.5	6.6	360.3	69.8	60.1
6.90		156.2	35.9	8.1	193.7	99.6	38.9
9.57		112.1	28.6	9.8	71	76.5	45.7
11.94		56.3	30.5	13	36.1	62.3	45.2
12.61		45.1	43.6	22.7	80	58.9	88.5
13.78		78.4	24	12.9	49.3		95.2
18.53		11	44.2	15	40.8		101.3
23.53		7.3	49.1	11.8	36.1		106.5
23.82		7.3	48.6	11.7	23.3		89.5
24.53		22.9	47.6	12.5	54.2		54.5
29.78		1.1	46.9	13.7	106.7		47.6
30.65		1.5	81.9	6.9	19.7	23.5	36.5
32.65		4.2	89.3	7.5	4.2		41.2
34.65		0.8	78.6	9.8	2.8		16.5
40.65		0.2	46.6	8.8	2.9		10.2

appendix d-II
Experiment #2 Sand
Bold=peak conc
Blank=no measured data

Concentration ppb

202

5b	6.00	7.00	8.00	10b	12.00	14.00	15.00
1.73	1.73	1.73	1.73	1.54	1.34	1.15	0.77
0.00	0.62	-0.26	-0.37	0.00	0.00	0.00	0.54
0.12	0.54	0.54	0.48	0.48	0.30	0.30	0.54
12.8	7.7	34.5	11.9	4.5	56.4	133.4	0.7
17.2	9.5		9.7		110.5	160.8	2.8
17.2	12.1		18.2	7.9	124.5	179	130.9
65.3	10.4		17.5	14.5	144.1	1126.5	184.5
92.5	9.4		13.9	23.5	247.5	1123.6	151.6
76	7.5		31.5	43.2	251.3	769.5	100.9
100.4	6.3		43.4	58.4	238.6	769.5	44.1
136.8	4.9		53.1	60.6	230.1	587.1	43.1
227.6	6.8		102	44	205.6	456.9	36.8
200.3	5		67.5	72.3	213.6	402.3	9.9
124.6	4.8		45	27.8	154.8	397.6	29.9
291	4.3		36.5		128.2	384.3	12.4
398.6	4.9		24.4	35.5	115.4	356.9	3.3
114.2	4.8	33.7	41.2		154.2	201.6	16.9
170.2	11.5	143.1	40.3	23.3	128.2	156.7	99.1
38.3	3.6	24.8	35.2	30.2	115.2	105.2	7.1
34.4	3.5	21.3	36.5	14	101.3	115.4	18.3
577	5.8	10.1	21.4	8.7	98.6	125.4	3.1
	2.8	6.1	22.6	11.3	56.9	120.6	6.4
12.9	2.6	4.8	15.4	8.9	36.3	139.5	4.2
26.1	2.2	4.6	14.1	6.6	23.5	124.7	0.7
28.1	2.2	2.9	10.1	3.2	35.8	120.2	39
14.6	1.3	4.6	0.2		36.9	104.1	1

NOTE TO USERS

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202

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appendix d-II
Experiment #2 Sand
Bold=peak conc
Blank=no measured data

Concentration ppb

202

16.00	17a	17b	17c	18b	18a	19a	19b	20a
0.68	1.13	1.13	1.13	0.68	0.68	0.98	0.98	0.98
0.00	0.00	0.00	0.00	0.44	0.44	0.35	0.35	-0.35
0.24	0.60	0.48	0.30	0.24	0.48	0.48	0.24	0.48
56.4	133.4	78.4	92.4	127.4	191.7	92.4	78.5	62.9
110.5	560.2	124.5	136.5	143.7	271.8	136.5	98.5	78.4
124.5	752.6	136.9	528.6	150	491.3	528.6	102.3	148.6
144.1	1569.6		689.1	268.4	2086.3	689.1	789.5	526.9
247.5	1769.5		1000.6	1317.9	3642.8	1000.6	1256.3	852.6
251.3	1658.2		906.5	2690.6	3792.8	906.5	1526.3	1452.8
238.6	1145.3		1050.6	1677.3	2592.5	1123.2	1587.4	1629.5
230.1	1152.2		895.2	1125.5	2198	895.2	1402.2	1555.4
205.6	852.6		800.1	1217.5	2206.9	800.1	989.6	
213.6	602.3		778.4	528.3	1869.5	778.4	785.6	
154.8	397.6		793.2	418.7	2097	793.2	748.2	
128.2	384.3		600.5	793.4	3363	600.5	845.2	
115.4	356.9		598.4	825.2		598.4	698.6	
154.2	201.6		505.1			505.1	589.4	
128.2	156.7		302.1	828	2284	302.1	458.6	
115.2	105.2		258.2	227.5	2721	258.2	589.5	
101.3	115.4		198.5	147.7		198.5	145.6	
98.6	125.4		201.2	109	1238	201.2	258.9	
56.9	120.6		197.6	15.9		197.6	187.2	
36.3	139.5		215.2	20.4	763	215.2	145.2	
23.5	124.7		205.4	79.6	1247	205.4	133.3	
35.8	120.2		97.1	83.3	722.7	97.1	134.6	
36.9	104.1		69.8	16.7		69.8	78.4	

Experiment 1: Gravel
 Bold=Peak Conc
 Blank=no data

Conc ppb

203

	d/s	1a	1b	1c	1d	2	3	4
x coord		2.11	2.11	2.11	2.11	1.92	1.92	1.92
y coord		0.00	0.00	0.00	0.00	0.00	0.13	-0.07
z coord		0.6	0.48	0.30	0.12	0.42	0.60	0.60
time (d)								
0		256.1	6.6	285.0	9.3		28.3	
0.0625		278.5	455.7	223.3	9.2	381.6	408.1	
0.270833	42.7	402.6	373.8	571.2	17.5	682.0	358.8	
0.5625	59.8	321.5	540.8	187.2	51.1	661.5	313.1	
0.729167	71.9	329	600.2	256.8	60.0	452.6	201.5	
1.020833	88.1	265.2	640.5	142.8	75.6	332.1	379.5	
1.520833	107.9	241.2	489.5	282.9	96.0	325.9	162.0	
1.854167	113.8	151.2	379.1	219.6	149.1	320.1	133.5	
2.854167	109.9	149.3333	348.3	227.6	111.8	180.2	99.2	
3.5625	107.0	127.6	194	203.5	149.4	151.8	102.4	
4.645833	103.7	125.8	161.6	186.7	133.2	131.4	84.0	
7.645833	78.5	95.6	133.1	147.1	73.4	86.8	62.5	
9.854167	58.3	59.2	73.9	123.8	47.1	46.8		
10.72917	54.9	45	42.7	115.0	37.8	39.2		
13.47917	41.6	31.7	41.6	103.2	27.9	31.0		
14.5625	25.0	28.2	34	98.9	24.1	25.3		
17.0625	18.0	16	14.6	70.4	19.8	13.9	5.1	

Experiment 1: Gravel

Conc ppb

204

Bold=Peak Conc

Blank=no data

5a	5b	6	7	8	10b	12	14
1.73	1.73	1.73	1.73	1.727	1.54	1.343	1.151
0.00	0.00	0.62	-0.26	-0.37	0.00	0.00	0.00
0.48	0.12	0.54	0.54	0.48	0.48	0.30	0.30
695.2	31.4	186.1			641.7	208.0	108.4
352.8	30.6	458.3	519.8	430.0	674.7		
495.9	42.9	423.1	260.4	745.5	820.0	378.0	660.0
421.7	34.3	259.1	276.1	578.1	662.4	586.5	938.4
318.8			213.2	479.4	400.0	569.8	647.8
253.8	41.8	210.9	282.7	321.3	212.4	917.6	3477.6
212.1	20.3	165.0	286.7	363.9	166.4	1268.8	984.0
177.1	15.9	131.9	289.8	316.8	127.9	1157.3	1111.1
102.7	27.5	100.8	179.8	270.6	109.2	1008.3	2750.8
124.5	42.3	114.8			123.6	1407.5	697.2
114.8	51.5	112.8	174.4	156.8	117.5	460.1	1989.0
106.7	32.0	68.9	132.6	51.9	107.3		
53.8	9.9	38.3		9.8	45.5	496.0	410.6
48.6	9.8	32.8		12.4	39.3	310.8	300.1
33.0	7.6	27.3		8.2	30.6	227.6	245.8
70.1	6.2	18.1	25.5	4.4	19.4	140.3	195.2
22.7	3.9	13.2		4.6	12.9	134.4	105.7

Experiment 1: Gravel

Conc ppb

205

Bold=Peak Conc

Blank=no data

15	16	17a	17b	18b	19a
0.767	0.675	1.13	1.13	0.68	0.98
0.54	0.00	0.00	0.00	0.00	0.35
0.54	0.24	0.60	0.48	0.24	0.24
	1112.9	209.6	1212.5	659.4	
	888.3	676.0	1178.6	595.2	
75.4	1440.0	490.6	1283.1	241.8	
84.6	675.3	420.8	1589.6	145.6	
95.4	546.7	262.3	1785.9	111.6	
135.3	593.1	248.8	1785.9	88.2	
68.0	315.4	225.6	1261.8	98.4	
67.1	380.8	153.1	1052.8	70.4	
47.0	358.8	209.2	840.0	57.2	
72.0	290.4	164.4	838.5	50.7	
133.7	908.8	166.6	1518.0	152.4	
50.0		120.5		36.7	
21.2	204.4	101.2	576.0	29.0	
21.3	92.3	63.9	497.4	20.3	
15.2	78.0	45.3	432.2	30.6	
8.2	42.0	28.5	172.0	15.9	
10.7	27.7	22.8	145.8	16.1	

Sand Experiment 2: Mass Efflux Data

days	d/s	1st	2nd	mg/day	V=	256.65 L	mg mass	cum mass
0.00	0	0	0	0			0.00	0.00
0.01	0.1	25.67	0.04	2.570028			0.03	0.03
0.03	0.3	51.33	0.25	2.879042			0.05	0.08
0.53	6.5	1591.23	119.95	3.422364			1.71	1.79
0.82	10.5	1026.60	174.93	4.119531			1.20	2.99
1.28	19.1	2207.19	478.63	5.859975			2.69	5.68
1.99	35.2	4132.07	1356.96	7.749208	Q	70.56 L/day	5.49	11.16
2.65	48.1	3310.79	1959.22	7.905002			5.27	16.43
3.57	53.3	1334.58	3279.28	5.033297			4.61	21.05
4.57	55.1	461.97	3824.35	4.286322			4.29	25.34
6.90	54.2	-230.99	8997.58	3.75711			8.77	34.10
9.57	47	-1847.88	9520.90	2.877381			7.67	41.77
11.94	43.3	-949.61	7566.24	2.78595			6.62	48.39
12.61	35.2	-2078.87	1846.32	-0.348818			-0.23	48.16
13.78	32.3	-744.29	2778.30	1.743441			2.03	50.19
18.53	20.3	-3079.80	8814.71	1.207349			5.73	55.93
23.53	21.1	205.32	7302.96	1.501656			7.51	63.44
23.82	19.1	-513.30	413.66	-0.34163			-0.10	63.34
24.53	19.6	128.33	967.11	1.546501			1.10	64.43
29.78	21.6	513.30	7631.06	1.551307			8.14	72.58
30.65	20.1	-384.98	1287.28	1.031205			0.90	73.48
32.65	18.7	-359.31	2737.73	1.189209			2.38	75.86
34.65	18.3	-102.66	2610.72	1.25403			2.51	78.36
40.65	11.4	-1770.89	6286.90	0.752669			4.52	82.88
51.30	2.3	-2335.52	5146.12	0.263979			2.81	85.69

Gravel exp 3
mass flux
appendix D-III

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Gravel Experiment 3: Mass Efflux Data

days	d/s	1st	2nd	V=	256.65	L	mg mass	cum mass
0.00	0.00	0.00	0.00	0			0.00	0.00
0.01	0.30	77.00	0.16	7.7157			0.08	0.08
0.02	0.32	5.13	0.36	0.507295			0.01	0.08
0.04	0.40	20.53	0.81	1.024416			0.02	0.10
0.07	0.55	38.50	1.45	1.410035			0.04	0.14
0.08	0.60	12.83	0.62	1.34535	Q	108 L/day	0.01	0.16
0.11	1.00	102.66	2.59	3.5084			0.11	0.26
0.23	1.13	33.36	13.80	0.393058			0.05	0.31
0.39	11.80	2738.46	111.72	17.81357			2.85	3.16
0.68	31.20	4979.01	673.38	19.491			5.65	8.81
0.90	44.20	3336.45	895.75	19.23728			4.23	13.04
1.10	47.50	846.94	990.36	9.186525			1.84	14.88
1.70	49.90	615.96	3155.76	6.2862			3.77	18.65
2.00	50.20	77.00	1621.62	5.66205			1.70	20.35
2.50	51.30	282.31	2740.50	6.04563			3.02	21.68
3.04	48.40	-744.29	2916.23	4.009735			2.17	23.85
5.04	50.10	436.31	10638.00	5.537153			11.07	34.92
5.92	45.30	-1231.92	4507.65	3.743691			3.28	38.20
6.79	40.80	-1154.93	4068.23	3.329486			2.91	41.11
8.79	25.60	-3901.08	7171.20	1.63506			3.27	44.38
9.92	23.10	-641.63	2958.53	2.059467			2.32	46.70
13.92	18.30	-1231.92	8942.40	1.92762			7.71	54.41
14.83	17.00	-333.65	1747.35	1.542224			1.41	55.82
16.63	16.20	-205.32	3212.10	1.678203			3.01	58.83
18.60	11.50	-1206.26	2954.21	0.885038			1.75	60.58
25.60	12.20	179.66	8958.60	1.305465			9.14	69.72
27.63	9.10	-795.62	2329.16	0.757304			1.53	71.25
35.20	2.20	-1770.89	4622.27	0.37642			2.85	74.10

Appendix D-III

Initial Tailings gravel exp (2)

	test tube mass g	wet sample mass + tube g	sample mass g	estimated water content in sample mass mL
1	11.25	14.5	3.25	0.490566038
2	11.1	11.2	0.1	0.01509434
3	10.9	14.2	3.3	0.498113208
4	11.2	12.5	1.3	0.196226415
5	11.3	14.3	3	0.452830189
6	11.4	12.6	1.2	0.181132075
7	11.6	12.1	0.5	0.075471698
8	10.9	15.3	4.4	0.664150943

Final Tailings

	test tube mass g	wet sample mass + tube g	sample mass g	estimated water content in sample mass mL
1	11.25	15.57	4.32	0.652075472
2	11.1	16.2	5.1	0.769811321
3	10.9	11.9	1	0.150943396
4	11.2	12.05	0.85	0.128301887
5	11.3	14.1	2.8	0.422641509
6	11.4	13.6	2.2	0.332075472
7	11.6	15.9	4.3	0.649056604
8	10.9	13.2	2.3	0.347169811

water added mL	measured conc ppb	dilution factor -	actual conc ppb	mass micro	mass mg
8	548.9	17.30789231	9500.19231	296406	296.406
8	20.1	531	10673.1	333000.7	333.0007
8	479.6	17.06060606	8182.26667	255286.7	255.2867
8	205.4	41.76923077	8579.4	267677.3	267.6773
8	471.2	18.66666667	8795.73333	274426.9	274.4269
8	426.5	45.16666667	19263.5833	601023.8	601.0238
8	101.4	107	10849.8	338513.8	338.5138
8	700.2	13.04545455	9134.42727	284994.1	284.9941
		average=	10622.3129		331.4162

water added mL	measured conc ppb	dilution factor -	actual conc ppb	mass micro	mass mg
5	502.3	8.667824074	4353.84803	135840.1	135.8401
5	500.6	7.495098039	3752.04608	117063.8	117.0638
5	205.3	34.125	7005.8625	218582.9	218.5829
5	200.1	39.97058824	7998.11471	249541.2	249.5412
5	465.3	12.83035714	5969.96518	186262.9	186.2629
5	458.9	16.05681818	7368.47386	229896.4	229.8964
5	289.5	8.703488372	2519.65988	78613.39	78.61339
5	589.2	15.40217391	9074.96087	283138.8	283.1388
		average=	6005.36639		187.3674

Appendix DIII
Initial Tailings sand experiment

	test tube mass g	wet sample mass + tube g	sample mass g	estimated water content in sample mass mL
1	11.25	13.2	1.95	0.294339623
2	11.1	11.9	0.8	0.120754717
3	10.9	13.2	2.3	0.347169811
4	11.2	15.9	4.7	0.709433962
5	11.3	17.1	5.8	0.875471698
6	11.4	16.5	5.1	0.769811321
7	11.6	16.9	5.3	0.8
8	10.9	12.1	1.2	0.181132075

Final Tailings

	test tube mass g	wet sample mass + tube g	sample mass g	estimated water content in sample mass mL
1	11.25	16.2	4.95	0.747169811
2	11.1	17.5	6.4	0.966037736
3	10.9	16.5	5.6	0.845283019
4	11.2	18.9	7.7	1.162264151
5	11.3	13.6	2.3	0.347169811
6	11.4	13.8	2.4	0.362264151
7	11.6	17.4	5.8	0.875471698
8	10.9	19.5	8.6	1.298113208

water added mL	measured conc ppb	dilution factor -	actual conc ppb	mass micro	mass mg
10	342.3	34.97435897	11971.7231	373517.8	373.5178
10	165.6	83.8125	13879.35	433035.7	433.0357
10	179.5	29.80434783	5349.88043	166916.3	166.9163
10	455.1	15.09574468	6870.0734	214346.3	214.3463
10	458.9	12.42241379	5700.64569	177860.1	177.8601
10	569.8	13.99019608	7971.61373	248714.3	248.7143
10	564.2	13.5	7616.7	237641	237.641
10	520.6	56.20833333	29262.0583	912976.2	912.9762
		average=	11077.7556		345.626

water added mL	measured conc ppb	dilution factor -	actual conc ppb	mass micro	mass mg
10	276.2	14.38383838	3972.81616	123951.9	123.9519
10	320.2	11.3515625	3634.77031	113404.8	113.4048
10	215.3	12.83035714	2762.37589	86186.13	86.18613
10	566.2	9.603896104	5437.72597	169657.1	169.6571
10	315.6	29.80434783	9406.25217	293475.1	293.4751
10	204.5	28.60416667	5849.55208	182506	182.506
10	205.8	12.42241379	2556.53276	79763.82	79.76382
10	399.6	8.703488372	3477.91395	108510.9	108.5109
		average=	4637.24241		144.682

Appendix E: Photos of Construction of Physical Model

Picture 1: Preparation of Limestone Base Layer

Picture 2: Cutting Steel Girder

Picture 3: Painting of Steel Girder

Picture 4: Placement of Steel Girder (Up-gradient location)

Picture 5: Bottom Four Layers of Block/Sand

Picture 6: Hollow Steel Drum, Reinforced with Wood at Both Ends

Picture 7: View of Pit after Completion of 12 Block/Sand Layers, Bottom Lined with Pervious Surround Material

Picture 8: Completed Physical Model (Upgradient Side)