Quantifying groundwater discharge at various spatial and temporal scales

Henley, M
Department of Earth Sciences – St. Francis Xavier University, Antigonish, NS, Canada
Ferguson, G
Department of Earth Sciences – St. Francis Xavier University, Antigonish, NS, Canada
Baechler, F
ADI Limited, Sydney, NS, Canada

ABSTRACT
Groundwater-surface water exchange varies spatially as a result of the heterogeneity of aquifer and streambed properties as well as channel morphology. These flux patterns can be examined at a variety of scales, with the majority of recent studies focusing on reach scale investigations in order to obtain high-resolution measurements in an inexpensive and time efficient manner. Current efforts to rectify groundwater discharge on a 10th order meandering reach in Melford, Cape Breton involve temperature measurements, hydrograph separation, mass balance and Darcy's law. Large-scale estimates indicate significant amounts of groundwater discharge in comparison to smaller scale measurements, which are likely representative of local throughflow or bank storage events.

RÉSUMÉ
Les échanges entre eau de surface et eau souterraine varient dans l'espace en raison de l'hétérogénéité de la couche aquifère et des propriétés du lit du ruissellement. Ces modèles de flux peuvent être examinés à différentes échelles. La majorité des études récentes se concentrent sur l'obtention de mesures de haute resolution d'une façon efficace. Les récents efforts de correction de la décharge d'eaux souterraines à l'échelle du méandre de 10ème ordre dans Melford, Cap Breton impliquent des mesures de la température, la séparation d'hydrographes, le bilan de masse et la loi de Darcy. Les évaluations à grande échelle indiquent des quantités significatives de décharge d'eaux souterraines par rapport aux mesures aux échelle plus petites, qui représentent probablement des transports locaux ou des événements de stockage.

1 INTRODUCTION

Understanding and quantifying exchange processes between groundwater and surface water is crucial in the functioning of aquatic ecosystems, development of water supplies and water resources management. Surface water and groundwater exhibit distinct properties however their interactions unite them as one single entity. By identifying the chemical, physical and biological properties within each reservoir one can begin to examine the processes and interactions occurring within the transition zone termed the hyporheic zone. However, studies based on these shallow subsurface flows constrains the spatial scale and attempts at upscaling these local observations may not be an accurate representation of the entire catchment.

A wide range of both spatial and temporal scales are involved in the study of groundwater processes. A mosaic of controlling factors, each varying independently in time and space contribute to a spectrum of exchanges occurring between groundwater and surface water. Entire stream reaches can easily be conceptualized as gaining or losing systems. The challenge lies when down-scaling to the finer scale where localized flow systems also develop creating an additional environment with unique interactions and processes. Groundwater flux is further complicated by the interplay of aquifer and streambed heterogeneity as well as channel morphology, including the role of beaver dams and large woody debris (Kalbus 2008). Scenarios arise when one or more of these factors may present a stronger influence than the other. Thereby assessing individual controlling factors at multiple spatial scales is essential in order to properly address variability.

A field scale study based in Cape Breton, Nova Scotia has been devised to investigate the complex groundwater patterns acting at these various scales. Based on preliminary results the selected stream appears to be receiving sufficient groundwater input as illustrated in Figure 1, where an exponential decline in conductivity occurs as discharge increases. At low discharge conditions, nutrient rich groundwater is maintaining base flow indicative of the elevated electrical conductivity values. Based on these initial findings groundwater discharge estimates were obtained using four separate techniques each varying in spatial and temporal measuring scales.

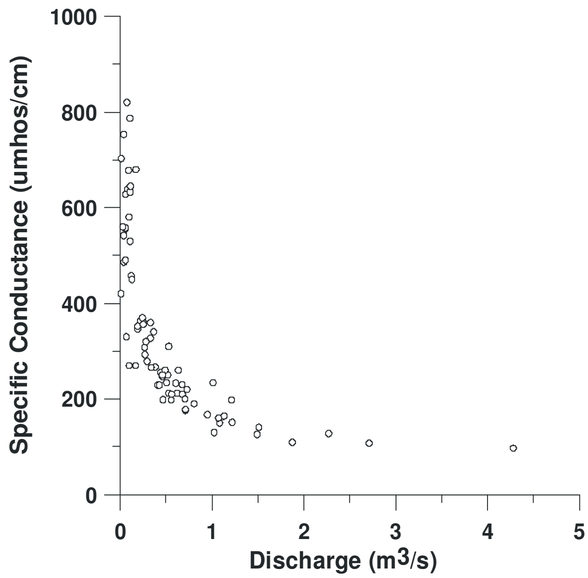

Figure 1. Increased levels of conductivity during periods of low discharge suggest the presence of groundwater discharge.

2 BACKGROUND

Hierarchical classifications of temporal and spatial scales occur in groundwater surface water interactions (Fig.2). It has proven difficult to relate small-scale groundwater-surface water interactions to basin-scale effects (Sophocleous, 2002). The problem in quantifying basin-scale effects of hyporheic reactions is due in part to the disparity of scales between small-scale (1–10 cm) hyporheic processes and larger basin scale effects. It is essential to identify processes at the small-scale, yet results are usually too variable from site to site to reliably quantify cumulative effects (Harvey & Fuller 1998). Harvey and Fuller (1998) were able to extrapolate small-scale (sediment-grain scale through stream-reach scale) hyporheic data to basin-scale effects for a small creek. Results demonstrated that river-reach and river-stretch gain and loss measurements apparently correspond to groundwater-surface water interactions at local and regional scales, respectively, providing a step towards developing an understanding of large-river-basin scale groundwater-surface water interactions (Hinkle et al., 2001)

In order to determine the scale for investigation, appropriate methods applicable in this zone must be examined. Method selection varies depending on the preferred resolution, sample volume, and the time scales to be represented. Point estimates of flux can be retrieved from seepage meters or temperature probes while continuous monitoring with data loggers can allow for observations of temporal variations. The measurement scale significantly influences the results in heterogeneous media, for example the tendency to overlook small heterogeneities, such as high conductivity zones results in underestimates, whereas dense measurements may have accounted for this (Kalbus, 2006). However when conducting densely instrumented field investigations in order to obtain adequate spatial coverage, natural flow conditions can be unknowingly altered while measurements at a broader scale may lead to significant under or over-estimation of groundwater discharge values.

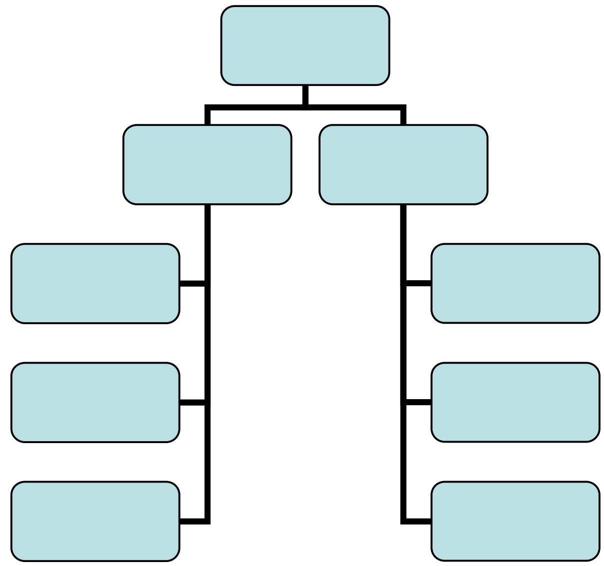

Figure 2. Range of spatial and temporal scales commonly investigated in groundwater-surface water studies.

3 STUDY SITE

Glen Brook is located adjacent to the Georgia Pacific Canada Inc.’s gypsum mine in Melford, Cape Breton, Nova Scotia (Fig.3). The study area is located within a 10th order reach draining a 16.8 km^2 highland watershed draining from the Creignish Hills to River Denys. The approximately 10 m wide meandering channel is incised into a glacio-fluvial sand/gravel aquifer, which underlies a broad, terraced valley floor. The permeable, saturated, sand and gravel deposit associated with a glacial-fluvial system developed during de-glaciation controls the present day groundwater stream interactions (ADI 2000). The aquifer supports a potable water supply; the channel provides a significant fresh water aquatic habitat for salmonids.

In 1999, Georgia Pacific assigned a 2.7 km reach adjacent to the mine site, as a Salmonid Management Zone (SMZ). Ongoing monitoring to protect and enhance aquatic habitat consists of two stream monitoring stations and five monitoring wells located perpendicular to the stream. The results of this research are intended to support the on-going research onto how to best protect, improve and manage salmon and trout populations in the SMZ.

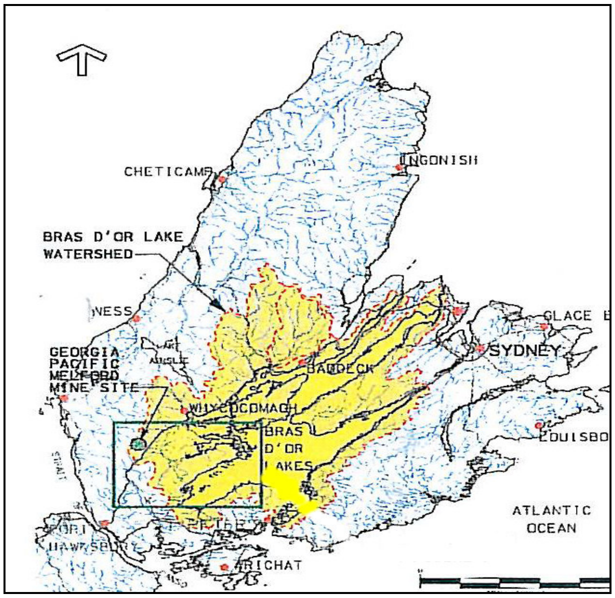

Figure 3. Location of Melford Mine site within the Bras d'Or Lake Watershed

4 ANALYSIS

The range of techniques available to determine interactions between groundwater and surface water is extensive. Depending on the study focus and the channel morphology, the suitability of the different methods and their applicability on different spatial and temporal scales needs to be assessed. Often the choice of methods constitutes a trade-off between resolutions of heterogeneities and sampled subsurface volume (Hubbard et al., 2000).

In the current study groundwater discharge values are estimated using techniques applied to alternate hydrologic units representing different spatial and temporal scales.

4.1 Darcy's Law

Darcy's Law (Darcy, 1856) states that water flux is a function of hydraulic gradient and hydraulic conductivity. Thus if these two parameters can be measured, water flux can easily be calculated using the Darcy equation:

$$q = -K\, dh/dl \qquad [1]$$

where q is specific discharge (m^3/s), K is hydraulic conductivity (m/s), h is hydraulic head (m) and l is distance (m). Using measurements of hydraulic head obtained from monitoring wells and stage level in the brook is a quick, easy and straightforward method appropriate for small-scale applications and allows a detailed survey of the heterogeneity of flow conditions in the aquifer (Kalbus, 2006). Head values from the six available monitoring wells, located intermittingly to a distance of 78 meters perpendicular to the stream are plotted in Fig.4 illustrating a sharp decrease in head nearest to the stream (Table 1). This behaviour is typical of streambank storage where water is temporarily stored in streambanks during the wet season for later release as stream levels decline. Hydraulic conductivity is obtained by grain size analysis, permeameter tests and slug tests. However the first two sampling methods disturb the initial packing and grain orientation influencing the hydraulic conductivity.

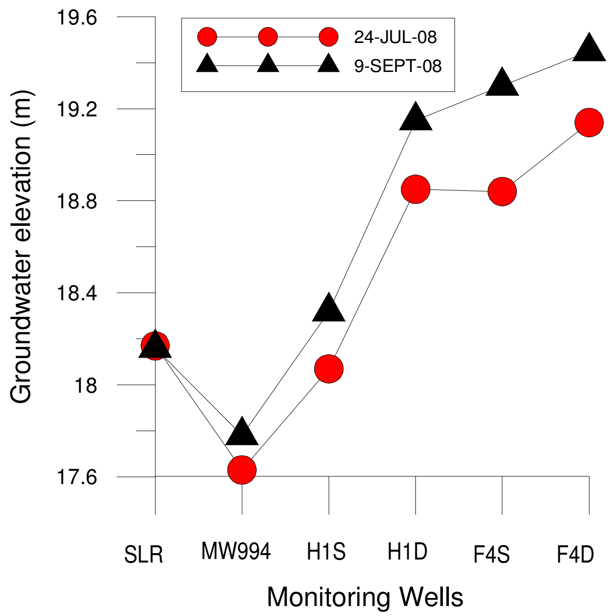

Figure 4. Groundwater head values from corresponding monitoring wells located perpendicular to the stream. Low value near the stream indicates possible streambank storage.

Table 1. Monitoring well information.

	MW994	H1S	H1D	F4S	F4D
Distance (m)	0.5	15.2	15.2	76	78
Depth (m)	4	5	30	5	30

4.2 Hydrograph Separation

An estimation of groundwater contribution to stream flow can be evaluated by separating a stream hydrograph into base flow components assumed to represent groundwater discharge into the stream (Meyboom 1961). In situations where drainage from bank storage, snow packs and lakes contributes to groundwater discharge this assumption may not hold.

In this study a two year period (2001-2003) was plotted on semi-log paper (Fig. 5) and analyzed with the baseflow recession equation:

$$Q_{tp} = K_1 K_2 / 2.3 \qquad [2]$$

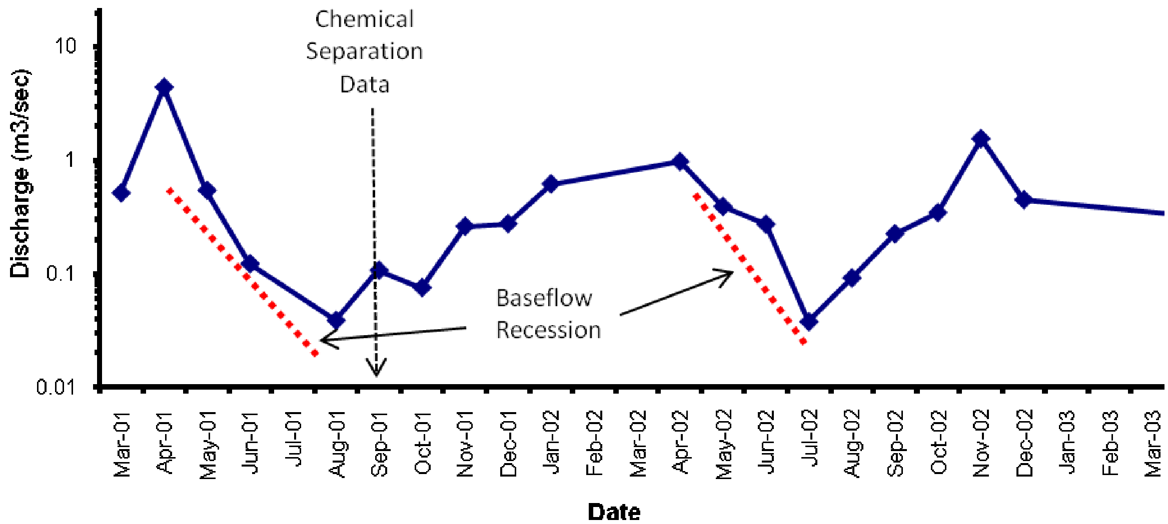

Figure 5. Hydrograph separation of Glen Brook from 2001-2003. Date of chemical separation data is indicated.

K_1=groundwater discharge at beginning of baseflow recession
K_2=time increment for 1 log cycle

Results obtained using hydrograph separation are representative of the groundwater discharge upstream of the gauging station therefore rates are averaged over the upstream length, throughout the two year time period.

4.3 Mass Balance

Mass balance approaches can be used to infer estimates of groundwater flux to the stream. In this investigation chloride was used as a geochemical indicator coupled with incremental stream flow measurements located 2.7km apart. Data collected in October 2001 was applied to Equation 3 with the assumption that an increase in stream flow is due to groundwater discharge and not due to stream bank or quick flow components. This method provides estimates of groundwater contribution to stream flow averaged over the reach length, making it insensitive to small-scale heterogeneities.

(Outflow conc.)(Outflow rate) = (GW conc.)(GW discharge) + (SW conc.)(SW input) [3]

4.4 Temperature Measurements

Groundwater surface water interactions have been studied using temperature as a tracer in numerous studies (Constantz, 1998; Conant, 2004; Anderson, 2005; Selker et al., 2006; Schmidt et al., 2006; Arrigoni et al., 2008; Constantz, 2008; Kalbus et al., 2008). This method utilizes the contrasting temporal fluctuations in temperature between groundwater and surface water; groundwater temperature is relatively constant whereas surface water varies diurnally and seasonally. These temperature signatures can then be used to infer groundwater discharge rates and locations throughout a reach.

In this study temperature measurements along with groundwater elevations were monitored during a rainfall event that occurred in August 2008 (Figure 6). A datalogger recording temperature and head levels was deployed within a monitoring well located 1m perpendicular to the stream. Results indicate a Darcy flux in the order of 10^{-6}m/s out of the stream as a result of this event.

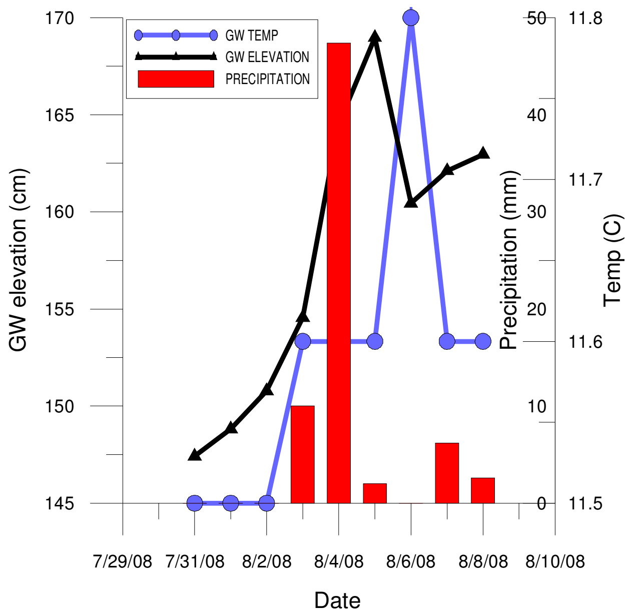

Figure 6. Groundwater temperature and elevation response to an extreme precipitation event in August 2008.

4.4.1 Streambed Temperatures

Groundwater flux was also estimated based on additional spot measurements of streambed temperatures. This method utilizes the contrasting temperatures of groundwater and surface water which creates a signature in the streambed, representative of areas of groundwater discharge to the stream or surface water infiltration into the streambed. For example, during summer when surface water is warmer than groundwater, shallow sediments in high discharge zones would be cooler than those in low discharge zones.

A simplified and rearranged version of Turcotte and Shubert (1982) analytical solution developed by Schmidt et al (2007) was used to estimate the minimum apparent groundwater discharge to the stream. Temperature probes were inserted into the streambed at 50 spot measurements to a depth of 0.2m along a 1.2km reach of the stream. Equation 4 can be applied to single measurement under the assumptions that Darcy's flux is vertical and flow is quasi steady state at depth z (Schmidt et al., 2007).

$$q_z = -(K_{fs}/\rho_f c_f z) \ln (T(z) - T_L)/(T_o - T_L) \qquad [4]$$

where
$T(z)$ = streambed temperature at depth z
$\rho_f C_f$= volumetric heat capacity of the fluid ($Jm^{-3}K^{-1}$)
K_{fs}= thermal conductivity of the solid-fluid system ($Js^{-1}m^{-1}K^{-1}$)
q_z= Darcy flux (ms^{-1})

Calculations indicate Darcy flux estimates in the order of 10^{-8} m/s to 10^{-6} m/s. The largest variation in flux occurred within a 100m section where obstructions from beaver dams created morphologically heterogeneous sections (Fig. 7).

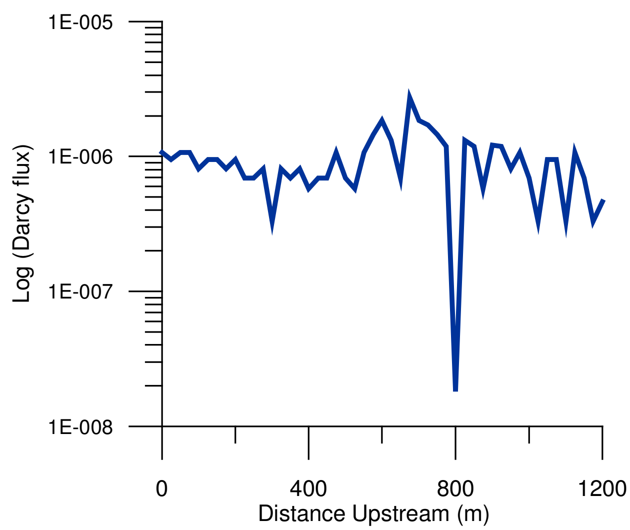

Figure 7. Variation in flux estimates with distance upstream. Beaver dam located within the 750-850m area.

Upstream of the dams the accumulation of fine material creates deep, stagnant pools of lower permeability limiting groundwater influx to the channel. Whereas downstream the water velocity increases and coarser deposits create riffle sequences with higher permeability therefore the probability of groundwater-surface water exchange is enhanced.

5 DISCUSSION AND CONCLUSIONS

The resultant groundwater discharge fluxes from the applied methods are displayed in Table 2. Darcy's law based estimates provided a range that included the hydrograph separation and chemical mass balance but also included negative values indicating that there are losing portions to the stream.

Table 2. Results of groundwater discharge (m/s) obtained from various methods.

Method	Groundwater Discharge per unit area of streambed (m/s)
Hydrograph Separation	2×10^{-6}
Mass Balance	1×10^{-6}
Darcy's Law	-1×10^{-5} to 1×10^{-5}
Temperature Measurements	-1×10^{-6} to 1×10^{-6}

Hydrograph and mass balance approaches may have overestimated groundwater discharge as they both assume changes in streamflow are directly correlated to groundwater flux ignoring other recharge components. Darcy's equation requires point measurements of hydraulic conductivity and hydraulic head to represent the entire spatial domain, which may lead to significant under or over estimations due to the uncertainty related to heterogeneous media. Utilizing temperature as a heat tracer drew from both continuous and instantaneous measurements in time however it is representative of a single location subject to uncertainty. The flux estimates derived from spot measurements of streambed temperature in the vicinity of the beaver dam illustrated the range of fluxes occurring at relatively small spatial scales. Given that the large-scale estimates from the stream hydrograph separation indicate a significant amount of groundwater discharge, it is likely that the smaller scale measurements are indicating local throughflow or bank storage events.

Groundwater movement is dictated by hydraulic gradients and hydraulic conductivity which are in turn influenced by the surrounding topography, climate etc. This understanding illustrates the extent of scales that can be investigated when quantifying flux rates. From a large scale approach, such as hydrograph separation, several assumptions limit the validity within the results, specifically when discussing the zones between measurement gauges. Several subsystems exhibiting additional flow patterns may be operating within the section of interest thus resulting in contradictory outcomes upon analysis. This situation is commonly encountered creating challenges specifically related to the transferability of results not only between alternate sites but among various scales within the selected watershed. This study presented a simple comparison of the range of groundwater fluxes obtained using 4 common methods, corresponding to alternate spatial and temporal scales (Fig.8).

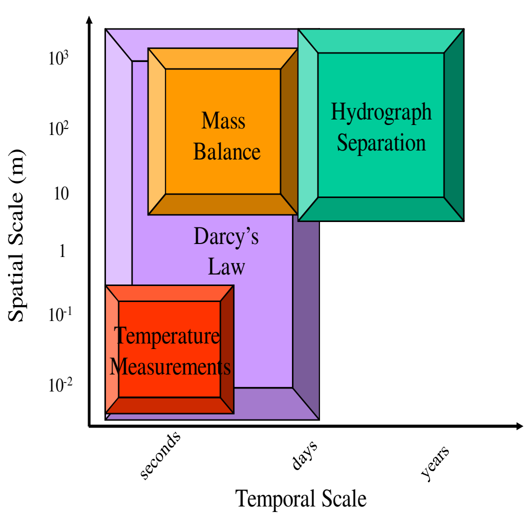

Figure 8. Diagram illustrating the range in spatial and temporal scales corresponding to the methods used to quantify groundwater flux.

In order to bridge the gap between spatial scales in hydrological studies a multi-scale approach is beneficial but advancements in technology have also provided hope for future success. While higher temporal resolution can be achieved by using continuously recording devices such as dataloggers and pressure transducers the spatial variability still requires attention. The use of fibre optics appears to be promising in improving our understanding of groundwater-surface water dynamics in both the temporal and spatial context (Selker, 2006). Fibre optics can be looped back and forth within a reach covering a greater spatial range than traditional methods while continuous temperature measurements are made concurrently in various locations. Incorporating this fine scale variability within a reach analysis will be the focus of future study at this site in hopes of revealing a relationship of scale dependency within the system.

In addition, the hydrological data collected from this study will be assessed individually for their overall applicability in relation to various research goals. Freeze et al (1992) suggests that the fundamental questions to address in field investigations are (1) what to measure? (2) how many measurements to make, and (3) where to make them? Thereby a set of parameters beneficial to habitat management issues would differ from those related to stream flow management decisions. Ultimately is it really necessary and beneficial for a researcher to undertake an extensive field investigation in order to address the issue of heterogeneity? Or does the time and financial investments outweigh the resulting uncertainty within these examined parameters? Having an effective framework for a set of investigations would aid in justifying the design decisions made by researchers.

ACKNOWLEDGEMENTS

The authors would like to thank NSERC, Georgia Pacific and Manitoba Hydro for funding this research.

REFERENCES

ADI Limited. (2000). Glen Brook Salmonid Management Plan, prepared for Georgia Pacific Canada Inc.'s Melford Gypsum Mine.

Anderson, M. (2005). Heat as a ground water tracer, Ground Water, 43(6), 951–968.

Arrigoni, A.S., G.C. Poole, L. A. K. Mertes, S. J. O'Daniel, W. W. Woessner, and S. A. Thomas (2008), Buffered, lagged, or cooled? Disentangling hyporheic influences on temperature cycles in stream channels, *Water Resources Research*, 44, W09418, doi: 10.1029/2007WR006480.

Conant, B. (2004) Delineating and quantifying ground water discharge zones using streambed temperatures, *Ground Water* **42** (2), pp. 243–257

Constantz, J. (1998). Interaction between stream temperature, streamflow, and groundwater exchanges in Alpine streams, Water Resour. Res., 34(7), 1609–1615.

Constantz, J. (2008). Heat as a tracer to determine streambed water exchanges. Water Resources Research. Vol. 44, W00D10, doi:10.1029/2008WR006996

Darcy, H., 1856, Les fontaines publiques de la ville de Dijon, Dalmont, Paris.

Freeze, R.A., B. James, J. Massman, T. Sperling, and L. Smith. 1992. Hydrogeological decision analysis, 4. The concept of data worth and its use in the development of site investigation strategies. Ground Water. V. 30, no. 4, pp. 574-588

Harvey, J. and C. Fuller. (1998). Effect of enhanced manganese oxidation in the hyporheic zone on basin-scale geochemical mass balance. Water Resources Research, Vol. 34, No. 4: 623–636.

Hinkle, S.R., J.H.Duff, F.J. Triska, A. Laenen, E.B. Gates, K.E. Bencala, D.A. Wentz, S.R. Silva. (2001) Linking hyporheic flow and nitrogen cycling near the Willamette River – a large river in Oregon, USA. Journal of Hydrology, 244; 157-180.

Hubbard, S.S., and Y. Rubin. 2000. Hydrogeological parameter estimation using geophysical data: A review of selected techniques. Journal of Contaminant Hydrology 45, nos. 1-2; 3-34.

Kalbus, E., F. Reinstorf and M. Schirmer (2006) Measuring methods for groundwater, surface water and their interactions: a review. Hydrol. Earth Syst. Sci. Discuss. **3**: 1809-1850.

Kalbus, E., C. Schmidt, J.W. Molson, F. Reinstorf and M. Schirmer (2008) Influence of aquifer and streambed heterogeneity on the distribution of groundwater discharge, *Hydrology and Earth System Sciences Discussion*, *5*, 2199-2219.

Meyboom, P. (1961). Estimating groundwater recharge from stream hydrograph. Journal of Geophysical Research, 66 (4); 1203-1214.

Schmidt, C., M. Bayer-Raich, and M. Schirmer (2006) Characterization of spatial heterogeneity of groundwater–stream water interactions using multiple depth streambed temperature measurements at the reach scale, *Hydrol. Earth Syst. Sci.* **10** (6) pp. 849–859.

Selker, J., N. van de Giesen, M. Westhoff, W. Luxemburg, and M. B. Parlange. (2006). Fibre optics opens window on stream dynamics, Geophys. Res. Lett, 33, L24401, doi:10.1029/2006GL027979.

Sophocleous M. (2002) Interactions between groundwater and surface water: the state of the science. Hydrogeol J (in press). DOI 10.1001/s10040010170-8

Turcotte, D.L., Schubert, G., 1982. Geodynamics: Applications of Continuum Physics to Geological Problems. John Wiley & Sons, New York.

Woessner, W. W. (2000). Streams and fluvial plain ground water interactions: Rescaling hydrogeologic thought. *Ground Water* 38:423–429.