Dear G360 Collaborating Colleagues & Friends,

This past year has been a year like no other! 2020 presented many new challenges, from implementing additional health and safety protocols and scaling field work to meet COVID-19 rules, to adjusting to life in a virtual environment and hosting our first virtual University Consortium Annual Meeting and Fall Focus Meeting. We have accomplished and learned a lot from these experiences, including how to increase our UC Annual Meeting attendance to over 200, the largest number of participants in our 34-year Consortium history. We are currently planning our third virtual UC event scheduled for June 1-3, 2021 and, thereafter, expect to implement hybrid virtual / in-person options to broaden participation and interactions.

Despite the pandemic, G360 continued to be very productive both in our ‘home offices’ and in the field. Local hydrogeology research field projects within the Guelph area advanced with approximately 1,400 linear feet of sediment and bedrock core drilled and logged, using our graphical logging methods, and nearly 4,000 linear feet of borehole hydrophysical and geophysical logs collected. Additionally, we deployed 150 transducers and processed approximately 450 rock and sediment samples among the Guelph South, Elora, Erin and Halton field sites. Across the border in Wisconsin, our international G360 team members collected 85 rock and sediment samples for contaminant analyses, deployed 19 transducers for dynamic head monitoring and filled 1364 sample bottles from 115 groundwater sampling ports over 142 days to send to 6 different analytical laboratories for a bedrock groundwater natural attenuation study. Field measurements at the California research site continued with collection of hydraulic head measurements using transducers deployed in 47 conventional wells recording data at one second intervals and giving us over 1.5 billion measurements in 2020 alone. As you can see, data capture and analysis is a key component of our workflow!

The G360 group continues to develop new insights on many fronts, including the addition of field work in new hydrogeologic environments, research on new and emerging contaminants, and the addition of new partners to the G360 network. We were awarded two new NSERC Alliance Grants where the Canadian Federal Government matches partner funding contributions, each for 5-years. The first project, with BP and Ecometrix, encompasses assessment of multiple in-situ remediation technologies with toluene in shallow bedrock; and the second focuses on the establishment of a 3-D groundwater monitoring network and baseline groundwater assessment within the Liard Basin, the second largest unconventional oil and gas reservoir in Canada, in collaboration with the Government of Northwest Territories, the Acho Dene Koe First Nation, and the Hamlet of Fort Liard.

As always, we are grateful for these opportunities to work together with our sponsors, partners and collaborators and we look forward to a conversation with you soon.

Sincerely,

Dr. Beth Parker

Field Work in Fort Liard, Northwest Territories (August 2019)
New Team Members

**Students**

**Cameron Myshok** has a BSc in Environmental Science from the University of Windsor. His undergraduate research led him to develop a 1-D reactive transport model to investigate the hydrogeochemical impact of landfill leachate entering an underlying aquifer. As a MASc student, he hopes to advance field methods for monitoring and remediating contaminated groundwater.

**Emily Finger** has recently completed a BSc in Geology, with an emphasis on Hydrogeology and Water Chemistry, from the University of Wisconsin – Eau Claire. She will be pursuing a MASc in Water Resources Engineering at the University of Guelph in the G360 group with a drive to develop the proper skills as a hydrogeologist.

**Mitchell Brown** completed his BSc at the University of Waterloo in Earth Sciences with a specialization in Hydrogeology. He is looking forward to the opportunity to apply the skills he developed throughout his undergraduate degree with the G360 group.

**Zakia Ahmad** is a graduate from the University of Waterloo with a BASc in Chemical Engineering. Her work experience before G360 includes chemical process and environmental engineering. At G360, Zakia will focus on evaluating permanganate oxidation of chlorinated ethene contamination in fractured sedimentary rock.

**Preksha Surana** completed a BSc in Environmental Geoscience from the University of Toronto in 2017 and is now a consultant at Wood as a Junior Geoscientist-in-Training within their hydrogeology group. Currently, she is pursuing her MEng degree in the G360 group while working part-time at Wood.

**Dustin Brown** began his MASc in Water Resources Engineering under the supervision of G360 PI, Dr. Jana Levison, and G360 alumni, Dr. Rachael Marshall in January 2020. Dustin’s research is focusses on risk assessment as part of a source water protection framework for First Nations communities.

**Sarah Rixon** has a MASc in Water Resources Engineering and is now pursuing a PhD degree part-time under the supervision of G360 PIs Dr. Andrew Binns and Dr. Jana Levison on groundwater-surface water interactions and nutrient transport in agricultural watersheds.

**Ceilidh Mackie** successfully defended her MASc in Water Resources Engineering in August 2019 and has since started her PhD under the supervision of Dr. Jana Levison focusing on pathways of chloride contamination in the Great Lakes basin.
New Team Members

Staff

Oliver Conway-White recently graduated from the University of Guelph with a MASc in the School of Engineering under the supervision of Dr. Parker. Oliver’s research expertise includes applying geophysical methods to the study of groundwater by combining multiple geophysical techniques (both surface and airborne) to resolve the hydrostratigraphy of buried bedrock valleys.

Giacomo Medici has a MSc in Exploration Geology and a PhD in hydrogeology and reservoir geology from the University of Leeds. He has joined the G^360 group as a Post-Doctoral Research Fellow with expertise on the interpretation of hydrogeological datasets and spatial analysis of rock discontinuities to develop 3-D Discrete Fracture Network models.

Vinu Raj is the Purchasing Coordinator for the G^360 group and is a supply chain professional with a mechanical engineering background. His expertise stretches over the entire breadth of procurement and logistics operations within oil & gas, mining, construction, and manufacturing sectors. He believes in delivering 3Rs to the team; right services at right value at the right time.

James Hommersen recently completed his MSc in Environmental Sciences (Hydrogeology) and is now a Research Hydrogeologist with the G^360 group. His research focuses on using high-resolution methods to characterize groundwater flow systems and the local distribution of nitrate impacting two paired municipal water supply wells completed in a shallow bedrock aquifer.

Interns

Emily Cline joined the G^360 group for an 8-month internship after completing her fourth year of the Water Resources Engineering undergraduate degree at the University of Guelph. Emily gained practical experience as she explored possible career paths working in groundwater research.

G^360 PI Active Students 2020 – March 2021

G^360 Principal Investigators
Included in Student Count
Dr. Aaron Berg
Dr. Andrew Binns
Dr. Beth Parker
Dr. Colby Steelman
Dr. Emmanuelle Arnaud
Dr. Erica Pensini
Dr. Jana Levison
Dr. John Cherry
Dr. Kari Dunfield
Buried bedrock valleys (BBVs) are common geological features found worldwide. They are characteristic of previously glaciated landscapes and are typically infilled with Quaternary aged sediment. Within these BBVs, permeable material can store and transmit significant amounts of water, making them attractive targets for groundwater resource development. Understanding the relationships between the depositional architecture, bedrock topography, and hydrostratigraphy is crucial to adequately characterize their complex geology and hydrogeology. A BBV was identified in Elora, Ontario in the 1970s through geophysical investigations and has since been investigated using an airborne electromagnetic survey to define its shape and extent (Figure 1). A second phase of study is underway in partnership with the Township of Centre Wellington to drill eight boreholes along two transects. The goals of this phase are: i) ground truth previous geophysical efforts, ii) constrain sedimentary and bedrock lithology and iii) look for physical evidence of enhanced groundwater flow around the valley. So far, four boreholes have been completed: two in the Quaternary overburden and two deeper in the bedrock. The two Quaternary overburden boreholes were completed using a dual casing, rotosonic drilling. Dual casing rotosonic drilling vibrates the drill bit while it is being pushed down the hole, which allows for excellent core recovery compared to conventional air rotary drilling. Rock core was collected and logged along the entire length of each borehole and subsampled (Figure 2). Core samples will be used for grain-size analysis to determine hydraulic conductivity estimates. Each Quaternary cored hole was completed with a G$^{360}$ MLS. The two bedrock boreholes were advanced using an air rotary rig to drill through overburden material and a PQ, triple tube, wireline diamond drilling method to drill through the bedrock. Continuous rock core was collected and logged along the entire length borehole and subsampled every 10 ft for physical properties. The bedrock boreholes will be logged using a suite of borehole geophysical methods, including gamma-ray, full waveform sonic, temperature vector probes, acoustic televiewer, and electrical conductivity. The boreholes will then be lined with blank FLUTE™ liners and A-DTS and ALS testing will occur. Four additional holes are planned along a second transect to identify variability and lithostratigraphy and hydrostratigraphy within the BBV.

**Figure 2:** Jesse Brown (left) and Oliver Conway-White (right) logging a bedrock core run.
Building high-resolution monitoring systems to monitor groundwater pumping in Erin Township

Ten G360 staff members and students worked to log and sample rock core (Figure 1 and 2); conduct borehole geophysical and hydrogeological testing; and install blank FLUTE™ liners have been installed in the bedrock boreholes to allow for closed borehole tests of hydrologic properties, including A-DTS and ALS testing. In addition, two multi-level monitoring systems (MLS) were designed and installed in the shallower, Quaternary sediment boreholes. Future work planned for Spring 2021 will include removal of the FLUTE liners and installation of MLSs in the bedrock holes. Data from this study will be shared amongst partners and the Community of Erin. Findings from this study are relevant to understanding regional groundwater flow within the Grand River watershed.

G360 PROJECT TEAM
Emily Finger (MASc Candidate), Chrystin Skinner, Dr. Emmanuelle Arnaud, Dr. Jonathan Munn and Dr. Beth Parker

The G360 Institute is collaborating with Nestlé and their consultants Golder Associates Inc. to bring the newest, state-of-the-science methods to this study site by installing multi-depth, high-resolution monitoring systems (G360 MLS or FLUTE) in cored holes. These systems, combined with continuous core and logging methods, provide high resolution geological, geophysical and hydrological data that enhance our understanding and characterization of the groundwater flow system. The project site is located 25 kilometers northeast of Guelph near the groundwater divide of the Grand River and Credit River watersheds along the Orangeville Moraine in Erin, Ontario. This unique location raises some key questions: What is the position and thickness of aquitards in the Quaternary sediment and the multi-layered dolostone bedrock in the area? Is the watershed boundary accurately represented? and; What hydraulic responses are observed in the various hydrogeologic units (HGUs) due to local groundwater pumping?

Four boreholes have been drilled since November 2020 in partnership with the Town of Erin and drillers Aardvark Drilling Inc. and Underground Sonic Drilling Services Inc.: two in Silurian dolostone bedrock and two in overlying Quaternary sediment.

Figure 1: G360 project manager Chrystyn Skinner (left) and G360 student Emily Finger (right) log dolostone rock core for lithology and fractures / features.

Figure 2: G360 students Cameron Myshok (left) and Mitchell Brown (right) prepare the rock core for photography.

G360 Student and Staff Acknowledgements:

Students: Cameron Myshok, Jesse Brown, Andrew Stockford, Mitchell Brown

Staff: Dr. Pete Pehme, Ryan Kroeker, Philip Taylor, James Hommersen, Oliver Conway-White, Marina Nunes

Sponsors, Partners & Collaborators:
Using high-resolution datasets is imperative to develop hydraulically-informed conceptual site models (CSMs) that can be used to build numerical models to predict groundwater system behaviour under various scenarios. This study investigates the conditions around a bedrock borehole, HBP5, where geology and topography cause a flowing artesian condition. HBP5 is cored through a Silurian-aged dolostone aquifer that is an important water supply source regionally, serving approximately 1M people in southern Ontario, Canada.

A suite of novel DFN-M field techniques have been used to characterize the subsurface, including hydraulic testing using straddle packers; multi-level monitoring systems; and geophysical logging (ATV, gamma, TVP, heat pulse, impeller flowmeter) under open and sealed-hole conditions. These datasets are used to inform the CSM, with new insights about the properties of major flow features. The groundwater system is modeled using the ‘equivalent porous medium’ (EPM) approach. The hypothesis of this research is that the hydraulic cross-connection occurs in HBP5 under open hole conditions. The aim of this study is to examine how the natural flow regime is disturbed by cross-connection, and how this may lead to erroneous estimation of hydraulic conditions. Moreover, the intent is to demonstrate the utility of detailed DFN-M datasets to address this issue.

Based on the robust CSM informed by the high-resolution data, a 3D numerical model has been developed using FEFLOW (15 layers; total thickness of 100 m; areal extent of 100 km²; triangular mesh with 131,274 elements and 71,876 nodes). The modelling provides insight regarding hydraulic head responses, changes in flow direction/velocity field (via particle tracking), and qualitative/quantitative analysis of flow across the borehole. Qualitatively, the field data and model agree well (Figure 1). A quantitative analysis was more challenging in a portion of the borehole where turbulent conditions are observed. This study provides insights about the local flow regime under ambient and open hole conditions, and about hydraulic responses in a multi-layered bedrock aquifer subject to open hole conditions (Figure 2).

Figure 1: Modeled flow response vs. flowmeter response

Figure 2: Particle tracking (red lines) demonstrates the impact of cross-connections on flow pathways
Fractured dolostone aquifers are heterogeneous and anisotropic due to the frequency and orientation of rock discontinuities, lithostratigraphic variation and karstification. Understanding heterogeneity and anisotropy requires a rigorous approach that integrates multiple datasets including geological information from continuous core logs, orientation of rock discontinuities from acoustic televiewer logging, and high-resolution pumping tests.

In this work, we apply this multi-dataset approach to the 100 m thick Silurian dolostones of southwestern Ontario (Figure 1), in the City of Guelph (~90 km²). From a mechanical point of view, analyses of rock discontinuities were performed in a total of 1,360 m of continuous acoustic televiewer logs from 26 vertical and 9 inclined boreholes. Preliminary results indicate a correlation between the lithology and fracture density (see Figure 2). Considering only high angle (50 – 90° dip) joints, stratigraphic units with thick beds are characterized by low fracture intensity, whereas units with thinner beds tend to have a higher fracture intensity. This is a typical characteristic of stratabound fractured systems.

From a hydraulic perspective, historical pumping tests indicate drawdown cones of elliptical shape suggesting anisotropy with possible preferential pathways through the high-angle joints. Future analysis of high-resolution pumping test data collected using multilevel monitoring systems will further refine the nature of the anisotropy in the fractured dolostone.

Overall, the number of features analyzed place this research as one of the most-intensive hydro-structural characterizations of stratabound fracture systems in the world. This study relates the mechanical and hydraulic properties of the multi-layered system to evaluate flow anisotropy in distinct hydrogeologic units due to lithostratigraphic heterogeneity and the orientation of rock discontinuities.
The heterogeneous nature of ice marginal settings and the dynamics of groundwater flow in multilayered systems make these spatially complex environments difficult to define and require detailed information to manage from a water resources perspective. The study area, in Guelph, Ontario, is situated in a complex end moraine setting overlying the Silurian dolostone aquifer system with a new bedrock municipal supply well proposed adjacent to a sensitive wetland.

The objective of this study is to determine the vertical hydraulic connectivity throughout the bedrock and overlying quaternary sediments to determine sustainable pumping rates. Multiple high-resolution datasets were collected to characterize the subsurface geological and hydrogeological variability and used to create a Conceptual Site Model (CSM) of the multilayered flow system. Logging of continuous cores (Figure 1) and natural gamma through the full quaternary sedimentary sequence down to the top of bedrock at 4 locations oriented perpendicular to the trend of the moraine show a transition from end moraine front slope fans into mixed outwash plain and lacustrine depositional environments where a wetland is now located (Figure 2).

Depth discrete Multilevel Systems (MLS’s) were installed in these boreholes and instrumented with transducers, providing depth-discrete vertical profiles of hydraulic head and transient responses to recharge and bedrock aquifer pumping. These data will be used to delineate Hydrogeologic Units (HGU’s) and lateral continuity of low K beds. The groundwater flow system is dynamic in the study area due to multiple pumping locations with municipal and private wells for drinking water and industrial operations with a nearby gravel pit. The resolution of spatiotemporal data is unprecedented and provides insights on the multiple interactive natural and anthropogenic hydraulic influences. The ongoing monitoring will support decisions regarding municipal well capture zones and sustainable pumping rates to minimize impacts to shallow groundwater and wetland.

**Figure 2:** Guelph South CSM informed by multiple high-resolution datasets. Quaternary and bedrock stratigraphy with MLS and port locations are displayed in a N-S orientation. The Paris Moraine with recharging groundwater conditions is in the south end of the study area and transitions into a wetland in the north with discharging groundwater conditions, reflecting a change in vertical gradients.

**Sponsors, Partners & Collaborators:**

- G360
- Guelph
- Golder
- S360
- Underground

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**G360 PROJECT TEAM**

Andrew Stockford (MSc Candidate), Dr. Jonathan Kennel, Dr. Emmanuelle Arnaud and Dr. Beth Parker
Engineered multilevel systems (MLS) are one of the few viable options for collecting spatial and temporal datasets in 3-D complex groundwater flow systems. These monitoring systems present challenges for hydraulic testing due to small port tubing diameters. However, the G360 MLS allows for the use of larger diameter port tubing (5/8” OD) so that transducers can be deployed inside the tubing. In this study, equipment was developed to enable pneumatic slug testing of a G360 MLS. Of the eight ports tested, four exhibited overdamped slug test responses, while underdamped responses were observed in the remaining four ports.

Friction becomes important when tubing diameter is small, and additional flow constrictions are introduced when installing a transducer in the tubing, effectively changing the open tube geometry to an annulus around the transducer body (1.35 mm) and around the transducer cable (3.5 mm). For underdamped tests where the flow changes direction periodically, a mathematical solution for unsteady flow through an annulus was derived to assess the steady flow assumption. Because the transducer annulus is only 1.35 mm, it is possible that during the slug test, the transducer is not in the center of the tubing, but instead is pressed against the tubing wall. Therefore, a smooth parallel plate (PP) model was used to represent the transducer against the wall to compare with the results of an annulus. The results of this study show that assuming steady flow through small annuli will not introduce appreciable error when calculating the water level because the velocity profiles in these annuli are parabolic. However, assuming steady flow through the open tube below the transducer will result in the overestimation of the formation head because flow is unsteady in the open tube (i.e. velocity is not parabolic). Overall, using the steady model results in the smallest transmissivity (T) value, using an unsteady PP model for the transducer results in a slightly larger T, but using an unsteady annular flow model results in the largest T. The difference in these T values results from the calculated formation head losses using the different models and the phase difference between the flow and formation head, which is largest for the steady flow model (63°).

**Figure 1:** Geometry of test setup with associated velocity profiles for flow in the annulus around the transducer cable (parabolic), around the transducer body (parabolic), and in the open pipe below (NOT parabolic). The velocity profile for when the average velocity is zero is shown in black, and water in the center of the tube is moving in the open tube below.
The Groundwater Project (GW-Project) advanced in 2020 with 10 books published in both PDF and eBook form. The project continues to attract authors with outstanding credentials with 315 authors writing 150 books for future publication. To date, over 35,000 books have been downloaded in 125 countries globally.

The first Making Groundwater Visible event from the GW-Project was held February 3 to 26th. The event attracted 4,000+ people from more than 30 countries and resulted in 7,300+ views of the YouTube videos.

A series of meetings and discussions were held during the event that focused on relevant and innovative themes presented by leading experts in hydrogeology from around the world. The event sessions may be viewed at the GW-Project channel at www.youtube.com/c/GroundwaterProject

An important goal of the GW-Project is to benefit developing countries. The first step in the GW-Project “Teams Initiative” is focused on a particular country or group of countries for which a team of experts is assembled including persons from the developing country. The aim is to establish interactive dialog that will benefit all, including GW-Project books focused on groundwater conditions and problems in the country of focus and to the global groundwater community who will learn about these conditions largely unknown outside of the focus country, but with global relevance. The first functioning team is the Central America Team composed of experts from Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama. The GW-Project is seeking to set up teams for Bangladesh, the MENA region, Nepal and Brazil in the near future.

Many volunteer opportunities exist at the GW-Project. To learn more and volunteer please visit: www.gw-project.org

Figure 1: The 1st Groundwater Project Event Available

Figure 2: Next Publications on the GW-Project
Integrated Characterization of a Phytoremediation System for Risk-based Closure of a Toluene Contaminated Site

The goal of this partnership, between University of Guelph, BP and Ecometrix, is to integrate several Enhanced Attenuation approaches, in order to assess their viability for remediating and managing risk of petroleum hydrocarbon (PHC) contamination in fractured, sedimentary rock.

The project is in the second phase of R&D. In the first phase of research, several key scientific findings were established: a) demonstration that toluene was being phytoextracted by the trees and quantification of toluene phytoextraction rates (Ben-Israel, 2019); b) delineation of the source area and characterization of toluene phase and mass distributions in fractures and matrix (Fernandes, 2017); and c) definitive evidence that the plume migration is strongly retarded, with evidence for slow plume retraction over time, and of toluene degrading microbial communities in the groundwater (Roebuck, 2018).

Toluene biodegradation under both aerobic and anaerobic conditions in groundwater and soil was demonstrated by paired compound-specific isotope analysis (CSIA) and high-throughput amplicon sequencing approaches (Wanner et al., 2019, Ben-Israel, 2020). Higher concentrations of toluene were found to cause shifts in bacterial microbiomes in soil, groundwater and in-planta to greater numbers of toluene degraders.

In the Fall of 2020, a sampling event targeting the full characterization of the phytoremediation system took place at the end of natural cycle of poplar trees. Groundwater samples were collected from all existing wells in the system to elucidate the microbial community response to toluene concentrations. Moreover, the full extent of the poplar root system was exposed for the first time during the project, where the team sampled roots and adhering soil.

Excavation of the Quaternary sediments down to bedrock provided a unique opportunity to investigate the nature of the top of rock at the site firsthand. To map out potential flow features such as fractures and karstic features on the bedrock surface, a drone survey was completed at the site. The drone photogrammetry provided a georeferenced and scaled model of the bedrock from which fracture statistics, such as length and orientation, can be determined. Preliminary results indicate fewer fracture features on the top of rock than expected.

Cobbles and soil sampling event at the site focused on assessing toluene concentrations and moisture content of cobbles from targeted areas, and to assess toluene diffusion and mass storage in cobbles. A total of 35 cobbles and 16 soil samples were collected from different locations between 1 and 1.9 m below ground surface.

Figure 1: Kamini Khosla and Eduardo Mitter sampling for roots and rhizosphere soil (left); Chrystyn Skinner sampling for cobbles and soil (right).

Figure 2: Aerial view of site (left); final excavation area (right).

Sponsors, Partners & Collaborators:
Given its strategic position between land surface and groundwater and the potential to enhance natural attenuation, the unsaturated zone represents the first protection against groundwater contamination. In most instances the degree of contaminant attenuation will be largely dependent on unsaturated zone pollutant pathways and residence times. Moreover, hydrologic processes in the unsaturated zone influence recharge rates that, in turn, control the flux of groundwater available to transport contaminants towards environmental receptors. Thus, understanding groundwater recharge mechanisms, in terms of flow rates and pathways in the unsaturated zone, is a key step for site characterization.

In this study, we use time series analysis and cross-correlation to identify the relationship between precipitation and water level responses and gain insight on recharge mechanisms in a sandstone aquifer in southern California. At 16 locations, water pressure was collected every second and analyzed to identify and remove the effects of barometric pressure changes, Earth tides and earthquakes on water levels. This helped to improve the accuracy and minimize uncertainties of the study results. From the analysis of the time series, we found that the water table rises only when a threshold value of precipitation is reached (Figure 1). This likely represents the water content deficit from the previous season that needs to be replenished before getting any observable flow to the water table.

The cross-correlation indicates two time periods of statistically significative lag-times: 0-3 and 20-50 days (Figure 1). The analysis of hydraulic diffusivity in the unsaturated zone based on these time lags suggests that the quick responses are related to fast flow through fractures whereas the longer time lag are associated with piston-type movement in the matrix blocks. The type of response at each well is controlled by the intensity of precipitation and by the thickness of the unsaturated zone. Fast responses are more likely for shallow water tables in response to high-intensity precipitation events and vice versa. Based on these findings, we develop a conceptual model of recharge for the sandstone aquifer to explain when and how recharge occurs (Figure 2).

**Figure 1:** Cross-correlogram for RD-109, January to March 2017 showing a first significant response the same day of the rainfall event and a delayed response 27 days after the event. This is likely the effect of fracture (fast response) and matrix (delayed response) flow.

**Figure 2:** Conceptual model of recharge. (a) In the first part of the rainy season, the water content deficit from the previous season is replenished. (b) Recharge through the matrix occurring as piston-flow displacement. (c) Recharge through fractures. When water via fractures reaches the water table, a fast rise is observed as the fractures are filled with water and the matrix remains unsaturated (t1). As the water is redistributed in the surrounding matrix because of imbibition, the water level declines (t2) and finally settle at the new water level (t3).
Eutrophication in surface water within the Great Lakes Basin (GLB) is a perpetual and critical concern. Since the 1970s, recurrences of increased nutrient loading have caused frequent and widespread algal blooms affecting human health, the environment and the economy. Moreover, climate change will result in changes to the amount and timing of rain and snow resulting in variations to stream flow, soil moisture and groundwater levels. Nutrient fluxes in agricultural watersheds will be impacted by these hydrological changes, since the rate and quantity of phosphorus (P) and nitrogen (N) transport through various pathways is often controlled by climate conditions, such as winter freeze-thaw cycles. The primary objective is to improve knowledge and understanding of the underlying processes related to groundwater and surface water interaction, and spatiotemporal evolution of nutrients (P and N) in all components of the hydrologic cycle (soil water, tile water, groundwater, creek, including in-stream sediment transport) using an integrated approach in an agriculturally-intense clay plain system in the GLB (Fig. 1). This project began as a collaboration with the Ontario Ministry of the Environment, Conservation, and Parks (MECP) and Ausable Bayfield Conservation Authority (ABCA) in 2017, with current project funding from MECP (COA/GLS program; 2020-2023) and the Ontario Agri-Food Innovation Alliance (2018-2021).

In addition to the Parkhill Creek Integrated Water and Climate Monitoring Station (IWCMS) (Fig. 2), four new locations in the Upper Parkhill watershed, Lake Huron Basin, have been instrumented for combinations of stream water, groundwater, tile water, soil water, and stream bed sediment sampling. Published research to date includes integrated modelling to assess climate change impacts on groundwater and surface water using diverse climate forcing (Persaud et al. 2020, J. Hydrology), investigating N transport through various water pathways (Rixon et al. 2020, Sci. Total Environ.,) and a preliminary study of groundwater-surface water interactions and agricultural nutrient transport (Mackie et al. 2021, J. Great Lakes Res.). Work in progress includes examining the geomorphological evolution of Parkhill Creek, quantifying sediment transport and how sorbed nutrients move under a variety of flow regimes, conducting a groundwater quality risk assessment under changing land use and climate, and delving deeper into our understanding of groundwater-surface water (i.e. creek, drainage tile) interactions.

Figure 1: Parkhill Creek algal growth; PhD student Scott Gardner installing a stream bank piezometer.

Figure 2: Graduate students collecting data at the IWCMS. (Photos by C. Mackie)
How does hyporheic exchange occur within a fractured bedrock river?

The Eramosa River, Guelph

Bedrock rivers represent a hydrogeological environment in which surface water flows along an exposed bedrock surface. Studies of hyporheic exchange have exclusively involved rivers composed of unconsolidated (i.e., granular media) fluvial sediments, leaving a critical gap in our understanding of groundwater-surface water interactions. This study evaluates the conditions that could support bedform-scale hyporheic exchange within a fractured sedimentary bedrock river based on field data collected near Guelph, Canada. Hyporheic exchange at the bedform-scale was evaluated by numerically modelling the migration of a conservative solute tracer through a bedrock riverbed within a two-dimensional vertical cross-section along the flow direction. A stochastic discrete fracture-matrix framework was developed to represent measured subsurface fractured bedrock properties, producing a probabilistic distribution of potential hyporheic exchange pathways. Flow and transport model results indicate that: (1) bedform-scale hyporheic exchange within a bedrock river exists with high fluid flow velocities in fractures, yet long solute residence times due to diffusion across the fracture-matrix boundary; (2) the coincidence of fractures and hydrodynamic head gradients across the riverbed controls the spatial extent of bedform-scale hyporheic exchange; and (3) the potential variability in hyporheic exchange residence time is large (i.e., tens of years) due to the inherent variability in fracture network connectivity and properties (e.g., fracture spacing, length, orientation, and aperture). Our field-based numerical study indicates that the bulk or average (median) residence time may not be a good proxy for the potential natural attenuation capacity of a fractured sedimentary bedrock riverbed and that hyporheic exchange has the potential to emplace surface water contaminants within the fractured porous rock matrix that could become a long-term source of trace contaminant concentrations.
The Liard Basin is the second largest reservoir for unconventional oil and gas in Canada and is situated in the transboundary region of British Columbia, Yukon, and Northwest Territories. Significant growth in the unconventional oil and gas sector due to improvements in drilling and hydraulic fracturing has led to a growing public concern about the impacts of gas production on local freshwater supplies. Dr. Beth Parker with co-principal investigators, Dr. Colby Steelman and Dr. Bernhard Mayer (University of Calgary), and partners, including the Government of the Northwest Territories and the Acho Dene Koe First Nation based in the Hamlet of Fort Liard, have been awarded an NSERC Alliance Grant in January 2021 to conduct a baseline groundwater monitoring study in and around the community of Fort Liard, NWT. This project will support the development of groundwater monitoring infrastructure needed to understand baseline hydrologic and geochemical conditions in a multi-layered sedimentary rock sequence, focused on the Dunvegan Formation aquifer. The project team includes collaboration with Dr. Uli Mayer (University of British Columbia), Dr. Tom Darrah (The Ohio State University), and Dr. Janok Bhattacharya (McMaster University) to provide a multi-disciplinary approach to this important study. The scope of the Alliance Grant will build on work completed by G360 and its collaborators, including surface geophysics in 2018 and preliminary drilling activities in 2019 (Glas MASc Thesis, 2021). We anticipate advancing the project with an airborne geophysics survey in 2021 and drilling at three locations with deployment of permanent multi-level monitoring systems and transducer strings for long-term monitoring of groundwater chemistry and hydraulic head in Spring 2022.
A new joint research project between G³⁶⁰ and Sanborn Head and Associates began in late 2019 at a large-scale landfill site in the Northeastern U.S. The landfill is no longer accepting waste, but legacy groundwater quality issues persist at low concentrations from previous operations. As part of the closure requirements, robust groundwater studies must be conducted to assess the nature and extent of the groundwater contamination with interests in 1,4-dioxane as a focus constituent. The site overlies fractured metamorphic and igneous rocks including schists and pegmatitic intrusions. Two field events occurred, one in December 2019 and a second in June 2020, with the goal of identifying the position of hydraulically significant fractures within three deep boreholes (one 147 m, and two 305 m deep) to inform the positioning of multilevel monitoring intervals. The boreholes have low total transmissivity, are quite deep and one has a large diameter (25 cm, 10-in) making other methods such as straddle packer testing time consuming and expensive. Instead, we adapted and applied G³⁶⁰ fibre optic Active Distributed Temperature Sensing (A-DTS) techniques to help identify the location and relative transmissivity of fractures within each borehole. Data collection involved installing a custom fibre optic cable (developed by G³⁶⁰ and Silixa) in the open borehole, heating the cable using the integrated heating wires, and measuring the continuous temperature profile with a Silixa ULTIMA S Distributed Temperature Sensor (DTS) (Figure 1). After an extended heating period to warm the water column in the borehole, a submersible pump was lowered, and the borehole was pumped for 3.5 h causing cool formation water to enter the borehole at the position of transmissive fractures. This thermal response, and thus the location and relative magnitude of the fracture flow was measured using the depth-discrete temperature data from the DTS (Figure 2). The A-DTS data in the open hole efficiently identified dozens of transmissive fractures and provided full vertical coverage of each borehole. The results were used with other datasets to inform the monitoring port positioning of one Water FLUTE multilevel and two Westbay multilevels in the boreholes. G³⁶⁰ would like to thank Sanborn Head and Associates, specifically Lilly Corenthal, Sam Jacobson, Tim White, and Bradley Green for their enthusiasm and contributions to this project.

**Figure 1:** (Left) Fibre optic Distributed Temperature Sensor (DTS) equipment inside a trailer at the site; (Right) the black fibre optic cable installed in the 10-inch diameter borehole.

**Figure 2:** ATV image (left) and DTS temperature data (right) showing colder water entering the borehole at a transmissive fracture (A) and moving upward to the pump.

**Sponsors, Partners & Collaborators:**
This study, a collaboration between G^360 researchers, Dr. Tom Al (University of Ottawa) and U.S. EPA staff and their consultant (CH2M Hill, now Jacobs Engineering), applied a combination of conventional and high-resolution field and lab methods to investigate processes causing attenuation of a hexavalent chromium plume in sedimentary bedrock at a former industrial facility. Groundwater plume Cr(VI) declines by more than 3 OoM over a 900 m distance down gradient from the site and internal plume Cr(VI) also exhibits stable to declining trends due to a combination of diffusion and reaction processes and declining plume inputs from the source due to natural depletion processes and active remediation efforts.

To complement the EPA data collection efforts, the DFN-M approach was applied to a “golden spike” borehole at a targeted location within the plume to assess matrix diffusion and reaction processes. This required development of new lab methods for chromium assessment in rock samples (Zhao et al. 2015, 2017). Site data for the fracture network and matrix properties were used to inform 2-D discrete-fracture matrix (DFM) model simulations to quantify the key controlling processes showing consistency with field datasets and providing insights on future plume conditions (Chapman et al. 2021). This combined field-lab-model study confirmed that the strong attenuation is attributed to diffusion from mobile groundwater in fractures to immobile porewater in the rock matrix, and reactions causing transformation of aqueous Cr(VI) to low-solubility Cr(III) precipitates. This has important implications influencing future remedial actions and characterization of other sites with redox sensitive metals contamination for improved Site Conceptual Models (SCMs) and remediation decision-making.

Publications:

Sponsors, Partners & Collaborators:
Dr. Jana Levison Receives IAH-CNC Early Career Hydrogeologist Award

The IAH-CNC Early Career Hydrogeologist Award was awarded to Dr. Jana Levison in June 2020 in recognition of her leadership and engagement in the hydrogeological community. Dr. Levison is an active researcher in the areas of agricultural impacts on groundwater quality and quantity, impacts of climate change on hydrological systems, groundwater flow and contaminant transport in fractured geologic media, and source water protection for Indigenous and rural communities. Dr. Levison’s impact on research and contributions to the field of hydrogeology are impressive and she has established research domains with new colleagues in a collegial and highly collaborative manner.

Tage Erlander Professorship Awarded to Dr. Beth Parker

Dr. Beth Parker was awarded the Tage Erlander Professorship by the Swedish Research Council for an 8-month visiting professorship at Lund University for 2021. This professorship was created in 1981 to mark the eightieth birthday of the late Mr. Tage Erlander, who was the Swedish Minister of Education 1945-1946 and then Prime Minister until 1969. Appointments are by invitation only and scientists of the highest distinction are invited. The professorship is meant to contribute to the Swedish researcher society with the personal influence of an excellent scientist and to the building of lasting scientific networks.

Dr. Beth Parker Recognized as a BCEEM by AAEES

The American Academy of Environmental Engineers and Scientists (AAEES) has recognized Dr. Beth Parker as a Board-Certified Environmental Engineering Member (BCEEEM) by Eminence in the category of Hazardous Waste Management and Site Remediation in April 2020. The BCEEM title is internationally recognized as a premium credential that is awarded to experienced professionals who have demonstrated expertise in one or more areas of specialization.

BSc Intern Emily Cline Awarded 2020 Mitacs RTA

The Mitacs Research Training Award (RTA) provides opportunities for undergraduate and graduate students to enhance their skills through interaction with faculty and hands-on research and training experience by undertaking a short-term paid research training internship at a Canadian institution. G360 BSc Intern Emily Cline was awarded a Mitacs RTA to focus on the deployment and assessment of sensors for real-time, depth discrete measurement of in-situ oxidation reduction potential (ORP) at a fractured dolostone contaminated site in Guelph, Ontario. The aim of the study is to highlight temporal variability of groundwater reactions due to seasonal variability of recharge and possibly temperature.

MASc Student Faran Vahedian Awarded 2020 Mitacs RTA

Faran Vahedian was awarded a Mitacs RTA to focus on 3-D static ‘equivalent porous medium’ (EPM) model, representing a multi-layered aquifer system with distinct hydrogeologic units (HGU’s) for the Guelph South area in Ontario, Canada. High-resolution field datasets will be utilized to inform a detailed conceptual site model (CSM) for advanced EPM simulations of the groundwater flow system.

MEng Student Zakia Ahmad Awarded 2020 Mitacs RTA

A Mitacs RTA awarded to Zakia Ahmad focuses on the application of permanganate as an Insitu Chemical Oxidation (ISCO) remedial technology for chlorinated solvent contamination in fractured porous media, including rigorous analysis of several unpublished rock core data sets with the intent to publish the results to support industry professionals with best practice recommendations.
Masters Graduates

**Oliver Conway-White, MASc (June 2020)**  
Primary Supervisor: Dr. Beth Parker  
Thesis: Lithostratigraphic Characterization of a Buried Bedrock Valley Using Airborne and Surface Geophysics  
Current Position: Research Assistant at G360 Institute for Groundwater Research

**Kathleen Johnson, MASc (October 2020)**  
Primary Supervisor: Dr. Beth Parker  
Thesis: High-Resolution Dynamic Pore Pressure Monitoring to Determine Hydraulic Parameters in a Multi-Layered Bedrock System for Improved Aquifer Vulnerability Assessment and Monitoring  
Current Position: Civil EIT at Klohn Crippen Berger - Mining Environmental Group

**James Hommersen, MSc (November 2020)**  
Primary Supervisor: Dr. Beth Parker  
Thesis: Assessing the Hydrogeological Properties Influencing Nitrate Distribution in a Shallow Unconfined Dolostone Aquifer and Supply Well Vulnerability  
Current Position: Research Hydrogeologist at G360 Institute for Groundwater Research

**Sam Jacobson, MSc (January 2021)**  
Primary Supervisor: Dr. Beth Parker  
Current Position: Project Geologist at Sanborn, Head and Associates

**Teresa Pilato, MASc (January 2021)**  
Primary Supervisor: Dr. Beth Parker  
Thesis: Exploring the Statistical Method of Moments for Solute Transport in Fractured Polous Rock Aquifers: Bridging the Gap between Local and Regional Scales  
Current Position: Staff Researcher at G360 Institute for Groundwater Research

**Daniel Nobel, MSc (January 2021)**  
Primary Supervisor: Dr. Jana Levison  
Thesis: Temporal and Spatial Dynamics of Nutrient Retention on Conventional Farms in Southwestern Ontario  
Current Position: TBD

PhD Graduates

**Jonathan Kennel, PhD (February 2020)**  
Primary Supervisor: Dr. Beth Parker  
Thesis: High Frequency Water Level Responses to Natural Signals  
Current Position: Post Doctoral Research Fellow at G360 Institute for Groundwater Research
Conferences Attended in 2020

- Yukon Workshop on Hydrogeology in Yukon, Whitehorse
  - February 19-20, 2020

Upcoming Conferences in 2021

- 47th IAH Congress
  - August 22-27, 2021
- GAC-MAC London 2021
  - November 1-3, 2021
- SAGEEP 2021
  - March 9-11, 2021
- NORDROCS 2021
  - September 7-8, 2021
- REMTEC Symposium
  - March 9-11, 2021
- AGU Fall Meeting
  - November 30 - December 4, 2020

G³60 PI Presentations in 2020

- Graph showing groundwater-focused and directly associated studies

Upcoming Conferences in 2021

- ALGA High Resolution Site Characterisation Seminar
  - March 2, 2020
- University of Guelph 3MT Three Minute Thesis Competition
  - March 3, 2020
- University of Waterloo ALGA High Resolution Site Characterisation Seminar
  - March 10-11, 2020
- The Westin Westminster
- GSA 2020 Connects Online
  - October 28-30
- GEOCONVENTION 2020 Virtual Event
  - September 21-23
- AGU Fall Meeting
  - November 30 - December 4, 2020
- Northwest Territories and Nunavut Geoscience Conference
  - February 16-18, 2021
- Virtual Meetings

G³60 PI Presentations in 2020

- Graph showing count of 2020 Conference Presentations

Upcoming Conferences in 2021

- Kathleen Johnson
  - Wins UoG 3MT CEPS College Heat
- Dr. Jana Levison
  - Moderates GSA Connects Session
- Dr. Beth Parker
  - Gives Keynote Talk at ALGA
- Dr. John Cherry
  - Gives Keynote Talk at IWRA Online
Updates from Alumni

Alumni Donovan Capes (MSc Graduate 2017) started a new role in November 2020 as an Environmental Monitoring Networks Data Scientist at BC Public Service. Donovan provides leadership in the field of data science, partnering with technical and policy partners, and other stakeholders to design, develop, and manage data science projects with the objective of informing and achieving the policy and operational objectives of government; and to oversee, design, and conduct detailed statistical analysis, and data visualizations.

Alumni Adam Gilmore (MSc Graduate 2010) has started a new role as the Manager of Engineering at the Township of Centre Wellington in January 2021. The G360 Group looks forward to working with him and his team in our collaborations with the Township focused on a buried bedrock valley informed by an airborne survey, and new cored holes with monitoring systems. When not busy at work, Adam enjoys spending time with his wife and two children.

Alumni Amelie Dausse (Post-Doctoral Fellow, 2020) and Nicolas Guihéneuf (Post-Doctoral Fellow, 2020) are currently living in France and recently published their G360 work in the Journal of Hydrology in two manuscripts; one titled Impact of flow geometry on parameter uncertainties for underdamped slug tests in fractured rocks, and the other, Flow-bearing structures of fractured rocks: Insights from hydraulic property scalings revealed by a pumping test.

Alumni Matthew Nelson (MSc Graduate 1999) is a Senior Project Manager at GM BluePlan Engineering Limited in Owen Sound, Ontario and enjoyed spending his summer with his family in the Canadian woods.

Soon to be graduated, Nathan Glas (MASc Candidate) is working as an Environmental Scientist for Pretivm at their Brucejack Gold Mine, with a focus on alpine hydrogeology. He is responsible for managing the groundwater monitoring program and associated regulatory reporting for the site, working to understand the natural flow system and impacts associated with mine development and dewatering processes.
Parker Published Papers Jan 2020 – March 2021


Selected Groundwater Focused G360 PI Published Papers 2020


Selected Groundwater Focused G360 PI Published Papers 2020


Bivins, A., Lowry, S., Murphy, H.M., Borchardt, M., Coyte, R., Labhasetwar, P., & Brown, J. (2020). Waterborne pathogen monitoring in Jaipur, India reveals potential microbial risks of urban groundwater supply. npj Clean Water, 3(1), 1-10. DOI: 10.1038/s41557-020-00081-3


G³60 Project Sites: Informing Our Global Datasets

Canada
- Brooks, AB
- Victoria, BC
- Whiteshell, MB
- Fort Liard, NWT
- Angus, ON
- Borden, ON
- Cambridge, ON
- Centre Wellington, ON
- Chatham, ON
- Clarington, ON
- Cobalt, ON
- Cornwall, ON
- Eden Mills, ON
- Elmvale, ON
- Erin, ON
- Guelph, ON
- Halton Hills, ON
- Kapuskasing, ON
- Kitchener, ON
- Ottawa, ON
- Puslinch, ON
- Sarnia, ON
- Wyoming, ON
- PEI (5 sites)
- Shawinigan, QC
- Varennes, QC
- Fort Saskatchewan, SK

United States
- Fort Smith, AK
- Canoga Park, CA
- Vandenberg AFB, CA
- Bridgeport, CT
- North Haven, CT
- Central Florida
- Cocoa, FL
- Fort Lauderdale, FL
- Gainsville, FL
- NAS Jacksonville, FL
- Olathe, KS
- Plaquemine, LA
- Cape Cod, MA
- Lowell, MA
- Southbridge, MA
- Wilmington, MA
- Lincoln, NE
- Pease, NH
- Deepwater, NJ
- Garfield, NJ
- Middlesex, NJ
- South Plainfield, NJ
- Trenton, NJ
- Binghamton, NY
- East Fishkill, NY
- Holley, NY
- Hudson Falls, NY
- Leroy, NY
- Rochester, NY
- Watervliet, NY
- Florence, SC
- Cottage Grove, WI
- Madison, WI
- Cheyenne, WY
- Fe Warren, WY

South America
- Camaçari, BR
- Sao Paulo, BR
- Manaus, BR
- Barra Mansa, BR
- Schkopau, DE
- Tubingen, DE
- Barcelona, ES
- Montpellier, FR
- Ferrara, IT
- Helsingborg, SE
- Hovmantorp, SE

Europe
- Schkopau, DE
- Tubingen, DE
- Barcelona, ES
- Montpellier, FR
- Ferrara, IT
- Helsingborg, SE
- Hovmantorp, SE

Africa
- Bloemfontein, ZA

Asia/Australasia
- Adelaide, AU
- Chengdu, CN
- Guilin, CN
- Hong Kong, CN
- Shenzhen, CN
- Taiwan, CN
- Nepal
- Singapore
Thank You!

The G³60 Institute would like to sincerely thank all who supported us in 2020, presently, and in our long-standing relationships.

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If you would like more information on any of the material presented in this newsletter, please contact us. You can join our blog by visiting our website.

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