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INTERPRETING THE IMPACTS OF LAND USE ON WATER QUALITY USING GROUNDWATER FLOW AND TRANSPORT SIMULATIONS IN THE GRAND TRAVERSE BAY WATERSHED

By

David F. Boutt

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ABSTRACT

INTERPRETING THE IMPACTS OF LAND USE ON WATER QUALITY USING GROUNDWATER FLOW AND TRANSPORT SIMULATIONS IN THE GRAND TRAVERSE BAY WATERSHED

By

David F. Boutt

Groundwater contributions are often overlooked in approaches that attempt to quantify the impacts of land use on surface water quality. This is surprising because it is known that surface water chemistry at base flow is representative of the groundwater chemistry in humid regions and that vegetation and land cover effects the distribution of recharge/evapotranspiration throughout a watershed. The Grand Traverse Bay Watershed (GTBW), which is undergoing large land use changes, is an excellent area to examine these relationships. A groundwater flow model linked with GIS inputs was used to demonstrate how groundwater links land use to surface water quality in the GTBW. It was demonstrated that a regional scale groundwater flow and solute transport model could help separate the impact of different land use related solute sources in a watershed. This work also shows that groundwater is a key linkage between land use and surface water quality. Groundwater flow processes are also neglected in studies that examine the influence of land use/cover changes on the environment. It has been shown that the integration of these changes is possible and they do have effects on the distribution of simulated groundwater heads across the GTBW.

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CHAPTER 1: DEVELOPMENT OF A HIGH RESOLUTION GROUNDWATER FLOW MODEL TO DESCRIBE POTENTIAL LAND USE IMPACTS ON WATER QUALITY IN A LARGE WATERSHED

INTRODUCTION

Groundwater contributions are often overlooked in approaches that attempt to quantify the impacts of land use on surface water quality. This is surprising because it is known that surface water chemistry at base flow is representative of the groundwater chemistry in humid regions (Modica et al., 1997). Groundwater chemistry in turn represents time-weighted averages of anthropogenic inputs from the land surface. These spatially and temporally varying impacts of land use on surface water quality can be evaluated using sophisticated tools such as groundwater flow models and geographic information systems (GIS). In this paper we use a groundwater flow model linked with GIS inputs to demonstrate how groundwater links land use to surface water quality in humid regions.

Establishing and quantifying linkages between land use and water quality is best accomplished at a regional scale because factors driving land use change operate at a variety of scales, and regional scale groundwater flow models are more robust. For example, true hydrologic boundaries can be represented at a regional scale with a reasonable degree of certainty. These regional scales models can also provide estimated fluxes between surface water and groundwater, delineate groundwater source areas for lakes, rivers and bays, develop boundaries for site specific transport models, and demonstrate the influence of land use on water quality. Unfortunately, few cases have been examined with large-scale high-resolution models.

Numerous field studies have demonstrated that changes in land use/cover affect groundwater dynamics and surface water quality. Pucci and Pope (1995) identified

significant differences in groundwater systems between the developed and undeveloped areas in the northern Coastal Plain of New Jersey. They found that development affected the redistribution of recharge and discharge areas, and reduced groundwater discharge to streams. Thorburn et al. (1991) observed that forest clearing had a substantial effect on groundwater recharge with average rates of 29 to 70 mm per year in two cleared catchments, compared with 7 mm per year in an uncleared catchment. Researchers have also found correlation between land use patterns and stream chemistry. For example, Flintrop et al. (1996) showed that land use patterns affect the major ion and nutrient geochemistry in selected tributaries of the Rhine River. These observed changes underscore the need to study the effects of land use on stream water quality, groundwater quality, and related hydrologic processes.

Many researchers have examined the effect of topography and land use on surface water processes using a popular code called TOPMODEL (Beven and Kirkby, 1979), which is based on the concept that topography exerts a dominant control on flow routing through watersheds. This code, which uses the conservation of mass equations for reservoirs within a watershed, is primarily designed to explore surface water runoff processes.

Numerical models have been developed to examine groundwater and streamflow response to a variety of vegetation changes. For example, Hookey (1987) developed a 2-D model to simulate delays in groundwater response to clearing a catchment. Mcphereson and Peck (1987) simulated an increase in stream water salinity after forest clearing. Few studies have coupled groundwater flow and solute transport models to quantify potential influences of altered landscapes on solute fluxes at a regional scale.

Dunn and Mackay (1995) and Dunn et al. (1996) were one of the first groups to use coupled models, SHETRAN with a solute transport code, to examine the fate of nitrates from agricultural sources in a large watershed. Coupled regional groundwater flow and solute transport models could provide a method of predicting land use related solute transport through watersheds.

Groundwater models are commonly used to describe regional flow patterns (Anderson and Woessner, 1992), while solute transport models are less commonly explored at this scale. Two-dimensional basin hydrodynamic models have been used to explore a range of scales from 40 to 1000 km across, and up to 8 km deep (Person et al., 1994, Bethke, 1986, Garvin, 1986). On a regional scale (10,000 – 100,000 km²), the USGS Regional Aquifer Systems Analysis (RASA) initiative supported model development for aquifers throughout the United States (i.e., Mandle, 1992). However, the RASA model grid parameterization was generally too large to effectively explore solute transport processes. One example of a large transport model was presented by Martin and Frind (1998), who developed a high-resolution groundwater model of a 750 km² heterogeneous aquifer system to identify capture zones of municipal wells.

Our large-scale (3300 km²) high-resolution (100x100 m cells) model enables us to quantitatively explore the influences of land use and land cover on water quality. Our regional scale groundwater flow model simulates hydraulic heads using real hydrologic boundaries. We integrate land use/ land cover changes into this model using relationships between specific land use types and their associated chemical inputs to groundwater; and describe the potential influence of non-point source solutes on surface water quality.

STUDY AREA

Michigan's Grand Traverse Bay Watershed (GTBW) provides a good opportunity to explore linkages between land use and water quality. The GTBW, located in the northwestern portion of Michigan's Lower Peninsula (Figure 1), is an important natural and economic resource for the State of Michigan and the Great Lakes Region due to its great scenic beauty, excellent water quality, and recreational opportunities. However, the watershed is currently undergoing some of the most rapid population growth and land use change of any region in the United States (Vesterby and Heimlich, 1991). From 1990 to 1998, the watershed increased its resident population by over 10%, making it one of the fasting growing areas in the Midwest. Traverse City, with a resident population of approximately 100,000 and a summer recreational population often exceeding 500,000, is the largest city in the watershed. We are currently examining the effects of these land use changes on water quality to help manage the region's superior water quality, which is of considerable importance to watershed stakeholders (Pijanowski et al., unpub.).

The regional geology is characterized by the Quaternary glacial advances and retreats, in which glaciers carved deep valleys into the shale and limestone bedrock and deposited sediment accumulations as thick as 365 meters. Sediment characteristics vary widely across the watershed, in some areas changing from a thick lacustrine clay to a coarse grained moraine within 100 meters. The regional geology has been characterized in a variety of reports and papers (e.g., Leverett and Taylor, 1915; Martin, 1957; Eschman et al., 1973). Martin (1957) found that most of the glacial sediments in the southern portion of the watershed are coarse-grained moraine and outwash deposits. Blewett and Winters (1995) were the first to conduct a detailed study of the Port Huron

moraine system, which crosses the GTBW. They found that the deposits of this system were stratified and had more characteristics of an outwash setting, despite its earlier classification as a moraine. The northeastern and northwestern portions of the watershed are highly drumlinized, which controls surface water flow patterns in these regions. Devonian limestone and shale outcrop along the east Grand Traverse Bay shore, and Mississippian shale outcrops northeast of Torch Lake (Kesling, 1974).

The Boardman river is the main tributary draining the GTBW, which is one of the few oligotrophic bays in the Great Lakes region. This watershed contains over 100 lakes, including Torch Lake and Elk Lake (Figure 1), which are likely quite sensitive to environmental change. The region receives an average annual rainfall of 105 cm, of which approximately 40 cm is recharged to the water table, 50 cm is evapotranspired, and 15 cm becomes overland flow to streams (Cummings et al., 1990).

Relationships between land use and water quality have been documented in the GTBW. Rajagopal (1978) examined land use impacts on groundwater quality near Old Mission Peninsula and Traverse City (Figure 1), and found high levels of nitrate in wells surrounded by cherry orchards. From 1984 to 1986, a USGS study examined relationships between land use and water quality in Grand Traverse County (Cummings et al., 1990). Thirty-four water wells and 24 surface water sites were sampled throughout their study, which showed possible correlation between nitrogen input (fertilizer, septic, etc.) and groundwater nitrate concentrations. Although this study demonstrated linkages between agricultural land use and water quality in the GTBW, they did not explore the land use impact of road salt (halite) application on stream and groundwater Chloride concentrations.

MODELING APPROACH

Data Collection and Analysis

One of the challenges to regional scale groundwater flow modeling is compiling the necessary data for an effectively parameterized model. The approach that we take in this paper is to parameterize our groundwater flow model using a small number of zones based on the shallow aquifer geology. We use Geographic Information Systems (GIS) approaches, specifically ARC/INFO (ESRI 1998a) and ArcView (ESRI 1998b), to manage, manipulate, and analyze the spatial data for our groundwater flow and solute transport modeling, because managing and analyzing these large spatial databases is difficult with traditional modeling tools.

A large geologic database was compiled for the GTBW region from oil/gas and water-well drilling logs and regional geologic maps. A digitized kilometer-scale surficial geology map for the region (Farrand and Bell, 1984) provided a hydrogeologic framework for the unconfined aquifer. To refine this framework, we used more than 11,000 residential water-well logs from the Michigan Department of Natural Resources and approximately 7,000 oil and gas well logs from the Michigan Department of Environmental Quality - Geological Survey Division (Figure 2). The residential waterwell logs provided information about degree of aquifer heterogeneity, and were used to develop initial hydraulic conductivity values for delineated aquifer zones. Many of the water well logs were incorrectly located or had inadequate and unreasonable geologic characteristics. As a result a series of quality checks were performed on the database before any data was incorporated into our model. Water wells were removed from the database if the recorded elevation did not match the regional 30-meter Digital Elevation



Figure 2: Well logs. Map of the roughly 11,000 residential water well logs and approximately 7000 oil and gas well logs were used for estimating geological properties of the watershed.

Model (DEM) within +/- one-meter, which removed about 6,000 of the 11,000 residential wells. Oil and gas well logs were also examined using this method, but only 300 of these 7,000 wells were rejected because the location and elevation values were more reliable. In addition, well logs were removed if the geologic characteristics were unreasonable, such as bedrock on top of unconsolidated sand and gravel.



Figure 3: Bedrock Variogram. The bedrock elevations were kriged using an exponential variogram with a variance of 1300, and a isotropic range of 3500 meters.

The elevation and lithology of the bedrock surface in the watershed was mainly provided from the oil and gas well logs. Additional bedrock elevation values were taken from the few water wells that were deep enough to reach bedrock and the few bedrock outcrops in the northeastern portion of the watershed. The bedrock elevation data were interpolated to the groundwater model grid using ordinary kriging using an exponential variogram with a variance of 1300, and an isotropic range of 3500 meters (Figure 3). The interpolated bedrock elevations define the bottom of the glacial aquifer for the groundwater model. The glacial sediment thickness was calculated by subtracting the bedrock elevation grid from the 30-meter DEM (Figure 4). Notable features in these



elevation (b) was calculated from the well logs shown in figure 2 and the glacial sediment 1:24,000 30-meter Digital Elevation Models available from the USGS. The bedrock thickness (c) map was calculated by subtracting (a) from (b).

maps include bedrock valleys in the southeastern portion of the watershed, and the deeply incised valley of the Boardman River in the lower central portion of Figure 4b.

The hydrophysiographic database for the GTBW was obtained from the Michigan Department of Natural Resources MiRIS Office. MiRIS is a statewide land use database developed in the late 1970s from 1:24,000 aerial photography. MiRIS line files of the transportation network and locations of rivers, lakes, and the bay boundary were integrated into our GIS database to identify model boundaries and potential solute sources for water quality scenarios.

Groundwater model development

Our conceptual model for the GTBW was developed using all available hydrogeologic information. Based on the available geologic maps and well log data, we chose to develop a two layer model that accounts for flow and transport through the glacial sediments. The computational resources for data processing a model with more than two layers were prohibitive. The bedrock underlying the glacial sediments is mostly low-conductivity shale, which limits vertical movement of water in or out of the shallow aquifer, although a small amount of limestone exists in the northern areas of the watershed (Kelly, 1968).

We developed a 3-dimensional groundwater flow model of the GTBW with a 100-meter by 100-meter finite difference grid cells using MODFLOW (Macdonald and Harbaugh, 1988). The model has over 1 million active cells, with more than 34,000 river cells (including the lakes). The Groundwater Modeling System (BYU, 1994) preprocessor allowed us to convert GIS based data into model input files. This ability to incorporate GIS coverages into the model is necessary to examine the influence of land use and land cover on groundwater flow and solute transport at these scales.

The hydraulic conductivities for the region are parameterized into zones that are concordant with the mapped glacial units (Figure 5). Both layers have the same horizontal conductivities except in areas where the lacustrine sand and gravel high conductivity units overlie low conductivity clays. Initial hydraulic conductivity values for the zones are consistent with the measured lithologies recorded in reliable well logs (Freeze and Cherry, 1979). For example, conductivity values in the sand and gravel outwash deposits will be higher than values in areas with till or fine-grained lacustrine deposits. Assigning a single hydraulic conductivity value for each geologically parameterized zone is one of several possible methods to incorporate geology into groundwater models.

The hydrologic boundaries used in our model are shown in Figure 6. Constant head boundaries are used along the perimeter of Grand Traverse Bay, Lake Michigan, and Lake Charlevoix, with the head values set to known lake elevations. The remaining boundaries are significant surface water flow divides, which are represented as no-flow boundaries. The northeast and northwest boundaries of the model were extended beyond the surface water divides because of the uncertainty in the location of these divides, as discussed in the "Delineating Groundwater Flow Divides" section. Uncertainty in model boundaries commonly leads to poor prediction of hydraulic heads (Anderson and Woessner, 1992).

Effective recharge for the model was estimated by taking the total annual precipitation (105 cm) and subtracting losses due to estimated evapotranspiration and



Figure 5: Surficial geological map. Surfical geology for the region was digitized to a one-kilometer grid from the map by Farrand and Bell (1982).



Figure 6: Simulated groundwater elevations. Predicted hydraulic heads varied between 378 masl and 177 masl, which is the elevation of the Grand Traverse Bay. Boundaries for the flow model are also shown.

overland flow for the region (See Study Area Section). Annual precipitation varies only by a few centimeters across the watershed, but soil type and land use/land cover types could result in spatially variable recharge. For example, in areas where the soils are predominantly sand, recharge would be higher than in areas with clay rich soils (i.e., till). Since the necessary soil data were not readily available at the time of this model development, we used a single recharge value of 40 cm/yr for the entire region. Evapotranspiration was not directly simulated in the model, since it is subtracted from the effective recharge value.

River cells for the model were developed based on topography due to problems with the regional MiRIS river coverage. Problems with this coverage included incorrectly coded lines, such as roads, and inconsistent river gradients obtained by overlaying the river coverage with the DEM. River elevations increased as well as decreased downstream which is clearly unrealistic. This oscillatory effect was likely caused by the spatial averaging of the DEM and slight errors in the locations of the digitized MiRIS line locations. To address these problems, ARC/INFO was used to delineate drainage networks based on a DEM with 30x30 meter cells. First, the FLOWDIRECTION function was used to calculate the direction water would flow on the land surface based on this high resolution DEM, then the FLOWACCUMULATION function was used to calculate the number of cells flowing into each grid cell. Cells with a high-calculated flow accumulation are areas of concentrated flow, and can thus be used to identify likely stream channel locations. A threshold of 400 cells was placed on this process to define river reaches that approximated the extent of the MiRIS files. Occasionally rivers were generated that did not exist, so the method was compared with

1:24000 topographic maps and aerial photographs where possible. Generated river cells that were not in the maps and photos were deleted to better represent actual hydrologic conditions. The modified drainage networks were then upscaled to a 100 by 100 m model grid using the lowest 30-m cell elevation within each cell as the river elevation.

RESULTS

Model Calibration

The seven hydraulic conductivity values were slightly modified in the model calibration process to minimize the squared residuals between observed and simulated heads (Figure 7). Conductivity values from pump tests in the region (Cummings et al., 1990) compared very well to the values in the calibrated model. Several head datasets are available for the region, with monthly readings between January 1985 and January 1986, and another set in August 1998. The steady state calibration, using the 1998 values, provides a reasonable match between simulated and observed heads (Figure 7). The simulated heads also match the trend in the large regional database of heads measured during well installations (Figure 8). These regional data were limited to the well locations that matched the DEM elevations within +/- one-meter, as discussed in the Data *Collection and Analysis* section, although there is still a large degree of uncertainty in these values. Even if the measurements were accurately recorded, they were measured during a wide range of hydrologic conditions. As a result, the measured heads will vary across a wide range relative to the steady state simulated values. For example, Cummings et al (1990) found that the hydraulic head near Fife Lake in the Grand Traverse Bay region varied by approximately 2 meters from 1976 until 1988, with average seasonal changes of roughly 0.5 meters.

Hydraulic heads in the GTBW vary from 177 meters at the Grand Traverse Bay boundary to over 350 meters in the eastern high topography areas (Figure 4a). It is apparent from Figure 5 that significant groundwater flow divides exist on both the



Figure 7: Simulated versus observed plot. Modeled hydraulic heads for the region was plotted against observed data for the USGS wells in Grand Traverse County.



Figure 8: All wells calibration. The simulated versus observed plot for all the water well information follows the trend of the one to one line very nicely. These wells were not used in the calibration process.

northeastern and northwestern boundaries of Grand Traverse Bay. The drumlinized topography in the northeastern portion of the watershed results in significant variability in these simulated heads. The Boardman River southeast of Traverse City (Figure 1) is a significant groundwater discharge area due to the large topographic changes. This can be observed in the high simulated hydraulic gradients in this portion of Figure 6.

Groundwater Flux Estimates

We estimated groundwater fluxes into Grand Traverse Bay using the groundwater model because it is very difficult to obtain measurements of groundwater fluxes in the field. Approximately 8 cubic feet per second of direct groundwater discharge to Grand Traverse Bay was calculated based on the calibrated flow model. This estimate was calculated by summing fluxes into all the cells bordering the bay (Figure 6), accounting for approximately 7% of the model outflow. Since groundwater is also the primary source of river water, it also accounts for nearly all the streamflow into the bay.

Previous studies (such as Brater, 1972) have estimated direct groundwater inputs into Grand Traverse Bay using mass balance approaches. They estimated the inputs and outputs of the system, including the discharges of streams, total precipitation, and evapotranspiration. The difference between inputs (rainfall) and the outputs (streams and evapotranspiration) was assumed to be the groundwater discharge to the bay. This approach estimated that between 0 and 4 cfs of groundwater was directly entering the Grand Traverse Bay. In contrast, our method can estimate the spatial distribution of discharges and can predict solute fluxes into lakes and rivers.

Delineating Groundwater Flow Divides

Groundwater divides commonly mimic surface water divides in large watersheds, thus if significant topography exists surface water divides can often be represented as noflow boundaries. An alternative method of defining these divides is to predict their locations based on flow models that use true hydrologic boundaries. In our model, the northeast and northwest boundaries were extended beyond the surface water divides because of uncertainty in these groundwater divides. Since there is little topography in these areas and the bottom the aquifer has a significant slope (Figure 4b), we allowed the model to delineate these groundwater divides. Differences in these divides can yield discrepancies in the predicted groundwater and solutes fluxes if significant solute sources are located above regions where groundwater and overland flow paths do not drain to the same location.

The simplest technique to develop groundwater divides is to plot simulated groundwater flow vectors and digitize the boundary between regions that flow into the watershed and regions that flow out of the watershed (Figure 9). An alternative is to import the simulated hydraulic heads into ARC/INFO and calculate flow directions and flow accumulations, using the approach we used to delineate our river network. This method is similar to delineating watershed boundaries for surface water catchments (Hornberger, 1998). Figure 7 illustrates a few of the differences between the region's surface water and groundwater divides, with the white line representing the surface water divide and the flow vectors indicating the groundwater divide. In this western portion of the watershed, the surface water divide clearly deviates significantly from the groundwater divide.



watershed were not always the same as the groundwater divides for the watershed. Note here that in the top of the figure the groundwater flow vectors (shown in black) differ from the surface water divide.

Simulating Land Use Water Quality Impact Scenarios

A coupled groundwater flow and solute transport model allowed us to infer potential impacts of land use on surface water quality. The groundwater flow model provides flow velocities for the solute transport simulation. The scenario we chose to examine represented the fate of chloride, which is a common solute found throughout the GTBW. Chloride is a stable conservative anion that is commonly derived from the dissolution of halite applied to roads in the winter months and also from urban sources such as septic fields. An additional source of chloride in the GTBW region is the improper disposal of subsurface brines brought to the surface by the drilling of oil and gas wells (see Figure 10a). This scenario illustrates the potential influence of the dominant source of chloride, although other scenarios could explore alternative solute sources. The goal of conducting this scenario was: (1) to determine if observed chloride concentrations in stream samples are the related to the application of halite to roads, and (2) to demonstrate that groundwater transport of halite is likely a significant factor that influences the observed stream chloride concentrations.

Road salting with halite is a common practice in the Midwestern United States to manage icy roads. Many groups (e.g., D'Itri, 1992; Jones and Sroka, 1997) have studied the influence of halite on groundwater quality. In this simulation, we used chloride concentration as an analog for halite, which is primarily sodium chloride but can include small percentages of magnesium chloride or potassium chloride. Since chloride is conservative, no retardation factors or reactions were simulated.

The simulation was run for 50 years, with a constant recharge source along salted roads in the GTBW. Local county road commissions provided the locations of roads with



Figure 10a: Chloride spatial distribution. Spatial plots of the residual concentrations of chloride show that most underestimated values lie in the regions where other sources chloride is found.
applied halite. Although road salt is only applied in the winter months, some halite is likely retained in the unsaturated zone and distributed to the water table throughout the year, hence we simulate the average annual input.

Measurements of solute concentrations discharged to surface water bodies were calculated from groundwater flow and solute transport model. In the simulations, chloride concentrations were saved every 5 days for cells along the shoreline of Grand Traverse Bay, while chloride concentrations were saved every ten years for the entire watershed. Simulated chloride concentrations in streams were calculated every ten years for each of our sampling sites noted on Figure 10a. At each stream node the flux (m³/day) of water discharged from the aquifer and the concentration of chloride (mg/L) were used to determine a total mass flux (mg/day) of chloride at that stream node. Both the mass flux of chloride and the flux of water were summed down stream paths to sampling locations. Simulated concentrations (mg/L) of chloride in the stream at each sample site were then calculated by dividing the total mass flux of chloride (mg/day) by the total streamflow (m³/day). Since we are comparing our simulated concentrations to observed concentrations that were taken at low-flow hydrologic conditions, we are only concerned with groundwater inputs into the stream.

Figure 10a shows the location of sample points relative to potential solute sources. The striped horizontal lines refer to an area where there is a great risk for groundwater contamination by the improper disposal of subsurface brines and the hollow triangles indicates sites with documented groundwater contamination by brines (Skillings, 1982; Fryer, 1982). The striped vertical lines refer the Traverse City region, which has potential septic and urban chloride sources.

Our simulation appears to identify road salt transported through groundwater as a significant chloride source to the stream water in the GTBW. The only simulated chloride source was halite application to roads. Figure 10b shows two primary trends in the simulated versus observed chloride concentrations that support this concept. Our initial concentration of 100 mg/L was reduced to 70 mg/L to provide a better fit to the lower trend (plus symbols) in simulated and observed concentrations, because these were measured in regions where there are not known oil brines or urban sources (Figure 10a). As a result, the most likely chloride source in these areas is halite application to roads. The upper trend (solid black circles) represents simulated concentrations that are underestimated with respect to observed chloride concentrations in streams. These locations are all either in, or downstream from, the noted oil/gas trend region (horizontal stripes) or the portion of the Traverse City without municipal sewer service (vertical stripes). The decrease in the chloride concentration from the Boardman's upper reaches to the region just upstream of Traverse city are likely due to dilution from groundwater with little chloride input due to the Pere Marquette State Forest, which is a region with few salted roads.

Figure 11 shows predicted chloride concentrations for 10 and 50 years after the initiation of halite application. Areas with high simulated chloride concentrations are mostly within urban areas, such as Traverse City, due to the high density of salted roads. The change from the 10-year to the 50-year concentration profile (Figure 11) shows the expected increase in chloride concentrations across the watershed through time.

The temporally varying fluxes into the Grand Traverse Bay from 10 to 50 years is illustrated in Figure 12a as a histogram of the difference of the total chloride flux to the



Figure 10b: Simulated versus observed chloride plot. The comparison between simulated and observed concentrations of chloride show two distinct trends that can be explained by a separate sources of chloride, road salt, chloride from septic systems, and improper disposal of brines.



areas is responsible for the differences in the simulated chloride concentrations at 10 and 50 years. The 10 and 50-year Figure 11: Spatial distribution of chloride across the watershed. The advective transport of water from chloride source simulations show a high chloride concentration surrounding urban areas where road density is higher.





Figure 12a: Chloride flux histogram. This histogram show the differences in chloride flux between 10 and 50 years for cells bordering Grand Traverse Bay.



Figure 12b: Chloride flux. The flux of chloride into The Grand Traverse Bay shows a significant lag time due to transport of chloride from distant source areas.

Grand Traverse Bay. According to this simulation, these fluxes have increased dramatically during this time period. Although a few cells have significant increases in flux, the majority of the flux comes from a high percentage of cells with small flux increases. This simulation is based on steady state flow rates and solute inputs; thus the differences are entirely due to the solute transport times. Figure 12b shows the expected time lag between halite application, and the corresponding asymptotic chloride flux of roughly 3640 kg/day to the bay due to an chloride input of 70 mg/l.

DISCUSSION

Groundwater flow and transport processes need to be described to effectively interpret the influence of land use on water quality. We have demonstrated that a regional scale groundwater flow and solute transport model can help separate the impact of different land use related solute sources in a watershed. This work also shows that groundwater is a key linkage between land use and surface water quality.

Groundwater models provide a critical component to evaluate the linkage between land use/cover scenarios and water quality. The halite scenario simulates transport of halite from roads through groundwater into streams. This method is extremely powerful for two reasons. First it allows us to evaluate the magnitude of solute inputs by providing simulated values of stream water concentration, that can be compared to measured values. Second, it helps determine the relative importance of specific land use/cover contributions to measured solute concentrations. In our example chloride from the dissolution of halite applied to roads did not turn out to be the sole contributor to chloride concentrations in streams. Chloride from urban sources, such as septic systems, and subsurface brines likely contribute to the chloride concentrations in streams.

The methods developed in this paper use groundwater simulations to predict longterm solute loadings due to land uses/covers. We estimated groundwater fluxes into Grand Traverse Bay by summing all cells bordering this water body. This information can be used to estimate contaminant loadings into the bay. Our calculated discharge of 8 cubic feet per second was somewhat higher than earlier estimates, which has significant implications about the potential solutes fluxes into the Grand Traverse Bay. The halite impact scenario estimates that significant fluxes of chloride will enter Grand Traverse

Bay using a reasonable value for halite input. In addition, the simulations show the long legacy of land use in predicted solute fluxes to surface water. An ability to estimate the impact of past and current land uses provides land use managers with a powerful tool to examine the impact of past and future management decisions. Non-conservative solutes, such as nitrate, can also be evaluated using the developed methods.

The model was also used to constrain watershed boundaries, which has implications to the magnitudes of estimated solute flux to the GTBW. Surface water divides and groundwater divides often mimic each other in areas of high topography, but in the GTBW, there are areas with relatively low topography where these divides differ. If solute flux predictions use the incorrect divides, the estimates would be biased by the amount of solute applied to the region between the divides. Therefore proper development of groundwater divides ultimately leads to more accurate water and solute budgets for the watershed. This technique can also be used to decipher groundwater source areas for to smaller regions of a watershed.

CHAPTER 2: COUPLING A THREE-DIMENSIONAL GROUNDWATER FLOW MODEL TO A SPATIALLY EXPLICIT LAND TRANSFROMATION MODEL

INTRODUCTION

Groundwater flow processes are often neglected in studies that examine the influence of land use/cover changes on the environment. Likewise, regional-scale groundwater flow models rarely incorporate the effects of vegetation and land cover on the distribution of recharge/evapotranspiration (ET) in their models, despite their observed effects on groundwater and surface water dynamics (Thorburn et al. 1991; Pucci and Pope 1995; Taniguchi 1997). This paper will address these issues by simulating land use changes and their associated influences on groundwater, using literature derived relationships between groundwater processes and land uses/covers. The developed approaches will be able to predict the magnitude of future land use/cover changes, as well as the resulting changes in hydraulic head distribution.

Land use/cover changes have caused various observable effects on watershed processes. These include changes in: 1) streamflow (Bosch and Hewlett 1982; Hibbert 1971; Rothacher 1970); 2) chemistry of major ions (Cl) and nutrients (N and P) in streams (Herlihy et al. 1998; Field et al. 1996; Flintrop et al. 1996); 3) stream ecology related to changes in stream flow and temperature (Wiley et al. 1997); and 4) the magnitude of groundwater discharge and the distribution of recharge and discharge areas (Pucci and Pope, 1995). Although these studies have documented the influences of land use/covers on watersheds, few modeling studies have described the processes responsible for these influences. Dunn and Mackay (1995) presented an example of a successful incorporation of land use/covers into models. Their model, termed SHETRAN, evaluated the influences of changes in evapotranspiration (ET) in selected catchments of the Tyne

Basin in Northeast England. They estimated ET rates using climatological data and information on vegetation cover, which decreased ET and increased streamflow.

Groundwater flow models are commonly developed both to examine regional flow patterns and to establish boundary conditions for smaller-scale site-specific models. Such models commonly neglect the influences of specific land uses/covers on evapotranspiration and recharge values. ET and recharge are commonly estimated by examining the steady state mass balance of a watershed (Anderson and Woessner, 1992). These methods use reasonable average inputs, but do not adequately represent spatial variability in such fluxes, which can be important for regional scale groundwater studies.

Spatial variability in ET and the resulting variations in effective groundwater recharge have a direct influence on water table elevations. ET and effective recharge are altered by land-use/cover changes (Taniguchi, 1997). Thus, land-use/cover changes must influence water table elevations. Relationships between ET/recharge and groundwater levels are well established. In order to test the hypothesis that land-use changes will affect the distribution of water table elevations, we must infer how different land uses/covers effect water table recharge.

Pijanowski et al. (1995; 1996; 1997) have developed a conceptual modeling framework called the Land Transformation Model (LTM) that describes how policy, as well as socioeconomic and environmental factors, drive land-use change. This GISbased model includes a variety of land use change driving variables such as: land ownership; local and regional population change; economics of land ownership; transportation effects on urbanization; and local and farm-level agricultural economics. The model calculates driving variable outputs, integrates all driving variable transition

probabilities, and infers future land use maps for the entire watershed. It projects land uses in watersheds over roughly a 100-year period with annual time steps. The original GIS-based Land Transformation Model (Pijanowski et al. 1995) was recoded in ArcView *Avenue* and redesigned and integrated with a variety of spatial-temporal tools. This new LTM includes a variety of historical land use/cover databases; a Land Use/Parcel Query and Analysis; and a graphical user interface. The land use drivers are integrated by one of several methods including a neural network simulation procedure and multi-criteria evaluation. A set of spatial-temporal calibration tools is also integrated into the LTM Toolbox, as will be discussed in a future paper.

Although other studies have modeled relationships between land use/covers and hydrologic processes, no known studies have researched these effects using real or predicted land-use changes. This study is unique because we have measured land use as shown in the land use coverages as well as the ability to predict future land use changes related in the watershed. The studies mentioned above, which have modeled these relationships, have observed changes in the hydrology due to drastic land use changes, such as the complete clearing of a forest to grassland. We can show that changes in recharge and ET, due to actual and predicted urbanization in the watershed, could have considerable effects on water table elevations.

APPROACH

We have developed a straightforward way to relate land use/cover changes with groundwater flow processes. This involves assigning different percentages of the region's precipitation to groundwater recharge by land use/cover zones. This assumes that the losses due to ET and overland flow are associated with land use/cover, and the remaining water becomes effective groundwater recharge. ET is likely the most important of these factors because of its large range of variability for land uses/cover types. ET incorporates both transpiration of moisture by plant activity and evaporation of water from the soil and plant surfaces, which will both be affected by land use/cover type. As a result, it is a very difficult process to quantify for areas with diverse vegetation types. For example deciduous and coniferous forests will have higher annual ET values than pastures, because of their greater leaf cover.

Effective ET values can be estimated using mass balance techniques, remote sensing methods (Mauser and Schadlich 1998; Sucksdorff and Ottle 1990), and modeling studies. Our goal is to simulate the influence of spatially variable water table recharge on groundwater levels by assigning ET percentages of the annual regional precipitation to different land use/cover types throughout the watershed. Table 1 shows literature derived annual ET percentages for land covers present in the GTBW. These percentages will be applied to similar land use/covers found in the modeled region (Table 2).

Recharge is the process by which precipitation is transported to the water table. The permeability of a soil and the magnitude of precipitation falling on the soil surface govern how much water will be recharged to the water table. The relationship between recharge and our land-use/land cover database depends on physical properties exhibited

ment month and			
types.			
Vegetation	Annual ET 9	6 Source	Comment
Pasture	~20	Scott and Sudmeyer, (1993)	Calculated from average Precipitation
Crops (Wheat, Barley, Oats)	~30	Scott and Sudmeyer, (1993)	Calculated from average Precipitation
Grasses	~10	Belijaars and Boseveld, (1997)	Micrometeologic
Forest (Decidous species with Confiers)	~60	Roberts and Roberts, (1992)	Water Balance

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able 2: Annual percentages of ET and recharge. Annual percentages of ET and	charge used in the flow simulations as well as the percent of each land use found in	e GTBW.	
[able 2: Annual percentages of ET and recharge. Ann	charge used in the flow simulations as well as the perc	e GTBW.	

Land use/Cover	Annual ET %	Recharge %	Total Area (%)
Urban	20	10	9
Agniculture (Orchards, vineyards, row crops)	30	80	20
Open Land (pastures)	20	80	14
Forests (Decidous and Coniferous)	<u>6</u> 0	30	49
Forest Wetlands	40	•	-
Water	•	•	6
Barren	30	06	1

Forest (Decidous species with Confiers)

by the land use/cover, such as the impermeable area used by the land use/cover. An example of a physical property that a land use/cover could exhibit is its ability to deflect or prevent water from entering the soil profile. For example, a parking lot will prevent more water from entering the soil profile than open grassland. Urban land-use/land covers (which comprise 6% of the total area of the watershed) will have lower recharge rates to the groundwater table with corresponding increases in overland flow to streams depending on the engineering applied to the area.

The recharge percentages presented in Table 2 were developed by considering properties of the land use/cover discussed above. Recharge percentages for land use/covers with higher impermeable areas are much lower than land use/covers with less impermeable areas. Variable soil properties were not incorporated into the calculation of these percentages due to incomplete soil coverages for the watershed. The recharge percentages were determined assuming that relatively permeable soil underlies the land use/cover. Multiplying recharge percentages by a factor that describes the soils ability to transmit water can ultimately incorporate soil properties into these calculations. An example of this would be a case where a very permeable sandy soil occurs where a high recharge value from a land use/cover existed. This soil would transmit almost the maximum amount of recharge, so 100% or 90% would be multiplied by the recharge value for this area. On the other hand a clay loam, which has very low permeabilities, may have a factor around 30% or 40%. Since we are concerned with just the effects of varying land use/cover, the spatial variability of soils in the GTBW averaged over a 100meter cell were assumed to not have a great influence on the recharge percentages.

The percentage of the water that becomes streamflow, via interflow and overland flow, is determined by the amount of water left over from the annual ET and recharge percentages. The ability of a land use/cover to direct water available to streamflow is embedded in the recharge percentage value. Of the total precipitation falling on the watershed the least amount annually becomes overland flow, although these values can change depending on how land use management practices. Our groundwater flow model does not simulate stream flow but maps showing the potential source areas of streamflow, such as Figure 13, may be developed.



Figure 13: Streamflow distribution. Cells with a lot of impervious, urban land use/cover, surfaces will direct more water via overland flow to streams possibly causing higher erosion rates.

STUDY AREA

Michigan's Grand Traverse Bay Watershed (GTBW) is a good site to simulate the influence of land use change on water table elevations by coupling the LTM with a groundwater model. The GTBW, located in the northwestern portion of Michigan's Lower Peninsula (Figure 1), is currently undergoing some of the most rapid population growth and land use change of any region in the United States (Vesterby and Heimlich, 1991). During the last 10 years, the watershed increased its resident population by over 10%, making it one of the fastest growing areas in the Midwest. Traverse City is the largest city in the watershed, with a resident population of approximately 100,000 and a summer recreational population often exceeding 500,000. We are also examining the effects of these land use changes on water quality, which will be presented in a later paper.

The watershed receives 105 cm of annual precipitation, of which approximately 40 cm is recharged to the water table, 50 cm is evapotranspired, and 15 cm becomes streamflow (Cummings et al., 1990). The Boardman River, which drains about 60% of the entire watershed, empties into Grand Traverse Bay near Traverse City. Two large lakes, Elk Lake and Torch Lake, drain the rest of the watershed into Grand Traverse Bay. Grand Traverse Bay is attached to Lake Michigan and receives most of its water from the watershed's streams. Most of the annual discharges to the watershed's streams (95%) come from groundwater sources. Groundwater flow in the study area is from areas of high topography towards the Grand Traverse Bay. In the southern portion of the

watershed, groundwater velocities tend to be high because of high conductivity sediments and high gradients.

Land use in the GTBW is predominantly forest (49%) and agriculture (20%). Much of the forested portions of this watershed are managed within the Pere Marquette State Forest, which encompasses most of the upland reaches of the Boardman River tributaries as shown in Figure 1. Urban land use comprises 6% of the total area of the watershed, with the other main land covers are open herbaceous/shrub/grasslands (15%), water (9%), and wetlands (1%).

A 3-dimensional groundwater flow and transport model (See Chapter 1 for complete description) has been developed and calibrated for the GTBW that incorporates recharge and ET as constant values. The model simulates groundwater flow through the glacial sediments that lie on top of older Paleozoic bedrock as discussed in Chapter 1. The Paleozoic rocks, which are mostly shale, act as good barriers to vertical flow in the region. The modeled region encompasses an area of 3300 km² with 500,000 100-meter horizontal cells divided into 2 layers. The computational resources for data processing a model with more than two layers were prohibitive. The 2-layer model provides a reasonable representation of measured head data (Figure 6). Important features to note on this map include the large discharge region of the Boardman River and the high gradients in the southern portion of the watershed. Overall the conductivity values in the model are higher in the southern portion of the watershed and become lower northward. The lower conductivity values in the northern portion of the watershed suggest slower travel times.

The Land Transformation Model has been developed to forecast land use patterns for the GTBW to the year 2030 (Figure 14). Our GIS-based Land Transformation Model (LTM) uses neural network simulation algorithms that integrate our spatial-temporal drivers with historical land use databases. This novel technology allows the computer to "learn" how socioeconomic drivers affect documented land use changes. These patterns are then used to forecast land use assuming a "business as usual" scenario. We have found that the LTM predicts urban change with an 89% accuracy using 100 m cells. This cell size was chosen to allow easy interaction with the groundwater flow models. Areas where land use change are not well predicted include new recreational areas (mostly golf courses) and large residential subdivisions, which will be addressed by incorporating new drivers that characterize these changes.



Figure 14: Current and predicted land-uses in the GTBW. The land use coverage on the left is the 1990 land projections, of the figure are projected future land use coverages generated using the Land Transformation use derived from aerial photos. The two land use coverages on the right hand side, 10 year and 50 year Model. All three of these coverages were used in the simulations.

METHODS

Studying the influence of land use on watershed hydrology requires the use of large datasets that often need significant preprocessing. In addition, managing and analyzing these large spatial databases is difficult with traditional modeling tools. As a result, we used Geographic Information Systems (GIS), specifically ARC/INFO (ESRI 1998a) and ArcView (ESRI 1998b), to manage, manipulate, and analyze the spatial data for our groundwater flow model. Fortran 90 codes were also written to perform operations on gridded datasets for model input.

Our land use database for the GTBW was obtained from the Michigan Department of Natural Resources MiRIS Office. MiRIS is a statewide land use database developed in the late 1970s from 1:24,000 aerial photography. Land uses were classified at Anderson Level I, which include: urban, agriculture, nonforested vegetation (grasslands, shrubs, herbaceous), forests, wetland, open water, and barren. Land use data for the GTBW region were acquired by township and compiled using ARC/INFO.

The three land use/cover datasets, shown in Figure 14, used in the study were gridded at 100 m horizontal cellsize. Each distinct land use/cover was given a unique numerical identifier which stayed was the same for the current, 10 year projection, and 50 year projected land use/cover datasets. A Fortran 90 routine was written to convert the gridded land use/cover datasets into recharge grids. Each land use/cover dataset was converted into an ASCII file format, where each land use/cover dataset was associated with an ET / recharge percentage. A single ET percentage was assigned to each 100-meter cell, which was considered to have a homogenous land use/cover. The ET percentage was then multiplied by the total annual precipitation to yield an average

annual ET for the watershed (Equation 2.1). The ET value calculated above was then subtracted by the average annual precipitation and multiplied by the recharge percentage to yield a recharge value. The recharge supplied to the model is a percentage of water left over after the ET processes occur. Lastly the streamflow component is the sum of water left over after ET and recharge processes have occurred for that land use/cover.

$$ET = \operatorname{Pr} ecip_{a}^{*}(ET_{\%})$$

$$\operatorname{Re} c = \left[\operatorname{Pr} ecip_{a} - ET\right]^{*} \operatorname{Re} c_{\%}$$

$$Oflw = \operatorname{Pr} ecip_{a} - \left[ET + \operatorname{Re} ch \operatorname{arg} e\right]$$

2.1

where:

ET – average annual Evapotranspiration Precip – average annual Precipitation ET_% - ET percentage factor for land use/covers Rec – average annual Recharge Rec_% - recharge percentage factor for land use/covers Oflw – average annual overland flow to streams

The recharge values calculated were then input into the groundwater flow model and ran until a steady state solution was achieved for that time step. Since MODFLOW does not simulate ET that takes place above the saturated zone, we were limited to remove the calculated ET rate and only provide the model with the calculated recharge value. This process was repeated for each land use/cover time step. Head maps for each land use/cover time step were saved and differential head, or drawdown, maps were calculated for current time against the preceding time. These maps were created by subtracting the head values in a cell of one simulation by the preceding simulation. In the case of the current land use/cover dataset, it was subtracted against the constant recharge case to provide a map showing how the incorporation of variable recharge as the result land use/change will change the groundwater heads in the watershed.

RESULTS

Positive numbers in the head difference maps correspond to increases in head over the simulation period and negative numbers correspond to decreases in head. The maps were calculated in the following order: the 1990 land use/cover simulation was subtracted by the constant recharge simulation (Figure 16), the 10 year projected land use/cover flow simulation was subtracted by the 1990 land use/cover simulation (Figure 17), and the 50 year projected land use/cover flow simulation was subtracted by the 10 year projected land use/cover simulation (Figure 18). Two maps were also developed to show the sensitivity of the model to positive and negative changes in recharge. This map, Figure 15, shows areas that will change in head due to overall changes in recharge in the watershed. Areas on these maps that are not green show a change in head relative to the constant recharge simulation. These areas are deciphered as regions that are extremely sensitive to changes in recharge and should not be used in the interpretation of the land use/cover simulations.

Incorporating land uses/covers into groundwater flow models provides a powerful approach for determining their influences on watershed hydrology. Recharge values are often difficult to measure and predict thus, constant values are often used in groundwater flow simulations. The incorporation of land uses/covers into a groundwater flow model allows users to specify a spatially variable recharge, based on real data. Figure 16 shows the changes in head between the integrated 1990 land use/cover simulation and the constant recharge simulation. This simulation shows the head differences expected due to variable recharge values associated with different land use/covers (Figure 16). This



Figure 15: Recharge Sensitivity. The groundwater flow model is sensitive to changes in recharge in areas that are not green on the maps above. The figure shows how small changes in recharge will effect the groundwater table elevations of the whole watershed.



Figure 16: Current land use - constant recharge simulation. The head difference map for the variable vs. constant recharge simulations show that an overall increase in head occurs but localized decreases in head are found near the Traverse City region.



Figure 17: 10 year land use projection - current land use simulation. The change in head between the 10 year projected land use and the current land use simulation show changes in the gradient developing as well as lower in the quickly urbanizing areas.



Figure 18: 50 year land use projection - 10 year land use projection simulation. The difference in heads developed in the 40 years between the two simulations still shows the influence that the Traverse City area will have on groundwater elevations.

simulation shows that heads are higher in most areas of the watershed. This result is related to the large agricultural and non-forested areas that have higher recharge values than the average simulated constant recharge value. In contrast, the variable recharge heads are lower in areas where the recharge value is smaller than in the constant recharge simulation, such as urban areas. Notice that heads around Traverse City (see Figure 1 for location), and neighboring areas are lower in the variable recharge simulation due to the high percentages of impervious surfaces in these urban areas (Figure 14).

The head difference map for the 10-year projection-current land use/cover (Figure 17) examines the potential effects of predicted future land use change on water table elevations. The current version of the LTM only predicts changes from any land use/cover to urban, so the changes in groundwater heads will show only the effects of urbanization. These effects can be noticed very clearly in areas surrounding Traverse City, which the LTM predicts increases in urban land uses in the next ten years. The rest of watershed shows little or no decrease in head values, besides areas that are highly sensitive to changes in recharge, over the same time period.

The changes in head between the 10-year projection and the 50-year projection are slightly larger in their influence (Figure 18). Changes are once again found to occur in the Traverse City area, but a new prominent decrease in head occurs directly east of Traverse City. The heads here are much lower than directly beneath Traverse City. The large changes east of Traverse City can be attributed to a large urban sprawl predicted by the LTM (Figure 14). This reduction in recharge is directly within an area that is somewhat confined from the regional flow field. The Boardman River runs south of this region and is of considerably higher head than this area, whose ground elevation is

considerably lower. This in essence isolates this region from the other areas and limits the ability of this area to receive groundwater. Another reason that this area has lower heads than in the previous simulation is the fact that this region of urbanization was not as large in the 10-year prediction. This results in a large decrease in head due to less recharge.

Changes in groundwater head between these two times have an effect on the regional gradients to the west of Traverse City and the eastern portion of the watershed. These changes in head are a direct result of the model's sensitivity to recharge in these areas.

DISCUSION

Simulating land use changes and their associated influences on groundwater processes is an important step in determining the impact of these changes on watershed hydrology. We have already shown (Part 1) that groundwater processes play an important role in interpreting the influences of these changes on water quality. Therefore in order to accurately describe groundwater processes, for the correct interpretation of water quality data, land use/cover change must be integrated into the groundwater simulation. In this last section we have shown that the integration of these changes is possible and they do have large effects on the distribution of simulated groundwater heads and gradients across the GTBW.

The variable versus constant recharge simulation demonstrated the impact of variable recharge on simulated heads. This simulation also depicts changes in head as the result of the redistribution of recharge areas due to the incorporation of high impervious surfaces in urban areas. Changes in groundwater heads as the result of 10 years of future land use change show the effects of urbanization near the Traverse City region. The lowered groundwater heads reflect that more water in these areas is directly flowing into Grand Traverse Bay through streams or sewer systems rather than groundwater. Significantly lower heads just east of Traverse City, in the 50 year versus 10 year projected land use/cover simulation, are indicative of the potential consequences of urban sprawl on wateshed hydrology. The reduction in recharge to these areas plus the geographic location of this region causes groundwater heads to drop considerably between the two time periods. This simulation also depicts the changes in regional

groundwater gradients as a result of land use/covers and the model's sensitivity to small recharge changes. Changes in regional gradients can disturb current flow paths and increase flow velocities.

The land use/cover datasets that are being used in this simulation are observed and predicted. The observed land use/cover dataset allows us to calibrate our model using real data to obtain more accurate estimates of aquifer parameters, such as hydraulic conductivity. The forecasted land use/cover datasets have allowed us to infer the future changes on groundwater heads as a result of land use changes. This is a powerful tool that can be used in unison with other approaches, such as solute transport models, that attempt to delineate areas in watersheds that are sensitive to small or large land use/cover changes.

Together these simulations underscore the need to better approximate and understand anthropogenic influences on watersheds. We have shown that considerable decrease in groundwater heads will occur if current land use practices continue. These changes were predicted only from the consideration of varying land use/covers. The simulations do not integrate the influences of groundwater pumping, which in its breadth and scale may have a larger effect on heads. Overall the changes and redistribution of recharge areas as a result of urbanization may have a considerable effect on the simulated water table elevations and gradients in the Grand Traverse Bay Watershed.

APPENDICES

APPENDIX A: GEOLOGY OF THE GRAND TRAVERSE BAY WATERSHED

INTRODUCTION

The sole reason for writing this section of the thesis lies in the amount of time that was spent researching and thinking about the geology of the watershed. The objective for researching the geology of the watershed was to develop a hydrostratigraphy of the water table aquifer for the input into a 3-dimensional flow and transport model. This section could serve as a guide for someone starting a project similar in scale to the GTBW, in which they might learn something from mistakes and assumptions that were made throughout the 2 years of research. Unfortunately there was little information on the glacial deposits of the region with the exception of the drumlinized till plains in the Charlevoix region. A lot of information was found on the bedrock of the region, because of the exploration interests of oil companies, but this information was not relevant at this point. Professor Grahame Larson proved to be an excellent resource on the glacial geology of the region, showing just where to search. This section will begin with a description of the oldest rock unit subcroping in the GTBW and progress forward into the present depositional systems noting mistakes made along the way and what was done to correct them.

BEDROCK GEOLOGY

The bedrock of the GTBW was not researched at great depth in this study because we are only concerned with the flow and transport through the water table aquifer. The bedrock serves as a barrier unit to the flow and transport of groundwater in the glacial materials. Middle Devonian rocks, deposited on a carbonate platform, are the oldest rocks found subcroping beneath the watershed, although older rocks are found beneath these rocks. The Devonian Period in the GTBW was a time of widespread but fluctuating seas, extensive limestone and dolomite, and shale accumulation, and some evaporite deposition (Dorr and Eschman, 1970). Near the end of the period black muds of the Antrim Shale were carried into the Michigan Basin from uplift in the Appalachian region.

The first unit subcroping in the GTBW is the Middle Devonian age Traverse formation. The Middle Devonian Traverse group is mostly fossiliferous limestone and dolomite that is commonly light olive-gray to brownish gray, fine-grained becoming silty upsection. The limestone is occasionally fractured and some slight deformation structures are observed in the uppermost units, the units above mainly the Jordan River formation (Kesling et al., 1974). Correlated limestones found in the Alpena area commonly have karstic characteristics, including sinkholes and conduit features. The Traverse Group is found outcropping and subcropping beneath both the Leelanau peninsula and in the Charlevoix region (Figure 19). Along the shore of northern East Grand Traverse Bay north and south of Norwood, Michigan (shown as the blue star on Figure 19) the Middle Devonian Traverse Group and overlying Upper Devonian Jordan River Formation (informally referred to as the "Norwood Shale", by Ehlers, 1938) and the type section of the Antrim Shale outcrop. Other exposures of the Middle Devonian


provides a good barrier to vertical flow in the region. The Devonian age Traverse Formation Figure 19: Bedrock Geology. The bedrock in the GTBW, which consists mainly of shale, is slightly fractured by appears not to have downward gradients.

Traverse Group in the watershed are found just south of the town of Charlevoix and along the shore of the Leelanau Peninsula. The Whiskey Creek Formation, which lies beneath one of our stream sampling sites, was examined at outcrop and found to be gray to brown limestone, contained some dolostone and chert and some unknown shelly fossils. The Jordan River, which lies between the Traverse Group and the Antrim Shale, is a formation composed of very thin limestones and nonresistant shales, about 1 to 2 meters thick (Gutschick and Sandberg, 1991a).

The transition from carbonate platform to deep basin was a time of dynamic change produced by the Acadian orogeny. The deep subsidence toward the end of the transition period had completely changed the seawater and sediment regimes in the newly formed Late Devonian Michigan Basin and produced a stagnant, black-mud sea floor devoid of oxygen (Gutschick and Sandberg, 1991b). The type locality of the Antrim Shale, deposited during this time, is 1.6 kilometers south of Norwood. The Antrim Shale is mostly a black fissile pyritic shale with thin fossiliferous limestone beds in the lower Norwood Member, and transitions into a "light-colored calcareous unit" in the Paxton and Lachine Members (Gutschick and Sandberg, 1991b). The Antrim Shale in the GTBW is overlain by the Ellsworth shale whose type section is in the Petosky Portland Cement Co. guarry pit, 2.4 km south of the town of Ellsworth, Antrim County, Michigan (yellow star Figure 19). The Ellsworth is greenish gray (Figure 20), bluish gray, light gray, and dark gray shale with some sandy and oolitic limestone interbeds in the subsurface (Gutschick and Sandberg, 1991b). The base of the Ellsworth is defined as the change from brown or black Antrim Shale to greenish gray shale; and the top is an unconformity overlain by Mississippian rocks, a red limestone at the base of the



Figure 20: Shale Outcrop. The picture here is of the Mississippian Ellsworth shale that outcrops at quarry just east of Central Lake. Originally this deposit was thought to be a lacustrine clay.

Coldwater shale. The facies relationship between the Antrim and Ellsworth is an intertounging or alternation of greenish gray deltaic Ellsworth with the basinal, brown or black Antrim. The location of the Antrim and Ellsworth Shales are found in Figure 19. These shales underlie a significant portion of the GTBW.

As was stated above, the top of the Ellsworth shale is marked by an unconformity with the lowest member of the Coldwater Shale Group. The Mississippian Coldwater Shale Group is only known through subsurface drilling in the GTBW (Figure 19). The Coldwater is a gray shale with maximum thickness of up to 500 meters in the Michigan Basin with local thickness in the GTBW up to 200 meters. The Marshall Sandstone, which lies above the Coldwater, subcrops only slightly into the groundwater modeled domain. The contact between the Coldwater and the Marshall is gradational, as the Coldwater becomes coarser near its top. The Coldwater provides a nearly impermeable barrier to vertical flow throughout the whole state where the Marshall overlies it. It also appears to be a good barrier to vertical flow in the case where glacial deposits lie on top of the Coldwater, which occurs in the GTBW. The Coldwater in the subsurface is often confused with glacial lacustrine clay deposits. It some cases the shale and lacustrine clay (that has the Coldwater Shale as it's source) are indistinguishable. This provides a problem when trying to define the elevation of the bedrock in the GTBW. Many times it is just a blind guess as to where the bedrock starts. Occasionally the driller's would note a weathered zone that could be used to identify the top of the bedrock. This did not prove to be too much of a problem since the hydrostratigraphy in these areas was defined to have thick low conductivity lacustrine clay above the Coldwater shale. The only problem

this raised is when trying to interpolate the bedrock elevation grid for the watershed this caused small mounds, or an irregular surface, to develop in the output.

Overall four distinct bedrock units directly underlie the glacial sediments of the GTBW. From bottom to top, or oldest to youngest, they are the Middle Devonian Traverse Group, the Upper Devonian Antrim Shale, the Upper Devonian Ellsworth Shale, and the Mississippian Coldwater Shale. A typical North-South cross-section of these rocks in the GTBW is shown in Figure 21. All of these units provide a very good barrier to vertical flow, with exception where the Traverse Group is possibly fractured and this area was quite small.

The bedrock elevations for these units were calculated from the 7,000 oil and gas wells throughout the watershed and the few water well logs that reached the shallow Traverse Group in the northern parts of the watershed as well as the few outcrops along the shore of the bay and in Ellsworth, Michigan. All of the data for Oil and Gas wells were obtained from Steven E. Wilson at the DEQ – Geological Survey Division. Bedrock elevations were also obtained from hand drawn bedrock elevation maps acquired from the Michigan DEQ – Geological Survey Division (Millstein, 1983; Reska, 1983; Elowski and Bricker, 1982; Bricker and Lilienthal, 1976). Water well logs and all other related information were obtained from David Forstadt at the Michigan Department of Natural Resources -Real Estate Division. The data for the elevation of the bedrock (Figure 2) in the GTBW was interpolated using 2-dimensional ordinary kriging (Figure 22). The areas where the map has mounding represents kriging calculating a change from the mean of the dataset to the value located at this spot. One reason for this odd feature are not enough data points surrounding a local high in the bedrock causing a



Figure 21: North to south cross-section of the GTBW. A typical North-South cross section of the GTBW is shown above. This figure demonstrates how sediments with different characteristics associate in the watershed.



Figure 22: Bedrock elevation. Bedrock elevations were interpolated using a kriging technique from Oil and Gas wells, outcrops, and the few wells that penetrated the bedrock.

mounding effect or a bad elevation value for this well causing a deviation from the mean and other surrounding points. This first explanation has some validity because quality checked data on hand drawn maps show the same features as well as Melhorn (1954) and Leverett and Taylor (1917) describe bedrock knobs common throughout the region. The second explanation has little weight because most of the data from oil and gas wells are quality checked though misinterpretation of a lacustrine clay for a shale could happen. There are areas where the bedrock will have elevation changes of 100 meters in the vertical and laterally in distances of less than a kilometer. In the southern portion of the watershed, where more data exists, these features appear as bedrock valleys, which could be either preglacial drainage patterns or syn-glacial erosional features. Some of these valleys show the same trend as the large linear lakes in the watershed, notably Elk Lake and Torch Lake (See Figure 22). Overall the bedrock elevations are much higher in the northern portion of watershed and slope along the same trend as dip of the Michigan Basin, which is toward the southeast.

GLACIAL AND RECENT DEPOSITS

The stratigraphic descriptions above indicate that within the region there are formations of greatly different hardness and lithology. These initial variations probably produced a preglacial topography in which a northward facing cuesta had been developed on the Marshall Sandstone (Melhorn, 1954). This cuesta faced a lowland belt to the north developed on the softer Antrim, Ellsworth, and Coldwater shales. The Traverse, as well as younger Devonian limestones, formed another upland district toward the north. The presence of sinkholes in the Alpena area indicates chemical weathering had been initiated on this upland. Glacial erosion and deposition modified this pattern but did not completely obscure it, so that the topographic relationships are still shown on the present surface. For example, the Port Huron moraine throughout the GTBW follows the approximate position of the scarp fronting the Marshall Sandstone cuesta (Figure 21). This cuesta may been have been a controlling factor in morainal deposition in earlier times, acting as a focus of building for the Port Huron moraine during the Late Wisconsinan. As was stated before, the Coldwater and even the Antrim and Ellsworth were important contributors because many of the tills and clays of the region are known to be derived from these shales.

Figure 23 shows this high accumulation of sediment in the southern portion of the watershed whereas in the northern portion the drift is very thin. This figure can be visualized as a wedge of sediment, where the sediment is thickest in the south and thin to almost bare in the north (Figure 21). Sediment thickness in the watershed range from over 250 meters in the bedrock valleys to no sediment in some spots of the northern part of the watershed. It should be noted here that within the large lakes present in the region,



Figure 23: Drift thickness. The drift thickness map for watershed was calculated by subtracting the elevation of the surface for each point by the bedrock elevation for the same point. Note that some prominent valleys exist in the watershed.

specifically Elk Lake and Torch Lake, the drift thickness is not accurate and may even overestimate the amount of sediment. This is because data for the depth of lakes was not available to us and was not used in the calculation of sediment thickness. It is my guess that these lakes are seated in the soft Ellsworth and Antrim Shales, and may contain some lacustrine clays that were deposited in the Late Wisconsinan. If this statement is correct, then the depression where these lakes now exist must have been present during the last retreat of the glaciers and probably contains a large amount of sediment from the deposition during the glacial lake stages of the Great Lakes Basin. With reported lake depths in excess of 100 meters, this means that these depressions may have been well below sea level initially, possibly remnants of the preglacial drainage network.

Throughout the Pleistocene there were close to 11 glacial advances in the Great Lakes Basin. Unfortunately our sediment deposits in the GTBW only reflects the last of these great glaciations. Figure 24 is a digitized 1 km scale map of the surficial deposits in the GTBW (Farrand and Bell, 1982). The deposits of the GTBW are mostly Late Wisconsinan in age but the sand dunes found along the shores of Lake Michigan and Grand Traverse Bay and within the Mancelona Outwash Plain are Holocene (recent) in age. The retreat of the Wisconsinan ice sheet began about 20,000 years ago near the northern Ohio River valley. 13,000 years BP the ice sheet stopped and started advancing for a short period. As this ice sheet stood stagnating, this pause built the Outer Port Huron Moraine that now forms the southern watershed boundary of the GTBW (Figure 25). The ice sheet again retreated but stopped again and formed the inner Port Huron Moraine and the Mancelona Outwash Plain where the Boardman River has carved a huge valley (Figure 26). In most of the watershed the Outer Port Huron is at an average 40



Figure 24: Surficial geology of the GTBW. The surficial geology of the Grand Traverse Bay Watershed is dominated by the high topography moraines separated by the broad Mancelona Outwash Plain. The crossection line A-A' is found in Figure 19.

Formation of Outer Port Huron Moraine



Figure 25: Outer Port Huron Moraine. The Outer Port Huron Moraine, which formed between 13,500 and 13,000 years BP, rises to almost 200 meters over Grand Traverse Bay.

Formation of Inner Port Huron Moraine



Figure 26: Inner Port Huron Moraine. The Inner Port Huron Moraine formed the Mancelona Outwash Plain, which consists of over 150 meters of sand and gravel that is home to the Boardman River valley.

meters above the Mancelona Plain and the Inner Port Huron is about 8 meters above the Mancelona Plain. The Mancelona Outwash Plain once served as a major dicharge valley for an enormous glacier that occupied the region just to the north and east of the plain. Now the Mancelona Plain is home to the Boardman River, which has cut a roughly 50meter valley into the plain before cutting through the area where the Inner Pt. Huron merges with the Manistee Moraine.

The crests of the Inner and Outer Port Huron Moraine trend northeast-southwest in parallel fashion for about 40 km. In cross section (normal to trend) each moraine has a pronounced asymmetrical profile with steep northwest facing proximal slopes (Figure 21). The surficial sediment in the moraines and outwash plain are predominantly glaciofluvial sand and gravel, with lacustrine clays and tills limited to areas up-ice from the moraines (Blewett and Winters, 1995). Subsurface data suggest that tills may be more common, though thin and separated by stratified sand and silt. Blewett and Winters (1995) suggest that the Inner and Outer Port Huron may not be actual moraines but more likely associated with an outwash setting. Outwash plains tend to have more stratified deposits and would more likely have higher conductivities than a morainal complex. Leverett and Taylor (1915) have classified this complex as a moraine, even though the calibrated hydraulic conductivities of the groundwater model suggest a higher conductive material such as stratified sands and gravels. I have discovered thick clay and gravel layers in some deep well logs that may suggest a morainal base to the whole complex.

The Manistee moraine is found in the western portion, mostly southeastern Leelanau County, of the GTBW where it appears to be closely blended with the main Port Huron system (Figure 24). The Manistee first appears as a massive ridge at

Manistee on Lake Michigan, and trends northward as a series of overlapping segments parallel to the lake in the vicinity of Glen Lake in Benzie County (Melhorn, 1954). Here it turns at a right angle to reach a point near the head of Grand Traverse Bay. When it crosses the Boardman River south of Traverse City, it again turns northeast so as to almost intersect the Inner Port Huron ridge near Rapid City. The Manistee loses its identity here, but it can be found extending northward in Antrim and Charlevoix Counties marked by small isolated morainal segments separated by parallel southeastward trending valleys. Melhorn (1954) believes that the ice front held steady at the head of Grand Traverse Bay while the Port Huron ice north of Rapid City was retreating westward to the position of the Manistee Moraine (Figure 27). The minor moraines of Leelanau County and the Old Mission Peninsula appear to be directly related to the Manistee morainic system. They could be interlobate ridges formed between ice bodies which occupied Grand Traverse Bay on the East and Lake Michigan on the west. Highest points on the Manistee moraine are just west of Traverse City between Grand Traverse and Leelanau Counties where the moraine achieves a total width of four miles. The Manistee Moraine shares many of the same characteristics as the adjacent Port Huron Moraines.

The best drumlins in the GTBW lie on ground moraine in northern Antrim and all of Charlevoix Counties, which are more or less parallel to the axis of Lake Charlevoix (S 30° E) (Figure 28). A few drumlins are found east of the chain of lakes near Bellaire and Ellsworth. In this area the forms are crowded into a narrow belt of ground moraine adjacent to segments of the Manistee moraine. Where the ground moraine is very thin, many of the ridges have been sculptured out of the Ellsworth Shale by ice. Between the north end of Torch Lake and Traverse City, drumlins trend only a few degrees south of



Figure 27: Manistee Moraine. The Manistee Moraine is responsible for forming the southwestern edge of the Grand Traverse Bay Watershed, where it meets the Inner Port Huron Moraine.



Figure 28: Drumlins. Drumlins, like the ones seen here, dominate groundwater flow and stream drainage patterns in the Northeast portion of the GTBW.

east. Since this is subparallel to the depressions occupied by Torch and Elk Lake, it is doubtful the same ice activity was the cause of the two features. Drumlins of Charlevoix and Antrim counties are composed of very stony, sandy, buff or light brown till (Melhorn, 1954). The drumlins of the Grand Traverse region are partly composed of red till. It has been hypothesized (Melhorn, 1954; Leverret and Taylor, 1915) that drumlins of the Grand Traverse region were formed during a minor readvance of ice onto ground moraine laid down subsequent to building the Manistee moraine. At a later time, ice moving out of the Lake Michigan basin advanced inland and plastered red till on older drumlins and in some cases secondary drumlins were built on older forms.

In addition to morainal ridges of the GTBW, a large percentage of the surficial geology is made up of ground moraine (Figure 24). Ground moraine usually forms by a quickly retreating glacier that is losing sediment by dislodgment or melting, which is often referred to as an ablation till. Ground moraine is unstratified and unsorted and may contain sand stringers and abandoned meltwater channels. The ground moraine in the GTBW is very loosely compacted in some places and very heavily compacted in others. This is due to the sand-clay percentage in the sediment composing the ground moraine. In general the ground moraine closer to the major morainic ridges will have higher sand content and thus have a looser texture. This could also play a large factor in the transport of groundwater through these sediments. Old Mission Peninsula is a dissected high level ground moraine, which reaches altitudes between 750 and 850 feet. The Old Mission Peninsula contains a few drumlins with the same composition as those on the west or the east.

The moraines found in the GTBW often exhibit high topographies and when water levels were higher they were probably not submerged. This leads to the development of highly different sediment characteristics on the moraine and on the flanks of the morainal complex. The lower areas are important to us because they can contain different (finer grained) sediments that can impede groundwater flow. In examining Figure 24 and Figure 4a areas can be chosen that have a high chance of accumulating finer grained sediments when lake levels in the Great Lakes basin were higher. These areas are depicted on the surficial geology map (Figure 24) as lacustrine sand and gravels. But we must remember that this is only a surficial geology map and does not reflect the entire sediment profile beneath the area depicted on the map. It is the case in these areas that they have a large accumulation of lacustrine clays some up 100 meters in the Traverse City region (Cummings et al., 1990). The normal shallowing upward profile in a basin filled with water has fine-grained sediments at the bottom and coarsening upwards. A good example of this is in the Traverse City area where thick lacustrine clays grade into sands and gravels related to the progradation of a delta into the west arm of the Grand Traverse Bay (Twenter et al. 1985). In other areas the transition is similar from lacustrine clay into beach and dune sands along most of the lowlands surrounding the Grand Traverse Bay shore. I have interpreted the areas on the surficial geology map depicted with lacustrine sand and gravels to have this same transition from finer to coarser grained materials. Thus low areas (chosen from the Digital Elevation Model) that are depicted as surficial lacustrine sand and gravel likely have some amount of lacustrine clays beneath.

After the ice had left the Great Lakes basin completely (about 8,500 B.P.) the level of water in the lakes varied due to the location of the lake outlet. Changes in the level of the lakes have had a great effect on the types of sediments that were being deposited in the GTBW. Sometimes the level of the lakes were 100 meters below the lake levels today. This could cause changes in the relative base level of streams and severe erosion of many of the deposits of the region. The Great Lakes basin has also undergone isostatic rebound due to the weight of the glaciers being removed from the system. This has caused a shift in the elevations of many of the beaches from previous lakes in the basin. What hasn't changed is the formation of sand dunes along the current shore as well as some the high areas of the watersheds. Along the west arm of Grand Traverse Bay and the east shore of the east arm dunes are quite common.

HYDROSTRATIGRAPHIC INTERPRETATION

The first approach that was used to develop the glacial stratigraphy and hydrostratigraphy of the GTBW focused on correlating a regional clay (till). We thought if we could find and correlate a regional clay, that this clay would act as the bottom of our water table aquifer. After many weeks of working with Microsoft Access and Arcview GIS trying to correlate water well drillers logs with the word clay, another approach was taken. This approach entailed obtaining a digitized map of surficial sediments and assigning zones of hydraulic conductivities. From that point on focus was shifted to creating a bedrock elevation for the GTBW and adding complexity in the form of conductivity zones.

The bedrock that outcrops or subcrops beneath the glacial sediments of the GTBW is mainly shales with some limestone and a very small amount of sandstone. This provides us with a very good bottom of the aquifer. Shales of the Michigan basin have over the years proven to be very good barriers to vertical flow (Sibley, Personal Comm.). The Ellsworth and Antrim shales reach thicknesses of up to 300 meters. The first major break came with the discovery of a 1-kilometer scale digitized map of Farrand and Bell's Surficial Geology Map of Michigan. This map gave us the framework for building a discrete number of hydraulic conductivity zones based on the sediment characteristics within those zones. We decided to use 6 zones for the GTBW; in no particular order they are; End Moraines - Coarse, Glacial Outwash, Glacial Till – medium, Glacial Till – coarse, Lacustrine Sand and Gravel, and Dune Sand. These zones were chosen to be homogenous in the horizontal direction with respect to the model. Even though we know this is truly not the case and even less the case in the glacial setting, this provided a

reasonable estimate of regional geology. Next we ground truthed these zones by comparing them as best as we could to the water well logs and oil/gas well logs by lithology. Obviously "Glacial Till medium and coarse" (refer to Figure 24) we could not tell apart in the logs but we could see if there were identifiers in the drill logs such as stony or pebbly. The glacial till – medium and coarse is the same as the ground moraine as discussed in previous sections. The northward extent of the Manistee is also digitized as glacial till.

After ground truthing the logs and the maps, which worked well, the next task was to assign properties to each of the characteristic zones. In the first model that was developed the model was only 1 layer thick, which meant we could only specify one conductivity value for the whole 100 by 100-meter cell. There were numerous factors to take into account such as clay layers not accounted for in the zones. We accounted for various heterogeneities by adjusting the vertical conductivity in zones that may be more acceptable to having a large continuous clay lenses. Table 3 shows the conductivity values used for the first model developed for the GTBW. This model proved to provide a reasonable estimate of hydraulic heads for the GTBW (Figure 6).

A code was developed that split the one layer model into two layers and smoothed the conductivity data for the outwash and moraine deposits. By smoothing, there was not one value of hydraulic conductivity for the whole zone but a transition from a high conductivity to a low conductivity much like what would exist in an actual outwash setting (Figure 29). Proximal to the head of outwash a higher energy environment exists and as you move distally the energy becomes less where there is finer grained sized material and hence a lower conductivity. The till and moraine zones were treated as

used in the groundwat	ter flow model.		
Sediment Zone	Layer 1 Horizontal Conductivity	Layer 2 Horizontal Conductivity	Vertical Conductivity
Dune Sand	10	0.01	0.001
Lacustrine Sand Gravel	21	0.01	0.001
Glacial Outwash	24	24	9
End Moraines - Coarse	19	19	2
Glacial Till - Coarse	3	ß	S
Glacial Till - Medium	1		Ĵ

Table 3: Conductivity values used in flow model. Horizontal and Vertical Conductivities for both layers



Figure 29: Smoothed hydraulic conductivity values. The hydraulic conductivity values for each sediment zone were smoothed using a interpolation scheme to better represent actual sedimentologic conditions.

having the same conductivities in both layers of the 2 layer model. This is because there is no justification to split these units into two distinct layers. But what we did was incorporate vertical conductivities in these zones by adjusting the leakance, which accounts for the anistropic behavior or sediments and rocks, factor between the two layers to account for the lower conductivities in the vertical direction in these deposits.

The lacustrine sands and gravels as well as the dune sand zones were believed to have a lower conductivity material beneath them, a thick clay probably lacustrine in origin due to the lack of pebbles and stones. All of the water well logs in these areas also showed relatively thick (sometimes up to 300 feet) clay, or less likely a till, beneath the surficial sands and gravels. This is integrated into the hydrostratigraphy by these units having higher hydraulic conductivities in the upper third of their thickness. This was checked with well logs in these cases and shows a very good correlation. The lower lacustrine clay units had very low conductivities, which transmit very little groundwater through these regions. This acts as the bottom of the aquifer and closely correlates with what other researchers (Twenter, 1985; Cummings et al., 1990) have found in well logs. These researchers only looked at small portions of the watershed and were not concerned with the big picture. These initial reports of thick extensive clay, and the field observation of the Ellsworth Shale (which we thought was an outcropping of clay) led us to think that it continued across the whole GTBW.

CONCLUSION

From these ideas and mistakes we have learned to take a step back from the fine detail and explore other ways of incorporating geology into groundwater models. We realize that we cannot incorporate all of the spatial variability of glacial deposits in our model, but we can break down the system into small manageable zones that will provide us with the best possible definition of the system in order to answer the questions at hand. If we were interested in modeling the transport of a contaminant plume at a small scale then we would be worried about the occasional clay or sand lenses that might provide a barrier or pathway to flow. But since we are modeling at a large enough scale, these heterogeneities will tend to average out. Thus it is justifiable to give one large zone of glacial sediments a single conductivity value if the results are interpreted in the context of your initial assumptions about the geology. In conclusion, the development of the hydrostratigraphy of the GTBW proved to be less complicated than initially thought when developed in the context of scales.

APPENDIX B: GENERATION AND EXAMPLES OF TOTAL AND DIFFERENTIAL SOURCESHEDS

INTRODUCTION

A sourceshed is defined as the total area that contributes to a selected drainage point. Dr. Bryan Pijanowski first coined the term "sourceshed" when he was explaining a method on how we could visualize chemistry data taken in the field. A sourceshed is simply a watershed for any point within a drainage basin. Sourcesheds can be used for a variety of purposes such as aggregating data (e.g. land-use percentage), visualizing chemical data between two water sampling stations, and analyzing the influence of landbased processes in a catchment context. Sourcesheds can be developed with respect to surface water flow over landscapes but can be easily transferred to watertable elevations or piezometric surfaces. Two types of sourcesheds have been developed: the total sourceshed and the differential sourceshed. The total sourceshed is the one defined above (Figure 30), which includes the total drainage area to a selected surface water sampling location. The differential sourceshed (Figure 31) is the area between two chosen drainage points of differing elevation that lie in the same drainage network. Each type of sourceshed has its strengths and weaknesses that will be discussed later in this section. The following section will include an in-depth discussion on the development of sourceshed from theoretical and applied viewpoints. The sections will also discuss sourceshed pitfalls and sourceshed applications. Throughout the rest of the section it will be assumed that we are talking about surface water sourcesheds unless otherwise noted.



Figure 30: Total sourcesheds. Total sourcesheds for the watershed are generated by calculating the total areas that contributes to a specified point.



Figure 31: Differential sourcesheds. The differential sourcesheds shown here are developed by calculating the drainage area between selected points, shown in red, that lie within the same drainage basin.

TOOLS AND PREPROCESSING OF DATA

Sourcesheds were initially developed for visualization purposes but have many other purposes. The development began as an attempt to define polygons that represented drainage areas for our surface water sampling locations. These polygons were then to be associated with chemistry data at a downgradient sample site in an effort to visualize spatially variable data. Data and tools needed to develop a sourceshed for a sampling location are:

- 1. Arc/Info with GRID module
- High resolution Digital Elevation Model (DEM) for region of interest (30 meters or less)
- 3. Relative location of drainage or sampling point
- 4. ArcView 3.0+

Arc/Info 7.2.1 (ESRI, 1998a) was used throughout the generation of the sourcesheds. At the time of writing, Arc/Info 8.0.1 is supposed to be released soon, so any commands that don't appear in the new version of Arc/Info refer back to the 7.2.1 version. Also included at the end of this section are lists of Arc/Info commands and functions used in the sourceshed generation. ArcView 3.1 was only used for visualization and in further processing of the sourcesheds after initial generation. It therefore is not absolutely necessary to have, but it is convenient and time saving.

It is important to have an accurate DEM on which to perform the sourceshed analysis on. Any gaps or errors in the DEM will cause severe problems when calculating the flow patterns through the drainage basin. This will in turn cause elevation values of drainage points to be inaccurate with respect to surface water drainage divides and will

result in inaccurate catchment delineation. DEMs can be downloaded for free from the USGS Geo Data website (http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html). The 10-meter and 30-meter DEMs are available by 1:24,000 quadrangles only, referred to as 7.5 minute DEM on the Geo Data website. In the spring of 1998 the USGS changed its data storage standard and went to a storage type referred to as SDTS (Spatial Data Transfer Standard). SDTS was such a new method of storing data that conversions in Arc/Info 7.2.1 did not even exist. Arc/Info 8.0.1 will have an SDTS to GRID file, probably *sdtsgrid* in the grid module, format command that will make the DEM generation process a lot easier. For the example in this section, each 1:24,000 quadrangle was downloaded in SDTS and converted into an Arc/Info ASCII grid format using a C program written by Sol Katz. The ASCII grid files were imported into Arc/Info grids using the *asciigrid* command in Arc/Info. About 1 out of every 4 USGS SDTS files had the wrong coordinates in them so time had to be taken to make sure that the files have the correct information and distribution. After that, quadrangles were aggregated together using the *merge* command in the Arc/Info grid module. But before using the *merge* command make sure that no gaps will occur between DEMs, as the USGS DEMs won't match up exactly with each other. You may have to use the gridshift command to move grids with respect to each other. Any missing data between grids must be filled in, possibly by using the *resample* command in the Arc/Info grid module. Data that falls on a border outside of a DEM that has no other DEMs next to it won't be a problem. Not all of the DEMs, a total of 48, were 10-meter by 10-meter, some were 30-meter by 30-meter. To get around this the 10-meter DEMs were all resampled to 30-meters before using the merge command. Make sure that all of the DEMs download has the same units for the

vertical datum. All of the 10-meter DEMs were in meters and all of the 30-meter DEMs were in feet. After merging the grids the last step in processing the elevation data is reprojecting. Arc/Info's *projection* command can be used to accomplish this task. The process from downloading to merging 48 1:24,000 quadrangles took about one and a half weeks of solid work.

The location of the drainage or sampling point, as you will read later, will change with the generation of the drainage pattern for your catchment. Since DEMs are spatially averaged small errors occur in the exact location of smaller streams and rivers. Thus it is necessary to move locations of sample points to the nearest stream cell based on the DEM.

METHODS

The next few paragraphs will discuss the direct generation of sourcesheds for multiple points on the topography of the GTBW. The generation of differential sourcesheds is much easier to do than total sourcesheds. This lies in the fact that when making differential sourcesheds the area between two points is of concern. Whereas in total sourceshed generation file preparation is much more difficult, which lies in the fact that you are concerned with total areas that overlap each, which Arc/Info polygons does not support. It takes one source file for all of the sample points in the differential sourceshed generation and it takes one file for each one of the sample points in the total sourceshed generation. This makes any analysis procedure with total sourcesheds very time consuming for any more than a few drainage points. A method will be discussed later to generate data for total sourcesheds from data generated with differential sourcesheds using a simple spreadsheet technique.

The first step in the generation process is to identify drainage patterns in your DEM. It is necessary to have a digitized stream network either from topographic quadrangles or Digital Line Graphs (DLGs) on hand at this point to compare with the delineated streams. Figure 32 shows streams as digitized from air photos (blue) and streams delineated from the DEM (green) for the GTBW. Differences, as discussed above, lie in the spatial averaging of the DEM. Note the red point and the yellow point on Figure 30. The red point refers to the actual stream sampling location as determined by GPS measurements. The yellow point refers to the location where the same point lies on the DEM generated drainage network. If a sourceshed technique were used on the red



between the digitized rivers used in the study and the DEM delineated rivers. Note that points Figure 32: MiRIS and DEM generated rivers. This figure illustrates the major differences located on these two different sets could be off by more than 0.5 kilometers.

point it would yield no drainage area because it lies off of the drainage path in the basin. In turn the yellow point yields a sourceshed depicted as the shaded area on the figure, which can be attributed to the real drainage area of the red point. It is very important that sampling locations are moved to the same drainage spot as depicted on the DEM delineated drainage pattern. In some cases where river or stream channels have valley widths less than the DEM cell size, sourceshed generation will not work for those rivers. This should not occur with natural stream systems but may occur with man made channels or human influenced drainage patterns (geologically new channels). As with the case in the GTBW many rivers are dammed where flow is restricted but still occurs through the river. This appeared not to affect sourceshed generation. Natural lakes, such as Elk Lake and Torch Lake (see Figure 1), have natural flow through them but the surface elevations are identical on the DEM. This caused problems because when flowdirections were developed no gradient existed, therefore no flow paths were developed. This obviously is not the real case, but occurred because the lakes are so large and in hydraulic connection with each other. The lake bottoms actually slope toward the drainage points, much like a river, but the lakes are so deep and have so much water they don't show a surface gradient at the resolution of a DEM. The way to get around this would be to obtain baythmetric data for the lakes and generate flow paths and sourcesheds for the points using that data.

In order to generate river or drainage networks with a DEM, small inconsistencies and depressions must be filled to avoid all flow paths from going towards a single point. Each step of sourceshed development will generate a new file. Filling can be accomplished using the *fill* command in the grid module of Arc/Info with the *sinks* option
selected. This will generate a DEM with sinks filled to a flat level. The next step is to generate a flowdirection grid with the newly filled DEM. The *flowdirection* command in the Arc/Info grid module is a cellular command that assigns each cell with a flow direction. It assigns the cell by examining the elevations of the 8 cells surrounding the central cell, where a direction towards the lowest cell will be assigned to the central cell. The *flowdirection* command provides input into the *flowaccumulation* command. The flowaccumulation command calculates where flow will accumulate with the information obtained from the *flowdirection* command. The command will follow flowdirection values until they leave the edge of the grid or reach a flat plane (such as Grand Traverse Bay). Values in the flowaccumulation grid refer to the number of cells flowing into that cell. A value of 1000 in the flowaccumulation grid designates that 1000 cells are flowing into that specific cell. The flowaccumulation grid serves as a drainage network for the whole DEM area if it was flooded with water. This grid will ultimately become your drainage network. In order to adjust the flowaccumulation grid to represent a realistic drainage network use the *con* function in the grid module. The *con* Boolean function separates all values above or below, depending on > or < sign, a chosen flowaccumulation value. A good value to start with is 100, but a value should be chosen to approximate the actual spatial distribution of streams and rivers. A value of 400 was the value that visually looked the best in the GTBW. If a value of 100 is used in the con function it will generate a grid that has cells labeled with a 1 that have 100 or greater cells flowing into them all other cells will designated a 0. This file will be used as a template for further drainage network generation. The gridline command can be used to generate this file into a line coverage for easier viewing. The most important thing about this step

is that the value that is chosen has no bearing on sourceshed generation. Remember that the *flowaccumulation* command is not used in the final sourceshed generation. In this case the value chosen is only for visualization purposes. When generating a river network for input into a model it is necessary to calibrate the flowaccumulation value.

Now that a drainage network is generated for the DEM, locations of where sample points exist are needed to generate sourcesheds. The easiest way to do this is to pick the x-y coordinate off of the generated drainage network for each point. Make sure to pick the coordinate off of the middle of the cell of the drainage network. Any mistakes such as picking a cell that is not part of the main drainage network will be readily apparent in the size of the sourcesheds that are generated. The x-y coordinate will be used as input into the *selectpoint* command in the grid module. Another way to input the points is to generate an Arc/Info point file from the x-y coordinates. The *selectpoint* function takes a filled DEM and sampling locations to generate a "source" grid that has elevation values only for cells that sampling locations fall within. The source grid will look empty but make sure that there are elevation values in cells where sampling points are located. The source grid will be used as direct input into the *watershed* function.

With the newly generated source grid as well as the flowdirection grid you are now ready to create sourcesheds for your drainage points. The *watershed* function will be used to create the areas of your sourceshed. This function calculates the contributing area above your selected drainage point, or if another point lies upgradient of the first point in the drainage basin, then the area above the first but below the second higher point will be calculated. Areas are output to a grid file with the sourceshed for a point designated as the elevation of that point. There is no way to have the watershed function

only generate differential or total sourcesheds. If any other points lie in the same drainage basin then differential sourcesheds will be generated if not total sourcesheds are generated. The grid of sourcesheds needs to be converted into polygons for further type of analysis. The *gridpoly* function will take a grid and convert each unique group of grid values into its own polygon. Be careful because if two drainage points are selected that have the same elevation, which also abut each other, they could be combined into one polygon. This step may need to be done many times to generate the correct sourcesheds for each point, modifying your x-y values for drainage points each time.

As was stated above calculating total sourcesheds for more than a few sites is a difficult task. It is also very difficult to visualize any information with total sourcesheds because when dealing with multiple sites their drainage areas may overlap each other thus obscuring information. Total sourcesheds tend to be better suited for data aggregating and analysis. In a situation where differential sourcesheds are already generated it is possible to calculate total sourcesheds from them very easily with a spreadsheet. The upper right hand quarter of Figure 33 shows an enlargement of Mitchell Creek with 3 sourcesheds for sample site 9, 65, and 63. The differential sourceshed for sample 9 is the grey area in between the two colored areas. The sourceshed for sample 65 is yellow and for 63 its green. The total sourceshed for site 9 is the thick black line that borders all of Mitchell Creek, or essentially the watershed for Mitchell Creek. If data that is collected for site 65 and 63 is added to the site 9 differential sourceshed the data output will be for the site 9 total sourceshed. This is a method that is simple to use with the aid of a spreadsheet and can be done for most situations without redoing the total sourceshed generation for each site.



differential sourcesheds can be combined with the differential sourceshed for site 9 to yield a total sourceshed for site 9.

SOURCESHED APPLICATIONS

There are countless ways to utilize the extreme versatility of sourcesheds. First of all, sourcesheds do not have to be generated for surface water studies. Groundwater sourcesheds have been developed using simulated heads from a regional groundwater flow model. In this unconfined aquifer we were dealing with a system that is strongly influenced by surface water discharges. Thus it was easy to develop sourcesheds in this case because major flow patterns were similar to those of the surface water drainage network. Secondly, sourcesheds don't have to just analyze or visualize the results of field sampling for stream chemistry, they can show where to sample for stream chemistry. Sourcesheds are an extremely powerful tool in this respect because they have the possibility to predict where and when a chemical of interest might be found if a known source point existed. Therefore, the sourceshed will help define a better sampling strategy to detect the occurrence of the chemical. Finally sourcesheds can be linked to other tools to provide an even more powerful tool. For example if a time factor is added to the sourceshed analysis sourcesheds will become dependent upon time. You can have a 10 year, 20 year, 30 year sourceshed for relatively slow systems such as groundwater or you can have 2 hour, 6 hour, 10 hour sourceshed for faster systems such as a surface water system undergoing a precipitation event.

Output from the high-resolution groundwater model can be used to develop spatial sourcesheds for each of potential stream sample sites within the GTBW. Potential stream sample locations can be determined by developing a spatial layer composed of river/stream and road crossings at even interval spacing along river nodes. Two types of sourcesheds could be developed with the land use and groundwater model data, "static"

groundwater sourcesheds and time-varying sourcesheds, thus enabling the definition of regions that drain into stream segments for increments such as 1 year, 5 years, 10 years, and 20 years.

Surface and groundwater sourcesheds can be used to assess the watershed's ecosystem health and studied spatially using ArcView. Each sourceshed (surface and groundwater are evaluated independently) is assigned the value of the absolute concentration of a parameter or concentration ratio of the water sample representing the sourceshed. Both types of sourcesheds are studied because at times during the year the dominant source for stream water changes (e.g., surface and groundwater for high flow and low flow, respectively).

The sourcesheds also provide for modeling the relation of land use to biogeochemical parameters. For example, each sourceshed can be characterized in terms of associated land uses. Results of this analysis could be used to determine if types of land use can be discriminated from one another in terms of the parameters. Interpretations regarding the biogeochemical controls on the data can then be inferred. In addition, the relative importance of the factors in describing the data can be used as an indication of the relative significance of each in controlling systems biogeochemistry.

CONCLUSIONS

Sourcesheds are powerful tools that allow researchers to spatially aggregate data into regions that reflect properties of the watershed of interest. Sourcesheds are more than just polygons, they are the area that contributes to a selected sample location. Therefore they provide researchers with the ability to visualize and analyze point or regional data within the context of possible source region. Overall, sourcesheds reflect the complexity and simplicity of the emerging tools available to researchers working in watershed hydrology.

ARC/INFO FUNCTION DEFINITIONS

FILL <in_grid> <out_grid> {SINK | PEAK} {z_limit} {out_dir_grid}

Arguments

<in_grid> - a grid representing a continuous surface.

<out_grid> - the output grid which has had its sinks filled or peaks cut.

{SINK | PEAK} - keyword indicating whether sinks will be filled or peaks will be cut.

SINK - all sinks which are less than the $\{z_{\text{limit}}\}$ lower than their lowest adjacent neighbor will be filled to the height of their pour point. A sink is a cell with undefined drainage direction; all cells around it are higher. The pour point is the boundary cell with the lowest elevation for the contributing area of a sink. If the sink were filled with water, this is the point where water would pour out.

PEAK - all peaks less than the $\{z_{\text{limit}}\}$ higher than their highest adjacent neighbor will be cut down to the height of that neighbor. A peak is a cell that is higher than all adjacent cells.

 $\{z_limit\}\$ - the maximum difference between a sink and its pour point or a peak and its highest adjacent neighbor. If the difference in z value between a sink and its pour point is greater than $\{z_limit\}\$, that sink will not be filled. If the difference in z value between a peak and its highest adjacent neighbor is greater than $\{z_limit\}\$, that peak will not be removed. The default is to fill all sinks (or remove all peaks) regardless of depth.

{out_dir_grid} - an optional output grid showing the flow direction from each cell of the <out_grid> to the steepest downslope neighbor. The output is the same as that of the FLOWDIRECTION function.

Example Expression: fill DEM DEM fill sink 100 flowdir

FLOWDIRECTION (<surface_grid>, {o_drop_grid}, {NORMAL | FORCE})

Arguments

<surface_grid> - a grid representing an elevation surface.

{**o_drop_grid**} - an optional output grid showing a ratio of the maximum change in elevation from each cell along the direction of flow, to the path length between centers of cells, expressed in percents.

{NORMAL | FORCE} - controls the direction of flow at the edges of the surface grid.

NORMAL - if the maximum drop on the inside of an edge cell is greater than zero, the flow direction will be determined as usual, otherwise the flow direction will be toward the edge. Cells that should flow from the edge of the surface grid inward will do so.

FORCE - all cells at the edge of the surface grid will flow outward from the surface grid.

Example Expression: flowdir = flowdirection (DEM)

FLOWACCUMULATION (<dir_grid>, {weight_grid})

Arguments

<dir_grid> - a grid showing direction of flow out of each cell. This can be created using the FLOWDIRECTION function.

{weight_grid} - the weight to be assigned to each cell. If no {weight_grid} is specified, a default weight of one will be applied to each cell. For each cell in the output grid, the result will be the number of cells that flow into it.

Example expression: flowacc = flowaccumulation (flowdir)

SELECTPOINT (<grid>, <x, y>, {INSIDE | OUTSIDE}) SELECTPOINT (<grid>, <point_file>, {INSIDE | OUTSIDE} SELECTPOINT (<grid>, <point_cov>, {INSIDE | OUTSIDE}) SELECTPOINT (<grid>, <*>, {INSIDE | OUTSIDE})

Arguments

<grid> - an input integer or floating-point grid. The <grid> identifies the cell values which will be selected inside or outside a specified point. The grid can also be created in an expression.

 $\langle x, y \rangle$ - identifies the coordinates of the point to be selected. The coordinates are specified in map units and are in the same units as the $\langle grid \rangle$.

{INSIDE | OUTSIDE} - identifies which cells should be selected, those contained in, or external to, the cell containing the selected point.

INSIDE - a keyword specifying that the cell in which the selected point falls will be written to the output grid. All cells outside the box will receive NODATA on the output grid.

OUTSIDE - a keyword specifying that the cells outside the input box should be selected and written to the output grid. The cell within which the selected point falls will receive NODATA on the output grid. <point_file> - the name of an ASCII text file containing coordinates of points to be selected.
<point_cov> - the name of the input coverage with point topology. The locations and attributes of the points from this coverage will be transferred to the respective cells in the output grid.
<*> - allows for the interactive graphical input of the input point which will be used to identify the

selection criteria. The graphics environment (i.e., the display window and the map extent) must be set. The grid specified by <grid> should be displayed.

Example Expression:

outgrid = selectpoint (DEM_fill, sample_points, INSIDE)

WATERSHED (<dir_grid>, <source_grid>)

Arguments

<dir_grid> - a grid showing direction of flow out of each cell. This can be created using the FLOWDIRECTION function.

<source_grid> - a grid representing cells above which the contributing area, or catchment, will be determined. All cells that are not NODATA will be used as source cells.

Example expression: wsheds = watershed (flowdir, source)

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