International Journal of Geospatial and Environmental Research

Volume 5 | Number 1 Article 4

3-2018

Variation of Groundwater Divides during Wet and Dry Years in the Wolf River Basin, Northeastern Wisconsin

Susan A. Borchardt
University of Wisconsin-Milwaukee, borcha48@uwm.edu

Recommended Citation
Borchardt, Susan A. (2018) "Variation of Groundwater Divides during Wet and Dry Years in the Wolf River Basin, Northeastern Wisconsin," *International Journal of Geospatial and Environmental Research*: Vol. 5 : No. 1 , Article 4.
Available at: https://dc.uwm.edu/ijger/vol5/iss1/4

Variation of Groundwater Divides during Wet and Dry Years in the Wolf River Basin, Northeastern Wisconsin

Abstract

Groundwater divides and surface-water divides do not always coincide, and groundwater divides are not as easy to detect as surface-water divides. Groundwater divides are also dynamic, moving in response to environmental and anthropogenic stresses. This study will investigate how different hydrological stresses can change the size and shape of the study basin and whether the stresses together mitigate or intensify the basin's response. This study looks at three factors that may affect the size and shape of the Wolf River basin: annual precipitation, soil permeability, and the presence of high-capacity wells. This study examined four groundwater basins that represent the groundwater contributing to the baseflow at the stream-flow gauge at Langlade, on the Wolf River in northeastern Wisconsin. The study consisted of two wet years (1985 and 2015) and two dry years (1989 and 2008); the two different time periods represent before and after extensive use of high-capacity wells, pre-1990 and post-2000. The study found an overall lowering of the groundwater elevation, attributed to the hydrological stresses created by both decreases in precipitation and increases in the number of high-capacity wells in the area. The lowering of the water table allowed groundwater flow to follow bedrock topography rather than surface topography leading to increases in the groundwater basin's area. This study highlights that the effects of one hydrological stress (groundwater pumping) can be amplified by another hydrological stress (decreased annual precipitation), resulting in similar numbers of wells having a significantly greater effect on groundwater in dry years than in wet years. This knowledge can help water-resource managers predict basin changes in similar basins.

Keywords

baseflow, groundwater, contributing basin, groundwater divides

Acknowledgements

The author would like to acknowledge the guidance and support of Professor Woonsup Choi at the University of Wisconsin-Milwaukee, who carefully read and copy-edited this manuscript to make sure I followed proper English and grammar. I would like to thank Robert Smail with the Wisconsin Department of Natural Resources for providing GIS well data for this study. I also appreciate Donna Genzmer from the UWM Cartography & GIS Center whose feedback helped to improve the clarity of the GIS maps.

1 INTRODUCTION

Since natural resource managers are increasingly using the watershed as the basis for managing both water supply and quality, it is increasingly important to know the extent of the groundwater basin that is discharging into the surface waters (Winter et al. 2003). Groundwater divides are not as easy to detect as surface-water divides since they are not observable from the surface and they can move in response to both environmental and anthropogenic stresses. Unlike surface water basins, which can change very slowly through time, groundwater basins are more dynamic. Groundwater basins can change in size and shape due to stresses in the hydrological system. Environmental stresses, such as precipitation and temperature changes, can affect the location of the groundwater boundaries. Human activity, such as groundwater withdrawal from irrigation wells, can also create hydrological stresses that cause changes in the size and shape of the groundwater basin. Hutchinson and Moore (2000) suggest that changes in basin size and shape are related to both bedrock contour and the relative depth of the water table. When the water table is low, the groundwater flow will follow the topography of the confining layer, and when the water table is high, the groundwater flow is more likely to follow surface topography (Hutchinson and Moore 2000). This study will investigate how different hydrological stresses can change the size and shape of the study basin and whether the stresses together mitigate or intensify the basin's response.

This study looks at three factors that may affect the size and shape of the Wolf River basin: annual precipitation, soil permeability, and the presence of high-capacity wells. The three variables have been well documented in separate publications, but little has been published on how these variables are related. A previous study (Borchardt et al. 2016) found a relationship between high-capacity wells and declining baseflows in the Wolf River basin; therefore, this study expects to find declining groundwater elevations with an increase in the number of high-capacity wells. The decrease in groundwater elevation is expected to be more profound in years with low annual precipitation. With the expected expansion of the groundwater basin, more high-capacity wells will fall within the groundwater basin boundaries. Increases in groundwater withdrawal can move groundwater divides away from the pumping source (Sheets et al. 2005), furthering basin expansion. Because the regional bedrock surface slopes toward the southeast, this study expects to find that as water table lowers the basin will expand to the northwest (Batten 1987). This study will also investigate if soil permeability affects the movement of the basin boundaries. Resource managers should consider variables outside the surface basin due to the dynamic movement of the groundwater basins. By observing how different stresses affect the basin divides in this study, it may be possible to predict changes in similar basins.

Groundwater divides move, vanish, and reappear with changes in precipitation due to variations in groundwater elevations (Holzbecher 2001). Several studies across the country corroborate Holzbecher's findings. A study in Nebraska examined recharge levels beneath sand dunes (Winter 1986). It was revealed that the groundwater divides moved laterally depending on the amount of precipitation received (Winter 1986). Another study, completed in North Dakota by Winter and Rosenberry (1995), examined groundwater divides between several wetland areas. The study found that during very dry conditions the high point between two of the groundwater basins lowered enough to allow the two separate groundwater basins to merge into one. The result of the merge was that the groundwater flow system contributing to the downhill wetland was significantly enlarged (Winter and Rosenberry 1995). The movement of groundwater divides due to changes in precipitation can alter the area in which high-capacity wells affect the baseflow. High-capacity wells that affect baseflow in a dry year may not affect the baseflow in a wet year after the groundwater divide shifts closer to the surface water. Having a knowledge of the extent of the groundwater basin in both wet and dry years will help to improve water resource planning.

Soil permeability and slope are both variables that control infiltration. Highly permeable soils not only have less runoff potential but also may allow for the easier flow of groundwater. Highly sloped soils have greater runoff potential and lower infiltration. Areas that have little slope and are primarily composed of glacial material may have significantly larger groundwater flow systems than are suggested by the surface topography. The ratio between recharge and hydraulic conductivity can predict if groundwater flow will mimic the surface topography or the subsurface topography according to Haitjema and Mitchell-Bruker (2005). They found a relationship between hydraulic conductivity, topography, and groundwater flow, but the groundwater-basin boundaries were not investigated. Areas with low permeability (~ 10^{-7} m/sec.) are more likely to have groundwater divides that coincide with the surface-water divides (Hinton et al. 1993; Swanson et al. 1988). In both the Swanson and the Hinton studies, the first in North Dakota and the second in Ontario, the groundwater basins are moderately larger than the surface basin. In both studies the topography of the water table has much more relief. This relief in the water table results in more groundwater divides coinciding with surface-water divides suggesting soil permeability has a relationship to the shape of the groundwater basin (Winter et al. 2003). This study will address how soil permeability in combination with hydrological stresses (precipitation and groundwater withdrawal) is affecting groundwater divides in the Wolf River basin.

The third hydrological stress, which has been shown to affect groundwater divides, is that of over-pumping from high-capacity wells. A compilation study of groundwater divides concluded that the groundwater divides in the Great Lakes region have changed over time due to pumping and natural processes (Sheets and Simonson 2006). A study on the effects of high-capacity wells revealed that the stress that high-capacity wells place on the hydrological system can move regional groundwater divides away from the pumping source (Sheets et al. 2005). Feinstein et al. (2004) found that intensive groundwater use has shifted major groundwater divides in southeastern Wisconsin. As early as 1959 high-capacity wells in the Chicago area were causing changes to the groundwater flow patterns in northern Illinois and southern Wisconsin (Sasman and Russell 1960). Changes were also observed in the Chicago area when the annual withdrawal rates of high-capacity wells decreased from 1995-2000. Groundwater elevations increased, and flow patterns changed when surface water was sourced instead of groundwater for municipal use. The use of surface water substantially reduced the need to withdraw groundwater, which reduced the annual withdrawal rate of the high-capacity wells in the Chicago area (Burch 2002). This study will analyze if the effects of groundwater withdrawal are mitigated or exaggerated by variations in annual precipitation.

This study aims to determine the variability of the size and shape of groundwater basins and factors influencing the movement of the groundwater divides. The study focuses on the Wolf River basin in northeastern Wisconsin. Declining mean annual baseflows in the basin over the last three decades suggest that there may also be changes to the groundwater elevations in the basin (Borchardt et al. 2016). The study will analyze groundwater-basin size and shape and the movement of the groundwater divides over different time periods with different annual precipitation totals. The results of the study will be useful in determining what area is contributing to baseflow at the gauging station, potentially extending the area that is used to determine if new high-capacity wells will affect baseflow in the stream.

2 MATERIALS AND METHODS

2.1 Study Area

The size of the Wolf River basin is approximately 380 km^2 and changes in elevation from 297 meters above sea level in Menominee County in the southern portion to 581 meters above sea level in Langlade County in the northern portion. The resulting slope is generally from the northwest to the southeast. Soil in the area is glacial unconsolidated sand and gravel overlying crystalline bedrock (Mickelson 1987). The bedrock surface also slopes from the northwest to the southeast from approximately 457 meters above sea level in northwestern portions of Langlade County to under 335 meters above sea level in the southeastern parts of Langlade County; the regional slope rate is 1.9 to 2.8 m/km (Batten 1987). The bedrock surface was leveled by erosional processes; therefore, it has less topographical relief than the overlying glacial deposits (Batten 1987). The soil is coarse textured and contains a large percent of sand- and gravel-sized particles (Batten 1987; Mickelson 1987). Soil of this type has high permeability (~10^{-5} m/sec) (Anderson and Mickelson 1997). The gauging station at Langlade (United States Geological Survey site 04074950) is located in the middle of the basin. The gauge is at an elevation of 378 meters above sea level. The surface-drainage area contributing surface water to the gauge is approximately 1200 km^2 (USGS 2016b). The contributing basin contains the northern portion of the Wolf River basin and both the Lily River Basin and the Upper Wolf River basin (Figure 1).

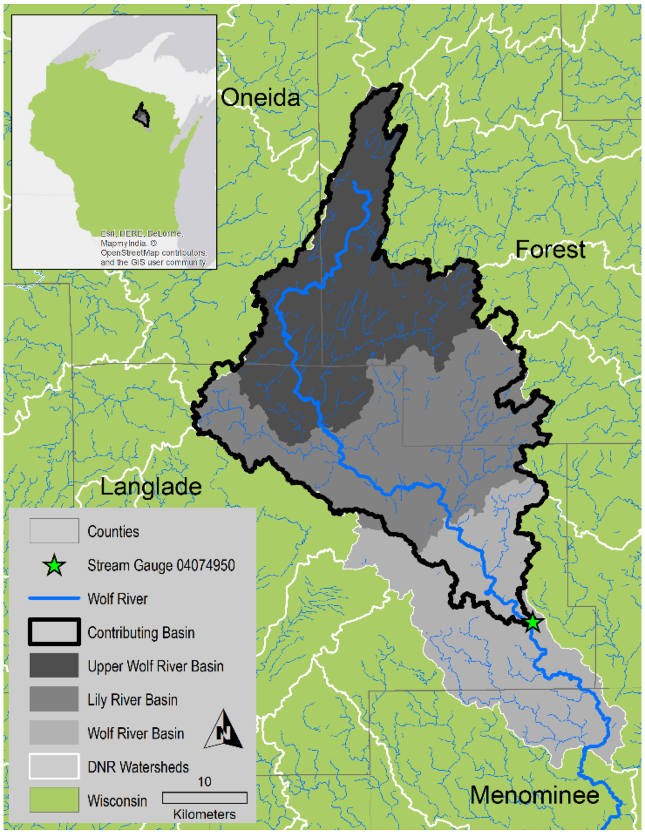

Figure 1. Boundaries of the Wolf River basin and the surface basin contributing runoff to the United States Geological Survey (USGS) gauging station at Langlade. The watershed boundaries were obtained from the Wisconsin Department of Natural Resources (DNR). The insert map of the state of Wisconsin includes the approximate location of the basins.

2.2 Overview of Methods

Four maps of groundwater elevation were created representing two precipitation periods, wet and dry, and two time periods, pre-1990 representing before extensive groundwater pumping and post-2000 to represent after extensive groundwater pumping began. The groundwater-basin maps were constructed using a raster file containing the elevation of the groundwater table. Digital Elevation Model (DEM) files are commonly used with the hydrology tools in ArcGIS to delineate surface-water basins. This study used the same tools to delineate the groundwater divides using a calculated digital elevation of the groundwater table. The elevation was calculated by subtracting the static depth of wells constructed during a 2- to 3-year period from the DEM file. The static depth-point data was first interpolated to raster data with the kriging program in ArcGIS. This was done because both sets of data needed to be in raster format to enable ArcGIS to perform the subtraction. The new static-depth raster file was then subtracted from the DEM data set, which was obtained from the USGS (2016a). The process was repeated for each of the four different time periods.

2.2.1 Static Depth

The static-depth data was obtained from a GIS layer file compiled by the Wisconsin Department of Natural Resources (DNR), containing well-construction data for wells drilled in the state of Wisconsin (Smail, Robert A. email correspondence, 5 October 2016). The data was sorted to contain only data from screened wells during both dry and wet periods. Wells drilled between 1 January 2014 and 31 August 2016 and between 1 January 1984 and 1 January 1986 were chosen to represent the wet years. Wells drilled between 1 January 2007 and 31 December 2008 and between 1 January 1988 and 31 December 1989 were chosen to represent the dry years. Screened wells were used in all years because they are more likely to extend only into the unconfined aquifer and not into the bedrock. Wells drilled in 2014-2016 and 1984-1986 were used because precipitation during these years averaged 15cm and 9cm respectively above the average of 78 cm, and wells drilled in 2007-2008 and 1988-1989 were used because precipitation during these years averaged 15cm and 17cm respectively below the average of 78 cm. (PRISM 2016). PRISM data was used because there is not a weather station in the Wolf River basin. Nearby weather stations White Lake and Antigo have 30-year averages of 80 cm and 74 cm, respectively (https://gis.ncdc.noaa.gov/maps/ncei/normals, last accessed on 9 June 2017).

2.2.2 Kriging

Each set of point data containing the static-depth information was transformed into raster data using the interpolation tool kriging in ArcGIS. 10.4.1 from Environmental Systems Research Institute (ESRI). Kriging weights the surrounding measured values to estimate a value in an unmeasured location using the formula in equation (1) (ESRI 2017):

$$Z(s_o) = \sum_{i=0}^{N} \binom{n}{i} \lambda_i Z(s_i), \qquad (1)$$

where $Z(s_i)$ is the measured value at the ith location, λ_i is the unknown weight for the measured value at the ith location, s_o is the estimation location, and N is the number of measured values. The raster file contains interpolated static-depth data in each raster cell with a resolution of approximately 2 km × 2 km). The static-depth data extends beyond the state of Wisconsin's boundaries, so a shape file of the state was used to clip the data. Since static-depth data is required for each study period, this process was repeated three more times.

2.2.3 Groundwater Elevation Calculation

The new static-depth raster files were then each subtracted from the DEM raster file on a cell-by-cell basis. Since static depth is the measure of the groundwater depth below the surface elevation, the calculation of the groundwater elevation is equal to the surface elevation minus the static-depth measurement. Therefore, the new raster file is the elevation of the groundwater above sea level.

2.2.4 Surface- and Groundwater-Basin Delineation

ArcGIS 10.4.1 was then used to delineate the groundwater basins using the tools within the Hydrology tool set. The Flow Direction tool and the Flow Accumulation tool were used to map groundwater-flow direction; both are hydrology tools within the Spatial Analysis toolset (ESRI). The flow-direction raster and the pour point, created at the location of the gauging station, were used with the Watershed tool to find and delineate the area of groundwater contributing to the stream flow at the gauging station. The tools in the Hydrology tool set typically delineate surface watersheds using a DEM raster file. This study used the groundwater raster calculated from a kriged static-depth raster file subtracted from a DEM in lieu of a DEM to delineate the groundwater basins. The process is repeated four times, once for each study period. Then the area contributing surface water to the gauging station at Langlade was delineated from surface-elevation data obtained from the USGS. The delineation of the surface watershed used the same steps as the groundwater basin. The surface area delineated was 1200 square meters. The delineated area agrees with the area posted on the USGS web site for the Langlade gauging station (site number 04074950, https://waterdata.usgs.gov/).

2.3 Soil Groups

Data obtained from the United States Department of Agriculture (USDA) was used to create a map of the hydrological-soil groups (HSG) in and surrounding the Wolf River basin (Figure 2). HSGs soils are grouped together by runoff potential. Group A soils have low runoff potential and a high infiltration rate, group B soils have a moderate infiltration rate, group C have a slow infiltration rate, and group D soils have a very slow infiltration rate. Figure 2 shows the HSGs in and surrounding the Wolf River basin. Along the southwest groundwater basin divide the soils are type A and B, while soils to the north and northwest are type C and D. Types A and B have a higher infiltration rate (0.38 to 1.27 cm/hour) versus types C and D which have an infiltration rate of (0 to 0.38 cm/hour) (USDA 2016). The texture clay plays a role in each of the textures within both the C and D soil groups. Although the soil map showed soil types of C and D, a review of the soil survey of Langlade County showed no soil groups in the county having a surface layer containing any clay-textured material.

3 RESULTS

Figure 3 shows the area of the groundwater basins in both wet years (1985 and 2015) and dry years (1989 and 2008) compared to the area covered by the surface-water basin. All the contributing groundwater basins have a larger drainage area at 1378, 1385, 1432, and 2436 km^2 than the surface-water basin, which is 1200 km^2. The groundwater divides closely match those of the surface-water divides in all four years along both the southeast and southwest borders. In the northern half of the each of the groundwater basins, the divides extend beyond the boundaries of the contributing basin and include the northern portion of the Wolf River basin and at least two additional basins to the northwest. In the wet years (2015 and 1985) the groundwater divide moves outward to the northwest and inward along the northern-most edge in the later years (Figure 3(a)). In the dry years (1989 and 2000) the groundwater divide remains nearly stationary along both the southwest and northwest edges but extends a far distance to the north in the later years (Figure 3(b)).

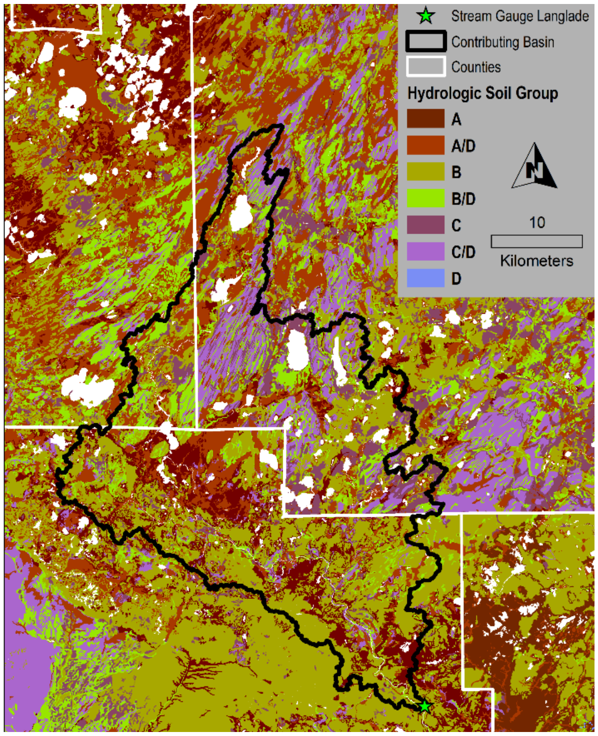

Figure 2. Hydrological soil group data from the United States Department of Agriculture, and the delineated surface area contributing runoff to the gauging station at Langlade.

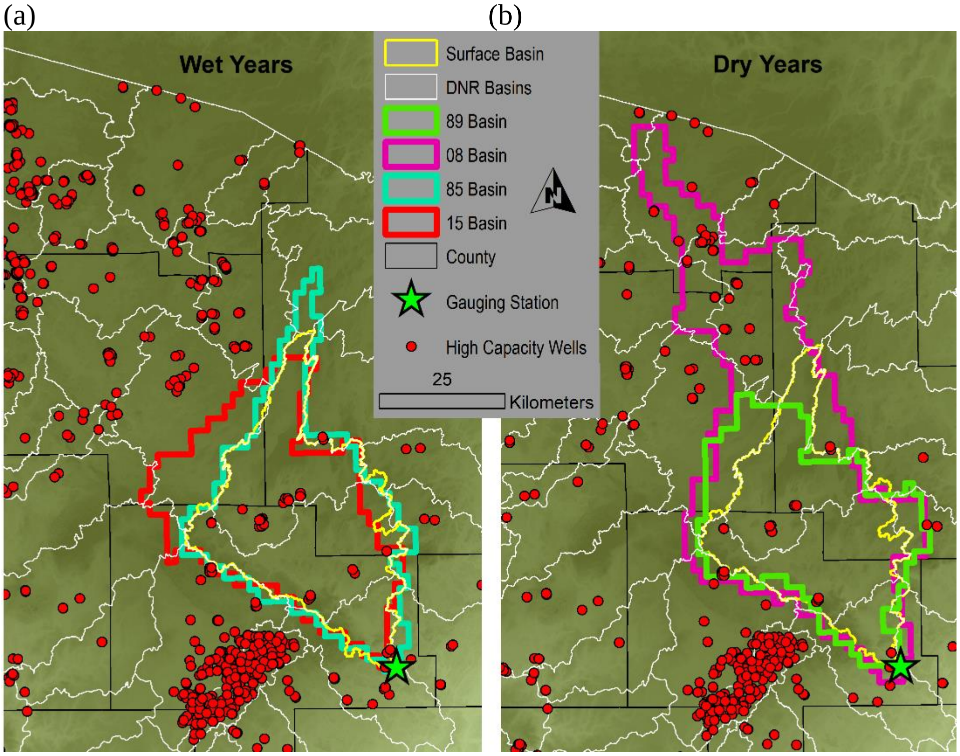

Figure 3. Delineated boundaries of the drainage basins contributing to gauging station at Langlade for (a) wet years (1985 and 2015) and (b) dry years (1989 and 2008).

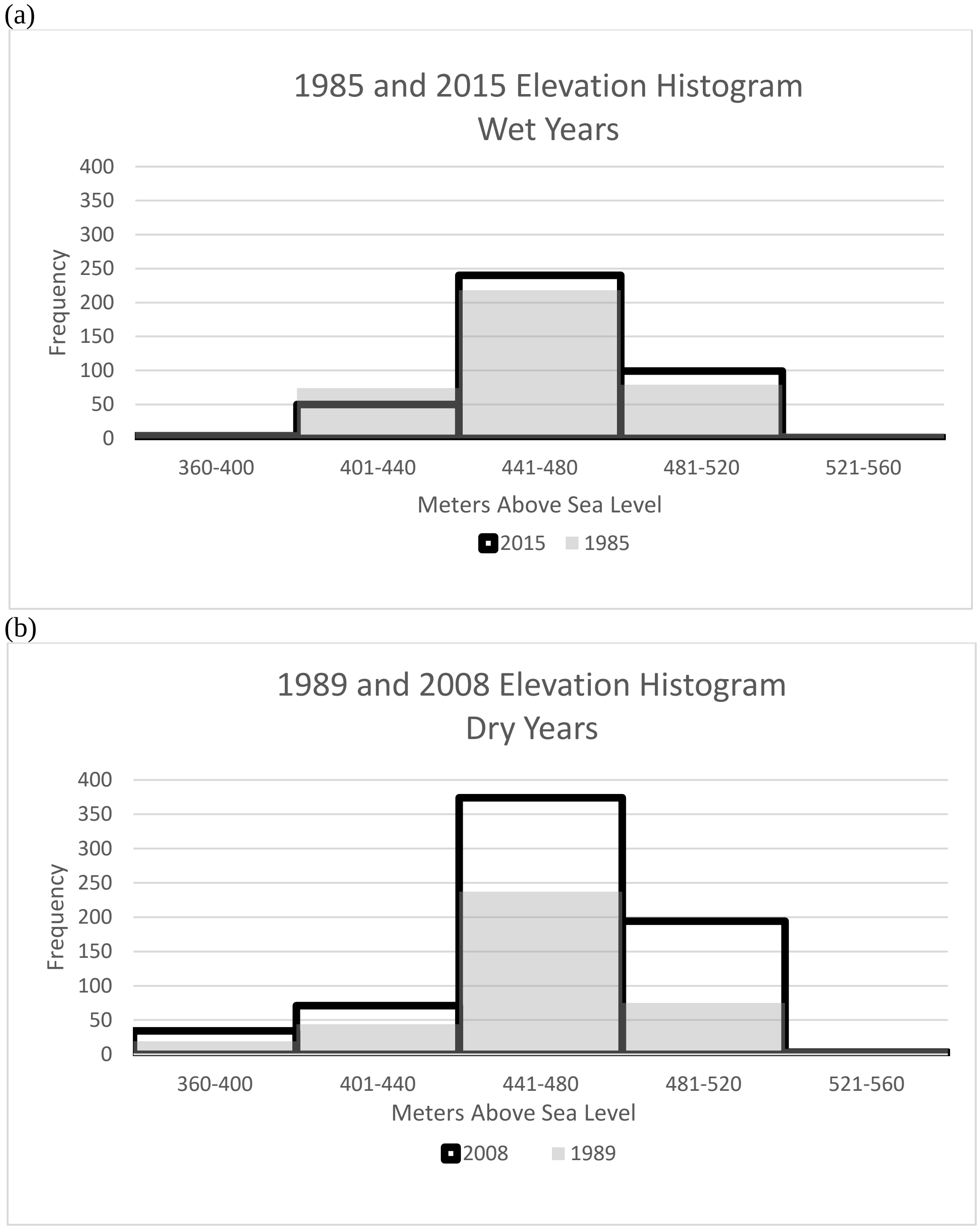

Figure 4. Histograms of groundwater elevation in drainage basin in 2015, 1985, 2008, and 1989

The elevation histograms show that elevation was normally distributed between high, medium, and low elevations in the earlier years (1985 and 1989) while in the later years (2008 and 2015) the relative frequency of high and low elevations had decreased significantly compared to the medium elevations (Figure 4). Both histograms show not only a lowering of the water table in later years but also a flattening of the water table contours. The elevation decreases and the decrease in contour variability is more profound in the dry years (1989 and 2008) than in the wet years (1985 and 2015).

Figure 5 shows that the groundwater flows generally from the northwest where the head is approximately 536 meters above sea level to the southeast of the basin at the gauging station where the groundwater elevation was approximately 374 meters above sea level in 2015. In 1985, the head was 3.75 meters higher, but the elevation of the groundwater at the gauging station was 360.15 meters above sea level, which is 13.43 meters less than it was in 2015. Both 2015 and 1985 were wet years, having an annual precipitation above the average of 78 centimeters (Table 1). Years 2008 and 1989 were dry years having less than the average annual precipitation. The groundwater basin elevation dropped 12.9 meters at the head from 546.9 meters above sea level in 1989 to 534 meters above sea level in 2008. Groundwater elevation similarly dropped at the gauging station between 1989 and 2008 by 8.05 meters from 355.12 meters above sea level in 1989 to 347.07 meters above sea level in 2008. Both wet (1985 and 2015) and dry years (1989 and 2008) saw a greater decline in groundwater elevation at the head of the basin than at the gauging station. Also, of note, the groundwater elevation was already being influenced by high-capacity wells in 1985; this can be seen in the lower elevations surrounding the high-capacity wells within the basin near the three-county intersection (Figure 5(a)). This water-table depression declines in depth in later years but increases in area mainly to the north and northwest.

The decrease in high and low elevations can also be seen in the elevation cross sections in Figure 6. There is a general decrease in elevation of the high points of the groundwater elevation in the later years as compared to the earlier years. The decrease in high-point elevation is related to an increase in groundwater-contributing basin area (Table 1). This area increase is limited to the north and west of the basin. The regional gradient for the groundwater is 0.3 % which agrees with the previous study completed by this author (Borchardt et al. 2016) because the elevations at each end of the transect did not vary as much as the groundwater elevations near the midpoint of the transect (Figure 5). In the wet years (1985 and 2015) the contributing groundwater basin was approximately 1385 km^2 in 1985, and in 2015 it expanded by 3.4% to 1432 km^2 (Table 1). In the dry years (1989 and 2008), the groundwater-contributing basin nearly doubled, expanding 76.8% from 1378 km^2 in 1989 to 2436 km^2 in 2008.

4 DISCUSSIONS

In this study, four groundwater basins were delineated representing the groundwater contributing to the baseflow at the stream-flow gauge at Langlade on the Wolf River, northeastern Wisconsin. The study consisted of two wet years (1985 and 2015) and two dry years (1989 and 2008). The study used groundwater elevations determined by subtracting the interpolated static depths of wells from the surface elevation. The study showed that the groundwater basins all extended beyond the boundary of the surface-water basin and that groundwater divides do not necessarily coincide with surface-water divides. This study showed that the groundwater and surface-water divides generally coincided in the downstream portion of the basin, and that these divides remained steady through time. In the upstream portion of the basin, the divides extend beyond the boundaries of the surface-water basin.

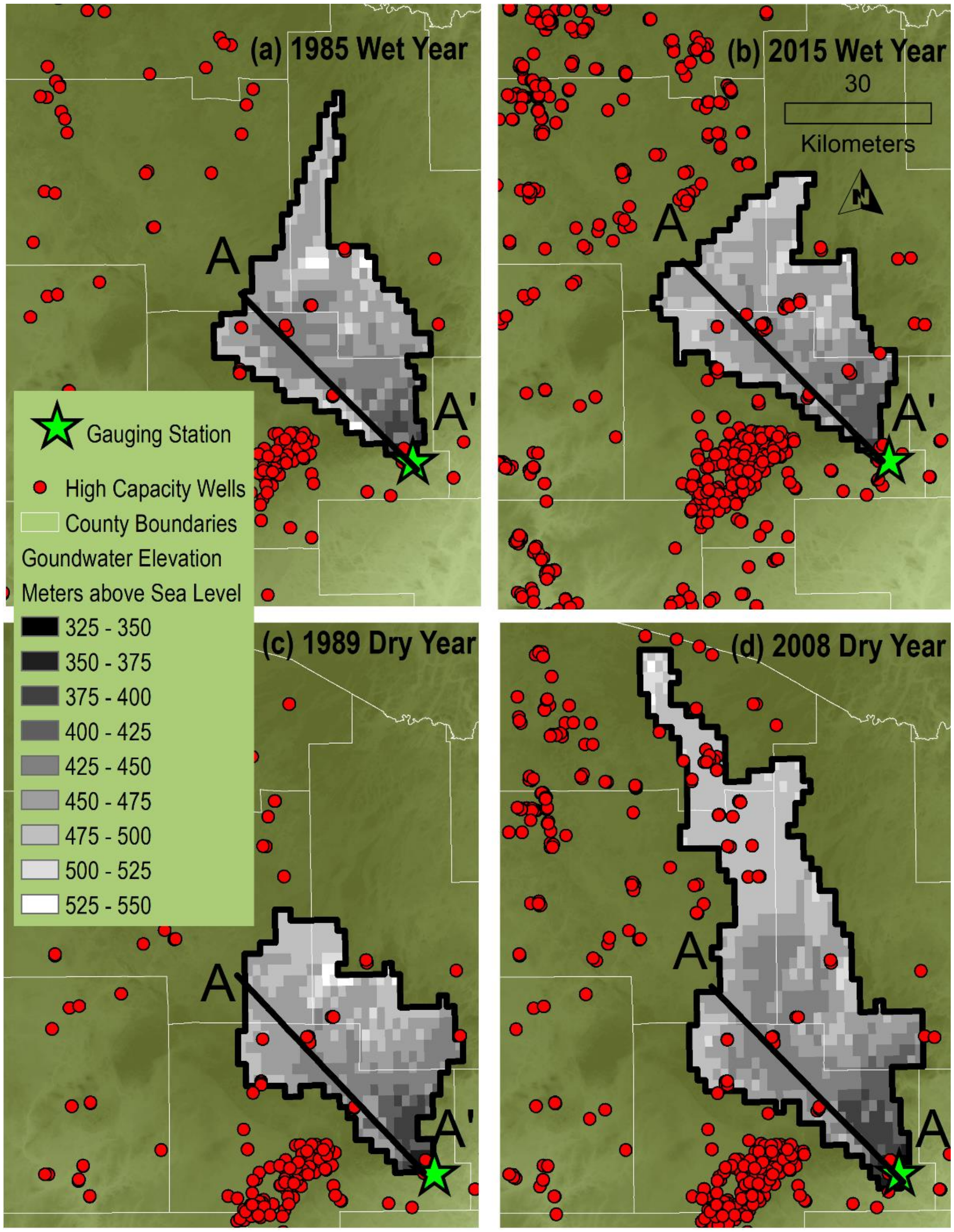

Figure 5. Elevations and boundaries of drainage basins contributing to the stream-flow gauge at Langlade in 1985 (a), 2015 (b), 1989 (c), and 2008 (d) interpolated from static well depths and surface elevations.

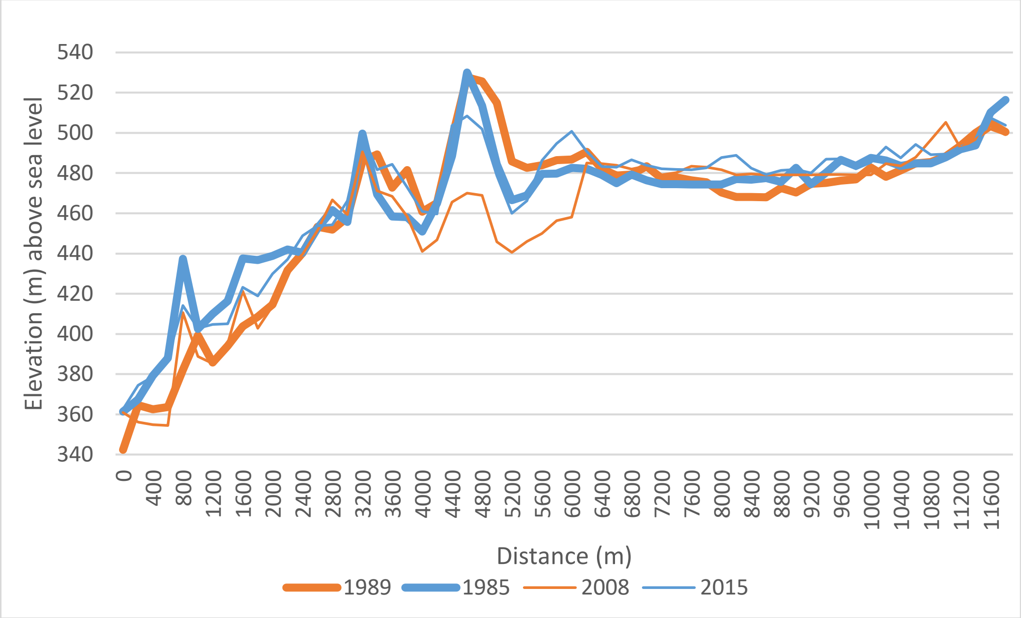

Figure 6. Elevation profile of groundwater aquifer for the transect A-A' from Figure 5 above. Transect represents groundwater elevations over four study years, two wet years (1985 and 2015) and two dry years (1989 and 2008).

Table 1. Area, number of wells within the basin, elevations, average annual precipitation, and annual Growing Degree Days base 10ºC of the drainage basins in the study.

	2015 Surface Drainage	2008 Groundwater Drainage	1989 Groundwater Drainage	2015 Groundwater Drainage	1985 Groundwater Drainage
Area (km^2)	1205	2436	1378	1432	1385
High-capacity Wells	34	75	13	40	12
Low Elevation (m)	381.47	347.07	355.12	373.58	360.15
High Elevation (m)	590.32	534.00	546.90	536.25	540.00
Precipitation (cm)	78	63.27	61.37	92.70	86.98
Growing Degree Days (base 10ºC)	1007	1117	1119	1025	996

The study shows that the divides have changed location in each year studied. This highlights that groundwater divides are not stationary but move in response to hydrological stresses. On the upstream portion of the basin, the divides moved over time. The boundaries in both the wet years (1985 and 2015) and the dry years (1989 and 2008) extended farther in the later year, than in the earlier year. This study is consistent with previous studies (e.g., Cheng 1994; Hunt et al. 1998; LaBaugh 1986; Winter 2003; Winter and Rosenberry 1997) which all revealed that groundwater-basin divides move due to environmental stresses and are often larger than the surface-water basin above. The elevation histograms and the elevation maps (Figures 4 and 5) exhibit decreases in both the high and low elevations. These decreases in high and low elevations flattened the groundwater surface contours presenting fewer but larger groundwater basins. This agrees with the Winter and Rosenberry (1995) study which found a lowering of the high point between two basins allowed them to merge, creating one larger basin. The elevation profile (Figure 6) also represents an overall lowering of the groundwater elevation in the years after the extensive use of high-capacity wells began. When water table levels are low, the groundwater flow is more likely to follow the bedrock topography versus the topography of the surface (Hutchinson and Moore 2000). In the Wolf River region, the bedrock slopes to the southeast. The direction of the groundwater divide movement and expansion is to the north and west of the basin, and this corroborates the work by Hutchinson and Moore (2000).

This study however shows the groundwater divides located in areas of well-drained soil are relatively stationary and the groundwater divides in areas of soil with low infiltration rates are more dynamic. This is contrary to the previous studies noted above. The discrepancy here can be explained by the differences in the surface HSG and the soil or parent material located in the saturation zone. Once water infiltrates past the upper soil horizons, its lateral movement is within the saturated zone. The average depth of the water table is 6-10 meters; soil horizons in the basin only extend 1-2 meters below the surface and lay above moraines to the north, and above outwash plains in the south. The outwash plains contain a greater percent of clay than do the moraines, which accounts for the lack of divide movement along the southern divide. Therefore, this study suggests that the parent material that the groundwater is flowing through is more important in determining groundwater-basin boundary movement, than surface-soil type.

The groundwater-basin boundary along the southwestern edge of the basin did not move significantly, although the number of high-capacity wells to the southwest of the basin have increased dramatically. This fact is contrary to the study completed by Borchardt et al. (2016). This is not to say that the high-capacity wells to the southwest are not affecting the baseflow of streams. The gauging station to the southwest of the wells (USGS 05397500 Eau Claire River at Kelly, WI) has also shown a decline of approximately 27% over the last 30 years (Borchardt et al. 2016). It is possible that high-capacity wells to the northwest of the Wolf River basin are influencing the size and shape of the groundwater basin by lowering the head, allowing more area to the northwest to contribute groundwater flow to the Wolf River, at the gauging station. Wells farther north near the state border with Michigan appear to have no effect on the basin in wet years (1985 and 2015) but may have a significant effect in dry years (1989 and 2008) as seen by the large increase in basin area during the dry years. Further study is warranted to determine how baseflows of streams, environmental stresses, and the dynamics of groundwater divides are interconnected.

5 CONCLUSIONS

This study attempted to investigate if hydrological stresses in the Wolf River basin were affecting the size and shape of the groundwater basin. The study used the static depths of wells drilled over periods 1984-1986, 1988-1989, 2007-2008 and 2014-2016 to create four groundwater elevation maps. The maps were created by subtracting an interpolated groundwater depth raster file from a DEM file. The resulting groundwater elevation maps were then used to delineate groundwater basins. The four basins represent differing hydrological periods, before and after extensive use of groundwater withdrawal, and above and below average annual precipitation.

All four groundwater maps show that the groundwater basins are larger than the surface-water basins. This study also found the impact of the high-capacity wells was greater in the dry years, than in the wet years, as seen by the contributing groundwater basin nearly doubling in size in years (1989 and 2008) versus the 3.4% increase in size seen during the years (1985 and 2015). The impact of the high capacity wells also lowered the water table and flattened the water-table contours. The overall lowering of the groundwater elevation allowed groundwater flow to follow bedrock topography rather than surface topography and enabled the groundwater basin to expand to both the north and to the west. The study also found that, in the Wolf River, basin hydrologic soil type had negligible effect on basin-divide movement. It was determined that surface soil permeability is less related to the movement of groundwater-basin boundaries than the texture of the parent material the groundwater is flowing through. This study highlights that the effects of one hydrological stress (groundwater pumping) can be amplified by another hydrological stress (decreased annual precipitation), resulting in similar numbers of wells having a significantly greater effect on groundwater in dry years than in wet years. This knowledge can help water-resource managers predict basin changes in similar basins.

REFERENCES

Anderson, N., and Mickelson, D.M. (1997) *Variation of hydraulic conductivity in areas of hummocky glacial terrain in northern Wisconsin*. Water Resources Center, University of Wisconsin-Madison.

Batten, W.G. (1987) *Water resources of Langlade County, Wisconsin (No. 58).* Wisconsin Geological and Natural History Survey.

Borchardt, S., Choi, W., and Han, W.S. (2016) High-capacity wells and baseflow decline in the Wolf River Basin, northeastern Wisconsin (USA). *Environmental Earth Sciences*, *75*(16), 1176.

Burch, S.L. (2002). A comparison of potentiometric surfaces for the Cambrian-Ordovician aquifers of northeastern Illinois, 1995 and 2000. *Illinois State Water Survey Data/Case Study 2002-02*.

Cheng, X. (1994). *Numerical analysis of groundwater and lake systems with application to the Trout River Basin, Vilas County, Wisconsin*. University of Wisconsin--Madison.

ESRI (Environmental Systems Research Institute) (2017) http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/minus.htm (last accessed 17 December 2017)

Feinstein, D.T., Hart, D.J., and Krohelski, J.T. (2004) *The Value of Long-term Monitoring in the Development of Groundwater Flow Models* (Vol. 116, No. 3). US Department of the Interior, United States Geological Survey.

Haitjema, H.M., and Mitchell-Bruker, S. (2005) Are water tables a subdued replica of the topography? *Ground Water*, *43*(6), 781-786.

Hinton, M.J., Schiff, S.L., and English, M.C. (1993) Physical properties governing groundwater flow in a glacial till catchment. *Journal of Hydrology*, *142*(1-4), 229-249.

Hutchinson, D.G., and Moore, R.D. (2000) Throughflow variability on a forested hillslope underlain by compacted glacial till. *Hydrological Processes*, *14*(10), 1751-1766.

Holzbecher, E. (2001) The dynamics of subsurface water divides—Watersheds of Lake Stechlin and neighboring lakes. *Hydrological Processes*, *15*(12), 2297-2304.

Hunt, R.J., Anderson, M.P., and Kelson, V.A. (1998) Improving a complex finite-difference ground water flow model through the use of an analytic element screening model. *Ground Water*, *36*(6), 1011-1017.

LaBaugh, J.W. (1986) Limnological characteristics of selected lakes in the Nebraska Sandhills, USA, and their relation to chemical characteristics of adjacent groundwater. *Journal of Hydrology*, *86*(3), 279-298.

Mickelson, D.M. (1987) Pleistocene geology of Langlade County: Wisconsin Geological and Natural History Survey. *Information Circular*, *52*, 32.

NOAA. National Oceanic and Atmospheric Administration (2017) (https://gis.ncdc.noaa.gov/maps/ncei/normals, last accessed on 9 June 2017).

PRISM. High-Resolution Spatial Climate Data for the United States: Max/Min Temp, Dew Point, Precipitation http://prism.oregonstate.edu/comparisons/anomalies.php (last accessed 10 October 2016).

Sasman, W.W.R., and Russell, R. (1960) Water level decline and pumpage during 1959 in deep wells in the Chicago region, Illinois. *Circular* 79, Illinois State Water Survey.

Sheets, R.A., and Simonson, L.A. (2006) Compilation of regional groundwater divides for principal aquifers corresponding to the Great Lakes Basin, United States. *Scientific Investigations Report* 2006–5102. U.S. Department of the Interior. U.S. Geological Survey

Sheets, R.A., Dumouchelle, D.H., and Feinstein, D.T. (2005) Groundwater modeling of pumping effects near regional groundwater divides and river/aquifer systems: Results and implications of numerical experiments. *Scientific Investigations Report* 2005–5141, United States Geological Survey.

Swanson, G.A., Winter, T.C., Adomeitis, V.A., and LaBaugh, J.W. (1988) Chemical characteristics of prairie lakes in south-central North Dakota: Their potential for influencing use by fish and wildlife. *Fish and Wildlife Technical Report* 18, Fish and Wildlife Service, Washington, D.C.

USDA (United States Department of Agriculture) (2016) http://websoilsurvey.nrcs.usda.gov/app/ (last accessed 29 November 2016)

USGS (United States Geological Survey) (2016a) http://viewer.nationalmap.gov/basic/?howTo=true#startUp (last accessed 10 October 2016)

USGS (United States Geological Survey) (2016b) http://waterdata.usgs.gov/usa/nwis/uv?04074950 (last accessed 16 October 2016)

Winter, T.C. (1986) Effect of groundwater recharge on configuration of the water table beneath sand dunes and on seepage in lakes in the Sandhills of Nebraska, USA. *Journal of Hydrology*, *86*(3-4), 221-237.

Winter, T.C., and Rosenberry, D.O. (1995) The interaction of groundwater with prairie pothole wetlands in the Cottonwood Lake area, east-central North Dakota, 1979–1990. *Wetlands*, 15(3), 193-211.

Winter, T.C., and Rosenberry, D.O. (1997) Physiographic and geologic characteristics of the Shingobee River headwaters area. Interdisciplinary Research Initiative: Hydrological and biogeochemical research in the Shingobee River headwaters area, north-central Minnesota: United States Geological Survey*, Water Resources Investigations Research*, 96-4215.

Winter, T.C., Rosenberry, D.O., and LaBaugh, J.W. (2003) Where does the ground water in small watersheds come from? *Ground Water*, *41*(7), 989-1000.