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Douglas S. Cherkauer
Craig J. LaCosse

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CAUSES OF HISTORICAL CHANGES IN GROUNDWATER RECHARGE RATES IN SOUTHEASTERN WISCONSIN

Project Number R/UW-HDG-005

Douglas S. Cherkauer, Professor
Department of Geosciences, University of Wisconsin-Milwaukee

Craig J. LaCosse, Research Assistant
Department of Geosciences, University of Wisconsin-Milwaukee

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BACKGROUND/NEED

Recharge is the process by which rain, snowmelt and surface waters infiltrate to and replenish groundwater. As such, it is the ultimate source of all of our groundwater resources. Yet it is also very difficult to measure, because of its diffuseness. Information on the rates of recharge is usually sparse. To date there has been very little examination of how recharge rates vary through time in response to climatic or land-use changes, making long-term planning difficult for groundwater-dependent communities.

The spatial distribution of recharge in SE Wisconsin was examined during a previous Groundwater Research Program project, showing that it can be quantitatively linked to a number of topographic, hydrogeologic and land-use properties. That work has successfully provided recharge influxes for regional groundwater flow models of southeastern Wisconsin and Fond du Lac County. It has assumed, however, that the recharge rates are static, which they clearly are not. As areas undergo droughts or extended wet periods, recharge undoubtedly varies. As regional or global climate changes, so too will recharge. The question is, how much?

OBJECTIVES

The purpose of this work was to define how recharge rates change through time in response to precipitation changes, to ascertain what factors control that response, and then to develop a mechanism for predicting future recharge changes.

METHODS

Stream baseflow was used as a surrogate measure for recharge. Baseflow is groundwater discharge, so it is equivalent to surface infiltration less evapotranspiration, or net recharge. The use of baseflow opens up the entire USGS streamflow monitoring database as a source of recharge information. There are hundreds of gaging sites in Wisconsin alone, and many have an extensive historical record. Net recharge was obtained for 14 study watersheds in SE Wisconsin using stream baseflow separation (with the USGS HYSEP program).

For each of the watersheds, precipitation and temperature were obtained using Thiessen polygon weighting of daily values from nearby NOAA weather sites. A 34-year time period (1963 through 1997) was selected for analysis. In addition, measures of topography (surface slope, watershed area and shape, among others), hydrogeology (depths to water table and rock, water table gradient, composite subsurface transmissivities and porosities), and land cover (natural, developed, and agricultural) were obtained using GIS databases.

The procedure used was to determine what factors control the baseflow/recharge response to precipitation change in southeastern Wisconsin, which has relatively uniform geologic conditions. Then these relations were tested on another 14 watersheds distributed throughout Wisconsin to ascertain whether they are universal. These test watersheds were selected to include very different bedrock and surficial geology from that in southeast Wisconsin.

RESULTS/DISCUSSION

Time series data (precipitation, temperature, baseflow) were plotted as cumulative departures from average conditions. During the study period, most of Wisconsin experienced drier than normal conditions from 1963 to 1971. The period 1971 to 1993 was wetter than average, and from 1993 to 1997, precipitation dropped below normal again. Baseflow in some watersheds in southeastern Wisconsin follows the precipitation trend almost identically; precipitation 20% below normal produces baseflow/recharge 20% below normal. In other watersheds, the baseflow response is smaller than the precipitation change, and in a few urbanized watersheds, baseflow and precipitation appear almost unrelated.

The rate of baseflow/recharge change with respect to precipitation change (dQ/dP) was compared to all the independent controlling factors for the study watersheds. It was found that dQ/dP is directly related to the product of land surface slope and length of overland flow (S*L), which explains 74% of the observed variation. No other factor or combination thereof (including temperature) showed any significant relation to dQ/dP. When the observed relationship was used to calculate dQ/dP for the 14 test watersheds, it explained 75% of the variance in all areas except the unglaciated southwest.

CONCLUSIONS/IMPLICATIONS/RECOMMENDATIONS

The temporal variation of recharge in Wisconsin is controlled directly by the temporal variation of precipitation. In areas of steep slopes, or where water must travel a long distance before it enters a main channel (often regions with less-developed drainage networks or very permeable soils), the response is essentially 1:1. In areas where slopes are gentle and/or main channels are more closely spaced, recharge changes at only a fraction of the rate of change of precipitation.

The relation uncovered is valid for all of Wisconsin except the Driftless Area. We do not have an explanation for its failure there. However, in glaciated areas, the relation can be coupled with climate change projections to give communities a handle on how much their groundwater supply is likely to change in the foreseeable future.

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INTRODUCTION

With the exception of the large urban areas located on Lakes Michigan and Superior, all other residents of Wisconsin rely solely on groundwater as their source of drinking water. Proper management of the groundwater resource requires understanding the magnitude and distribution of recharge, its primary source.

Recharge varies in both space and time. Previous work by the PI has shown that the spatial variation of recharge in southeastern Wisconsin is determined by a number of climatological, hydrogeological, topographical and land use characteristics as follows (Cherkauer, 2003):

$$R/P = 0.085\{(K/(S\,D^{0.3}))\} - 4.18\{D_w/(A_d/(2\,L_c))\} + 0.0025\,(N) + 0.022 \qquad (1)$$

where:
- R = net recharge (cm/yr),
- P = total annual precipitation (cm/yr),
- K = vertical hydraulic conductivity of the surface soil (cm/hr),
- S = average hillslope in a watershed (m/m)
- D = portion of the watershed which is developed (%),
- D_w = average depth to the water table (m),
- A_d = drainage area (m^2),
- L_c = length of the main channel in a watershed (m), and
- N = portion of the watershed which has natural land cover (%).

The recharge rates used to develop this relationship were derived by separating baseflow (groundwater discharge) from total streamflow in 11 small watersheds. They were selected as having conditions where recharge and baseflow are the sole inflows and outflows, respectively, for the groundwater system. In those watersheds, recharge rates vary directly with the amount of precipitation, soil permeability, the average length of overland flow to a channel and natural land cover. They vary inversely with surface slope, depth to the water table and developed land use. The relation has been successfully tested at watersheds throughout southeastern Wisconsin using a variety of alternative methods for determining recharge (Cherkauer and Ansari, 2003). It has been used successfully to provide recharge inputs to large scale groundwater flow models for the southeastern counties of Wisconsin as well as Fond du Lac County.

Of the factors which control recharge rates in equation 1, only precipitation and land use should change on a time scale of decades. Expressing equation 1 in terms of normalized recharge rates (R/P = relative rate of recharge per unit precipitation) only partially accounts for the effect of changing precipitation. Changes in recharge rates through time need to be understood for resource management purposes.

OBJECTIVES

The purpose of this project then was to determine: 1) how recharge rates have changed through time in southeastern Wisconsin, 2) how those changes have related to precipitation changes, 3) what factors influence the transformation of precipitation to recharge within the watersheds, and 4) to develop a mechanism for predicting how groundwater recharge should respond to possible future changes in precipitation (either in response to periodic, short-term variability or to long-term climatic change).

METHODS

Operating premise

In order to quantify the historical changes in recharge rates and determine what has controlled them, a historical record is necessary. The best available record is that from the network of gaging stations operated by the US Geological Survey. These stations provide essentially continuous records of streamflow over decades. Because baseflow (groundwater discharge to the stream) can be distinguished from total discharge by stream hydrograph separation, these stations provide a reasonable measure of groundwater flux out of each gaged watershed. In watersheds where other groundwater influxes and effluxes are minimal, and where stored volumes remain relatively constant through time, annual baseflow can serve as a surrogate measure of annual groundwater recharge. As no other record of historical recharge exists, baseflow has been used to quantify recharge in this study. In the study, annual recharge rate is defined as the annual total baseflow discharge per unit drainage area.

Watersheds included in the study had to have:

1. A gaging station with historical daily records for the period 1960 to 1996.
2. Drainage areas between 10 and 200 km^2,
3. Minimal natural or artificial water transfers across their drainage divides, and
4. Limited reservoir or lake storage above the gage.

The first criterion was to maximize the number of available stations with contemporaneous records. It was necessary to include some watersheds with shorter records in order to have coverage in urban areas. The second criterion allows comparison of this study's results to those of the spatial study described above (Cherkauer and Ansari, 2003), and the last two allow equating recharge rates to baseflow per unit drainage area. Using these criteria, 14 watersheds in southeastern Wisconsin were selected as the primary study sites (Table 1).

The relation of historical recharge rates to precipitation and watershed topography, hydrogeology and land use has been developed for these primary watersheds. A set of 14 test watersheds have been selected elsewhere in Wisconsin to determine whether the observed relations can be extended to other geologic regimes.

Data Acquisition

Baseflow has been separated from total streamflow for each year of record at each study gaging station using the program HYSEP (Sloto and Crouse, 1988). The program automates the hydrograph separation process and has been shown to compare well with manual methods (Sloto and Crouse, 1988). It has been used in its local minimum mode, which is believed to produce a relatively conservative measure of baseflow whose variation across the period of record is internally consistent.

For the primary study watersheds, precipitation data were assembled from 17 NOAA stations in southeastern Wisconsin and another two in northern Illinois. Missing daily precipitation values at a station were reconstructed from adjoining sites (LaCosse, 2003), and the average monthly and annual precipitations for each study watershed were calculated using Thiessen polygon spatial weighting.

Table 1 Location and geology of primary study watersheds.

Watershed	Latitude	Longitude	Dominant Soil	Dominant Glacial Till	Dominant Topmost Bedrock
Bark River	N42:57:37	W88:40:14	sand	New Berlin/Horicon	Sandstone
Cedar Creek	N43:19:23	W87:58:43	loam	New Berlin	Dolomite
Upper Fox River	N43:00:17	W88:14:37	loam	New Berlin	Dolomite
Kinnickinnick River	N42:59:51	W87:55:35	clay	Oak Creek	Dolomite
Menomonee at Falls	N43:10:22	W88:06:14	loam	Oak Creek	Dolomite
Menomonee at Tosa	N43:02:44	W87:59:59	loam	Oak Creek	Dolomite
Mukwonago	N42:51:24	W88:19:40	sand	New Berlin	Dolomite
Oak Creek	N42:55:30	W87:52:12	clay	Oak Creek	Dolomite
Pike River	N42:38:49	W87:51:38	loam	Oak Creek	Dolomite
Root Near Franklin	N42:45:05	W87:49:25	clay	Oak Creek	Dolomite
Root Near Racine	N42:48:55	W87:59:40	clay	Oak Creek	Dolomite
Root River Canal	N42:52:25	W87:59:45	clay	Oak Creek	Dolomite
Turtle River	N42:35:50	W88:49:45	loam	Walworth/Zenda	Sandstone
Underwood	N43:03:17	W88:02:46	loam	Oak Creek	Dolomite

For each of the study watersheds, digital elevation models with 30 meter horizontal resolution and the Wisconsin DNR's Geodisk 3 GIS data set were used to calculate the following attributes: drainage area; the average elevations of the ground surface, the water table, and the bedrock surface; the dominant soil type; the average effective vertical hydraulic conductivity of the surface soils; average ground surface slope; and the distribution of land cover. In addition, the average elevation of the base of the shallow (Silurian) groundwater aquifer was obtained from relevant geologic maps and cross sections. For the purposes of this study, land cover has been separated into four large categories: agricultural, open water (lakes and ponds), developed (residential, industrial, commercial, transportation and quarries), and natural (woodlands, wetlands and parks). Details on the measurement of these attributes can be found in LaCosse (2003).

Interpretation

One problem with using stream baseflow as a surrogate measure of recharge is that the two do not occur simultaneously. When the ground is unfrozen, recharge can occur in immediate response to rainfall or snowmelt whenever soil moisture deficiencies are met. In contrast, snow falling on frozen ground may accumulate and not generate recharge for weeks or months. In either case, once the recharge does occur, there can be a finite lag time before it appears in the nearest stream as baseflow. Therefore it is inappropriate to assume that a given year's baseflow was identically that same year's recharge.

To overcome this problem, analysis has been conducted on the cumulative deviations of annual precipitation and baseflow from long-term average values. They allow rapid identification of wet, dry or normal periods. They also readily allow determination of how baseflow responds to changes in precipitation during these periods.

RESULTS

Attributes of primary study watersheds

Table 2 provides the properties of each of the primary study watersheds. They cover the full spectrum of conditions present in the study area. The same information has been collected on the secondary, test watersheds (LaCosse, 2003).

Interpreting cumulative deviation plots

Figure 1 shows representative cumulative deviation plots for both annual precipitation and baseflow through the study period. The precipitation plot, for example, is developed by taking the difference between a given year's precipitation and subtracting from it the average annual precipitation for the study period. If annual precipitation is below normal, a negative deviation will result. These annual deviations are then cumulated for the entire study period. Periods where precipitation fell below normal for a number of years then plot with negative slopes, while wetter than normal periods have positive slopes and normal periods are horizontal.

Table 2A Topographic and hydrogeological properties of primary watersheds.

Watershed	Drainage Area (km2)	Length Channel (km)	Average Length Overland (km)	Average Surface Slope	Effective K Soil (m/day)	Depth to Water (m)
Bark River	304.5	77.7	1.96	0.030	4.03	9.5
Cedar Creek	314.3	48.0	3.27	0.014	1.70	8.3
Upper Fox River	326.7	35.9	4.55	0.029	1.42	8.4
Kinnickinnick River	56.3	12.4	2.27	0.020	0.28	12.3
Menomonee at Falls	89.1	18.9	2.36	0.024	1.26	3.4
Menomonee at Tosa	316.7	43.2	3.67	0.025	0.73	10.1
Mukwonago	210.2	36.1	2.91	0.035	3.75	14.9
Oak Creek	63.4	22.3	1.42	0.019	0.19	10.6
Pike River	111.7	29.2	1.91	0.017	0.77	11.0
Root Near Franklin	127.1	40.0	1.59	0.026	0.19	17.4
Root Near Racine	485.7	85.9	2.83	0.021	0.43	14.6
Root River Canal	151.8	37.6	2.02	0.020	0.22	14.1
Turtle River	575.9	51.8	5.56	0.019	1.12	10.4
Underwood	48.7	15.2	1.60	0.027	1.16	16.2

Table 2B Land cover and recharge response properties of primary study watersheds.

Watershed	Land Cover (percentage)				Response Type	Average dQ/dP
	Agric.	Devel'd	Natural	Open Water		
Bark River	0.390	0.153	0.354	0.103	A	0.58
Cedar Creek	0.569	0.079	0.284	0.068	A	0.73
Upper Fox River	0.200	0.396	0.275	0.129	A	1.18
Kinnickinnick River	0.004	0.884	0.109	0.003	C	0.14
Menomonee at Falls	0.372	0.291	0.281	0.056	A	0.33
Menomonee at Tosa	0.204	0.523	0.242	0.031	A	0.72
Mukwonago	0.384	0.162	0.363	0.090	A	0.74
Oak Creek	0.122	0.589	0.154	0.021	B	0.18
Pike River	0.628	0.194	0.160	0.018	B	0.29
Root Near Franklin	0.121	0.560	0.288	0.031	B	0.44
Root Near Racine	0.530	0.212	0.224	0.033	B	0.31
Root River Canal	0.773	0.051	0.151	0.025	B	0.44
Turtle River	0.758	0.110	0.105	0.027	A	0.85
Underwood	0.015	0.644	0.313	0.028	C	0.43

The same process is followed for annual baseflows. Both plots will terminate at a cumulative deviation of zero. The only significance to the starting position of a given plot is that it shows the value of the first year's deviation; if the first year is drier than normal, the precipitation plot will start below zero as in Figure 1.

Because the watersheds occur across a broad study area, the precipitation which fell on them in the study period should be considered site specific. It would be inappropriate to compare the temporal variation of baseflows among the study

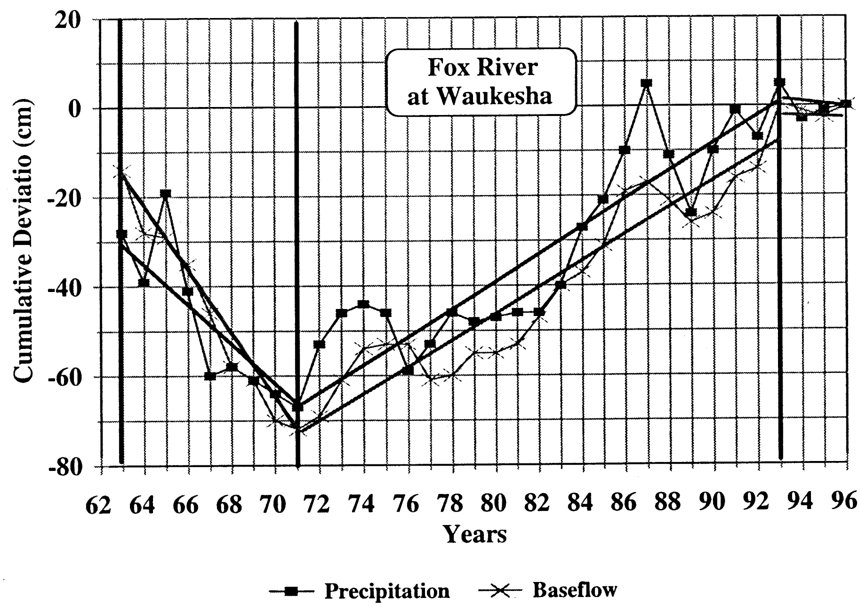


Figure 1 Cumulative deviations in annual precipitation and baseflow for the Fox River. Heavy lines in graph show

inferred trends. Vertical bold line mark changes in historical trends.

watersheds, because the historical precipitation they received could be entirely different. It is clear from Figure 1, however, that the baseflow response does show a direct reaction to precipitation. In periods of below normal precipitation (negative slope on Figure 1), baseflow is also below normal. The objective of this study is to determine the relation of the baseflow response to the precipitation variation and what hydrogeologic, topographic and land cover conditions control that relation.

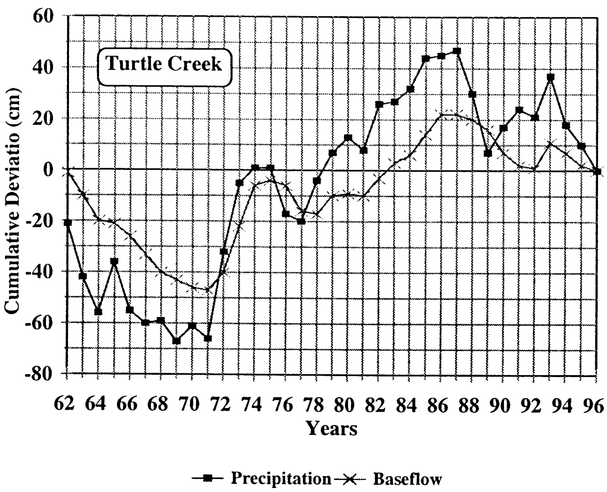
To achieve this goal, the cumulative deviation plots have been broken into distinct, broad periods of greater than, less than and normal precipitation. For the Fox River example (Figure 1), precipitation was below normal for the first eight years of the study period. This was followed by 22 years during which precipitation was dominantly greater than normal, and then by three years of essentially normal precipitation. There are certainly variations of slope in the precipitation line during these periods, but the decision was made to focus on the broader trends, not short-term variations of a few years duration. The baseflows separated from flow hydrographs cannot be resolved to a finer time period than a year, and it is not clear how long it takes precipitation to become baseflow in any given watershed. Using just the longer duration phenomena on the deviation plots avoids pushing the threshold of this limited resolution.

Once the precipitation periods were defined (separated by the heavy vertical lines on Figure 1), the rates of change through time of precipitation and baseflow (dP/dt and dQ/dt, respectively) were measured as the average slopes of the two deviation plots. The average rates of change for all the precipitation periods in each watershed were then calculated. The relation between the two rates is then expressed as their ratio (dQ/dP) (Table 2). If baseflow variation follows precipitation variation closely, dQ/dP will approach +1. If there's no relation, the ratio will approach 0. Once the dQ/dP values are defined, the objective is to determine what controls the ratio.

Baseflow response to precipitation change

In the primary watersheds, the rate of change of baseflows with respect to changes in precipitation shows three different responses. Seven of the watersheds show nearly parallel cumulative deviation plots for precipitation and baseflow (Figure 2). In other words, temporal changes in precipitation produce nearly identical changes in recharge and thus baseflow.. These watersheds have been designated Group A (Table 2) and their baseflows are highly sensitive to climatic changes through time. The resultant dQ/dP is very close to 1.0 in them. These watersheds mostly have their headwaters in the Kettle Moraine of southeastern Wisconsin, where soils and underlying glacial sediments have relatively high hydraulic conductivity and where ground surface slopes are high. Most then flow into areas where both the hydraulic conductivity and surface slopes decrease.

Another five watersheds (Figure 3) have a muted baseflow response. Temporal changes in precipitation of the same magnitude as observed in the Group A watersheds produce much smaller responses in recharge and baseflow. Labeled Group B (Table 2), baseflow in these watersheds is less sensitive to climatic changes, and their dQ/dP ratios are much closer to 0 than to 1.0. These watersheds all lie close to Lake Michigan and are underlain by clay-dominated glacial tills and soils, both of which have relatively low hydraulic conductivity.



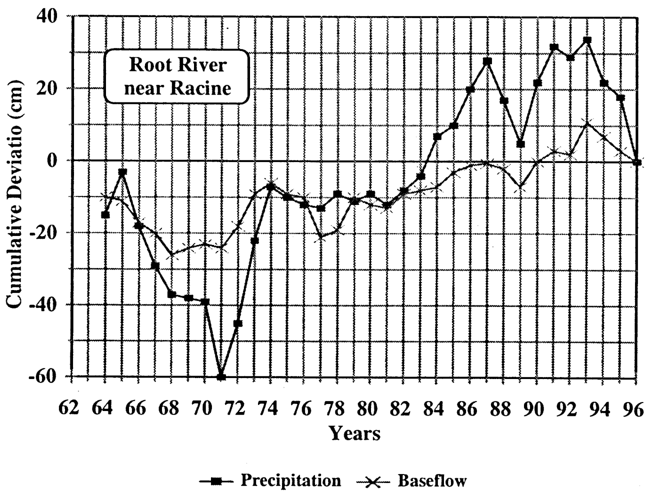


Figure 2 Type A watershed response:

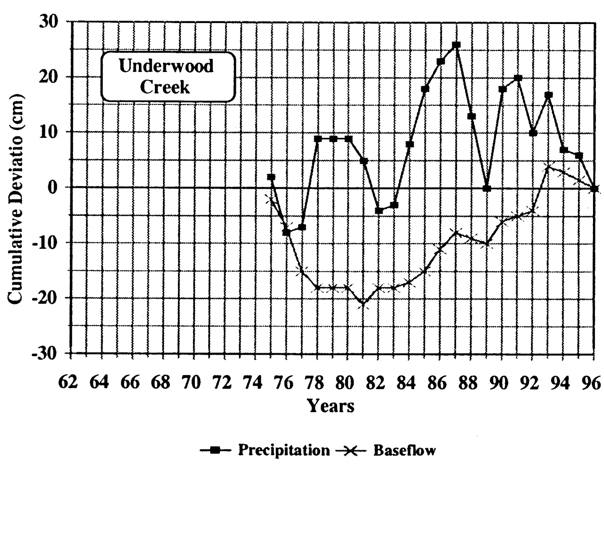
Cumulative deviation in baseflow closely parallels that of precipitation.

Figure 3 Type B watershed response:

Cumulative deviation in baseflow is a muted parallel to that of precipitation.

The remaining two primary watersheds exhibit entirely anomalous responses (Figure 4). In both there are significant periods of time when cumulative baseflow is increasing while precipitation is below normal (Years 1978 through 1981 on the Kinnickinnick and 1977 through 1978 on Underwood, Figure 4). The dQ/dP ratios on these watersheds are generally much less than 1.0 and can even be negative (as for the periods cited above). Both these Group C watersheds are heavily urbanized, which means they have an artificial drainage system imposed on them that probably diverts much of the precipitation away from its natural infiltration pathway to groundwater recharge. Both watersheds also have shorter periods of streamflow record than the other study sites, although this is not believed to be the cause of their unusual behavior.

Figure 4 Type C watershed responses. Both sites are urbanized and have cumulative baseflow deviations which exhibit little relation to changes in precipitation.



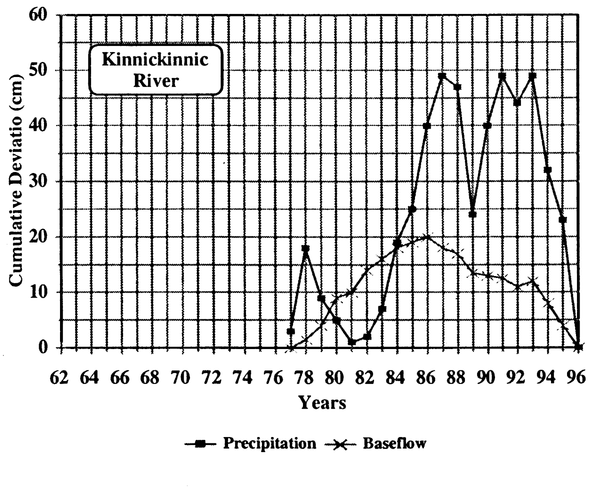
Identifying controls on transfer of precipitation to recharge and baseflow

Table 2 shows that there is a wide range of dQ/dP ratios within southeastern Wisconsin. They show no obvious relation to location, general morphology, or underlying glacial or bedrock geology. The three response types separate into different populations on plots of dQ/dP against the primary independent variables listed in Table 2 (Figure 5, for example), but no overall pattern was discerned. Factors which exert control on the temporal response of baseflow/recharge to precipitation changes should reduce (or eliminate) the scatter on plots like Figure 5. Ideally, it would work for all three response types.

Each of the independent variables listed in Table 2 and many combinations of them were tested (LaCosse, 2003). Analysis was restricted to these properties because: 1. they are those that have been shown to influence recharge (equation 1), and 2. they are readily measurable and thus useful in extrapolating results to other watersheds. Particular attention was paid to the dimensionless combinations of variables identified in equation 1. The analysis identified no individual topographic, hydrogeologic or land use parameters which could explain the observed variation of dQ/dP (LaCosse, 2003). It did demonstrate, however, that the product of hillslope and the average length of overland flow could account for 74% of that variability (Figure 6).

Figure 5 Absence of any obvious relation of dQ/dP to hydraulic conductivity

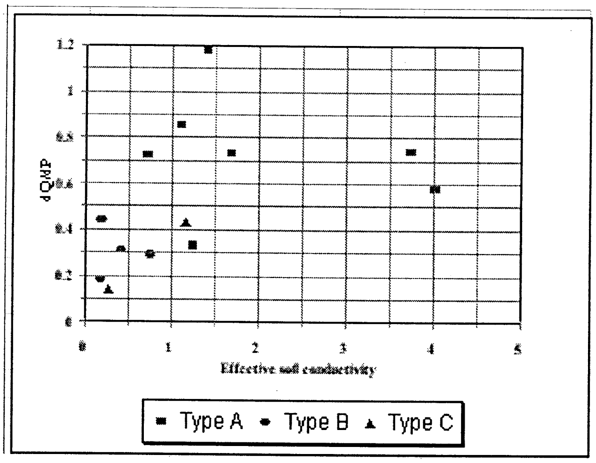
Figure 6 Relation of dQ/dP to the transfer function $S*L_{of}$

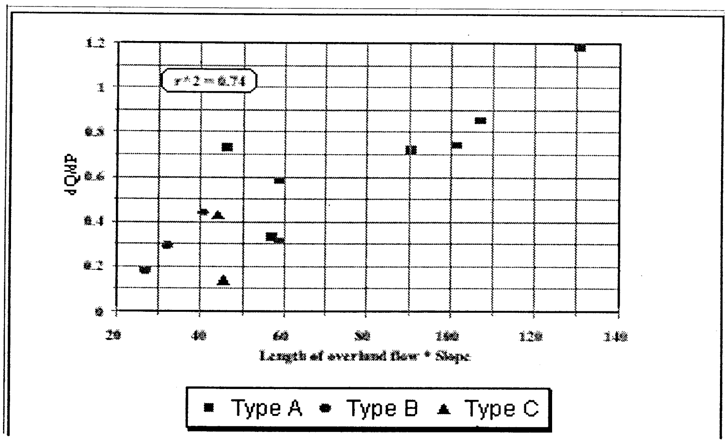


The relation can be expressed as:

$$dQ/dP = 0.0086 (S * L_{of}) - 0.031 \quad (2)$$

where: dQ/dP = the ratio of the change in baseflow to the change in precipitation per year,
S = average ground surface slope in the watershed (derived from digital elevation data)
L_{of} = average length of flow to the main channel in the watershed.





L_{of} has been calculated by conceptualizing the watershed as a rectangle with the long dimension being the length of the main channel and the short being twice the length of overland flow. So,

$$L_{of} = A_d/2L_c \quad (3)$$

where: A_d = the watershed's drainage area and L_c = the length of the main channel.

This conceptualization of the watershed shape is obviously a great simplification, but it does provide a first order value for L_{of}. LaCosse (2003) investigated a wide range of watershed shape measures to determine whether that factor might influence dQ/dP. In short, he found no shape measure which had any significant relation, nor any which improved upon the L_{of} from equation 3 as a predictor of dQ/dP.

The factor $S*L_{of}$ should be viewed as a transfer parameter which expresses how baseflow/ recharge responds to temporal variations in precipitation. Rearranging and expanding equation 2 produces:

$$dQ/dt = 0.0086 \{dP/dt (S * L_{of})\} - 0.031 (dP/dt) \quad (4)$$

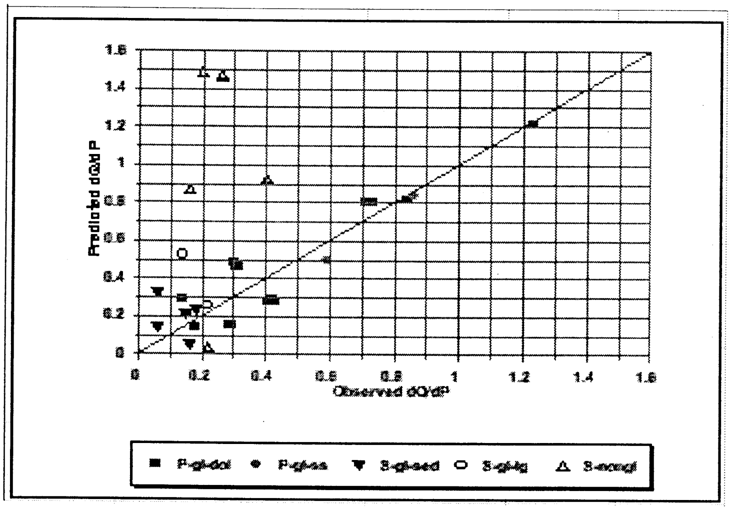
The $S*L_{of}$ parameter is a measure of how a given watershed transforms precipitation into recharge and then baseflow. Watersheds where water must travel long distances before reaching the main channel (L_{of}) and which have relatively steep ground surfaces (S) have recharge rates which are most responsive to changes in precipitation. It's believed that within the study area, the greater the surface slope measured from GIS the more frequent are local topographic lows that can serve as foci for depression focused recharge, particularly in glaciated areas. It's important to note that despite the apparent role of soil conductivity in defining the response types observed (Figures 2 to 4), it could not explain the observed variation in dQ/dP in the study watersheds.

Testing of the observed relation

Equation 2 was used to calculate what dQ/dP ought to be in both the study (primary) and test (secondary) watersheds (Table 3, Figure 7). The test of its viability will be how it performs in the test watersheds (those not used in its derivation). In seven other watersheds in glaciated parts of Wisconsin, the relation reproduces the observed dQ/dP reasonably well (Figure 7, Table 3). It works equally well for watersheds underlain by various rock types (carbonate or clastic sediments or igneous rocks; Table 3).

Figure 7 Comparison of observed and calculated values of dQ/dP.
Calculations done with equation 2. In the legend P indicates primary (study) watersheds and S is secondary (test).

Gl means glaciated, while dol, ss, sed and ig indicate underlain by dolomite, sandstone, sedimentary and igneous rock, respectively.



It does not work in non-glaciated watersheds (Figure 7). This suggests that the relation between ground slope and the transfer to precipitation to recharge is not the same as in glaciated areas. Determining what might cause this discrepancy is beyond the scope of this report.

Table 3 Observed and predicted dQ/dP for study watersheds across Wisconsin.

USGS Station ID	Station Name	Surficial Geology	Dominant topmost bedrock	Predicted dQ/dP	Observed dQ/dP	Error (P-O)/O
	Primary watersheds					
04086500	Cedar Creek	Glacial	dolomite	0.808	0.73	0.107
05543830	Fox River At Waukesha	Glacial	dolomite	1.211	1.23	-0.015
04087159	Kinnickinnick River	Glacial	dolomite	0.297	0.14	1.119
04087030	Menomonee River at Falls	Glacial	dolomite	0.808	0.71	0.138
04087120	Menomonee River at Tosa	Glacial	dolomite	0.460	0.31	0.484
05544200	Mukwonago River	Glacial	dolomite	0.819	0.84	-0.025
04087204	Oak Creek	Glacial	dolomite	0.144	0.18	-0.199
04087257	Pike River near Racine	Glacial	dolomite	0.155	0.29	-0.465
04087240	Root River at Racine	Glacial	dolomite	0.482	0.3	0.606
04087233	Root River Canal	Glacial	dolomite	0.275	0.43	-0.361
04087220	Root River near Franklin	Glacial	dolomite	0.286	0.41	-0.303
04087088	Underwood Creek at Tosa	Glacial	dolomite	0.297	0.42	-0.294
05426250	Bark River	Glacial	sandstone	0.493	0.59	-0.165
05431486	Turtle Creek near Clinton	Glacial	sandstone	0.841	0.86	-0.022
	Secondary watersheds					
04085281	East Twin River At Mishicot	Glacial	dolomite	0.231	0.18	0.285
04085200	Kewaunee River	Glacial	dolomite	0.210	0.15	0.397
05400650	Little Plover River at Plover	Glacial	sandstone	0.057	0.16	-0.643
05427948	Pheasant Branch at Middleton	Glacial	sandstone	0.329	0.06	4.489
05402000	Yellow River at Babcock	Glacial	sandstone	0.144	0.06	1.404
05394500	Prairie River near Merrill	Glacial	igneous	0.525	0.14	2.752
05393500	Spirit River at Spirit Falls	Glacial	igneous	0.253	0.22	0.151
05406500	Black Earth Creek	Non-glaciated	sandstone	0.874	0.16	4.460
05433000	East Br Pecatonica River	Non-glaciated	sandstone	1.472	0.26	4.663
05413500	Grant River at Burton	Non-glaciated	sandstone	1.483	0.26	4.705
05408000	Kickapoo River at La Farge	Non-glaciated	sandstone	3.007	0.17	16.690
05432500	Pecatonica River at Darlington	Non-glaciated	sandstone	0.928	0.4	1.320
04071858	Pensaukee R. near Pensaukee	Non-glaciated	sandstone	0.046	0.22	-0.790
05414000	Platte River near Rockville	Non-glaciated	sandstone	1.494	0.2	6.471

CONCLUSIONS

Historic recharge rates for 11 watersheds in southeastern Wisconsin have been inferred from baseflow discharge at USGS gaging stations. These rates vary through time in response to changes in precipitation, and the relation has been expressed as dQ/dP (the ratio of changes in baseflow (recharge) through time to changes in precipitation through time). Watersheds with more permeable sediments have relatively high response ratios (dQ/dP ranges mostly from 0.6 to 1.0). Those underlain by clay tills have much lower response ratios (0.1 to 0.5), and urban watersheds have scattered responses.

For all of these watersheds and response types, however, the dQ/dP is most closely related to $S*L_{of}$, a measure of the transfer of precipitation to recharge (and then to baseflow). This single parameter explains about 74% of the observed variation in dQ/dP in all 11 study watersheds (regardless of surface sediment type or land cover). It can also be used to calculate (via equation 2) the dQ/dP ratios in other glaciated watersheds in Wisconsin to within reasonable ranges. It does not work in non-glaciated terrains.

Equation 2 provides a mechanism to allow groundwater users to anticipate how much recharge in their areas will change in response to droughts or to future changes in precipitation resulting from long-term climatic change.

REFERENCES

Cherkauer, D. S. 2003. Quantifying the spatial variability of groundwater recharge using GIS and a distributed-parameter model. In final review. *Ground Water.*

Cherkauer, D.S. and S.A. Ansari. 2003. Estimating the spatial and temporal distribution of groundwater recharge using topography, hydrogeology, land cover and precipitation. Manuscript in review. *Ground Water.*

LaCosse, C.J. 2003. Causes of historical changes in groundwater recharge rates in southeastern Wisconsin. MS thesis in progress. Dept. of Geosciences, University of Wisconsin-Milwaukee.

Sloto, R.A. and M.Y. Crouse. 1996. HYSEP: A computer program for streamflow hydrograph separation and analysis. USGS Water Resources Investigations Report 96-4040,46 p.

APPENDIX A: Awards, Publications and Presentations

Awards:

LaCosse, C.J. 2000. Honorable mention for student poster at the national meeting of the American Institute of Professional Geologists, October, 2000.

Publications:

Cherkauer, D. S. 2003. Quantifying the spatial variability of groundwater recharge using GIS and a distributed-parameter model. In final review. *Ground Water.*

Cherkauer, D.S. and S.A. Ansari. 2003. Estimating the spatial and temporal distribution of groundwater recharge using topography, hydrogeology, land cover and precipitation. Manuscript in review. *Ground Water.*

Presentations:

Carlson, D.A., D.S. Cherkauer and S.A. Ansari. 1999. What is the groundwater recharge rate in southeastern Wisconsin? Wisconsin Section, American Water Resources Association.

LaCosse, C.J. and D.S. Cherkauer. 2000. Seasonal variation of groundwater recharge rates in southeastern Wisconsin for 1997 - 1999. Wisconsin Section, American Water Resources Association.

LaCosse, C. J. 2000. Causes of historical changes in groundwater recharge rates in Wisconsin. National meeting of American Institute of Professional Geologists.