UNIVERSITY OF MINNESOTA
**ST. ANTHONY FALLS LABORATORY**
**Engineering, Environmental and Geophysical Fluid Dynamics**

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# Baseflow Analysis of the Upper Vermillion River, Dakota County, Minnesota

by

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# Abstract

Estimates of groundwater recharge are important for water resources planning and management, e.g. to determine the sustainability of groundwater resources. Estimates of groundwater recharge can be obtained by streamflow, especially baseflow, analysis. The Vermillion River, located at the southern fringe of the Minneapolis-St. Paul Metropolitan Area, is a DNR-designated groundwater-fed trout stream. How the stream flow in the Vermillion River and its tributaries is affected by urban development encroaching into the watershed is a pressing question. The baseflow in the Upper Vermillion River was therefore analyzed to determine the river's groundwater recharge and minimum flow potential. The study site watershed includes approximately 129 square miles of the 338 square miles of drainage area within Dakota and Scott Counties.

Two methods, the baseflow-separation method and the recession-curve-displacement method, were applied to the streamflow data from the USGS stream gauging site #05435000 near Empire, MN, to estimate baseflow and groundwater recharge in the Upper Vermillion River. The USGS computer programs PART and RORA were used to perform the baseflow analysis. The results of the analysis were used in conjunction with a water budget to estimate other hydrologic variables in the Upper Vermillion River basin at the annual timescale. It was determined that about 24% of the average annual precipitation reaches the stream as either baseflow or direct runoff. About 20% of the annual precipitation or approximately 80% of the annual streamflow in the Upper Vermillion River is baseflow from cold groundwater sources. The average annual estimates were found to compare well with results of previous studies (Baker et al. 1979, Ruhl et al. 2002, Lorenz and Delin 2007).

Urban development has been encroaching into the Vermillion River watershed. A trend analysis on the time series (1982-2006) of the hydrologic variables for the Upper Vermillion River was conducted to detect possible effects of urban development in the watershed. Streamflow and baseflow in the Upper Vermillion River have a slightly increasing trend. Linear trends were found in the 1982-2006 records of most hydrologic variables, but none of the trends was statistically significant at or above the 95% confidence level when tested using the Kendall's tau test. The statistical significance of the trends increased when the variables were normalized to precipitation, but even then no trend reached the 95% significance level. It appears that the amount of urbanization in the watershed has not significantly lowered the groundwater discharge to the stream. The reasons for this finding are explored, including a slightly decreasing trend for precipitation in the Upper Vermillion River watershed.

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## 1. Introduction

Accurate estimates of groundwater recharge are needed for water resources planning and management, in our case the assessment of urbanization effects on coldwater streams. Many different methods are available for estimating groundwater recharge (Scanlon et al. 2002). Standard techniques include (1) tracking of soil moisture through time (Arnold and Allen 1996; Finch 1998; Simmons and Meyer 2000; Chen et al. 2005), (2) adjusting parameter-values of groundwater flow models (Yang et al. 1999; Lee et al. 2000, 2006; Jyrkama et al. 2002; McDonald and Harbaugh 2003), (3) multiplying temporal water-level fluctuations in wells by the specific yield of the aquifer material (Healy and Cook 2002) or (4) baseflow analysis of streamflow records (Rutledge and Mesko 1996; Lorenz and Delin 2007). The first three techniques require any or all of the following: an extensive knowledge of the land cover, soil types, and meteorological conditions within the study area; powerful computer resources to handle complex groundwater flow equations in search of an optimum, multi-dimensional parameter value; extensive well level data and simplification of temporal and spatially variable aquifer properties.

Groundwater recharge at the watershed scale can be estimated by baseflow analysis, using streamflow, or hydrograph analysis techniques. These methods are easy to use, and require only streamflow records. They are widely used to estimate groundwater recharge or validate empirical water-budget-based groundwater models (Rutledge and Mesko 1996; Chen and Lee 2003; Lorenz and Delin 2007). Baseflow is the water that discharges to the stream from groundwater and other sources, maintaining streamflow between storm-water or direct flow events. Although the concept of baseflow does not imply a specific origin of the water, hydrologists generally agree that most baseflow is produced by saturated flow from groundwater storage. Long-term baseflow rates are, therefore, commonly taken as indictors of basin-wide groundwater recharge rates (Meyer 2005).

A baseflow analysis for the Upper Vermillion River, in Dakota and Scott Counties, Minnesota will be described in this report. The Vermillion River is a coldwater stream known for world-class trout. The stream is located near the southern edge of the expanding Twin Cities Metropolitan Area of Minneapolis/St. Paul. There is fear that with progressive urban development in its watershed the stream might warm due to a decreasing cold groundwater resources and increasing storm water surface runoff, rendering the stream uninhabitable for trout. This study was conducted to see what effects urbanization has had on the baseflow in the Vermillion River and the groundwater recharge that is linked to it.

Urbanization can affect a watershed multiple ways. The construction of roads, buildings, and parking lots increases the amount of impervious surface area in a watershed. More surface runoff, less water infiltration into the soil, and less water recharge to aquifers are perceived to be the consequences of urban development. This is an important issue not only for groundwater withdrawal, but also for coldwater habitat in groundwater-fed streams. If the groundwater recharge rate is decreased, less groundwater will be available to feed coldwater streams, and more surface run-off is likely to raise stream temperatures. These expectations, based on land use only, may not materialize, however, for a number of reasons: (1) New stormwater management practices aim to delay surface runoff and increase infiltration. (2) Urban development also changes the drainage patterns in a watershed, sometimes dramatically, by earth movement, landscaping and installation of underground storm and sanitary sewer systems. (3) Urban development typically adds new water distribution systems for domestic or commercial/industrial water supply, and the source of the additional water is often outside the watershed. Water-uses in sprinkling systems, and leaks in the new drainage or water supply systems can add significant amount of water to the soils and the groundwater of a watershed. The overall effect of urbanization on baseflow and groundwater recharge is a function of the number, the type, and the extent of alterations of the watershed in addition to the climate, geology, and overall topography that may remain unchanged (Meyer 2005).

Urbanization may reduce groundwater recharge or baseflow rates in streams by altering the pre-development pathways for the flow of surface and groundwater. The storm water runoff, from impermeable areas, is conveyed through the storm sewer networks, shifting some of the annual streamflow from baseflow to storm flow. Simmons and Reynolds (1982) investigated the effects of urbanization on six streams on Long Island, New York. They found that increased storm sewerage, increased impervious surface area, and increased sanitary sewerage taken together reduced baseflow from 95 percent of total annual streamflow to 20 percent, whereas adjacent, un-urbanized watersheds showed no such changes in the percentages of streamflow.

Alternatively, urbanization may increase groundwater recharge or baseflow rates by increasing the number of pathways for precipitation to become groundwater. Water mains, sewer systems, storm water pipe networks, areas of irrigation, infiltration basins, and storm water detention ponds may all add to groundwater recharge leading to increased baseflow. Cities import large quantities of water for water supply, distribute it though underground pipe networks and collect most of it again in sanitary sewers or septic tanks. The leaks from these systems may produce substantial recharge (Lerner 2002). Appleyard (1999) collected data and estimated that groundwater recharge in non-urban parts of Perth, Australia, is approximately 15% to 25% of annual rainfall; by contrast groundwater recharge in urban areas, was as much as 37% of the annual rainfall.

This paper will (1) provide a background and review methodologies for baseflow analysis; (2) apply two baseflow analysis methods (the recession-curve-displacement and baseflow-separation) to the Upper Vermillion River; (3) investigate the balance between groundwater discharge and groundwater recharge and their relationship to streamflow in the Upper Vermillion River; (5) estimate hydrologic budget components from the Upper Vermillion River streamflow record and precipitation data; (6) investigate trends in the annual streamflow record of the Upper Vermillion River; and (7) review all results to detect and project the effects of urbanization on annual streamflows, baseflow and groundwater recharge.

# 2. Background

## 2.1 Definition of groundwater recharge

*Groundwater recharge* is defined in this paper as the amount of water that flows, by gravity, through the soil beyond the reach of the surface vegetation ultimately reaching the saturated zone, i.e. an aquifer, through the processes of vertical percolation or seepage. This water is then discharged to a stream as baseflow, unless it feeds natural springs or is withdrawn by wells for human use. Unlike precipitation and direct runoff, groundwater recharge is nearly impossible to measure directly. It is difficult because groundwater recharge depends not only on precipitation but also on meteorological conditions, as well as on soil type, land surface slope, soil-moisture status, vegetation cover and condition, cultivation practices, and most of all, on evapotranspiration, which is a function of the previously noted factors.

Many methods for estimating groundwater recharge assume that the groundwater discharge to surface waters plus any artificial withdrawal is equal to the groundwater recharge. This assumption implies that (1) the groundwater storage does not change over time (steady-state) or can be determined from field measurements, (2) the ground-watershed is equivalent to the surface watershed, and no groundwater flow crosses the boundary (divide); (3) leakage to deeper aquifers is negligible and (4) changes in baseflow from stream regulation, industrial water discharges, and return flows from irrigation and drainage tiles can be accounted for. These points will become clearer in the context of a groundwater budget.

## 2.2 Groundwater budget

A groundwater budget is a quantitative expression of the balance between the total water gains and losses of an aquifer over a period of time. The water entering the aquifer is equated to the water leaving the aquifer, plus or minus the changes in storage in the aquifer. The groundwater budget can be stated as

$$R + GW_{in} - Q_s - Q_w - GW_{out} = \Delta S/t \qquad [2.1]$$

where $R$ = recharge to the aquifer,
$GW_{in}$ = influxes from up-gradient portions of the ground water system,
$GW_{out}$ = effluxes to down-gradient portions of the ground water system,
$Q_s$ = discharge to or from surface water bodies,
$Q_w$ = abstractions from ground water system through wells,
$\Delta S/t$ = change in ground water storage in the system per unit time.

Each term in (2.1) has units of volume or depth per time, and artificial recharge and leakage through aquifers to deeper aquifers are assumed negligible. At the watershed scale, i.e. without lateral flows across any groundwater divide, (2.1) simplifies to

$$R - Q_s - Q_w = \Delta S/t \qquad [2.2]$$

The budget equation can be rearranged to give the discharge to surface water bodies. If well abstractions negligible or are included in the storage term, the budget can be given as

$$Q_s = R \pm \Delta S/t \qquad [2.3]$$

The groundwater in storage can fluctuate over time. If the long-term change in storage $\Delta S/t$ can be assumed to approach zero, the recharge $R$ in (2.3) can be taken as equal to the discharge $Q_s$ to a surface water body such as a stream, where it provides the baseflow. Baseflow is the streamflow minus the surface runoff from rainfall events. Equation (2.3) is the basis for estimating groundwater recharge from streamflow records using hydrograph separation methods such as the baseflow-separation method and the recession-curve-displacement method. To understand these streamflow analysis methods, an understanding of the storm hydrograph is needed.

## 2.3 Hydrograph

The *flood or storm hydrograph* is a graph of the discharge or flow rate ($m^3/s$) in a stream vs. time in response to a rainfall event. Such a hydrograph shows three runoff stages or phases (Figure 2.1):

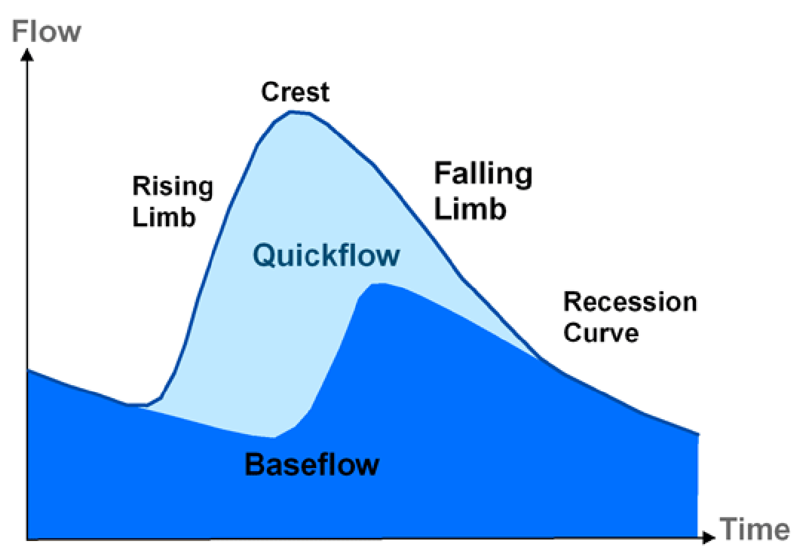


**Figure 2.1: Components of a typical flood or storm hydrograph (from www.connectedwater.gov.au/processes/baseflow.html).**

(1) Prior to a rainfall, low-flow conditions in the stream consist entirely of *baseflow* at the end of a dry period

(2) A *rising limb* starts after a rainfall, i.e. the streamflow increases with input of *quickflow* dominated by surface runoff and interflow. The rapid rise of the stream level relative to surrounding groundwater levels reduces or can even reverse the hydraulic gradient towards the stream. This is expressed as a reduction in the baseflow component at this stage.
(3) The *falling limb* of the flood hydrograph begins as the quick-flow component diminishes and the hydrograph passes its crest. With declining stream levels timed with the delayed response of a rising water table from infiltrating rainfall, the hydraulic gradient towards the stream increases. At this time, the baseflow component starts to increase. At some point along the falling limb, quick-flow ceases and streamflow is again entirely baseflow. Over time, baseflow declines as natural groundwater storage is gradually drained during the dry period - until the next significant rainfall event occurs.

It should be mentioned that the above description is specifically for streams connected to shallow aquifers (the aquifer is unconfined, i.e. has a free surface, and the water table is not far below the ground surface). Large portions of the Vermillion River system are embedded in shallow aquifers but there is also some evidence in groundwater temperatures that connections to deeper and possibly confined aquifers exist.

## 3. Baseflow estimation techniques

### 3.1 Basic concepts

Several methods exist to estimate groundwater discharge and groundwater recharge using streamflow records. Many of the methods assume that the groundwater discharge is equal to the groundwater recharge, an assumption that can be made only if a number of conditions stated in section 2.1 and justified by the groundwater budget in section 2.2, above, are met.

Two widely accepted and applied methods are (1) the recession-curve-displacement method, often referred to as the Rorabaugh (1964) method that consists of a set of calculations by which the groundwater portion of streamflow is estimated from each streamflow peak, and (2) the baseflow-separation method, by which the groundwater discharge is estimated from a continuous or daily record of streamflow (Rutledge and Daniel, 1994).

Both methods assume that the baseflow of a stream is equal to the groundwater discharge. It is important to remember that the assumption that baseflow is equal to groundwater discharge is not always valid (see section 2.2 above). A variety of natural phenomena and human interventions can affect the baseflow. Flow can be released from a variety of storage basins, such as lakes, wetlands, ponds or can be produced by snow-melt. Stream regulation, industrial discharges, irrigation and tile drainage can modify a stream's baseflow (see Schilling and Libra 2003). Large flood events create temporary stream bank storage that can contribute to baseflow. Riparian zone vegetation may affect the flow by using the water in the stream for evapotranspiration.

Despite these restrictions, methods based on streamflow records are widely used because they only require stream discharge data to estimate groundwater recharge. These methods do have a high degree of subjectivity associated with them. Computer programs have been developed to lessen some of the subjectivity or bias associated with having multiple persons perform the analysis. The methods, along with most groundwater recharge models, are hard to validate because groundwater recharge cannot be directly measured.

Below is a more detailed discussion of the methodologies used to estimate groundwater recharge using streamflow data: (1) the recession-curve-displacement method using the program RORA; and (2) the baseflow separation method using the program PART. Both programs were developed by the USGS (Rutledge 1993, Rutledge and Daniel, 1994, Rutledge and Mesko 1997, Rutledge 1998).

### 3.2 Recession-curve-displacement method

The recession-curve-displacement method (Rorabough method) is intended for analysis of flow systems that are driven by area diffuse-recharge where the stream is considered the sink (discharge boundary) of the groundwater flow system. Groundwater recharge is considered to be approximately concurrent with the peaks in the streamflow (Rutledge and Daniel, 1994). This method has the strongest theoretical basis of any of the hydrograph-separation techniques; it is based on the closed-form solution of the one-dimensional groundwater flow equation (Halford and Mayer, 2000). The method is only applicable to stream systems and catchments where regulation and diversion of flows are negligible, and where the entire watershed or drainage area is upstream from the gauging station where the discharge data have been collected. This method can be used to express groundwater recharge in units of specific discharge (such as mm per year per $m^2$), if the area of contribution (the groundwatershed) is known and equal to the drainage area of the surface water system (the watershed), i.e. no flow across the ground-watershed divides.

Many researchers have used this method to estimate recharge because daily or continuous streamflow records are the only required data. If the streamflow records are continuous, there may be no lower limit to the size of watershed that can be analyzed, but if daily streamflow data are used, the drainage area must be of sufficient size so that the time base of surface runoff exceeds the daily time increment. The upper limit of drainage area is dependent on the uniformity of the weather systems and the accuracy of the time base of surface runoff.

The recession-curve displacement method is based on the upward shift in the recession curve of the groundwater discharge. The only parameter of the streamflow hydrograph that relates to this upward shift is considered to be the total groundwater discharge (Rutledge and Daniel, 1994; Chen and Lee, 2003). The streamflow is considered as a total groundwater discharge (surface runoff is negligible) based on the antecedent recession. Lindley et al. (1982) proposed an empirical relationship (Equation 3.1) that gives the time base of surface runoff (N) as a function of surface area (A).

$$N = A^{0.2} \qquad [3.1]$$

where

N = time base of surface runoff (days),
A = area of drainage area or watershed (sq mi).

The time base of surface runoff is the number of days after a peak in the stream hydrograph when the surface runoff contribution to the streamflow can be considered negligible, i.e. the streamflow consists entirely of groundwater discharge if it is preceded by a period of recession equal to or greater than N.

Groundwater recharge will increase the total potential groundwater discharge (V) which is the total volume of water that will drain from the system if given an infinite time period without further recharge. Meyboom (1961) expressed V, based on a linear relation between the logarithm of groundwater discharge and time, and proposed equation 3.2.

$$V = \frac{Q \times K}{2.3026} \qquad [3.2]$$

where

V = total potential groundwater discharge,
Q = groundwater discharge at the initial time,
K = the recession index.

The recession index (K) is the time required for groundwater discharge to decline through one log cycle, i.e. $Q_0$ to $0.1Q_0$. The recession index (K) is a constant that represents the physical properties of the aquifer.

Rorabaugh (1964) expressed groundwater discharge to a stream as a complex function of time after a recharge event and found that the function can be approximated after "critical time" by an equation that expresses the logarithm of groundwater discharge as a linear function of time. He proposed equation 3.3a.

$$T = C_1\left(LogQ^2\right) + C_2\left(LogQ\right) + C_3 \qquad [3.3a]$$

where

T = time (T),
Q = discharge ($L^3/T$),
$C_1, C_2, C_3$ = coefficients.

Critical time can be expressed as:

$$T_c = \frac{0.2a^2 S}{TR} \qquad [3.3b]$$

where

$T_c$ = critical time (T),
a = the average distance from the stream to the hydrologic divide (L),
S = Storage coefficient (-),
TR = transmissivity ($L^2/T$).

A formulation that gives the critical time as a function of the recession index (K) can be obtained by combining (3.3b) with the following equation from Rorabaugh and Simons (1966):

$$K = \frac{0.933a^2S}{TR} \qquad [3.4]$$

By solving for $a^2S/TR$ in (3.4) and substituting into (3.3b), critical time can be expressed as equation 3.5.

$$T_c = 0.2144K \qquad [3.5]$$

Glover (1964) and Rorabaugh (1964) showed that the total potential groundwater discharge at critical time after the peak in the streamflow is equal to approximately one-half of the total volume of the water that recharged the system (Rutledge and Daniel 1994). Using their findings combined with the principle of superposition, the total recharge can be estimated for a recharge event from equation 3.6.

$$R = \frac{2(Q_2 - Q_1)K}{2.3026} \qquad [3.6]$$

where

R = total volume of recharge ($L^3$),
$Q_1$ = groundwater discharge at critical time as extrapolated from the streamflow recession preceding the peak ($L^3/T$),
$Q_2$ = groundwater discharge at critical time as extrapolated from the streamflow recession following the peak ($L^3/T$),
K = the recession index (T).

The recession-curve-displacement method can be applied using the following steps based on Figure 3.1 (after Rutledge, 1993):

1. Determine the recession index (K) from the hydrograph during prolonged periods of negligible recharge, e.g. during the winter months in cold climate regions.
2. Estimate the critical time ($T_c$) using equation 3.5.
3. Use the critical time to determine the time on the hydrograph to which the streamflow recessions will be extrapolated.
4. Determine the hypothetical groundwater discharge at critical time by extrapolation of the recession curve preceding the event.
5. Determine the hypothetical groundwater discharge at critical time by extrapolation of the recession curve following the event.
6. Estimate total recharge by applying equation 3.6.

Steps 1 and 2 only need to be executed once for a given streamflow gauging station and all other steps need to be executed for each streamflow peak.

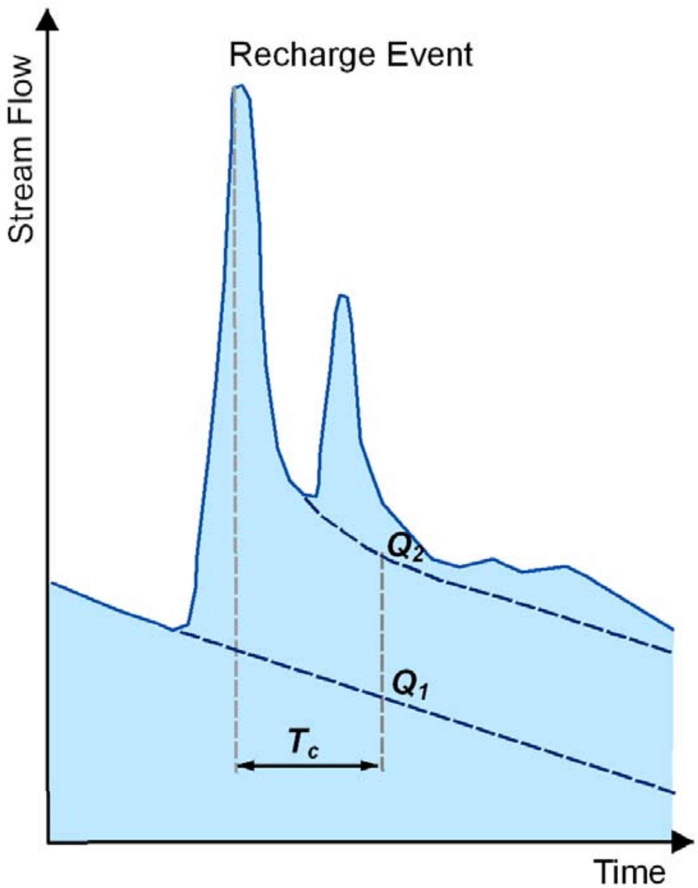


**Figure 3.1: Schematic of recession-curve-displacement method (after Rutledge and Daniel 1994).**

The recession-curve-displacement method starts by determining the recession index (K). The recession index can be estimated by taking periods of records where the streamflow recession is allowed to go undisturbed (by precipitation, regulation, etc.) long enough so that the trace of the hydrograph becomes a straight line and its slop can be determined (Rutledge and Daniel, 1994). Winter or non-growing season records should be used to eliminate effects of evapotranspiration and limit the effects of precipitation. Otherwise, the recession index can be determined from an average recession curve that is obtained from a graph on which numerous individual recession curves have been graphically superimposed (Figure 3.2).

Rutledge and Daniel (1994) automated the recession-curve-displacement method by developing a computer program called RORA (named after Rorabough, the developer of the method). Their goal was to remove some of the subjectivity found in the method when several people performed the method manually. When two persons applied the method manually to the same watershed and data set, they obtained different estimates of groundwater recharge. The RORA program removes this subjectivity and standardizes the results. Information about RORA and the programs script can be found on the USGS website at http://water.usgs.gov/ogw/rora/.

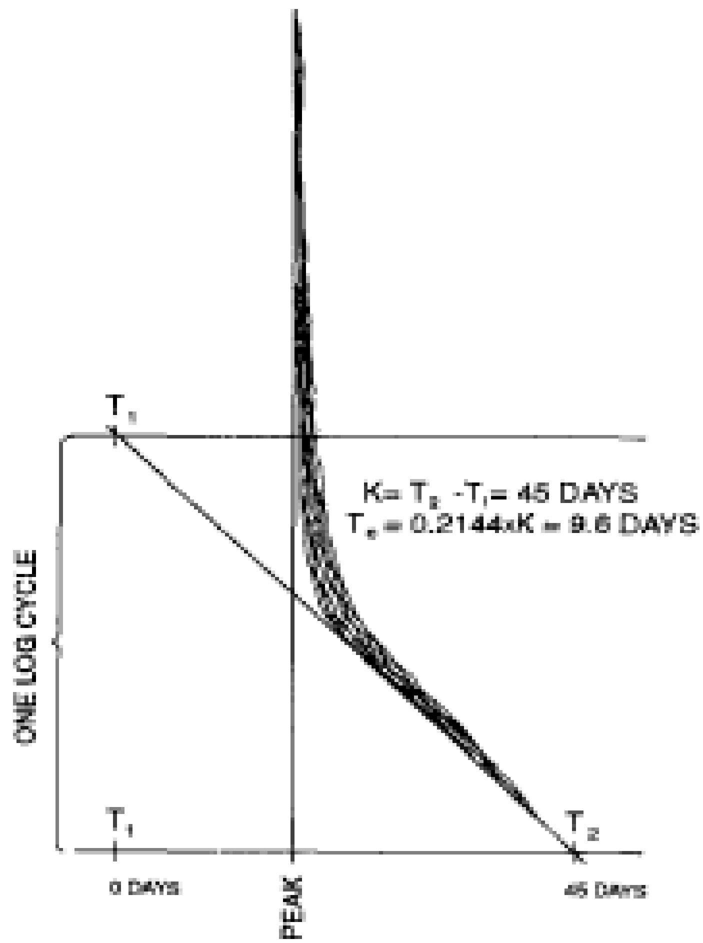


**Figure 3.2: Graphical determination of the recession index (K) and critical time ($T_c$) (from Rutledge and Daniel, 1994).**

### 3.3 Baseflow-separation method

Baseflow is the long-term discharge into a stream from natural storage, such as groundwater, usually sustaining flow between rainfall events. Streams that flow continuously throughout the year (called perennial streams) have a high baseflow component. Techniques, many of which give subjective results, have been developed to estimate baseflow as a record of groundwater discharge under the streamflow hydrograph. Many of the methods have two steps in common: (1) Locating the periods of negligible surface runoff and assuming that groundwater discharge equals streamflow at that time, and (2) interpolating groundwater discharge between periods of negligible surface runoff (Rutledge, 1993).

The decision that surface runoff is negligible can be based on antecedent recession curve data. Horton (1933) describes a method of shifting a 'normal-depletion-curve' horizontally across a hydrograph, noting that segments of the hydrograph that coincide with this curve represent periods during which streamflow is equal to groundwater discharge, then estimating groundwater discharge by simply connecting the points where the hydrograph departs from the normal depletion curve. Linsley et al. (1982) used the empirical equation 2.1 and postulated that for a given day, the antecedent recession requirement is met if the recession has been continuous for N days or more preceding the rain event. There are many other ways to execute step 2. Some are based on the assumption that the groundwater discharge peak is concurrent with the streamflow peak, while others assume that the recession of groundwater discharge continues after the time when surface runoff begins, i.e. the response of groundwater discharge is delayed relative to surface runoff (Rutledge, 1993). Other methods simply use a simple interpolation to estimate groundwater discharge between the start and end of the surface runoff event.

Figure 3.3 illustrates some of these interpolations: (a) the *constant discharge method* assumes that the baseflow is constant during the storm event and uses the minimum streamflow immediately prior to the rising limb as the constant value (Linsley et al., 1958); (b) the *constant slope method* connects the start of the rising limb with the inflection point on the receding limb and assumes instantaneous response in baseflow to the rainfall event; (c) the concave method attempts to represent the assumed initial decrease in baseflow during the rising limb by projecting the declining hydrographic trend evident prior to the rainfall event to directly under the crest of the storm hydrograph (Lindsley et al., 1958); this minimum is connected to the inflection point on the receding limb of the storm hydrograph to model the delayed increase in baseflow.

Computer techniques that produce faster and repeatable results have been developed and applied for baseflow-separation from streamflow records. A program called PART was developed by Rutledge (1993) using a method first described by Rutledge (1992) and based on antecedent streamflow recession. PART uses a form of streamflow partitioning that is similar to that of other investigators (see Rutledge 1993; Rutledge and Daniel, 1994) in that (1) daily values of streamflow are used and (2) linear interpolation is used to estimate groundwater discharge during periods of surface runoff (Rutledge, 1993).

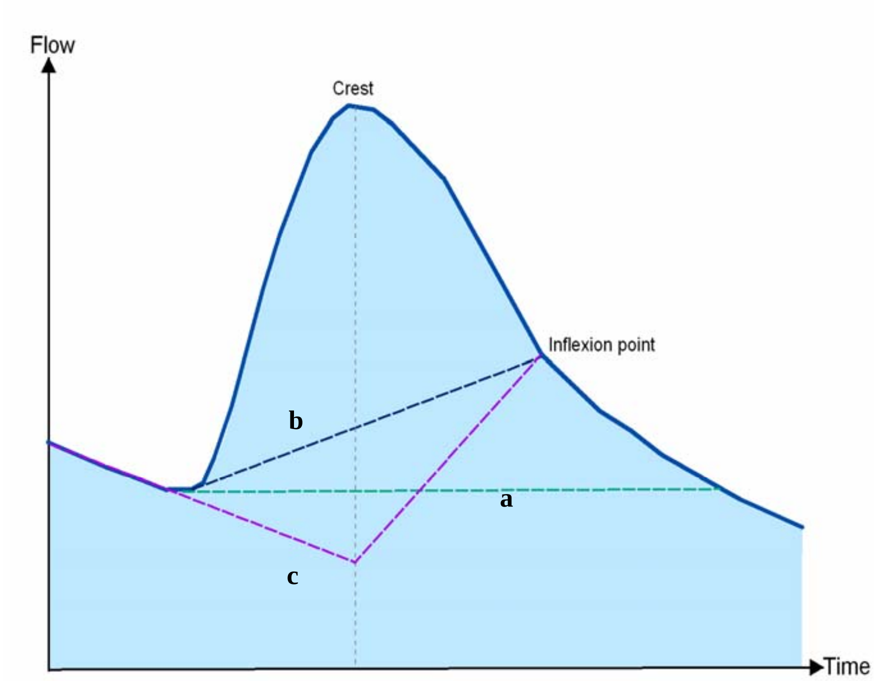


**Figure 3.3: Graphical baseflow separation techniques including:**
**(a) constant discharge method**
**(b) constant slope method and**
**(c) concave method (Linsley et al. 1958).**

A flowchart of the steps executed by the PART is shown in Figure 3.4. The program fills a one-dimensional array of for days that fit an antecedent recession requirement. On each of these days, groundwater discharge is designated equal to streamflow as long as it is not followed by a daily decline of more than 0.1 log cycles. It can be inferred from Barnes (1939) that a daily decline of more than 0.1 log cycles could indicate interflow (storm-flow) or surface runoff. The program searches the array again, and determines by linear interpolation the groundwater discharge on the remaining days. For some streamflow records, this interpolation can cause the calculated groundwater discharge to exceed streamflow for a few days in the record. The last step of the procedure corrects for this deficiency (Rutledge, 1993).

More information and the script for PART can be found on the USGS website at http://water.usgs.gov/ogw/part/.

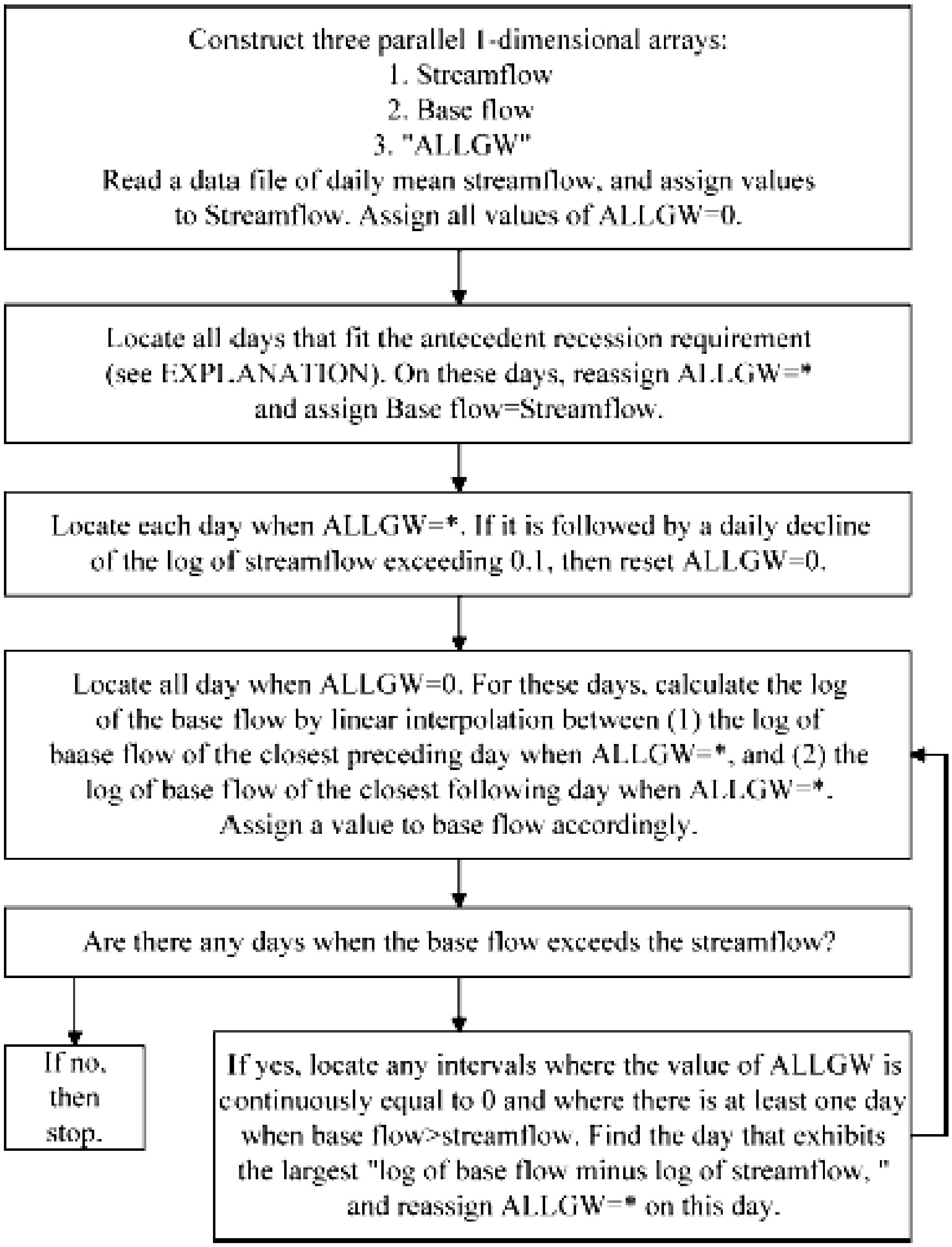


**Figure 3.4: Flow diagram showing the procedure of stream partitioning. Baseflow is considered to be the groundwater discharge (from Chen and Lee, 2003; after Rutledge, 1993).**

Explanation:

The antecedent recession requirement is met for the day in question if, for the part of the daily mean streamflow record that includes all days that precede the day in question by N days or less, the streamflow on each of these days is greater than or equal to the streamflow on the day that follows it. (N = time base of surface runoff.)

The entire procedure is executed for three values of N: one is the next integer smaller then the result of equation 3.1 and the other two are the next two integers that are larger than the result of equation 3.1. Curvilinear interpolation gives the final estimate of the base flow that corresponds to the precise result of equation 3.1

## 4. Upper Vermillion River watershed

The Vermillion River is a designated DNR trout stream, located near the southern fringe of the Minneapolis - St. Paul Metropolitan Area in south-central Minnesota. The watershed includes approximately 338 square miles of drainage area within Dakota and Scott Counties. The Vermillion River's headwaters begin flowing in southeastern Scott County and continue eastward through central Dakota County where they join the Mississippi River southeast of Hastings. The upstream portion of the watershed includes several cold-water tributaries that support a naturally reproducing brown trout population, which is dependent on groundwater and sustained cold-water temperatures for survival (EOR Report 2007).

Daily streamflow records were obtained for the USGS gauging station site #05435000, on the Vermillion River, near Empire, MN (Figure 4.1), from the USGS water data site for Minnesota at http://waterdata.usgs.gov/nwis/nwis/. The gauging station has continuous streamflow records starting in 1974 and continuing to the present (2007).

The USGS gauging site near Empire captures drainage from 129 square miles of the Vermillion River watershed, mostly the upper third of the watershed which is expected to see more urban development than any other land area within the watershed (EOR Report 2007). This section of the watershed has been and will be referred to as the Upper Vermillion River watershed.

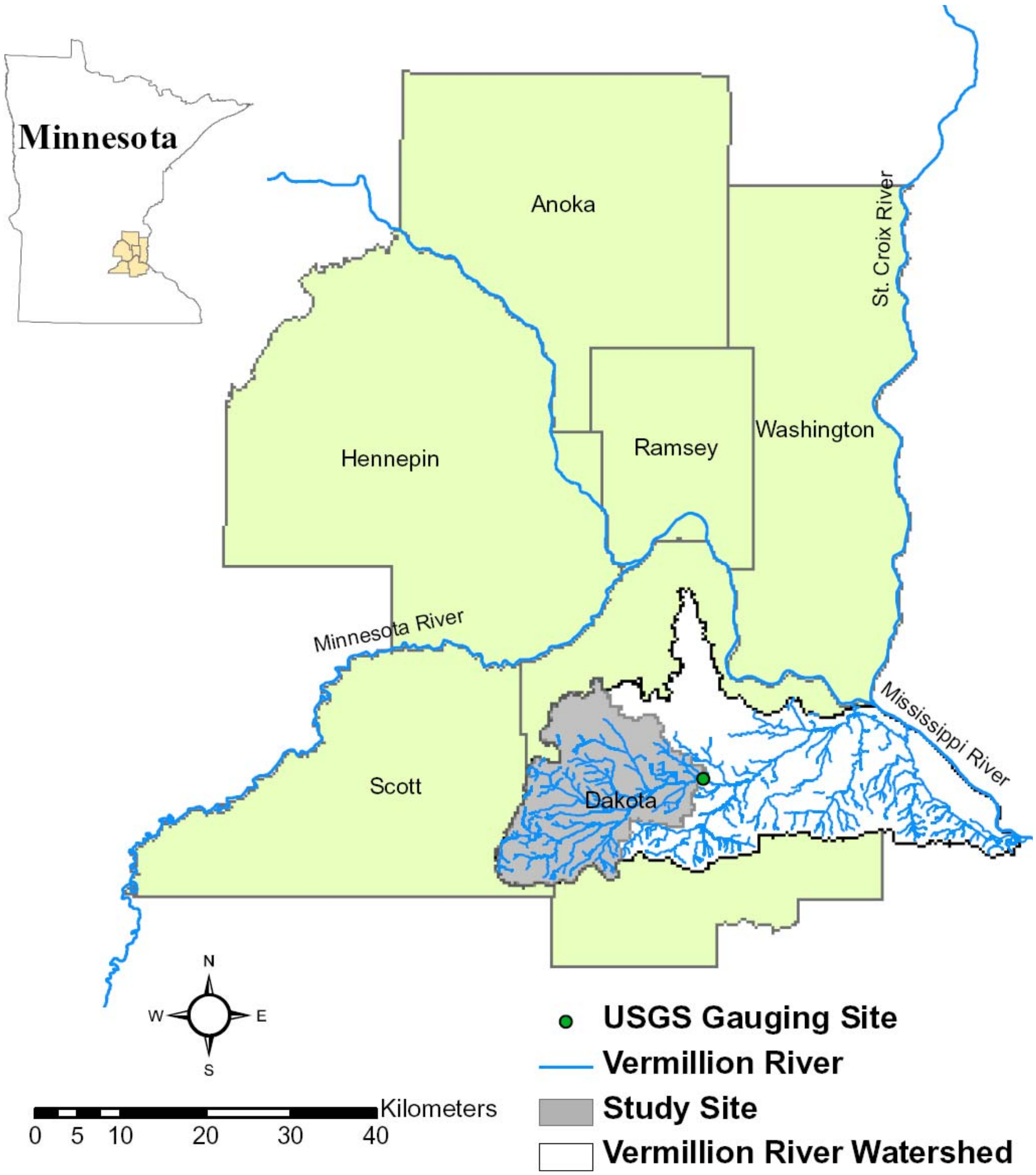


**Figure 4.1: Upper Vermillion River watershed and the USGS gauging site near Empire, Minnesota.**

Assumptions for streamflow analysis and baseflow separation are that the groundwatershed is similar to the surface watershed and that the Upper Vermillion River stream system (Figure 4.1) is the sink for the shallow aquifer system. Both assumptions are reasonable. The outlines of the groundwatershed and the surface watersheds of the Upper Vermillion River are compared in Figure 4.2a.

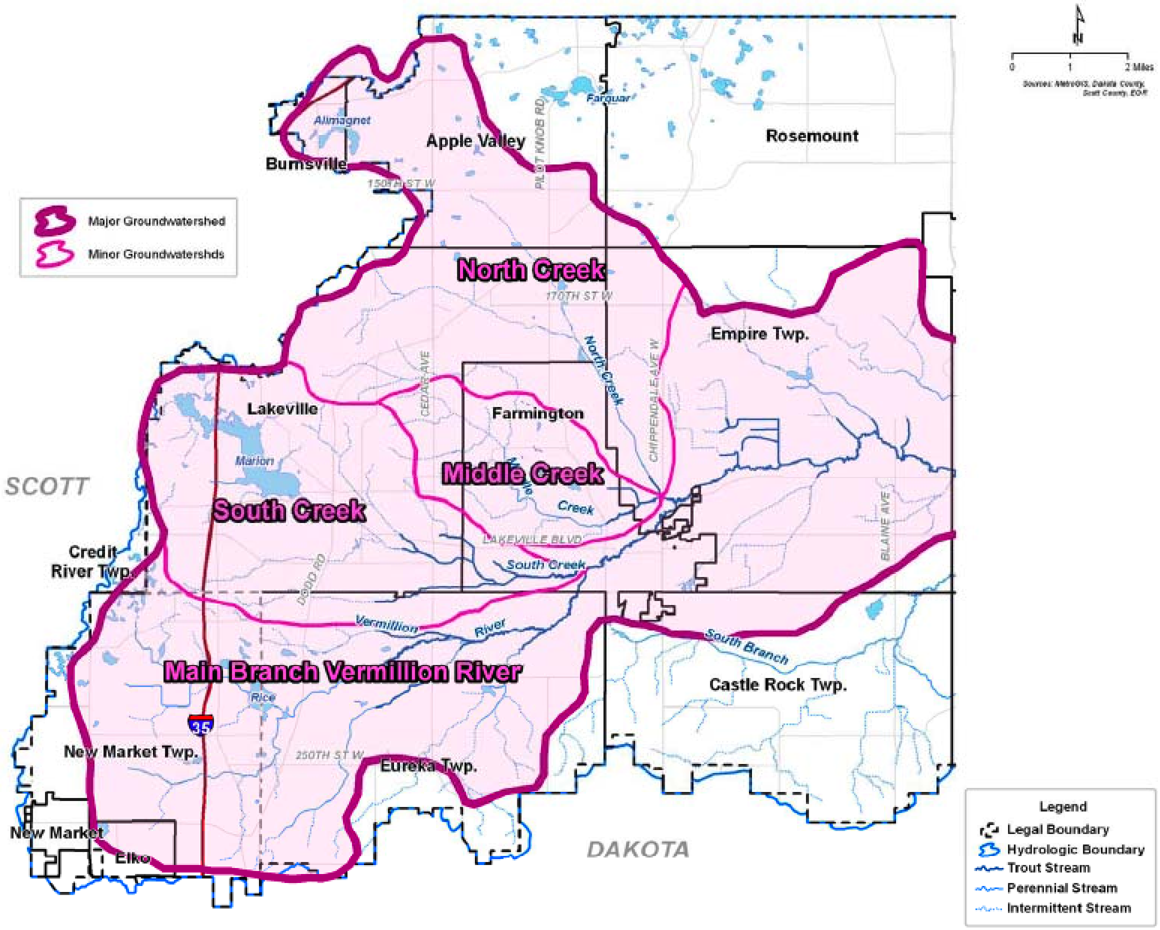


**Figure 4.2a: Groundwatersheds for the Upper Vermillion River (EOR Report 2007).**

The topography and soils of the watershed are remnants of glacial processes that shaped the region during the Pleistocene. Two prominent glacial moraine complexes are located within the watershed and visible on the landscape as steep to rolling hills and closed depressions. The Eastern St. Croix Moraine is located in the northwestern region of the watershed and marks the extent of the Superior Lobe advance in the region. The Prior Lake Moraine is located in the southwestern region of the watershed and marks the extent of the Des Moines Lobe advance in the region. The surficial geology of the Vermillion River Headwaters consists predominately of glacial outwash from two separate glacial advances. Des Moines Lobe deposits are the first encountered surficial geological deposits in the headwaters region of the watershed west of Farmington. Des Moines Lobe deposits are typically gray to yellowish brown fine textured deposits of shale and carbonate origin. East of Farmington, Superior Lobe deposits dominate the central watershed. Superior Lobe deposits are typically red coarse textured deposits of Precambrian origin. Large portions of the watershed contain mixed Des Moines and Superior Lobe deposits. The predominant soil type in the study area is the Group B soil. This soil type is moderately well-drained to well-drained (EOR Report, 2007).

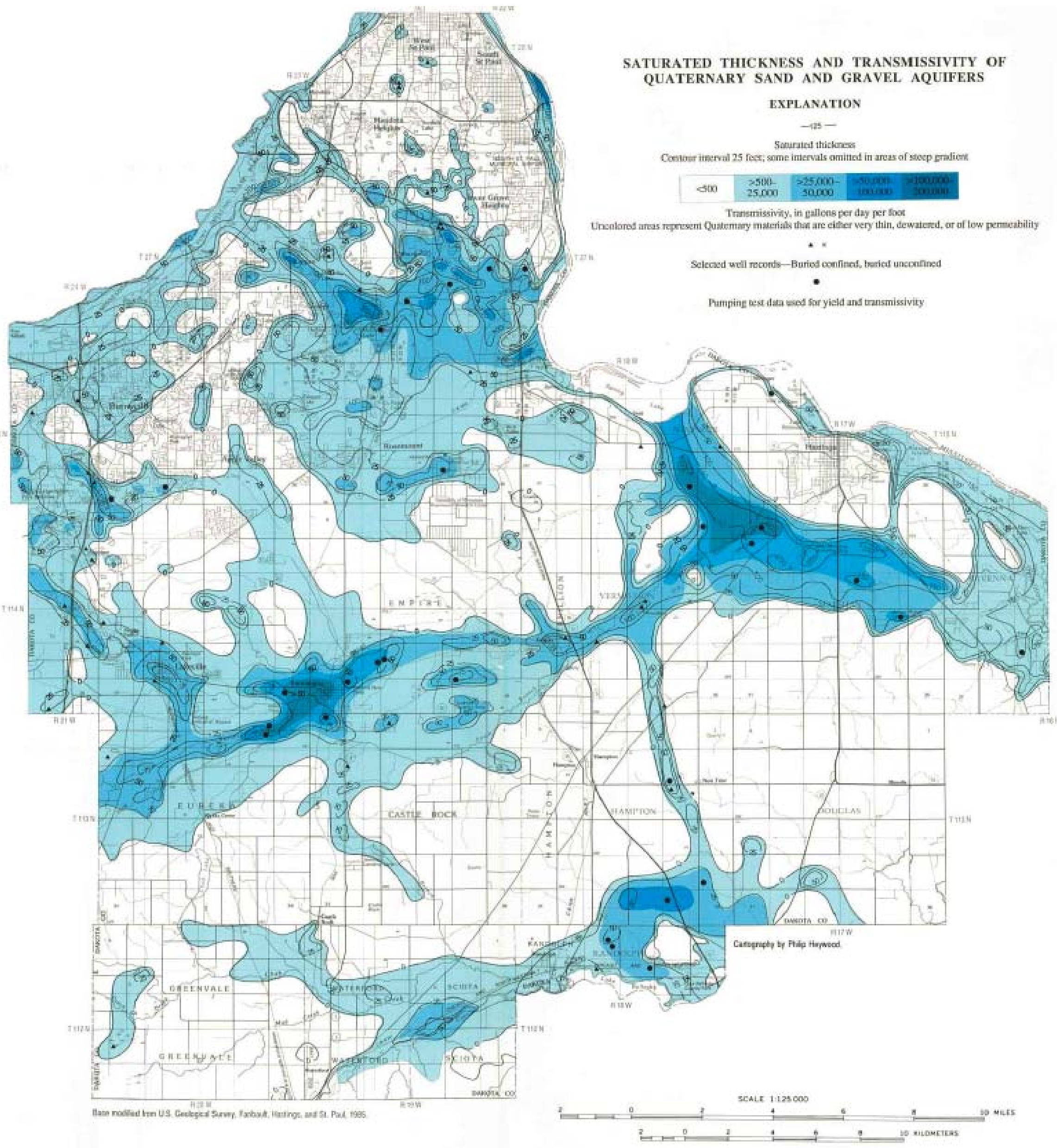


**Figure 4.2b: Hydrogeological map of Dakota County, MN. Saturated zone thickness is given as contour lines ranging from 0 to 200 ft. Transmissivities are given by color, ranging from < 500 gal/day/ft in white to 100,000 to 200,000 gal/day/ft in the dark blue (MN Geological Survey 1990).**

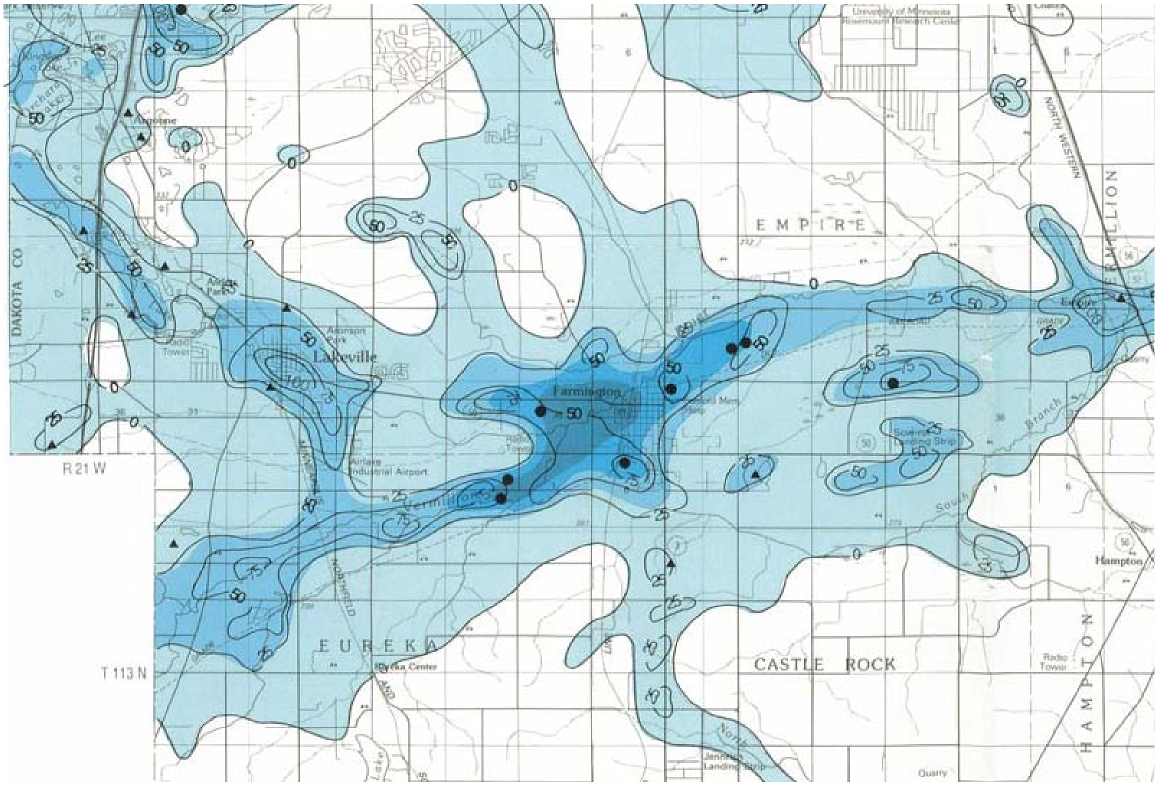


**Figure 4.2c: Enlarged view of hydrogeology, transmissivities and hidden valleys near Lakeville and Farmington, MN (Minnesota Geological Survey 1990).**

Figure 4.2b is a hydrogeolocial map for Dakota County, MN showing the saturated thickness of the aquifer and its transmissivity. Figure 4.2c is an enlargement of the study area, showing the buried valleys near Lakeville and Farmington more clearly. Both maps show transmissivity by darkness of the areas. The white areas show transmissivities of less than 500 gal/day/ft; the next darker areas are for 500 to 25,000 gal/day/ft; the third darkest areas are for 25,000 to 50,000 gal/day/ft; the fourth darkest areas show 50,000 to 100,000 gal/day/ft; and the darkest areas are for 100,000 to 200,000 gal/day/ft transmissivities. The contour lines in Figures 42.b and c show the saturated thickness of the aquifers, ranging from 0 ft in the white areas up to 200 ft in the dark areas with most of the valleys ranging from 25 ft to 100 ft.

The hydrogeologic map of the region (Figure 4.2b and c ) shows several buried valleys between Lakeville and Farmington (MN Geological Survey 1990). These buried valleys are filled primarily with sand and gravel and are primarily sitting on the Prairie Du Chien rock formation. Transmissivities in these valleys are high (up to 200,000 gal/day/ft or ~2500 $m^2$/day). The surficial (quaternary) aquifer thicknesses are on the order of 25 ft to 100 ft (7 m to 35 m) and as high as 200 ft (70 m).

The current land use is primarily agriculture mixed with developing urban residential/commercial communities such as Apple Valley, Lakeville, and Farmington. The watershed has seen increasing urban development in the last 30 years. The progressive change from primarily agricultural land use to suburban developments is documented in Figure 4.3. The figure was generated using land-use maps for 1984, 1990, 1997, 2000, and 2005. The developed areas represent urban land-use types such as residential (single- and multi-family homes), commercial, industrial, and institutional areas. The undeveloped areas include natural lands, parks, and agricultural areas. As the Minneapolis-St. Paul metro area grows, it is projected that substantial growth will occur in the Vermilion River watershed.

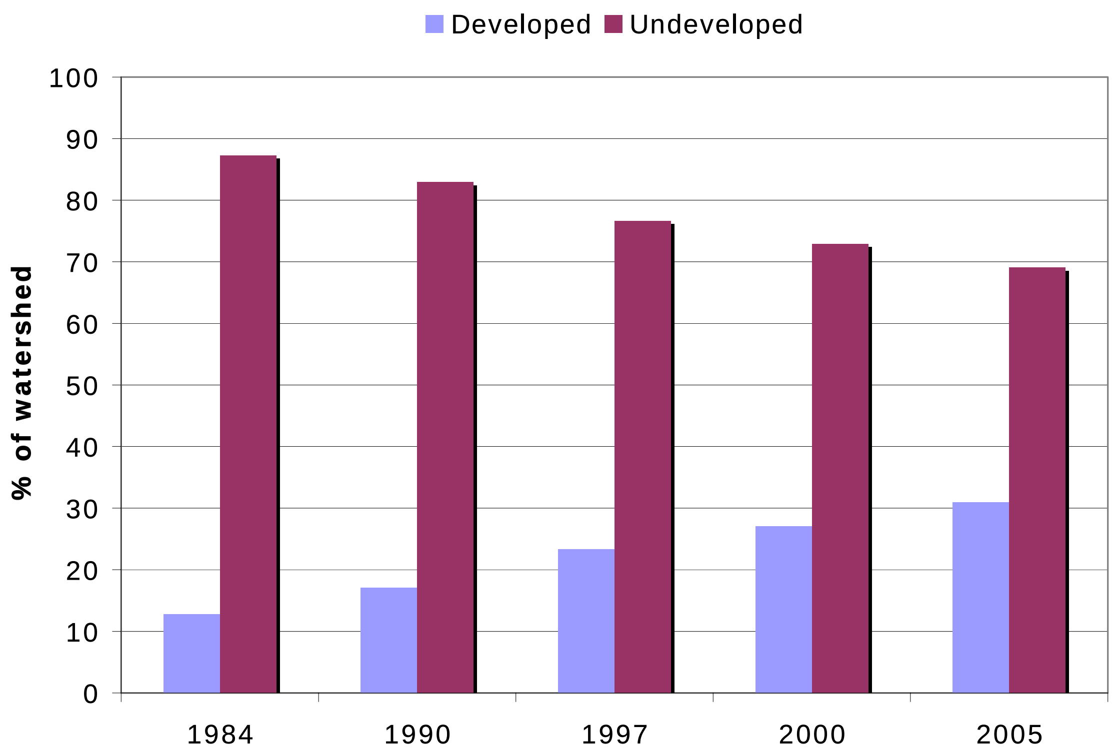


**Figure 4.3: Urban development in the Vermillion River watershed over time as a percentage of total watershed area.**

# 5. Groundwater recharge and baseflow in the Upper Vermillion River watershed

## 5.1 Results obtained with RORA and PART

Using the streamflow records from the USGS gauging station near Empire, the groundwater recharge and the groundwater discharge for the period 1982 to 2006 were calculated using the USGS computer programs RORA and PART, respectively. It may be recalled that the recession curve displacement method (RORA) estimates the groundwater recharge that reaches the shallow aquifer system by infiltration and percolation of precipitation through the soil column (Rutledge, 1993 and 1998), while the baseflow separation method (PART) estimates the groundwater discharge from the shallow aquifer system to the stream.

The USGS gauging station is a short distance downstream from the Empire Wastewater Treatment Plant outlet into the Vermillion River (the discharge was rerouted through a pipeline to the Mississippi River in November 2007). Since the methods described above assume that there is negligible human interference within the stream, the daily influent flows to the Empire treatment plant were obtained from the Metropolitan Council for the period 1981-2006. The daily effluent rate was assumed equal to influent, which increases from about 5 cfs in 1981 to 13 cfs in 2006. The influent flows were lagged 1 day, the residence time in the treatment plant, and than subtracted from the streamflow records to obtain an unimpeded, natural flow in the stream. These adjusted streamflows were used in the analysis. The results of the groundwater recharge/discharge analysis are shown as a time-series in Figure 5.1 and the statistical information is given in Table 5.1.

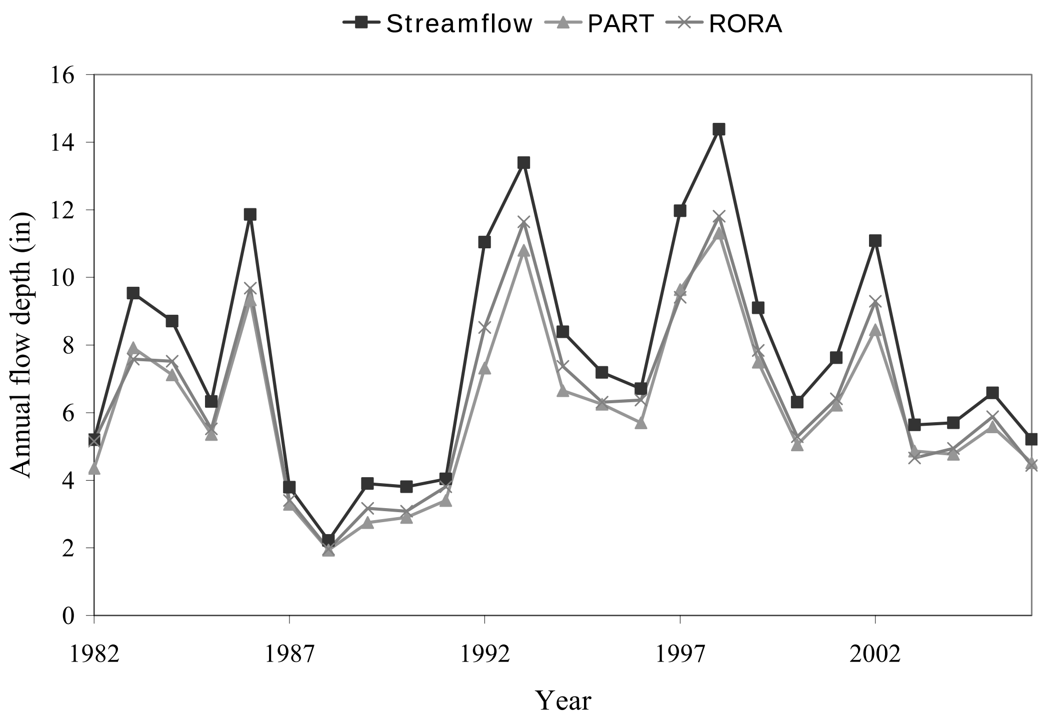


**Figure 5.1: Time-series of the adjusted streamflow components at the USGS gauging site (##05435000) near Empire, Minnesota on the Vermillion River.**

The recession index for the Vermillion River, upstream from the gauging station near Empire, was estimated to be 110 days per log cycle using the procedure described earlier. This value was used with the RORA program,

**Table 5.1: Statistical distribution of estimated baseflows in the Vermillion River at the USGS gauging station near Empire, MN (1982 to 2006).**

| | Streamflow[2)] | Baseflow | |
|---|---|---|---|
| | | PART | RORA |
| | in/year[1)] | in/year | in/year |
| Average | 7.6 | 6.1 | 6.4 |
| Std Dev. | 3.3 | 2.5 | 2.6 |
| | | | |
| Minimum | 2.2 | 1.9 | 2.0 |
| 25th percentile | 5.2 | 4.5 | 4.7 |
| Median | 6.7 | 5.7 | 6.3 |
| 75th percentile | 9.5 | 7.5 | 7.8 |
| Maximum | 14.4 | 11.3 | 11.8 |

[1)] 1 inch = 25.4 mm

[2)] Adjusted streamflow: streamflow minus Empire WWTP flow

The average adjusted streamflow in the Vermillion River at the USGS gauging site is 7.6 in/year, distributed uniformly over the watershed area. According to the PART results, approximately 6.1 in/year of the 7.6 in/year is groundwater discharge to the stream. The RORA result is that approximately 6.4 in/year of groundwater recharge occurs to the shallow aquifer system. Figure 5.2 shows groundwater discharge versus groundwater recharge. The small deviation from the unity line can be the error in the RORA and PART methods. The average difference between recharge and discharge (RORA and PART) estimates is 0.32 ± 0.37 in/yr. It could also be leakage to deeper aquifers or groundwater withdrawal from the surface aquifer. Dewatering of the shallow surficial aquifer is a common practice at construction sites in the watershed. The average difference of 0.3 in/year between the groundwater recharge and the groundwater discharge could also be interpreted as the riparian evapotranspiration (Rutledge and Mesko 1996). The riparian evapotranspiration is the water lost to the atmosphere by evaporation from the water surface of the stream and transpiration by vegetation.

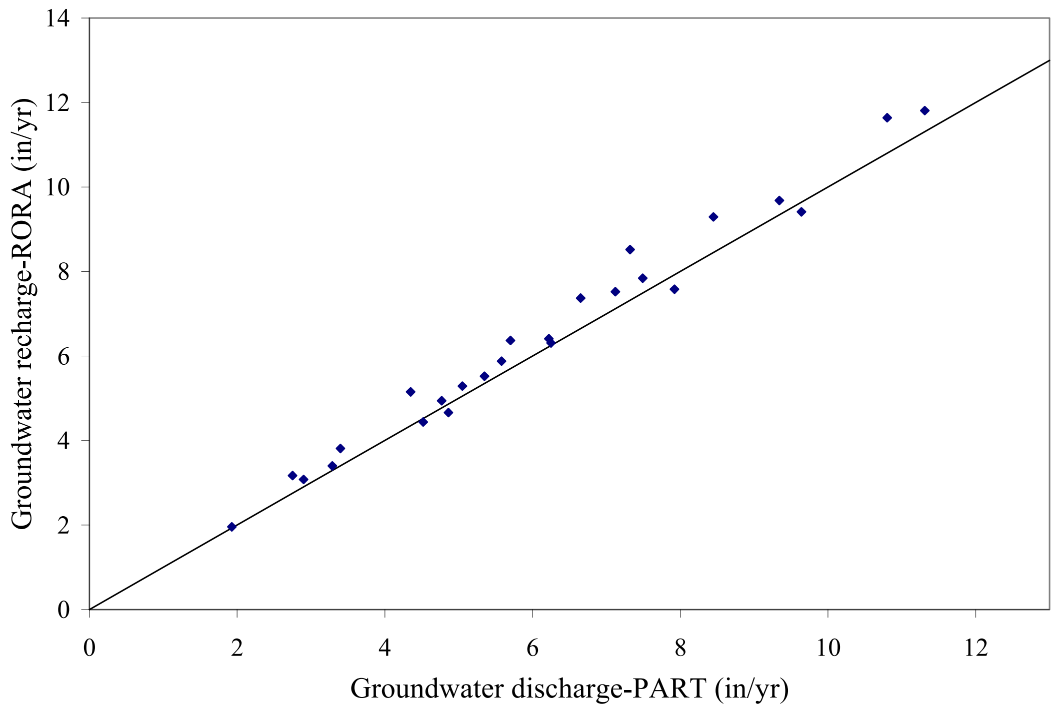


**Figure 5.2: Comparison between groundwater discharge (PART) and groundwater recharge (RORA) estimates. The line represents unity.**

### 5.2 Baseflow index (BFI)

The *baseflow index (BFI)* (Nathan and McMahon, 1990) is a simple metric of baseflow contribution to streamflow. It is primarily used in region scale studies. The BFI is defined as the ratio of the average rate of baseflow relative to the average rate of streamflow. It varies between zero and one and provides a way of normalizing groundwater discharge to climate conditions (Rutledge and Mesko, 1996). The BFI expresses the stream's dependence on groundwater sources. Annual baseflow estimates from the USGS program PART are plotted against the annual stream flow of the Upper Vermillion River in Figure 5.3. This figure shows a strong and consistent relationship between groundwater discharge (PART) and streamflow. Approximately 80% of the streamflow in the Upper Vermillion River is groundwater (baseflow), regardless of streamflow. The BFI value of 80% is the reason why the Vermillion River is a DNR designated cold-water trout stream.

Alternatively, the groundwater recharge (RORA) estimates plotted against streamflow (Figure 5.4) show the same type of relationship, leading to the conclusion that the streamflow is highly dependent on groundwater recharge. Figure 5.4 shows that a rough estimate for groundwater recharge in the Vermillion River is approximately 84% of annual streamflow.

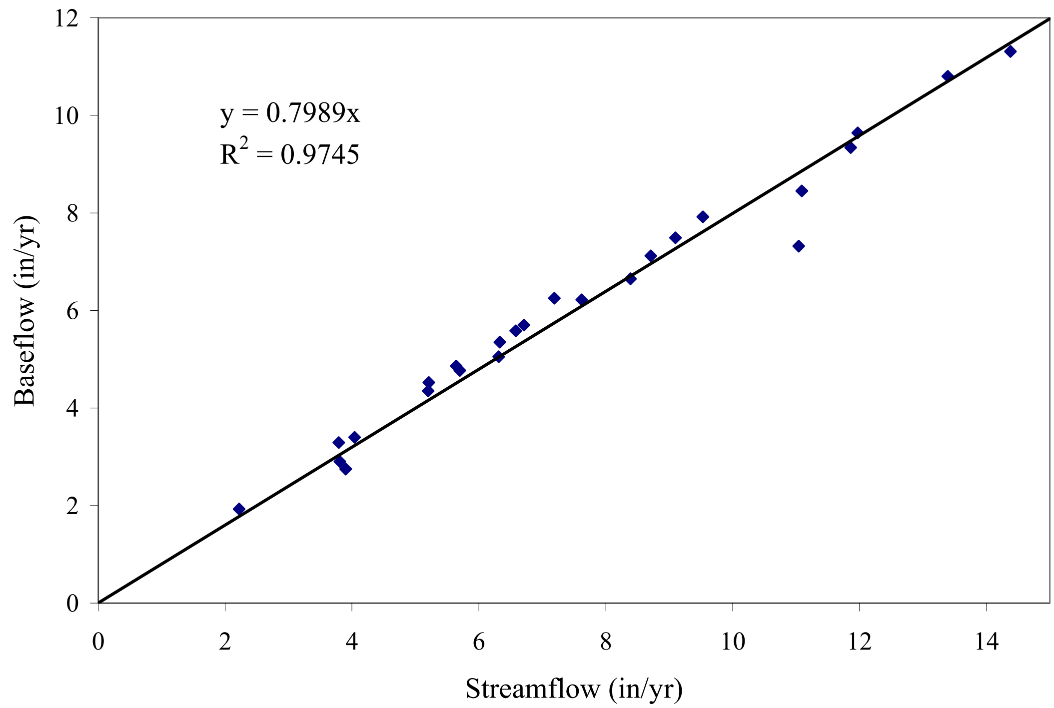


**Figure 5.3: Baseflow estimates by the USGS program PART plotted vs. streamflow. The baseflow index (BFI) is the slope of the line.**

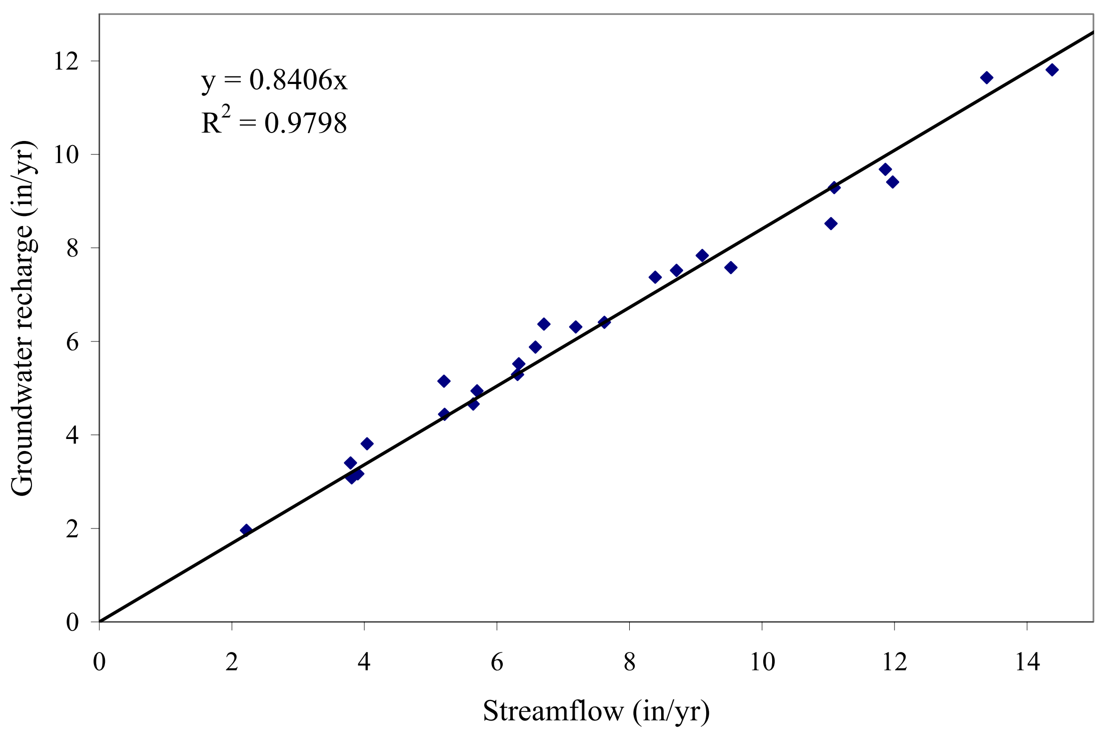


**Figure 5.4: Groundwater recharge estimates by the USGS program RORA plotted vs. streamflow.**

# 6. Water budget of the Upper Vermillion River watershed

## 6.1 Water budget relationships for the watershed

The hydrologic or water budget components of the watershed are: precipitation, evapotranspiration, direct (surface) runoff or storm flow, and infiltration/interception. Evapotranspiration includes riparian evapotranspiration. The components of the water budget for the watershed can be estimated using streamflow measurements, baseflow estimates, and annual precipitation measurements.

The simplest water budget relationship for the watershed is (Rutledge and Mesko 1996)

$$P = ET + SF \qquad [6.1]$$

where $P$ is the mean annual precipitation [in/year], $ET$ is the mean annual evapotranspiration [in/year], and $SF$ is the mean annual streamflow [in/year]. The mean evapotranspiration $ET$ is governed by the processes of evaporation and transpiration (of the plants), returning water to the atmosphere. Equation 6.1 shows conservation of mass for rain water and that precipitation will either leave the watershed as streamflow, as runoff or groundwater flow, or be returned to the atmosphere by evapotranspiration. It assumes that longer term storage and leakage to deeper aquifers are negligible. The streamflow $SF$ has two components (Figure 2.1): a surface flow (direct runoff) and a sub-surface flow (baseflow). The direct runoff $DR$, also called storm flow or quick flow, is the overland flow of water due to rainfall, and the baseflow $BF$ is the groundwater discharge into the stream. The sum of these two terms gives the total streamflow $SF$.

$$SF = BF + DR \qquad [6.2]$$

The fraction of annual precipitation that infiltrates into the soil or is intercepted by depression storage, storm water ponds, or lakes is designated by $I$ [in/year]. Infiltration and interception $I$ can be taken as the sum of evapotranspiration and baseflow or as the difference between precipitation and direct runoff, i.e.

$$I = ET + BF = P - DR \qquad [6.3]$$

Using equations 6.1, 6.2, and 6.3, the water budget components were estimated. A time series plot of the hydrologic budget components is given in Figure 6.1 and the associated statistical information is given in Table 6.1.

The estimates in Table 6.1 can be used to calibrate or validate hydrologic models for the Upper Vermillion River watershed. Groundwater recharge was estimated using the USGS computer program RORA and the storm-flow or direct runoff was estimated using baseflow estimates from the USGS computer program PART and equation (6.2). The precipitation data in Table 6.1 are from Farmington, which has the only precipitation station within the watershed that has a continuous record of precipitation measurements.

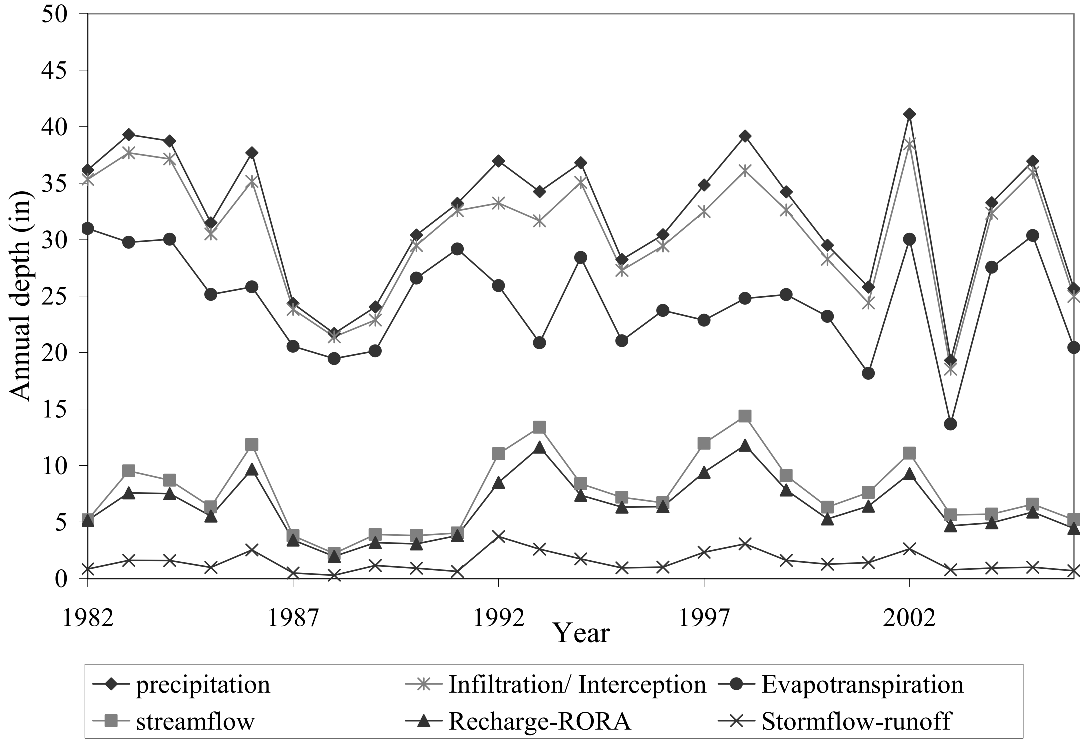


**Figure 6.1: Mean annual water budget components (1982 to 2006) for the Upper Vermillion River watershed up to the USGS gauging station near Empire, MN.**

**Table 6.1: Statistics of mean annual water budget components (1982 to 2006) for the Upper Vermillion River watershed up to the USGS gauging station near Empire, MN**

| | Precipitation | Streamflow | Recharge (RORA) | Storm flow (Direct runoff) | Infiltration/ Interceptio n | Evapo- transpiration |
|---|---|---|---|---|---|---|
| | in/yr | in/yr | in/yr | in/yr | in/yr | in/yr |
| Average | 32.1 | 7.6 | 6.4 | 1.5 | 30.7 | 24.6 |
| Std. deviation | 6.0 | 3.3 | 2.6 | 0.9 | 5.5 | 4.5 |
| | | | | | | |
| Minimum | 19.3 | 2.2 | 2.0 | 0.3 | 18.5 | 13.7 |
| 25th percentile | 28.2 | 5.2 | 4.7 | 0.9 | 27.3 | 20.9 |
| Median | 33.3 | 6.7 | 6.3 | 1.2 | 32.3 | 25.1 |
| 75th percentile | 37.0 | 9.5 | 7.8 | 1.7 | 35.2 | 28.4 |
| Maximum | 41.1 | 14.4 | 11.8 | 3.7 | 38.5 | 31.0 |

### 6.2 Water budget components of the watershed

The annual water budget components [in/yr] were plotted against annual precipitation and linear regression lines were fitted (Figures 6.2 to 6.6). The relationship between the water-budget components and precipitation was investigated. Plots were made of streamflow (Fig. 6.2), groundwater recharge (Fig. 6.3), evapotranspiration (Fig. 6.4), infiltration (Fig. 6.5), stormwater runoff (Fig. 6.6), and 1-day minimum flow (Fig. 6.7). All values, except 1-day flow, are given as mean annual depths (in/yr); 1-day flow is given in cubic feet per second.

Both streamflow (Figure 6.2) and groundwater recharge (Figure 6.3) increase with precipitation and a minimum annual precipitation (approximately 11 inches) needs to fall before streamflow and groundwater recharge will occur. This minimum precipitation is due to plant interception and evapotranspiration. Hypothetically if only 11 inches of precipitation occurred in any given year (10 in/yr is by definition a desert), no streamflow and no groundwater recharge would occur; all the precipitated water would be returned to the atmosphere by evapotranspiration. This may not be true, since the hydrologic processes in a watershed depend on more parameters than precipitation alone.

It is noteworthy that both Figure 6.2 and 6.3 have approximately the same minimum precipitation (~11 inches) before streamflow or groundwater recharge is generated. This is believed to ascertain the strong relationship between streamflow and groundwater recharge that was seen in Figure 5.3, proving that the Vermillion River is highly dependent on groundwater sources. In essence, Figures 6.2 and 6.3 are indicative of the minimum annual evapotranspiration depth and minimum annual precipitation depth needed (approx. 11 inches) before groundwater recharge occurs, leading to streamflow in the Upper Vermillion River watershed.

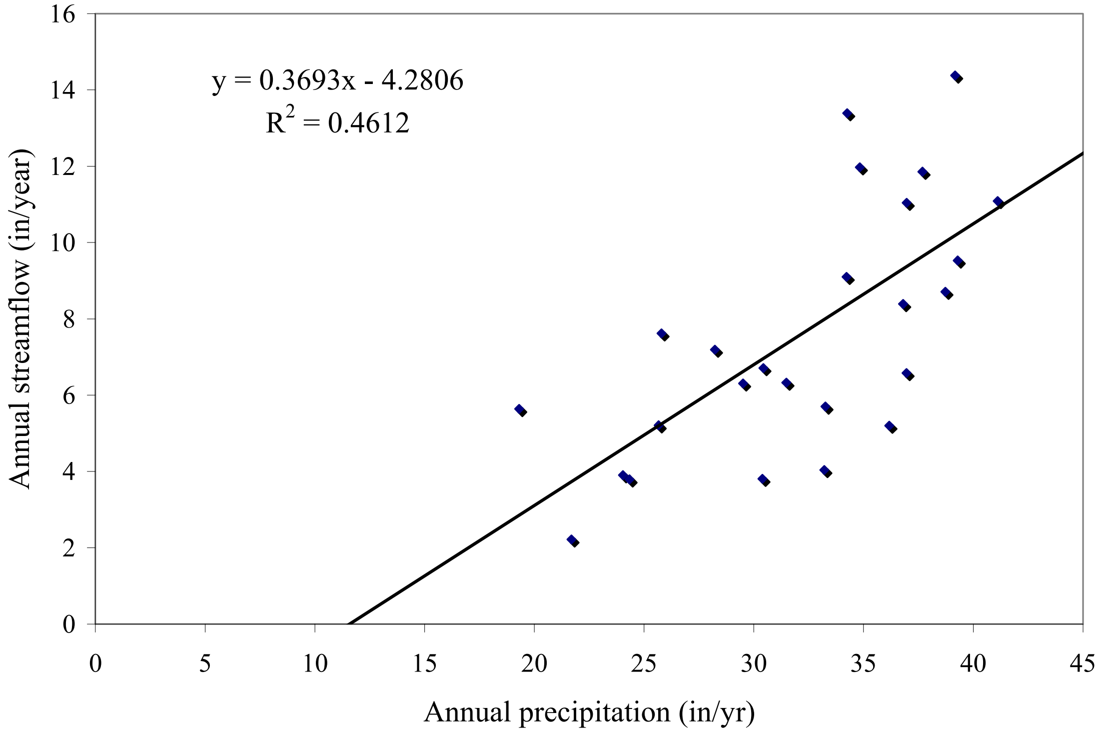


**Figure 6.2 Annual streamflow vs. annual precipitation.**

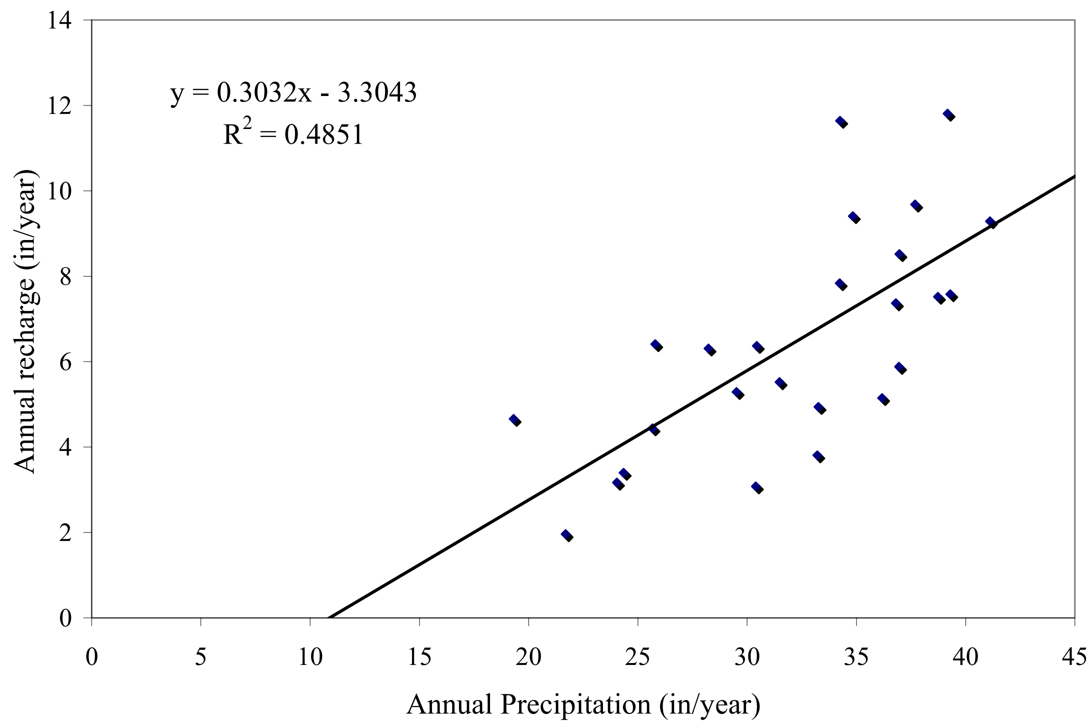


**Figure 6.3 Annual groundwater recharge vs. annual precipitation.**

Evapotranspiration increases with precipitation (Figure 6.4), i.e. more water becomes available to plants as precipitation increases, Figure 6.4 shows that approximately 76% of the precipitation in the watershed returns to the atmosphere through evapotranspiration. This follows average estimates for state-wide evapotranspiration, which is approximately 75% of annual precipitation (Baker et al. 1979).

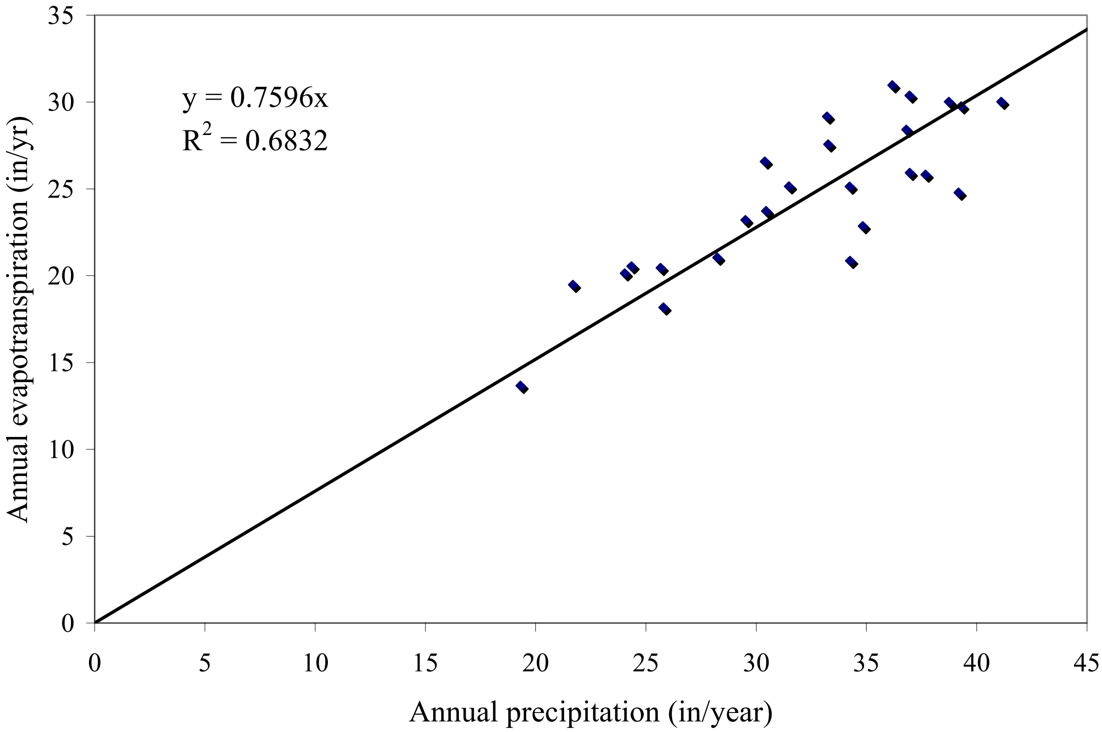


**Figure 6.4 Annual evapotranspiration vs. annual precipitation**

Infiltration/interception also increases with precipitation. According to Figure 6.5 about 95 percent of precipitation infiltrates into the ground or is intercepted and conveyed to storm-water detention ponds or other types of storage basins. This high percentage of infiltration reinforces the observation that the watershed is composed of mostly well-drained soils. Figure 6.5 also implies that very little (~5 %) of the annual precipitation becomes direct runoff. The high fraction (94%) of the annual precipitation that infiltrates from the watershed, leads to an excess of water in the soil column that becomes groundwater recharge, reinforcing the assumption that the Vermillion River is highly dependent on groundwater.

The relationship between direct surface runoff and precipitation is loose, but on average, linear. A minimum annual precipitation of approximately 16 in/yr must fall before significant runoff will occur. This minimum is higher than the minimum rainfall of 11 in/yr for streamflow and recharge to occur. The scatter of the data in Figure 6.5 indicates that runoff is affected by many factors other than precipitation, including the intensity and duration of a rainfall and/or the type of land use.

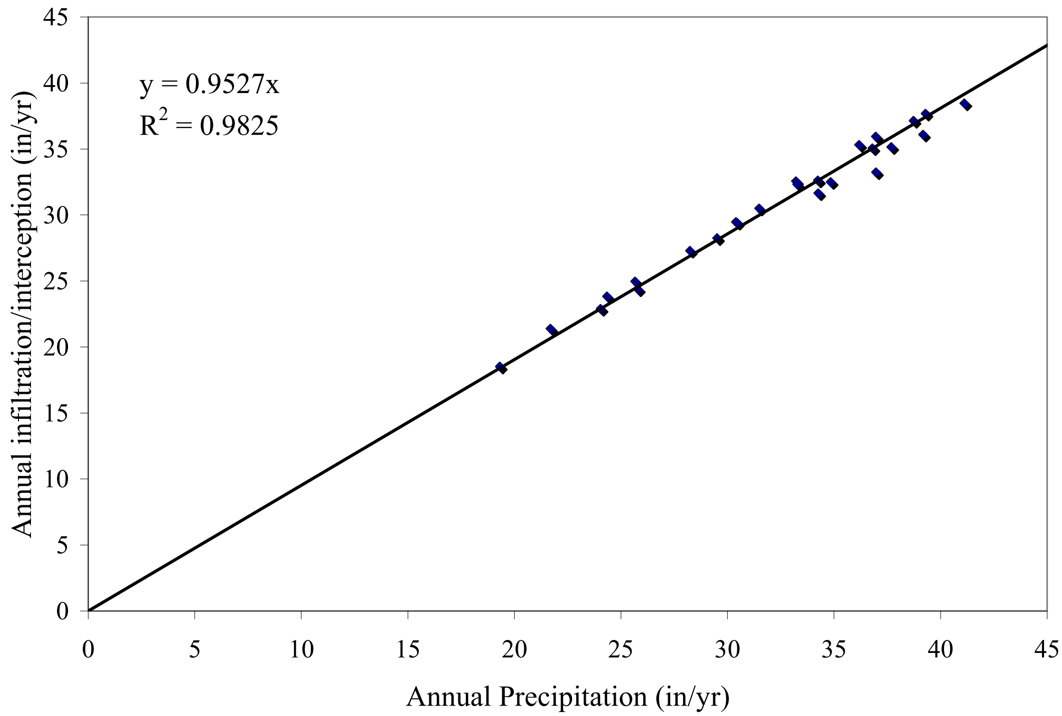


**Figure 6.5 Annual infiltration vs. annual precipitation**.

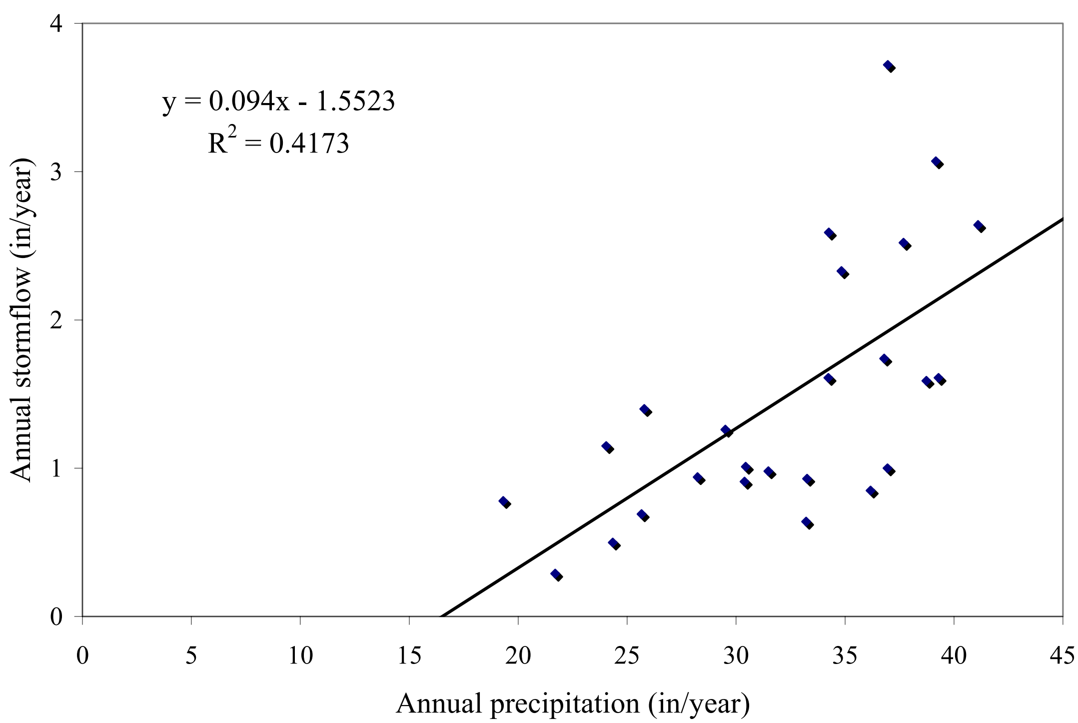


**Figure 6.6 Annual storm flow (direct runoff) vs. annual precipitation**

Figure 6.7 shows the relationship between annual 1-day low flow and groundwater recharge. As annual groundwater recharge increases, the annual minimum flow (1-day low flow) also increases. The relationship between 1-day low flow and annual groundwater recharge is fairly strong. This suggests again that the Vermillion River is highly dependent on its groundwater sources.

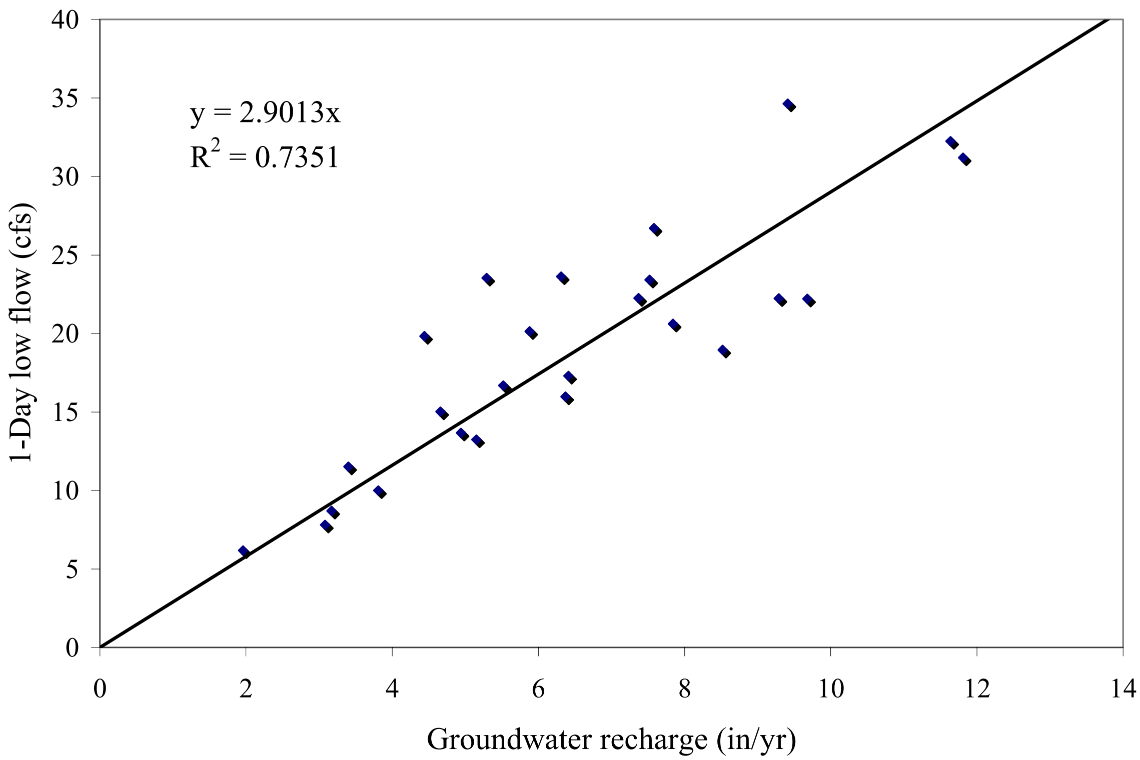


**Figure 6.7. 1-day low flow vs. annual groundwater recharge.**

The annual minimum 1-day flow may also be a reasonable predictor of the annual groundwater recharge. Figure 6.8 shows the relationship between 1-day low flow and annual groundwater recharge. Figure 6.8 shows a strong correlation between the 1-day low flow or annual minimum flow and the annual groundwater recharge. It shows that when the annual groundwater recharge increases, the 1-day low flow increases. This is reasonable since the more recharge occurs in any given year, the more water will be in storage in the aquifer, leading to higher groundwater discharges and higher minimum or 1-day low flows.

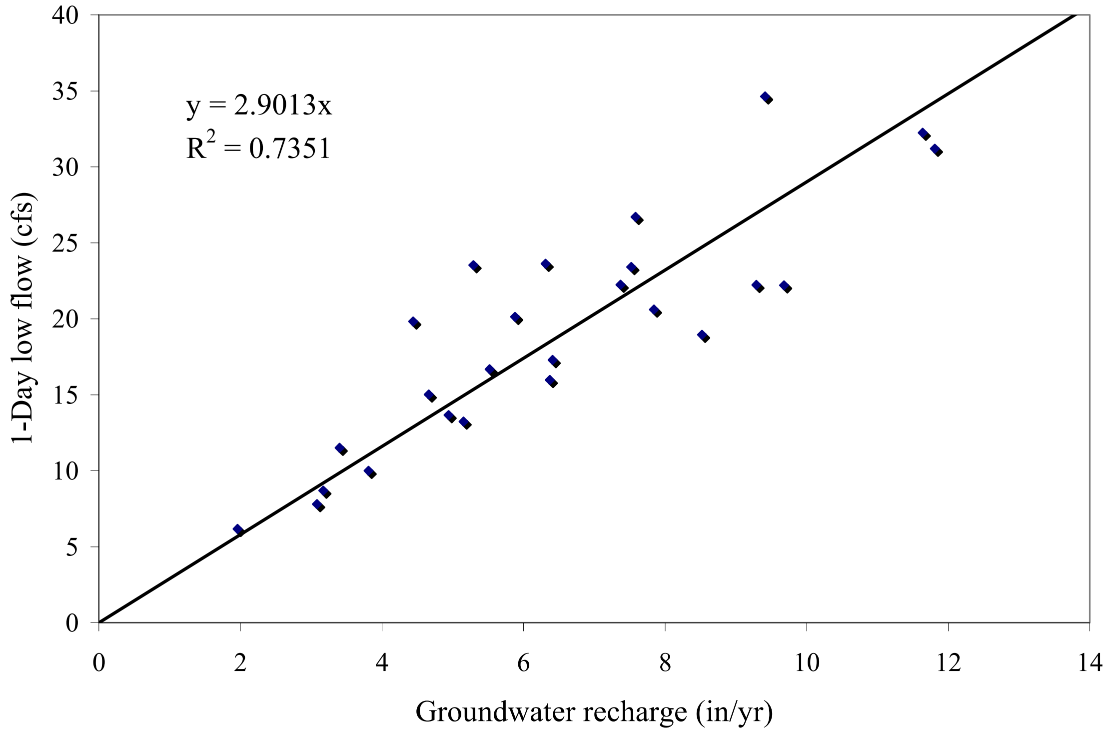


**Figure 6.8. Annual 1-day low flow vs. annual groundwater recharge.**

# 7. Trends in the Upper Vermillion River watershed

### 7.1 Land use and urbanization effects in other watersheds

Temporal trends in stream discharge can provide insight into changes that have occurred in the watershed, e.g. changes in land use and management practices caused by the urbanization of the watershed. Lins and Slack (1999) conducted a trend analysis on 395 stream gauging stations across the continental United States using the non-parametric Mann-Kendall test. Trends were calculated for selected quantiles of discharge, from the 0th to 100th percentile, to evaluate differences between low-, medium-, and high-flow regimes and over different time periods, ranging from 30 to 80 years of record during the twentieth century. They found that two general patterns; (1) trends were most prevalent in the annual minimum ($Q_0$) to median ($Q_{50}$) flows and least prevalent in the annual maximum ($Q_{100}$) flow; (2) at all but the highest quantiles, streamflow has increased across broad sections of the United States. The percentage of the stations showing statistically significant trends ranged from a low of 28% at 30 years of record to a high of 49% at 70 years of record, with upward trends exceeding downward trends by 4 to 1 when averaged over all time periods. The upward trend in low flows leads one to believe that baseflow has increased across the United States during the twentieth century.

Kramer et al. (1999) measured an increase in baseflow and a decrease in storm flow in four small watersheds (<150 acres) in the loess hills of western Iowa over a 30-year period. Schilling and Libra (2003) investigated the historical trends in annual discharge and baseflow characteristics for 11 gauging stations in Iowa. In nearly all the streams evaluated, annual baseflow, annual minimum flow, and annual baseflow percentage increased over time. Gebert and Krug (1996) examined annual flood peaks and the annual seven-day low flow records at 12 Wisconsin stream gauging stations, primarily in Wisconsin's driftless area, and found that annual low flows increased and annual flood peaks decreased in many agricultural watersheds from about 1930 to 1991. Gerbet and Krug (1996), Kramer et al. (1999), and Schilling and Libra (2003), all concluded that improvements in land management practices, such as terracing, conservation tillage, and contour cropping, may have played a role in modifying discharge variables in high relief agricultural watersheds. Many of these conservation practices were implemented to decrease field erosion during storm flow and to increase infiltration. Greater infiltration increases groundwater levels and sustains higher baseflow and minimum low flows in streams. In Wisconsin, many soil conservation practices began to be implemented by the U.S. Conservation Service in the late 1930s and the 1940s. In Iowa, the implementation of such practices is less known but was probably similar to Wisconsin. According to Schilling and Libra (2003), such improved conservation practices may have had their greatest impact on discharge in high relief watersheds. In low relief watersheds dominated by row crop agriculture, historical discharge trends may be linked to artificial drainage. Subsurface drainage tiles and ditches are used extensively throughout the Midwest to lower water tables and drain soils that are seasonally or perennially wet. Discharge from these drain tile networks may contribute both to storm-flow and to baseflow because surface outlets are connect to subsurface tiles. However, discharge from tile drains results predominately in increases in base flow discharge, annual minimum discharge, and a higher percentage of total discharge as baseflow. The passage of the Flood Control Act of 1944 and the 1954 Federal Watershed Protection and Flood Prevention Act increased artificial drainage, with the latter act authorizing the USDA to provide assistance with drainage projects (Beauchamp, 1987). The 1940 to 1960 period coincides with the period of significant increase in baseflow and baseflow percentage observed in nearly all streams studied (Schilling and Libra 2003).

The fore-mentioned studies focused on long-term general trends in streamflow, primarily in agricultural watersheds. These trends were general accounted for by the changing in land management practices through the twentieth century. Few studies have examined the impacts of urbanization on streamflow or base flow. This lack of investigation is brought on by the limited availability of suitable long-term streamflow record in streams in urban areas that are not affected by ungauged effluent discharges or flow regulation, or suitable rural streams for comparison. The problem is compounded by the complexity of the recharge process which depends on various climate parameters including intensity and duration of rainfall events, soil characteristic (such as soil's permeability, moisture content, and thickness) and depth, topography, vegetative land cover, and aquifer depth that can be hard to quantify due to the spatial and temporal variations that exist in natural systems leading to complications when trying to apply conclusions from one study area to other watersheds.

It is known that urbanization alters the hydrology in the watershed by changing water management practices and land use. These alterations may either increase or decrease groundwater recharge rates. According to Lerner (2002) the idea that cities reduce the amount of recharge to the underlying groundwater because of the increase in impermeable areas has been widely discredited since a mainly British group of hydro-geologists began to present research from various cities around the world. The sources and pathways for groundwater recharge in urban areas are more numerous and complex than in rural environments. Buildings, roads, and other surface infrastructure combine with man-made drainage networks to change the pathways for precipitation. Some direct recharge is lost because surface areas are made impervious, but additional recharge may occur through leaky pipes, lawn watering and other pathways. Large amounts of water are imported into most cities for supply, distributed through underground pipe networks and than collected again in sewer systems. Leaks from these pipe networks can provide substantial recharge.

The overall effect of urbanization on groundwater recharge depends on the number, type, and extent of each alteration of the watershed as well as such basin characteristics as climate, geology, and topography (Meyer 2005). Simmons and Reynolds (1982) studied the effects of urbanization on six streams in Long Island, New York over a 30-year period. They found that storm water sewerage, increased impervious surface area, and sanitary sewerage have reduced baseflow from 95 percent of total streamflow to 20 percent, where adjacent, un-urbanized watersheds showed no such decrease in percentage of streamflow. They compared streams in rural areas; unsewered and urbanized areas; and sewered and urbanized area. They found that baseflow was approximately 95% of streamflow for the rural streams, reduced to approximately 80% of streamflow for unsewered areas, and approximately 20% of the streamflow for the sewered areas. They concluded that the installation of sanitation sewer collection systems influenced the groundwater recharge the most, compared to unsewered areas. Meyer (2005) studied baseflow trends on urban streams in Cook County, Illinois. He found that no statistical significant trends occurred in the annual mean baseflow. Meyer (2005) did conclude that surficial deposits are relatively impermeable when compared to the deposits in Simmons and Reynolds (1982). He also pointed out that the water supply system in the Long Island study extracts water from deeper confined aquifers and returns the water to the surficial aquifer. During the early stages of development on Long Island, it is plausible that the baseflow actual increased beyond the predevelopment levels. Together, both studies show that groundwater recharge can increase, decrease, or remain the same, depending on the type and level of urbanization that takes place.

The Vermillion River watershed was primarily an agricultural watershed but has experienced a significant shift to urban development (Figure 4.3). An analysis was therefore performed to see if there are any trends in the streamflow data set from the USGS gauging station near Empire. The trend analysis consisted of two steps: (1) applying a linear trend-line using Microsoft Excel and (2) applying the Mann-Kendall test to determine if any of the trends are statistically significant.

### 7.2 Evidence of Trends in the Vermillion River watershed

To detect any trends that would indicate a changing hydrology in the Upper Vermillion River watershed, hydrologic variables were plotted as a time-series. Linear regression lines and their equations were added to the plots for the study period from 1982 to 2006. The variables plotted in Figure 7.1 are (a) annual precipitation (in/year), (b) annual streamflow (in/year), (c) annual flood peak flow (cfs), (d) one-day minimum flow (cfs), (e) annual groundwater recharge (in/year) estimated using the USGS program RORA, (f) annual baseflow as percentage of streamflow (BFI), and (g) storm flow or direct runoff (in/year). These plots are used to explore (1) if a trend is present, (2) what might cause this trend if it is present, (3) if the trend is due to changes in the hydrology of the watershed, and (4) if the trend is due to urbanization of the watershed.

The first sign that the hydrology in the Vermillion River watershed is changing are the trends of precipitation and of streamflow, especially when compared to each other (Figure 7.1a, b). There is a slightly decreasing trend ( -0.13 in/year) in precipitation from 1982 to 2006 and an increasing trend (0.04 in/year) in streamflow for the same time period. These opposing trends indicate that a larger percentage of the precipitation is reaching the stream. Had the hydrology of the watershed not changed, a decrease in annual precipitation would be expected to result in a lower streamflow (Figure 6.2). This evidence is, however, weak because the relationship in Fig. 6.2 has much uncertainty, and the trends are weak.

Annual maximum flood flow over the 24 year time period have a slightly decreasing trend but inspection of Figure 7.1(c) shows that the flood peaks are fairly random. One might expect an increase in maximum flood flow due to urbanization.

The trend line of the 1-day minimum flows is rising significantly. The 1-day minimum flows in the second half of the record are higher than in the first half. One would expect the minimum flows to decrease because of the decrease in precipitation over the time period. Since the minimum flow is a good indicator of groundwater recharge (Figure 6.8), one might conclude that groundwater recharge is increasing even though precipitation is decreasing, further supporting the idea that the hydrology of the watershed is changing.

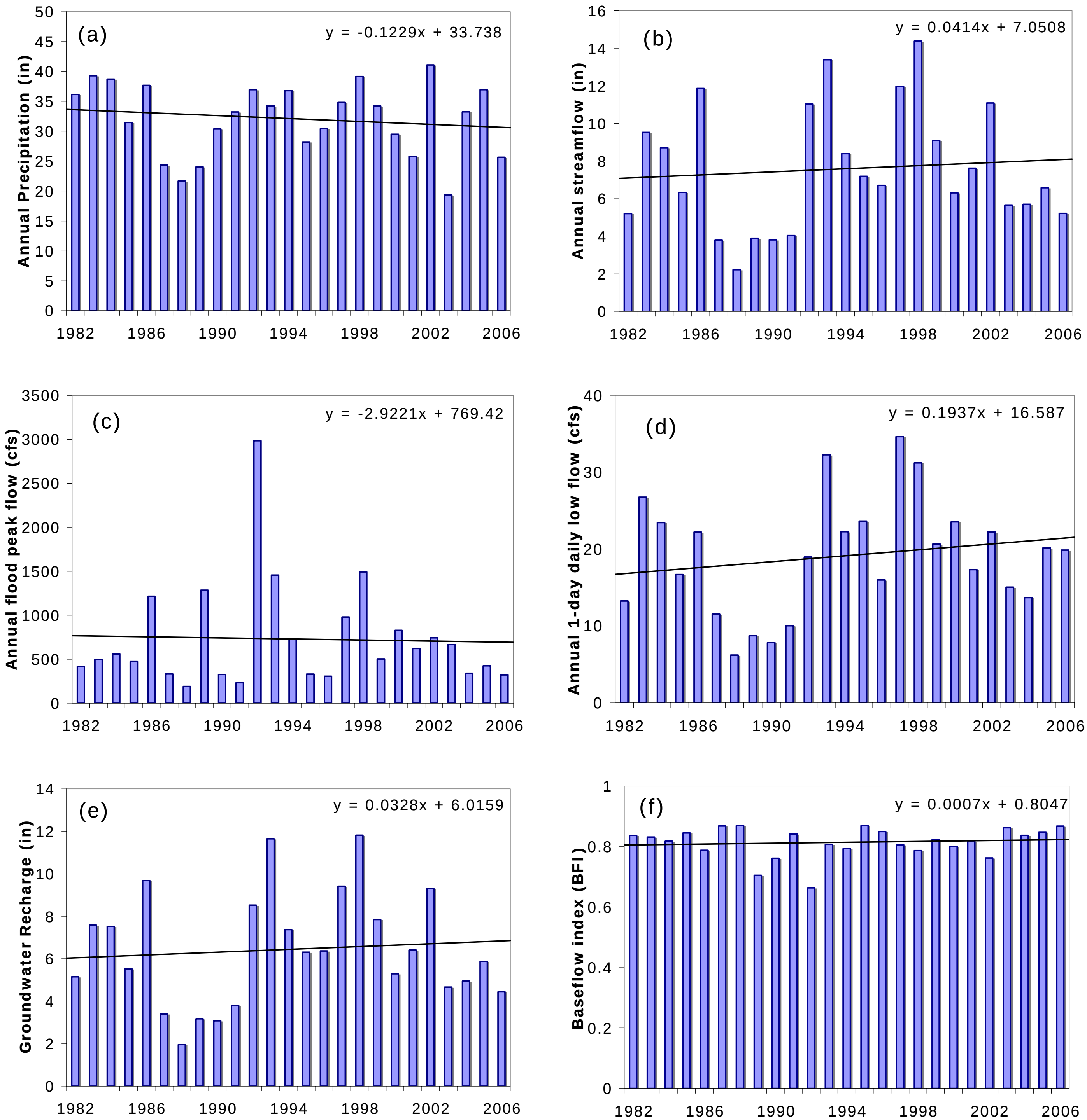


**Figure 7.1: Trends in the Upper Vermillion River watershed upstream from the USGS gauging site near Empire, MN: (a) annual precipitation (in/yr), (b) annual streamflow (in/yr), (c) annual maximum peak flow (cfs), (d) one-day low flow (cfs), (e) annual groundwater recharge (estimated using RORA) (in/yr), and (f) baseflow (estimated using PART) as fraction of streamflow**.

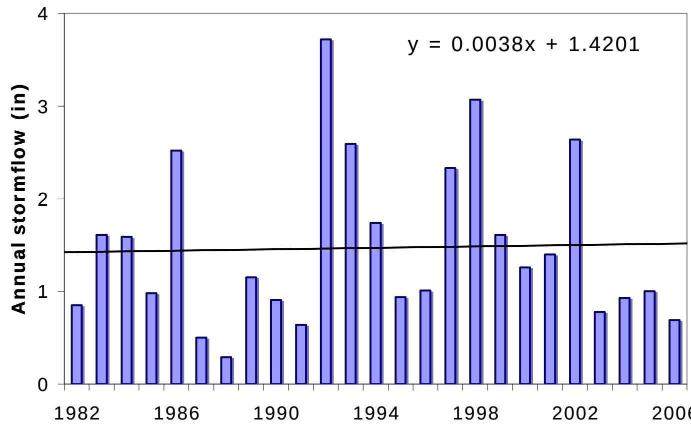


**Figure 7.1 (g): Annual stormflow or direct runoff (in/year) in the Upper Vermillion River watershed upstream from the USGS gauging site near Empire, MN.**

Figure 7.1(e) is a time-series plot of the annual groundwater recharge estimated using the USGS program RORA. The linear trendline indicates that groundwater recharge is increasing, confirming the trend seen in the low flow plot in Figure 7.1(d). As in plot (d), the groundwater recharge seems to be higher in the second half of the time period. One might expect that with decreasing precipitation, less water would be available for groundwater recharge, but the groundwater recharge is trending upward. This would indicate that the hydrology of the watershed is changing and that the change may be caused by the urbanization of the watershed.

The BFI (baseflow as a fraction of streamflow) shows only a slight variation throughout the time period. The BFI would be expected to be higher in years when annual precipitation is lower than average, because more of the stream flow would have to come from groundwater sources. The constancy of the BFI in plot (f) might indicate that the changes in the hydrology of the watershed might come from better land management practices. More of the precipitation infiltrates and reaches the stream through the ground, shifting the partitioning between recharge and direct runoff towards recharge.

Figure 7.1 (g) shows the direct runoff or storm flow as a function of time. The trend line indicates that direct runoff is trending upward slightly, but the data seem to be randomly distributed.

## 7.3. Statistical significance of trends

### *7.3.1 Methodology*

The trend lines in Figure 7.1 were tested for statistical significance. The formal hypothesis testing of the nonparametric Kendall tau test was employed. The test examines whether a random response variable monotonically increases or decreases with respect to time. It is a rank-based test, resistant to the influence of extremes. No assumption of normality is required, but there must be no serial correlation (Helsel and Hirsch 2002). The test has been found to be an excellent tool for discovering and testing trends in streamflows (Lins and Slack 1999; Zhang et al. 2001; Burn and Elnur 2002; Helsel and Hirsch 2002; Meyer 2005).

The Mann-Kendall test statistic (*S*) is given by (Burn and Elnur 2002) as

$$S = \sum_{i=1}^{n-1} \sum_{j=i-1}^{n} Sgn\left(X_j - X_i\right) \qquad [7.1]$$

where $X_i$ and $X_j$ are sequential data values, n is the data set record length, and

$$Sgn(\theta) = \begin{cases} +1 & \theta > 0 \\ 0 \quad if & \theta = 0 \\ -1 & \theta < 0 \end{cases} \qquad [7.2]$$

where θ is the difference between the the sequential values ($X_j$-$X_i$). By dividing S by n(n-1)/2, the possible number of comparisons in (7.1), the correlation coefficient, Kendall's τ, is given as

$$\tau = \frac{S}{n(n-1)/2} \qquad [7.3]$$

where τ ranges from +1 to -1, depending on the strength of the trend. If the data values are rising, the τ value will tend towards +1, if they are decreasing, the tau value will tend towards -1. Kendall's tau is a measure of the strength of the monotonic strength between the values. The closer the τ value is to 1, the stronger the trend.

To test the significance of τ, S is compared to what would be expected when a null hypothesis is truehe farther τ is from zero, the more likely the null hypothesis will be rejected. For large data sets (n > 10) the test statistic can be modified to be closely approximated by a normal distribution (Helsel and Hirsch 2002). Under the assumption of no trend, i.e. null hypothesis, the mean of τ is equal to zero and variance is given by

$$\sigma_S^2 = (n/18)(n-1)(2n+5) \qquad [7.4]$$

where n is the length of the data set. The standard normal variant, Z, computed using

$$Z = \begin{cases} \dfrac{S-1}{\sigma_S} & S > 0 \\ 0 \quad if & S = 0 \\ \dfrac{S+1}{\sigma_S} & S < 0 \end{cases} \qquad [7.5]$$

Thus, in the test for a trend at significance level of α, the null hypothesis should be rejected if $|Z| \geq z_{\alpha/2}$. A significance level of 95%, i.e. an alpha equal to 0.05, is commonly used (Lins and Slack 1999; Zhang et al. 2001; Burn and Elnur 2002; Helsel and Hirsch 2002; Meyer 2005) to disregard the null hypothesis.

The slope of the trend can be estimated by finding the Kendal-Theil slope. The slope estimate is closely related to Kendall's tau and is computed by comparing each data pair to all the others in a pairwise fashion (Heslel and Hirsch 2002). For each of the comparisons, a slope is computed and the median of all possible pairwise slopes is taken as the nonparametric slope estimate. The slope is estimated for each pairing using

$$m = median\left(\frac{Y_j - Y_i}{X_j - X_i}\right) \qquad [7.6]$$

for all i < j where i = 1,2,…(n-1) and j = 2,3,…,n. X and Y are the pairings being compared. In our case Y is the hydrologic variable, X is the year, and m is the slope of the trend. The slope found using equation (7.6) is different from the slopes of the trend lines in Figure 7.1. The Kendall-Theil slope is taken as the median slope of all pairwise slopes and is hardier against outliers than the slopes estimated in Figure 7.1, i.e. if outliers were removed, the slopes given in Figure 7.1 might change more than the slope obtained from equation (7.6).

### *7.3.2 Trend analysis results*

Kendall's tau, the p-value, and the slope m for each of the hydrologic variables for the Upper Vermillion River are given in Table 7.1. Kendall's $\tau$ in Table 7.1 is an indicator of a trend in the data. The closer the tau value is to 1, the stronger is the likelihood that a trend exists. The p-value in Table 7.1 is an indicator of the confidence interval (C.I.) for the null hypothesis, i.e. the hypothesis that no trend exists. The closer the p-value is to zero, the greater the confidence interval is to reject the null hypothesis. In many studies (Meyer 2005, Simmons and Reynolds 1982) a confidence interval of 95% is chosen to reject the null hypothesis, i.e. the p-value must be less than 0.05. The Kendall-Theil slope, m, is a measure of the linear trend if it exists.

**Table 7.1: Kendall statistics for hydrologic variables in the Upper Vermillion River watershed.**

| Variable | $\tau$ | p | C.I. (%) | m |
|---|---|---|---|---|
| Annual precipitation | -0.113 | 0.441 | 53.9 | -0.141 |
| Annual streamflow | 0.053 | 0.726 | 27.4 | 0.030 |
| Annual baseflow (PART) | 0.033 | 0.834 | 16.6 | 0.024 |
| Annual groundwater recharge (RORA) | 0.027 | 0.870 | 13.0 | 0.017 |
| Annual direct runoff | 0.013 | 0.944 | 5.6 | 0.001 |
| Baseflow/ streamflow (BFI) | 0.060 | 0.691 | 30.9 | 0.001 |
| Recharge/ streamflow | -0.047 | 0.761 | 23.9 | -0.001 |
| Annual peak flow | 0.000 | 1 | 0.0 | 0 |
| Annual 1-day min. flow | 0.073 | 0.624 | 37.6 | 0.139 |
| Annual evapotranspiration | -0.1667 | 0.253 | 75.7 | -0.1626 |

$\tau$ = Kendall's tau, m = Kendall-Theil slope, C.I. = confidence interval

The null hypothesis cannot be rejected for any of the hydrologic variables of the Upper Vermillion River watershed in Table 7.1 at a 95% confidence interval, because no p-value was found to be below 0.05. The p-values range from 0.25 to 0.94 meaning confidence intervals of 75% to 6%, respectively, for rejection of the null hypothesis. These confidence intervals are too small for rejection at a 95% confidence level. This does not mean that trends don't exist, just that the trends might not be noticeable in the data and cannot be confirmed statistically at a 95% confidence level.

Selected hydrologic variables were normalized to precipitation and trends of the new variables were determined. The selected hydrologic variables are streamflow, baseflow, groundwater recharge, direct surface runoff, and evapotranspiration. The statistics of the normalized hydrologic variables are given in Table 7.2.

**Table 7.2: Kendall statistics for selected normalized hydrologic variables in the Upper Vermillion River watershed. Variables have been normalized to precipitation.**

| Normalized variable | tau | p | C.I. (%) | m |
|---|---|---|---|---|
| Streamflow | 0.140 | 0.338 | 66.2 | 0.0026 |
| Annual baseflow (PART) | 0.167 | 0.252 | 74.8 | 0.0026 |
| Annual groundwater recharge (RORA) | 0.160 | 0.272 | 72.8 | 0.0023 |
| Annual direct runoff | 0.033 | 0.834 | 16.6 | 0.00015 |
| Annual evapotranspiration | -0.140 | 0.338 | 66.2 | -0.0026 |

Table 7.2 shows that there are no statistically significant trends at the 95% confidence level, i.e. all p-values are > 0.05. The normalized hydrologic variables in Table 7.2 do

show lower p-values than the p-values in Table 7.1, i.e. trends in the normalized variables have higher confidences intervals than the basic variables. For example, for annual streamflow, the 27% confidence level (Table 7.1) has risen to 66% that there is an increasing trend in the percentage of precipitation reaching the stream as streamflow. A discussion of trends is given next.

### 7.4 Discussion of trends

Even though the analysis shows that the null hypothesis cannot be rejected at the 95% confidence interval, trends exist at smaller confidence intervals. Annual precipitation was found to have a decreasing trend at a confidence interval of 54% over the study time period; streamflow was found to have an increasing trend at a 27% confidence interval. It is interesting that precipitation is decreasing and streamflow is increasing, pointing to an impact of urbanization. This impact could be attributed to an increase in impervious areas but the baseflow in the watershed is increasing with a confidence interval of 17% where direct runoff shows an increasing trend at 6% confidence interval.

Streamflow can be increased by baseflow or by surface runoff. If the increase is due to increased impervious areas, one would expect that baseflow is lower and surface runoff is higher. The BFI is increasing at a confidence level of 31%, meaning that the baseflow is contributing a larger percentage of the streamflow. The 1-day flow also shows an increasing trend - at the 38% confidence level, possibly also an effect of urbanization on groundwater recharge or baseflow. Another effect that could be attributed to urbanization is the decreasing trend in annual evapotranspiration at the 76% confidence interval. If urbanization means less vegetation on the ground surface, then less water will be return to the atmosphere through evapotranspiration. Since none of the trends meets the 95% confidence interval for rejecting the null hypothesis, the above explanations are plausible but not confirmed. The trend analysis found that no trend meets the 95% confidence interval criteria to reject the null hypothesis. This doesn't mean that trends don't exist; they may be just not noticeable by the methods employed by this investigation..

A longer data set than for the 1982 to 2006 time period may be needed to confirm the statistical trend shown in figure 7.1 and Table 7.1. Interestingly the trends had higher confidence intervals when the hydrologic variables were normalized relative to precipitation. The confidence interval for the rejection of the null hypothesis for annual streamflow increased from 28 % to 66 % when streamflow was expressed as a percentage of precipitation; likewise the confidence interval for baseflow increased from 17% to 75%, that for the groundwater recharge increased from 13% to 73%, that for direct runoff from 6% to 17%, and that for evapotranspiration decreased from 76% to 66%. These increases in the confidence interval, although not reaching the 95% level, can be interpreted to be indicators of changes in the hydrology of the watershed, and confirm that urbanization might have affected the watershed.

## 8. Summary and Discussion

Long-term estimates of groundwater recharge, evapotranspiration and infiltration were found by a baseflow analysis of the streamflow record from the USGS stream gauging station site #05435000 on the Upper Vermillion River near empire, MN. Precipitation measurements in the watershed were also used. The data analysis covered the period 1982 to 2006 and proceeded in three major steps.

**Step 1:** Annual groundwater recharge estimates for the Upper Vermillion River watershed were found using the baseflow-separation method (PART) and recession-curve-displacement method (RORA). A basic assumption underlying this analysis was that groundwater recharge from the ground surface is equal to groundwater discharge, baseflow, in the receiving stream. All flow and recharge and values were expressed as a representative water depth spread uniformly over the watershed (129 sq mi). The annual streamflow in the Upper Vermillion River was thus expressed as 7.6 ± 3.3 in/yr (193 ± 84 mm/yr). Using the USGS program PART, the annual baseflow was estimated as 6.1 ± 2.5 in/yr (155 ± 64 mm/yr). The USGS program RORA was used to estimate the groundwater recharge as 6.4 ± 2.5 in/yr (163 ± 64 mm/yr). Both programs gave thus similar results and showed good correlation to each other (Figure 5.2). The difference between the two estimates can be the riparian evapotranspiration (Rutledge and Mesko 1996), or just an error in the methodology. The recession-curve-displacement method (RORA) is considered to give a more accurate estimate of groundwater recharge since it is based on physical processes (Halford and Mayer 2000). It was found that about 80% of the streamflow is baseflow and comes from groundwater sources. The baseflow percentage of streamflow was fairly constant over the study time period showing a strong, stable relationship between baseflow and streamflow (Figure 5.3). Because of this relationship the Vermillion River has had a dependable coldwater source that was crucial to support the trout population in the stream.

**Step 2:** Long-term estimates of other hydrologic variables for the watershed were found (Figure 6.1) using the results of the baseflow/groundwater recharge analysis in conjunction with annual precipitation data and a simple water budget for the watershed. Using rainfall records from Farmington, MN, the annual rainfall in the watershed was estimated to be 32.1 ± 6.0 in/yr (815 ± 152 mm/yr). The analysis showed that 24% of the annual precipitation reaches the stream, either by direct runoff or as groundwater discharge. Streamflow shows a linear relationship to precipitation (Figure 6.2). Approximately 95%, or 30.7 in/yr (780 mm/yr), of the annual precipitation infiltrates into the ground or is otherwise intercepted, leaving about 5% of the annual precipitation, or 1.5 in/yr (38 mm/yr), for stormwater flow or direct runoff into the stream. Infiltration showed good correlation to precipitation (Figure 6.5), but this may be attributed to the large percentage of precipitation that is infiltrated. Runoff showed a loose relationship with precipitation (Figure 6.6),i.e. other factors influence the amount of runoff reaching the stream. About 79% of the infiltrated water or 76% of annual precipitation is returned to the atmosphere through evapotranspiration; that is 24.6 ± 4.5 in/yr (625 ± 114 mm/yr). The analysis also showed that at least 11 inches (279 mm) of precipitation must fall annually before streamflow occurs. This is because plants return so much water to the atmosphere by evapotranspiration. These annual estimates do not imply that an intense individual storm event cannot produce surface runoff or recharge, but they do imply that the minimum annual evapotranspiration in the watershed is 11 inches. Groundwater recharge was found to be about 21% of the infiltrated water or 20% of the annual precipitation. Annual groundwater recharge showed a weak correlation to annual precipitation (Figure 6.3). These annual estimates for a variety of hydrologic variables match estimates from previous studies (Baker et al. 1979, Ruhl et al. 2002, Lorenz and Delin 2007). The estimates can be used in the development of watershed models to investigate the effects of urbanization on the Vermillion River.

**Step 3:** Temporal trends in the mean annual values (estimates) of the hydrologic variables were analyzed to detect signs of progressive urbanization in the originally agricultural Upper Vermillion River watershed. While annual precipitation is trending downward, annual streamflow, groundwater recharge, and 1-day low flows were found to be increasing. The non-parametric Kendall tau test was employed to see if the trends are statistically significant. None of the hydrologic variables had a trend strong enough to reject the null hypothesis at the 95% confidence level Table 7.1.The hydrologic variables were also normalized with annual precipitation as the reference (Table 7.2). None of the trends of the normalized variables had higher confidence intervals, but could not reach the 95% confidence interval. One interesting finding is that annual groundwater recharge had an increasing trend while annual precipitation had a decreasing trend. Urbanization of the Upper Vermillion River therefore seems to have an effect opposite to what is expected.

Three possible explanations for the absence of significant trends in the hydrologic variables despite urban development in the watershed are:

(1) The urban development in the watershed might not be significant enough or in the 'wrong' areas to affect groundwater recharge and supply. Localized groundwater recharge might dominate the recharge processes. Unlike diffuse groundwater recharge, which is spread over a large area, localized recharge enters the aquifer in localized small areas such as depressions, 'soakways' or seepage from surface waters. To affect localized groundwater recharge, the urban development would have to be at the exact location of the recharge. If the urban development is not in the areas where most of groundwater recharge enters the aquifer, little or no effect on the baseflow in the stream will be seen.

(2) A large portion of the baseflow comes from deep, maybe confined, aquifers. One of the many assumptions of the streamflow/baseflow analysis techniques is that leakage to or from deeper aquifers is negligible. If a large portion of the baseflow comes from deep aquifers, the baseflow would be more resilient to urbanization since deep aquifers are most likely recharged by a source of water outside of the watershed. The reduction or increase of groundwater recharge to the surface aquifer – caused by urbanization - might therefore have a minor influence on the streamflow/baseflow. If this were the case, the stream might be more resilient to urbanization than expected. A larger portion of the watershed or the recharge areas of the larger, deep aquifer system will have to become urbanized to detect any effect in the streamflow.

(3). The reduction in natural recharge due to the increase in impervious surface area is replaced by artificial recharge sources. These artificial recharge sources include leakage from storm sewers or water supply networks, seepage from storm water detention ponds, or lawn irrigation during the growing season. In a study of the effects of urbanization in Nottingham, UK, Yang et al. (1999) found that the decrease in natural recharge from precipitation caused by the increase in impervious areas was mitigated by artificial recharge from leakage of sewer systems and water mains that import water from outside.

It is possible that all three explanations apply to the Vermillion River. It is likely that the watershed of the Vermillion River, a trout stream, receives some of its cold groundwater from deep aquifers. The decreasing trend in precipitation and the increasing trend in streamflow and baseflow point to an increase in groundwater recharge. This leads to the conclusion that groundwater recharge from precipitation in the watershed is being replaced by imported water.

Urbanization affects the pathways and source of water in a watershed. The effects of urbanization on groundwater and streamflow are therefore complex and difficult to analyze. Evidence of the effects of urban development on the amount of groundwater recharge and baseflow in the Upper Vermilion River watershed was weak. The decrease in groundwater recharge that would be expected to result from an increase in impervious areas, is apparently replaced by excess imported water or artificial recharge, leaving the streamflow relatively unaffected by current urban development. This study has focused on the quantity of groundwater recharge in the Vermillion River, and how urbanization is affecting it. How urbanization will affect the quality of groundwater was not studied but should also be considered for the management of the Vermillion River watershed.

## 9. Conclusions

1) Estimates of the annual average values of several hydrologic variables for the Upper Vermillion River watershed compared well to results of previous studies (Baker et al. 1979, Ruhl et al. 2002, Lorenz and Delin 2007).

2) Approximately 80% of the annual streamflow in the Upper Vermillion River is from groundwater sources, up to 15 cfs of mean annual streamflow

3) Urbanization in the watershed has not significantly affected the groundwater discharge to the Upper Vermillion River..

4) Streamflow and baseflow in the Upper Vermillion River have a slightly increasing trend.

5) Linear trends were found in the 1982-2006 records of most hydrologic variables, but no statistically significant trends were found at the 95% confidence level.

6) Mean annual values of hydrologic variables normalized to mean annual precipitation showed trends at higher confidence intervals than the non-normalized values.

7) Baseflow or groundwater recharge did not show any decreasing trends associated with urbanization and the associated increase in impervious areas. If anything, they tended to show a slight increase during the study time period (1982-2006).

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## Notations

A = area of drainage area or watershed (sq mi, sq km).
a = average distance from the stream to the hydrologic divide (L),
*BF* = mean groundwater discharge or baseflow [in/year],
*C1,C2,C3* = empirical coefficients.
DR = mean direct runoff [in/year].
*ET* = mean evapotranspiration [in/year]
$GW_{in}$ = influxes from up-gradient portions of the groundwater system,
$GW_{out}$ = effluxes to down-gradient portions of the groundwater system,
*I* = mean infiltration and interception [in/year]
K = recession index (T).
N = time base of surface runoff (days),
*P* = mean precipitation [in/year],
Q = groundwater discharge at the initial time,
$Q_1$ = groundwater discharge at critical time as extrapolated from the streamflow recession preceding the peak ($L^3/T$),
$Q_2$ = groundwater discharge at critical time as extrapolated from the streamflow recession following the peak ($L^3/T$),
$Q_s$ = discharge to or from surface water bodies,
$Q_w$ = abstractions from groundwater system through wells,
*R* = mean groundwater recharge [in/year] to the aquifer,
*RET* = mean riparian evapotranspiration [in/year],
S = Storage coefficient (-),
*SF* = mean streamflow [in/year].
T = time (T),
$T_c$ = critical time (T),
TR = transmissivity ($L^2/T$).
V = total potential groundwater discharge,
$\Delta S/t$ = change in groundwater storage per unit time.

## Appendix - Glossary

**Aquifer** is defined as the saturated zone in a soil column that holds groundwater.

**Adjusted streamflow** is the streamflow data from the USGS gauging site minus the Empire wastewater treatment plant (WWTP) effluent to obtain a natural streamflow record.

**Base-flow** is the portion of streamflow that generally comes from groundwater discharge, sustaining the streamflow between rainfall events.

**Base-flow Index (BFI)** (Nathan and McMahon, 1990) is a simple, physical metric of contribution of base-flow to streamflow that is primarily used in region scale studies. The base-flow index is defined as ratio of the average rate of base-flow relative to average rate of streamflow and varies between zero and one where increasing value indicate increase contribution of base-flow to streamflow and provides a way of normalizing groundwater discharge to climate conditions (Rutledge and Mesko, 1996).

**Direct runoff**, also called stormflow or quick flow, is the overland flow of water due to rainfall event.

**Evapotranspiration** represents the sum of the processes of evaporation and transpiration from the land surface to the atmosphere. Evaporation is the movement of water from wet surfaces (water, soils, pavements, bui;ldings) to the air, and transpiration is water movement out of vegetation (plants) into the air.

**Groundwatershed** is the subsurface area from where water drains to a defined discharge point.

**Hydrograph** is a graph on which streams discharge is plotted against time in response to a rainfall event

**Hydrologic variables** characterize the processes of water movement in a watershed. They include streamflow, infiltration, evapotranspiration, run-off, and recharge.

**Infiltration** is the process by which water enters the soil from the ground surface.

**Recharge** is the amount of water that flows, by gravity, through the soil beyond the reach of the surface vegetation ultimately reaching the saturated zone, i.e. an aquifer, through the processes of vertical percolation or seepage.

**Recession curve index (K)** is the time required for groundwater discharge to decline through one log cycle, i.e. $Q_0$ to $0.1Q_0$. The recession index is a constant that represents the physical properties of the aquifer.

**Stormflow**:  see direct runoff.

**Transmissivity** of an aquifer is a measure of how much water can be transmitted horizontally. It is proportional to the aquifer thickness and the permeability.

**Watershed**, also known as a drainage basin, is the land area from which water drains by over land flow, in streams or channels to a defined point.