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# Groundwater Recharge in a Coldwater Stream Watershed during Urbanization

by

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# Abstract

Urban development of rural land is of concern for water resources. The quantity and quality of surface runoff and groundwater recharge can be significantly affected by urbanization. Base flow in streams and cold water habitat, e.g. for trout, depend on groundwater. If water recharge to aquifers is reduced, and surface runoff is increased, cold-water fish habitat can be adversely affected. The change to groundwater recharge resulting from the urbanization of a rural/natural area in the Vermillion River watershed in Minnesota was investigated. The Vermillion River is a groundwater-fed designated trout stream at the southern fringes of the Minneapolis/St. Paul metropolitan area in Minnesota. In this watershed urban development has encroached on farmland and natural areas in the last 25 years. The process is projected to continue into the future.

Three studies related to groundwater recharge were conducted: (1) a soil water budget study to estimate the influence of changed imperviousness and surface vegetation on natural recharge in a small tributary watershed of the Vermillion River, (2) a trend analysis of stream/base flow at the USGS stream gauging site on the Vermillion River near Empire, MN, and (3) a water use study to estimate the influence of imported water on artificial recharge stemming from.

The results of the first study confirm that the increase in impervious surface area associated with urban development will decrease annual natural groundwater recharge. The trend analysis (second study) showed no statistically significant trend in the streamflow record during the period of 1982 to 2006 even though imperviousness in the watershed increased from 8% in 1984 to 13% in 2005. The third study revealed that groundwater recharge from urban water supply and drainage systems and from irrigation has more than doubled from 1982 to 2006; it accounts for nearly 10% of annual recharge in the watershed and matches the reduction in natural recharge predicted by the soil water budget models (first study). The net effect of urbanization on groundwater recharge, seen in the trend analysis of the Vermillion River base flow was close to zero

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# 1. Introduction

Developing rural and natural landscapes into urban environments can be a concern for water resources management. In 1900, only thirteen percent of the world's population lived in urban areas, up from three percent in 1800 (The Economist, 2007). Currently, about fifty percent of all people live in cities. By 2030, sixty percent are expected to live in urban areas. In developing countries, the percentage of urban population may be as high as eighty to ninety percent (Bugliarello, 2007).

Quantity and quality of surface water runoff and groundwater recharge can be affected by urbanization (Foster, 1999). Base flow in streams and cold water habitat, e.g. for trout, depend on groundwater. If infiltration and groundwater recharge to aquifers are significantly reduced by urban development, groundwater supplies decrease and more streamflow has to come from surface runoff rather than groundwater. The associated change in stream hydrographs and raising water temperatures can adversely affect cold-water habitat. When permits for urban development are issued the effect of urban encroachment on coldwater streams needs to be better understood to protect the habitat for coldwater fish species.

In this report the effect of urbanization on the quantity of water entering (recharging) an aquifer will be investigated. 'Groundwater recharge' or simply 'recharge' is defined here as the amount of water that flows by gravity (vertical percolation) beyond the root zone, i.e. beyond the reach of vegetation, in the soil. This water will usually reach an aquifer unless it is diverted to interflow in steep terrain.

The mechanisms and the spatial distribution of groundwater recharge can be divided into three types: direct, localized, and indirect (De Vries and Simmers, 2002; Lerner et al., 1990; Lerner, 2002). Direct recharge is defined as the water added to a groundwater reservoir by direct vertical percolation of precipitation through the unsaturated zone in excess of soil-moisture deficits and evapotranspiration (Lerner et al., 1990). This type of recharge is diffuse and usually occurs over large areas. Localized recharge is an intermediate form of groundwater recharge resulting from nondescript point or line sources (horizontal surface or near surface concentrations of water in the absence of well-defined channels). This type of recharge includes pipe leakage from water distribution networks, wastewater and storm-water collection systems, roof runoff soakways, or can occur along the edges of paths and roads where no formal storm drainage exists (Lerner, 2002). Indirect or focused recharge is the percolation of water to the saturated zone through the beds of surface watercourses or bodies, usually occurring as mappable features, such as rivers, lakes, storm-water detention ponds, or sinkholes. Indirect recharge is often call seepage when it stems for surface water bodies.

Urbanization can radically alter every aspect of the hydrologic cycle and water budget for urban areas (Lerner et al., 1990). Urbanization alters the hydrology in the watershed by changes in land use and by introducing new water collection and conveyance systems (Schilling and Libra, 2003). Understanding urban recharge and the effects of urbanization on groundwater recharge is a complex problem. Alterations of the landscape may either increase or decrease groundwater recharge rates. Urbanization may reduce infiltration and hence 'direct' groundwater recharge through "impermeablization" of the land surface by roads, buildings, driveways, and parking lots (Foster, 1999; Lerner, 2002; Meyer, 2005). This reduces direct infiltration of excess rainfall, but also tends to lower evapotranspiration and to increase and accelerate surface run-off (Foster,1999). When direct infiltration is decreased groundwater recharge rate is less, and less groundwater provided to base flow in coldwater streams. The increased and warmer surface run-off can raise stream temperatures.

The impact of the adverse effects of urbanization may be tempered by new man-made water distribution systems for consumption and irrigation (lawns) in urban areas, and additional pathways for water to reach aquifers (Lerner, 2002; Meyer, 2005). A portion of this water which is often "imported" from locations outside the watershed, will contribute either to 'direct' groundwater recharge as an addition to precipitation through lawn and crop irrigation or to 'localized' recharge through pipe leakage in water distribution networks or drainage from septic systems. In this paper, recharge will be characterized as having two water sources: (1) natural recharge, which derives from infiltration of precipitation and (2) artificial recharge, which comes from "imported" water, usually from sources outside of the watershed.

The effects of urbanization on groundwater recharge are complex and much of the research is site specific. Simmons and Reynolds (1982) investigated the effects of urbanization on base flow in streams on the south shore of Long Island, New York. They found that the percentage of streamflow that comes from groundwater sources has diminished from 95% to 20%, primarily due to the instillation of sanitary and storm sewer systems. Meyer (2005) analyzed base flow trends for urban streams in Cook County in northeastern Illinois. He found little or no statistically significant trends in base flow due to urbanization. Yang et al. (1999) investigated the effects of urbanization on groundwater recharge for Nottingham, UK. They used solute and water balances in conjunction with modeled groundwater flow. They found that natural recharge of groundwater had decreased from 179 mm/year to 53 mm/year from 1850 to 1995 but artificial recharge from leaky urban storm sewers and water distribution pipe networks had increased from 59 mm/year to 158 mm/year, with a net decrease for the area of only 27 mm/year. The overall effect of urbanization on recharge can be described as a function of the number and types of alterations in the watershed as well as basin characteristics such as climate, geology, and topography (Meyer, 2005).

In this study we will investigate the effect of urbanization on groundwater recharge in the Vermillion River watershed. The Vermillion River is a coldwater stream known for world-class trout. The stream is fed by groundwater and located near the southern edge of the expanding Twin Cities Metropolitan Area of Minneapolis/St. Paul in Minnesota. There is fear that with progressive urban development in its watershed the stream might warm due to decreasing cold groundwater resources and increasing warm surface runoff, rendering the stream uninhabitable for trout.

The effect of urbanization has on 'natural' and 'artificial' recharge will be studied to estimate the net effect on groundwater recharge. This report will provide

(1) a description of the watershed, its physical properties and the progression of urbanization in the watershed from 1984 to 2005,

(2) a summary of model simulations to project the effect of increased urbanization (imperviousness) on natural groundwater recharge in a tributary watershed to the Vermillion River watershed,

(3) results of a trend analysis to examine streamflow, baseflow, and other hydrologic properties of the upper Vermillion River, primarily to see if urbanization can be detected in the streamflow record,

(4) results of a water use study to examine the influence of 'imported' water on groundwater recharge, and

(5) an analysis linking the findings of the foregoing studies, and a discussion of the net effect of urbanization on groundwater recharge to the surficial aquifer that supplies baseflow to the Vermillion River.

# 2. The Vermillion River watershed

## 2.1 Geography

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 (Figure 2.1). The watershed includes approximately 338 square miles of drainage area within Dakota and Scott Counties. The Vermillion River's headwaters are in southeastern Scott County. The river flows eastward through central Dakota County and joins the Mississippi River southeast of Hastings near Lock and Dam No. 3. The upper portion of the watershed includes several coldwater tributaries that support a naturally reproducing brown trout population, which is dependent on groundwater and sustained coldwater temperatures for survival (EOR Report, 2007). Our study focuses on these upper reaches of the Vermillion River.

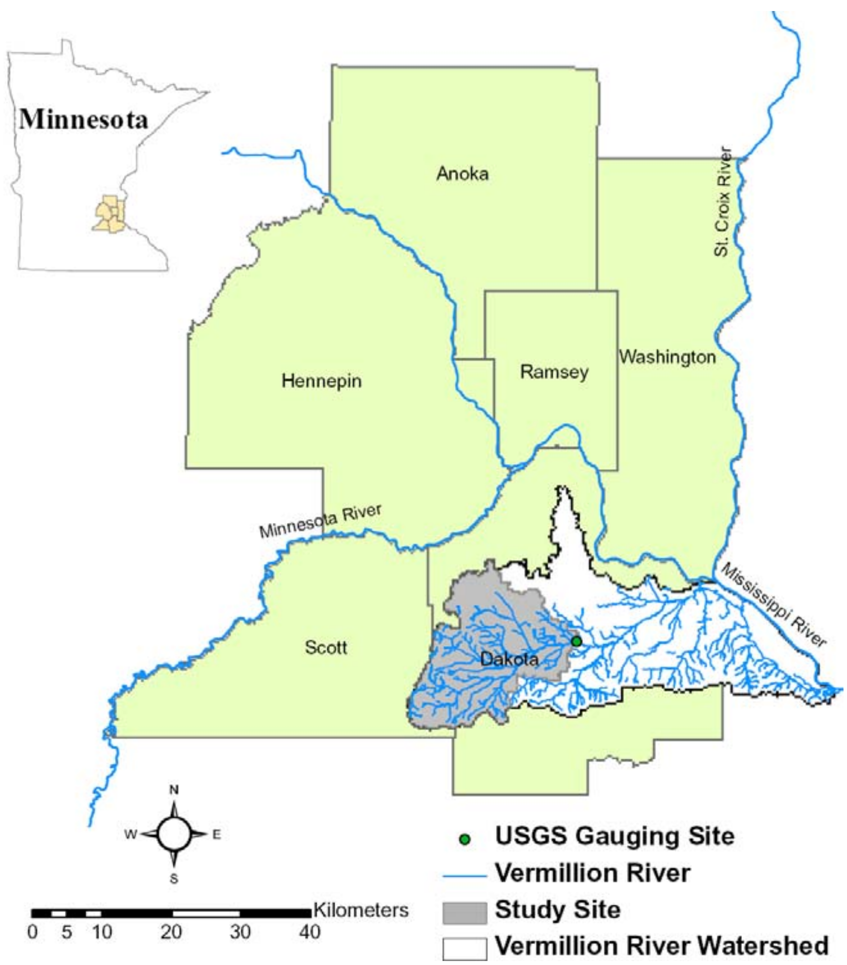


**Figure 2.1: Upper Vermillion River watershed and the USGS gauging site near Empire, Minnesota.**

The groundwater recharge study encompasses the upper third of the Vermillion River watershed as determined by the USGS stream gauging station at Empire, MN. A long-term daily stream flow record was obtained for the USGS gauging station site #05435000 on the Vermillion River near Empire, MN (Figure 2.2), from the USGS water data site for Minnesota at http://waterdata.usgs.gov/nwis/nwis/. The gauging station has the longest continuous streamflow record in the watershed, starting in 1974 and continuing to the present. The USGS gauging site near Empire captures drainage from 129 square miles of the Vermillion River watershed (Figure 2.2), 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.

The Upper Vermillion River watershed includes the cities of Apple Valley, Burnsville, Eagan, Elko, Farmington, Lakeville, New Market, and Rosemount and the townships of Castle Rock, Credit River, Empire, Eureka, and New Market. The percent of city area within the watershed is given in Table 2.1.

**Table 2.1 Cities within the watershed.**

| City | Total area sq km | Area in watershed sq km | City area in watershed % |
|---|---|---|---|
| Apple Valley | 45.2 | 28.4 | 62.7 |
| Burnsville | 69.9 | 12.4 | 17.8 |
| Castle Rock | 92.7 | 4.8 | 5.2 |
| Credit River | 61.7 | 1.9 | 3.1 |
| Eagan | 86.7 | 0.008 | <0.1 |
| Elko | 4.3 | 3.8 | 88.9 |
| Empire | 87.0 | 54.3 | 62.4 |
| Eureka | 92.7 | 57.8 | 62.4 |
| Farmington | 31.9 | 31.8 | 99.5 |
| Lakeville | 97.8 | 87.8 | 89.7 |
| New Market | 1.5 | 1.5 | 99.1 |
| New Market twp | 87.0 | 43.2 | 49.6 |
| Rosemount | 91.2 | 5.8 | 6.4 |
| Watershed Area | | 333.5 | |

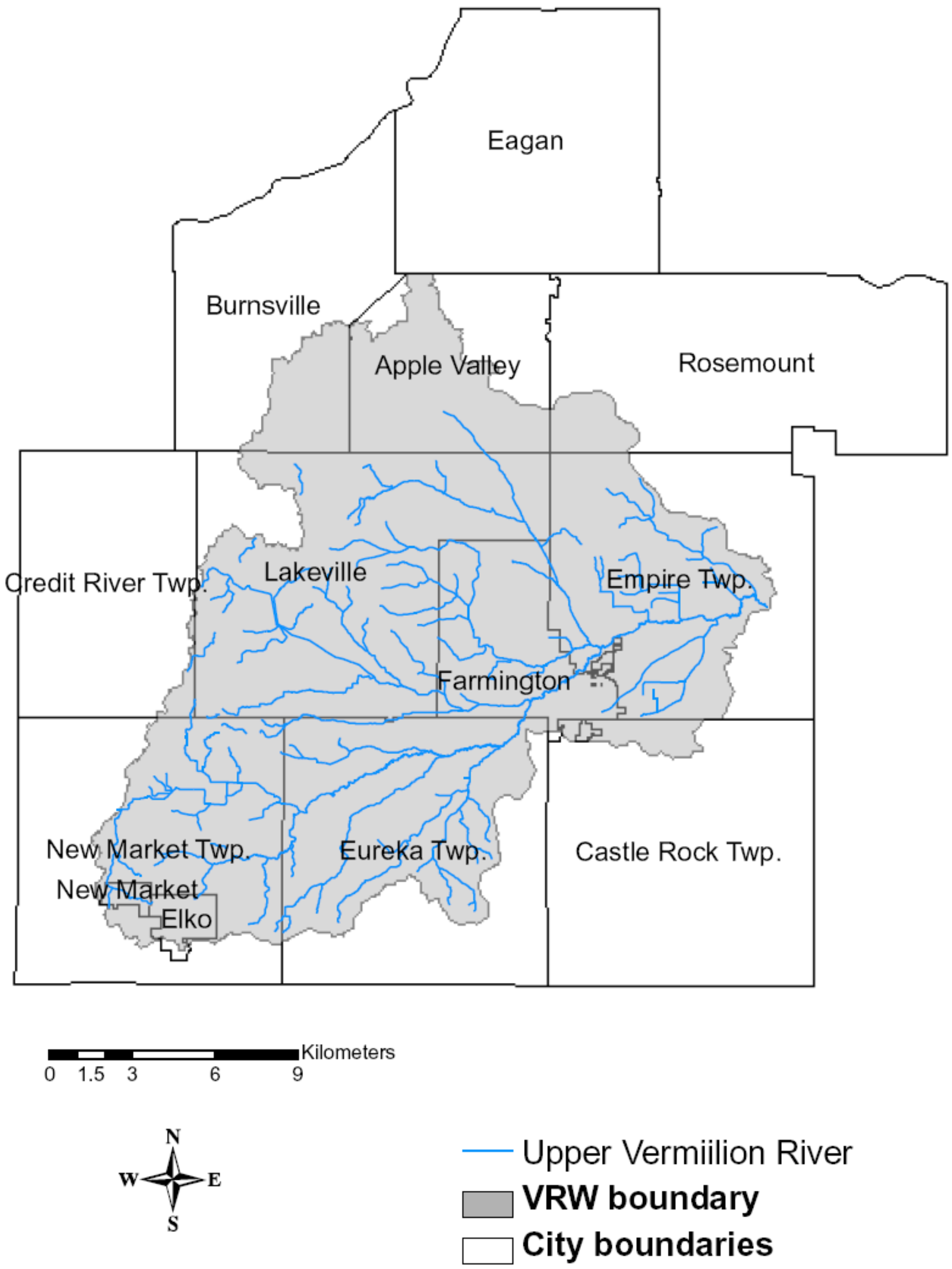


**Figure 2.2: Cities of the Upper Vermillion River watershed.**

## 2.2 Soils and hydrogeology

The topography and soils of the Vermillion River 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 (EOR Report, 2007). The predominant soil type in the study area is the group B soil (Figure 2.3) with the stream itself sitting in a buried valley of mostly hydrologic group A soil (Figure 2.3).

These soils are described as moderately well-drained to well-drained. The hydraulic conductivity of the soils ranges from a low of 15 mm/hr, mostly in the western portions of the watershed, to a high of 613 mm/hr in the eastern portion of the watershed, near the stream (Figure 2.4). The hydraulic conductivities are highest near the stream and tend to decrease farther away for the stream. These high hydraulic conductivities would be expected near a coldwater stream. Large portions of the precipitation would be expected to infiltrate in the areas of high conductivity. This water would then percolate through the soil column, recharging the aquifer and ultimately discharge to the stream. The areas with high conductivity are the reaches of the stream that have trout populations.

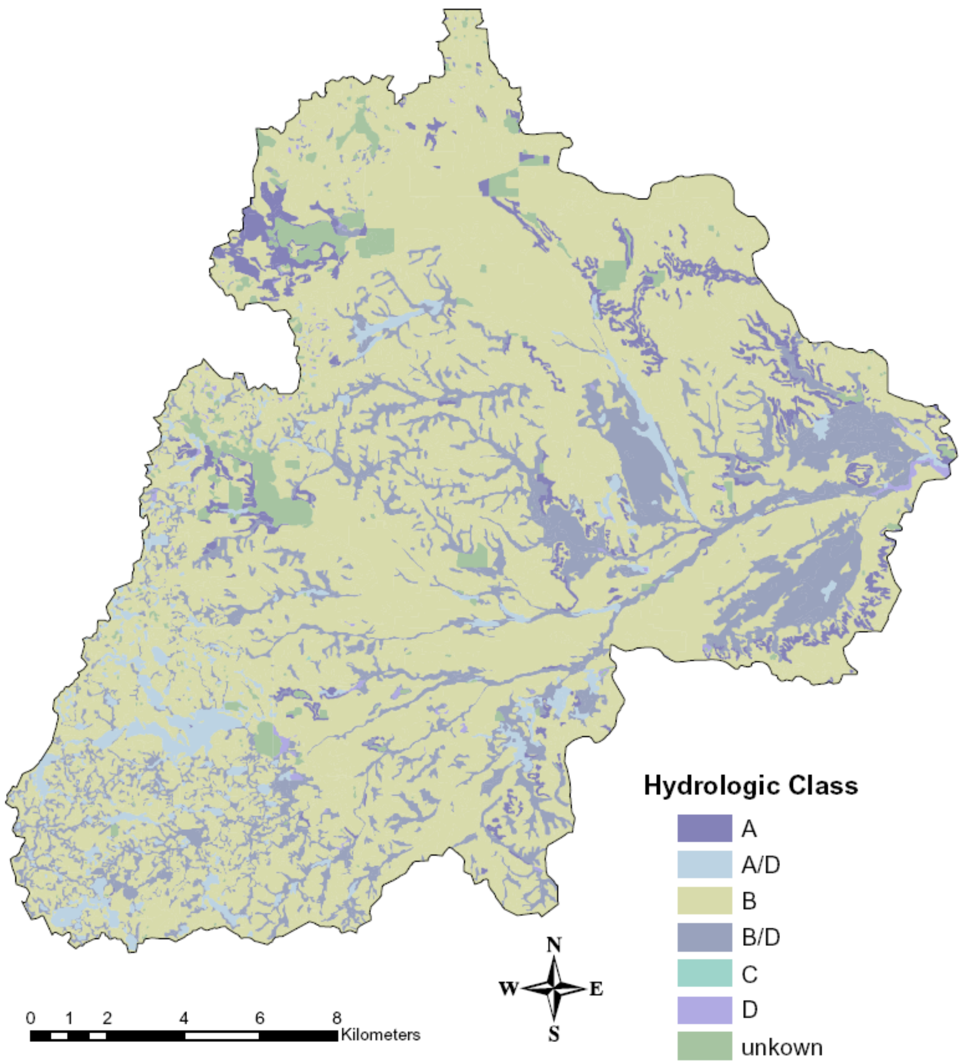


**Figure 2.3 Hydrologic classes of soils in the Upper Vermillion River watershed.**

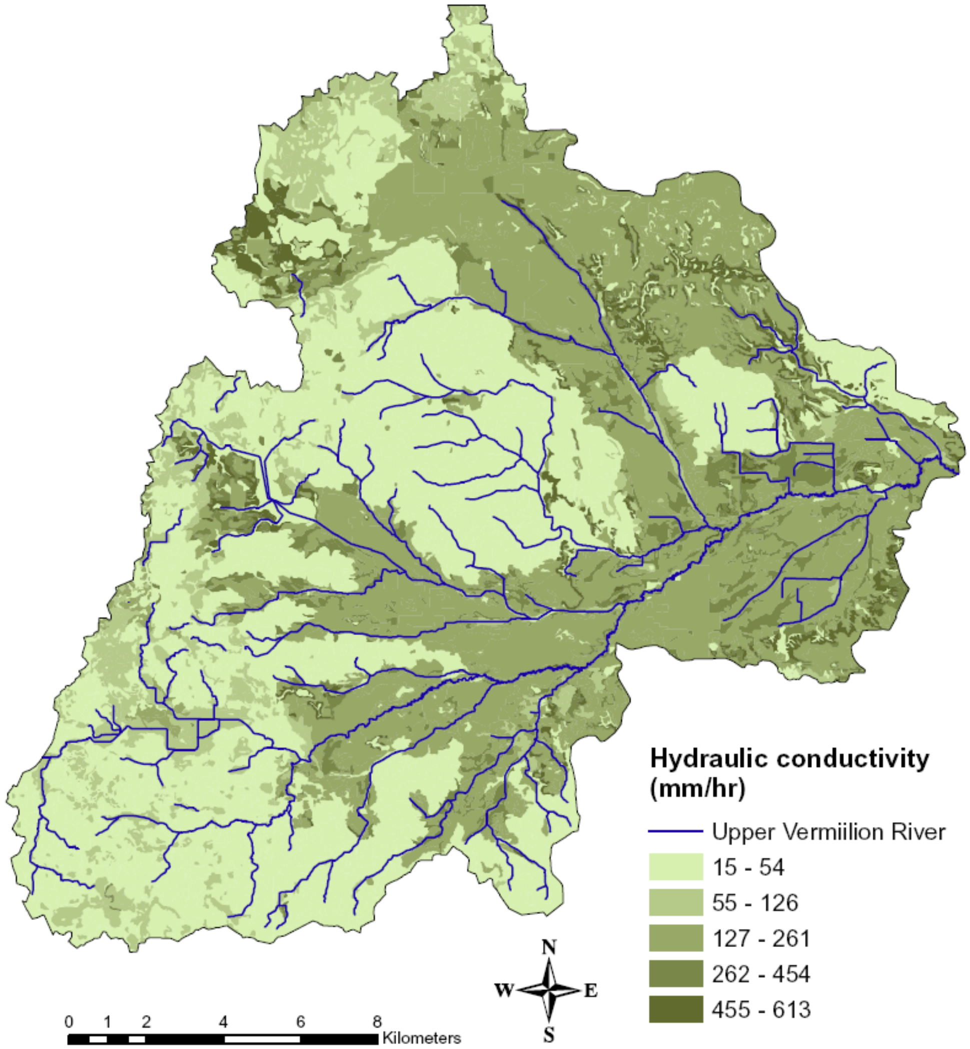


**Figure 2.4: Saturated hydraulic conductivity in the Upper Vermillion River watershed.**

A main assumption for most groundwater recharge investigations and models is that the groundwatershed is similar to the surficial watershed. In the Vermillion River the groundwatershed is approximately the same as the surface watershed (Figure 2.5). The boundaries for the groundwatershed and surface watershed are relatively close. This observation justifies assumptions that will be made in the streamflow analysis and in the water budget model.

The underlying aquifer system consists of a network of buried valleys formed during the last glaciation. (Figure 2.6). Figure 2.6 is a hydrogeologic map for Dakota County, MN, showing the saturated thickness of the aquifer and its transmissivity. It 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.

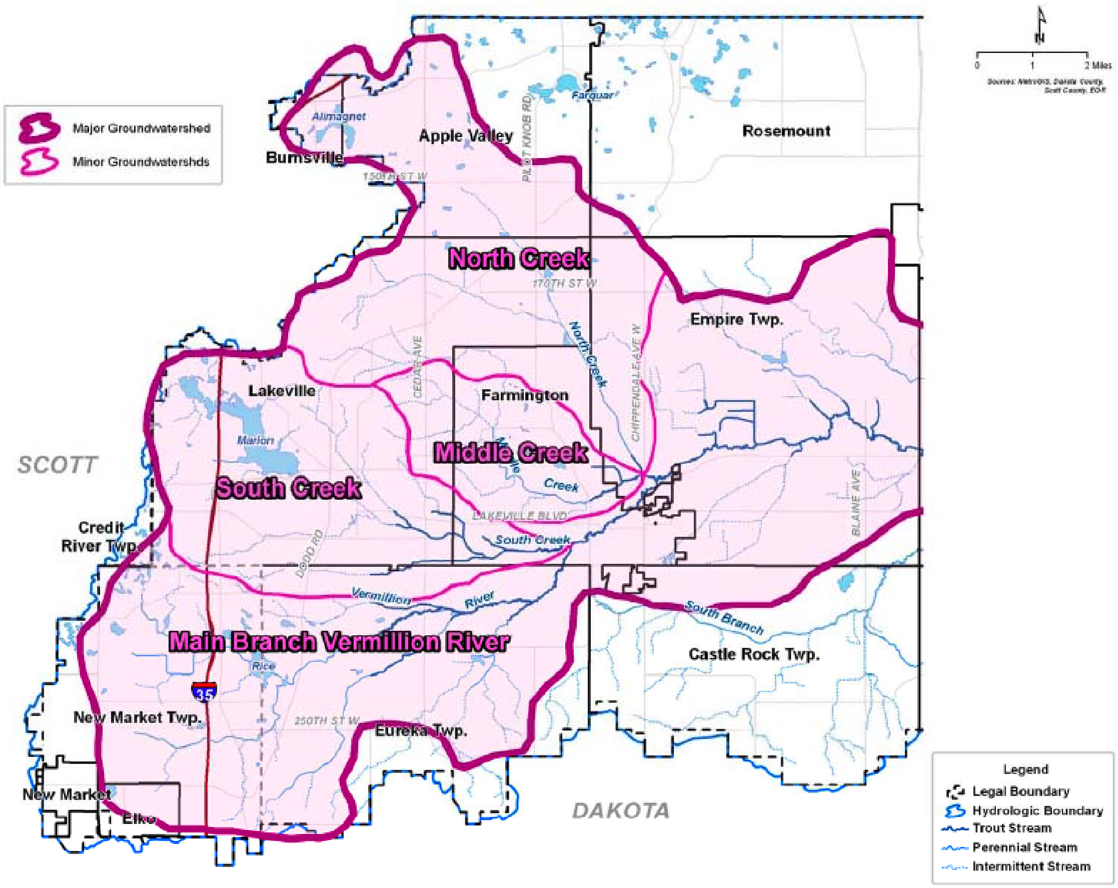


**Figure 2.5: Groundwatersheds for the Upper Vermillion River (EOR Report 2007).**

The contour lines in Figures 2.6 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 2.6) 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).

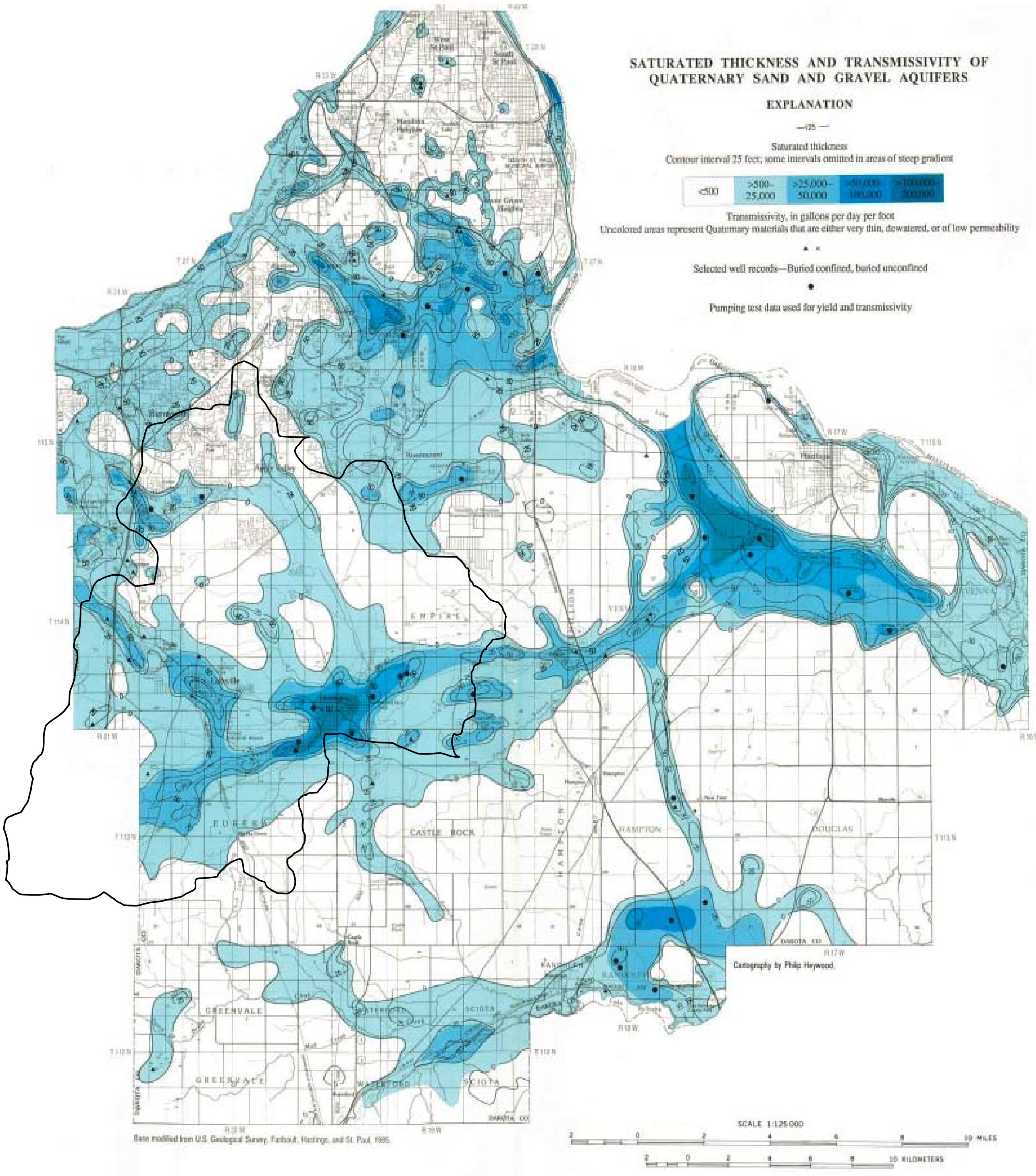


**Figure 2.6: Hydrogeological map of Dakota County, MN. Saturated zone thickness is given by contour lines and ranges from 0 to 200 ft. Transmissivities are given by color, ranging from < 500 gal/day/ft in white to 100,000 to 200,000 gal/day/ft in the dark blue (MN Geological Survey 1990). A rough outline of study watershed was added (black outline).**

## 2.3 Progression of urban development

Historical land use maps were obtained from the Metropolitan Council's (METC) public data catalog at www.datafinder.org (July 2007). The maps were in digital format and analyzed in ArcGIS. The historical land use maps included maps for 1984, 1990, 1997, 2000, and 2005 (See Appendix A for maps). The land use classification system used by the METC (METC 2006) for the historical land use map (1984 to 2005) evolved during the period of the maps. The construction of the maps shifted from a dominate parcel ownership method to an actual land use method. In general, over the land use years, more detailed land use information was captured (METC 2006). The classification system was reworked and expanded to add and redefine many of the categories. For more information on the creation of the land use maps and the classification systems, see the metadata for the historical land use maps (METC 2006). The accuracy of the maps is subject to the methods used to generate them. To simplify and have a common classification system for all 5 maps, the land use systems were reclassified (Appendix A, Table A.1). With a consistent classification system, levels of development, ratios of land-use and impervious areas may be extracted from the historic land-use maps for the purposes of modeling the effects of urbanization.

From the historical land-use maps the distribution of land-uses were found (Figure 2.7). In general, development in the watershed, in 1984, about 12% of the watershed was developed and 88% was undeveloped. Developed land-uses are farmsteads, residential, commercial, industrial, institutional, airports, and highways, where the undeveloped or natural land uses are agriculture, extractive, natural areas, green spaces, and water. In 1990 about 16% of the watershed was developed and 84% undeveloped, in 1997, 21% was developed and 79% undeveloped, in 2000, about 25% was developed and 75% undeveloped, and in 2005, 29% was developed and 71% was undeveloped.

Most of the development in the watershed between 1984 and 2005 is residential; the increase represents 11% of total watershed area. The residential increases are followed by increases in supportive land-uses (commercial, industrial, institutional, and highways). Green spaces, which include parks, preserves, and golf courses, also show a slight increase. This development coincides with a decrease of similar magnitudes in agriculture and natural lands.

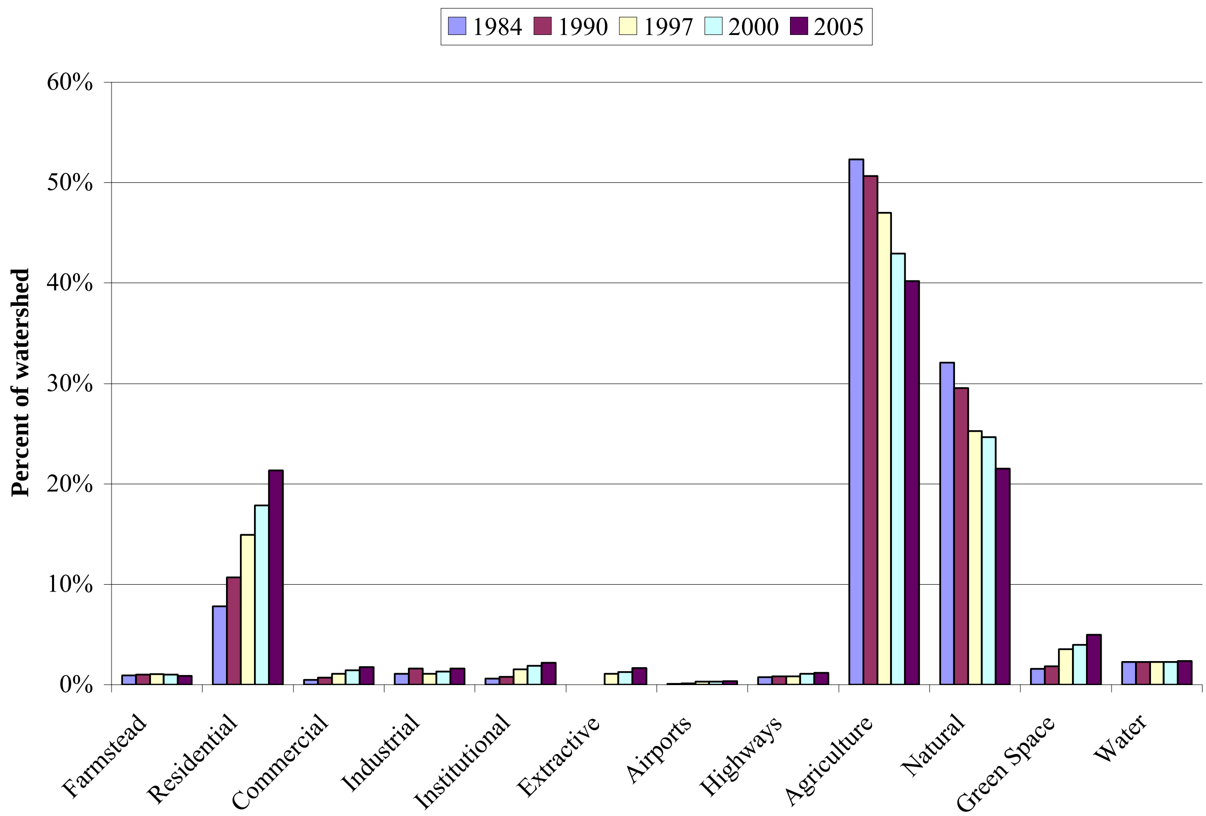


**Figure 2.7: Distribution of land uses in the Upper Vermillion watershed from historical land use maps (1984 to 2005).**

Overlaying the five land-uses maps, the areas of changed land-use relative to 1984 were found (Figure 2.8). Urban development relative to 1984 started on the northern side of the watershed, mainly in Apple Valley and Burnsville. Then development progressed to the northern parts of Farmington and into Lakeville between 1990 and 1997 while development in Apple Valley and Burnsville continued. Between 1997 and 2005, large areas of Lakeville and Farmington were developed along with sporadic development in the southwest tip of the watershed near Elko and New Market while much of the eastern half remained relatively unchanged.

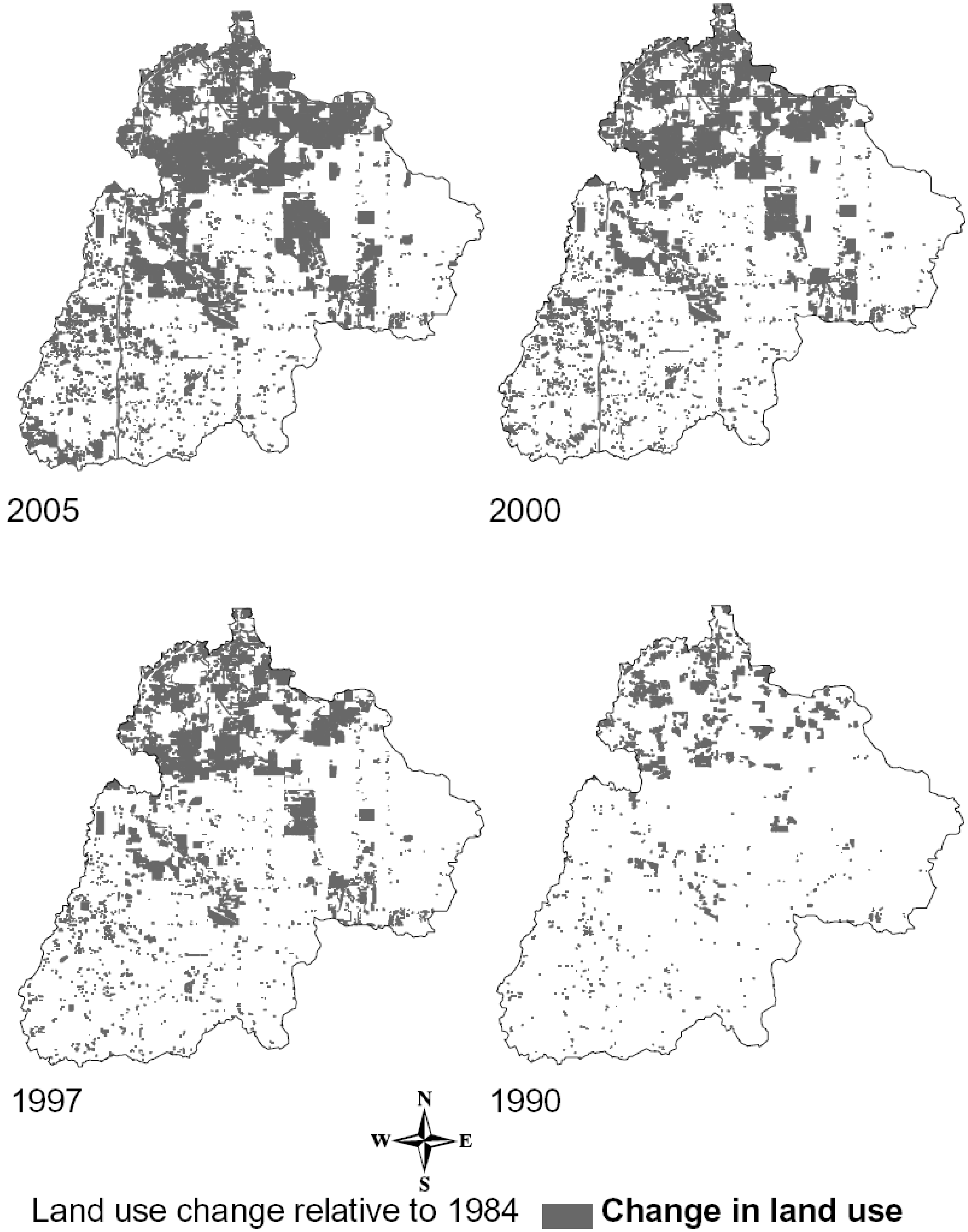


**Figure 2.8: Land use change relative to 1984 in the Upper Vermillion River watershed.**

## 2.4 Land Cover

A 2005 land cover map (Appendix A, Figure A.6) created by Applied Ecological Services (AES) was used to extrapolate the historic land cover. The level of urbanization is different across the watershed. Burnsville, Apple Valley, and parts of Lakeville and Farmington are largely urbanized and large portions are covered by roofs and other impervious surfaces, whereas most of the townships in the southern half remain natural with grasses and crops as the dominant land covers.

We first assumed that areas covered by water including ponds, reservoirs, and vegetated ponds, have not changed from 1984 to 2005. This assumption can be made because (1) these wet areas are unsuitable for building and (2) by Minnesota statue all wetlands must remain wetlands or be re-constructed elsewhere, i.e. no net decrease in wetlands. We then assumed that the proportions of land cover in each land-use type in a city remain fixed, and extrapolated the watershed's land cover for the five historic land use years, using the 2005 land cover map and the unchanged land-use areas. Overlaying the land-use maps, the areas of land-use that remained the same relative to 2005 were found. Using the 2005 AES Land Cover map, proportions of land cover in unchanged areas where found relative to land-use and city. Extrapolating these proportions to all land-uses in a particular city, the land cover for the entire watershed, for a particular year was estimated. The land covers were then generalized into the following groups: impervious areas including roofs, asphalt and concrete pavements; lawn and grass; other vegetation including tall grass and forests; crops; bare ground; and water including all ponds, reservoirs and vegetated ponds.

The estimated fractions (percent) of land covers for the entire watershed were plotted in Figure 2.9 to show the progression in time. The actual percentages of land cover for 2005 are also given to show that using the proportions of land cover for the unchanged land-use areas to represent the land cover in all the land-uses gives acceptable results. The estimated land cover and actual land cover are within one percent of the total watershed area. With urban development the area covered by impervious surfaces and lawn grasses should increase and the area covered by crops and natural grasses should decrease (Figure 2.9). The important component for this study is impervious area because it is associated with a decrease in natural groundwater recharge. In 1984, approximately 8.8% of the watershed was impervious with only 12% of the watershed developed, and in 2005, about 13.3% was impervious with 29% of the watershed developed.

Unexpectedly, a larger portion of the developed area was covered by impervious surfaces in 1984, but much of these surfaces were roads and structures in natural or undeveloped areas.

Other components of the land cover may have an influence on groundwater recharge but are not investigated in this report. Roof areas may reduce recharge if connected to streets and/or storm sewers, but may increase recharge if disconnected. Precipitation that falls on roofs and is diverted to lawns through gutter systems can increase infiltration on those lawn areas. In this report we investigate urbanization and groundwater recharge on a regional scale. To see the influence of factors such as roof connectedness, a finer scale is needed.

Converting cropland to lawns may increase evapotranspiration and therefore decrease recharge because lawn grasses are perennials and crops are mostly annual plants. Perennials may demand more soil water throughout the year than annuals use during the growing period, even with higher demand during peak growing months.

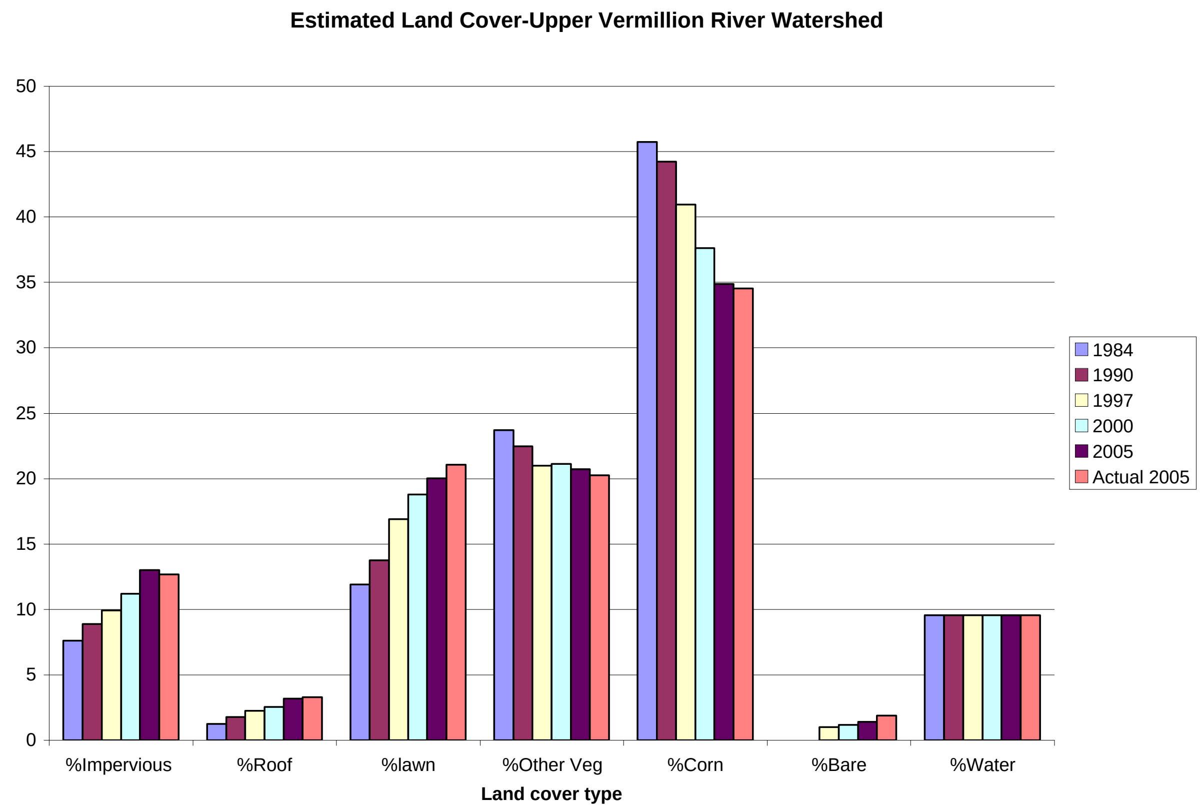


**Figure 2.9: Extrapolated land cover for the Upper Vermillion River watershed.**

## 2.5 Hydrology of the Upper Vermillion River

An analysis on the streamflow data from the USGS gauging station near Empire, MN was conducted (Erickson and Stefan, 2008).The USGS computer programs PART and RORA were used to separate base flow from streamflow. The base flow is the sustaining flow between rainfall events. Base flow separation techniques are widely used to estimate groundwater recharge in a watershed (Rutledge, 1992 & 1998; Chen and Lee, 2003). Baseflow is separated from streamflow using simple regression techniques. A description of these techniques can be found in papers by Rutledge (1992, 1993, 1998); Rutledge and Daniel (1994); and Erickson and Stefan (2008).

Low water temperature in reaches of the Vermillion River is evidence of groundwater inflow. Flow in the Vermillion River would be expected to be dependent on groundwater because of high transmissivities (Figure 2.6) and hydraulic conductivities (Figure 2.4) in the hydrogeology of the watershed. This dependence on groundwater can be seen when streamflow is plotted against baseflow. On a long-term (annual) timescale baseflow is groundwater inflow which under steady-state conditions must equal groundwater recharge. Figure 2.10 of annual flows shows that approximately 84% of the streamflow comes from groundwater recharge.

Knowing stream flow, base flow and precipitation, other hydrologic parameters can be estimated (Appendix B). These parameters are evapotranspiration, direct (surface) runoff, and infiltration/interception. A time series plot of the hydrologic budget components is given in Figure 2.11 and the associated statistical information is summarized in Table 2.2.

The precipitation data in Table 2.2 are from a weather station in Farmington with the exception of 2004 and 2005. Because some data were missing, another weather station in Rosemount was used for these years. The Farmington station is located near the center of the watershed and the Rosemount station is in the northern portion of the watershed.

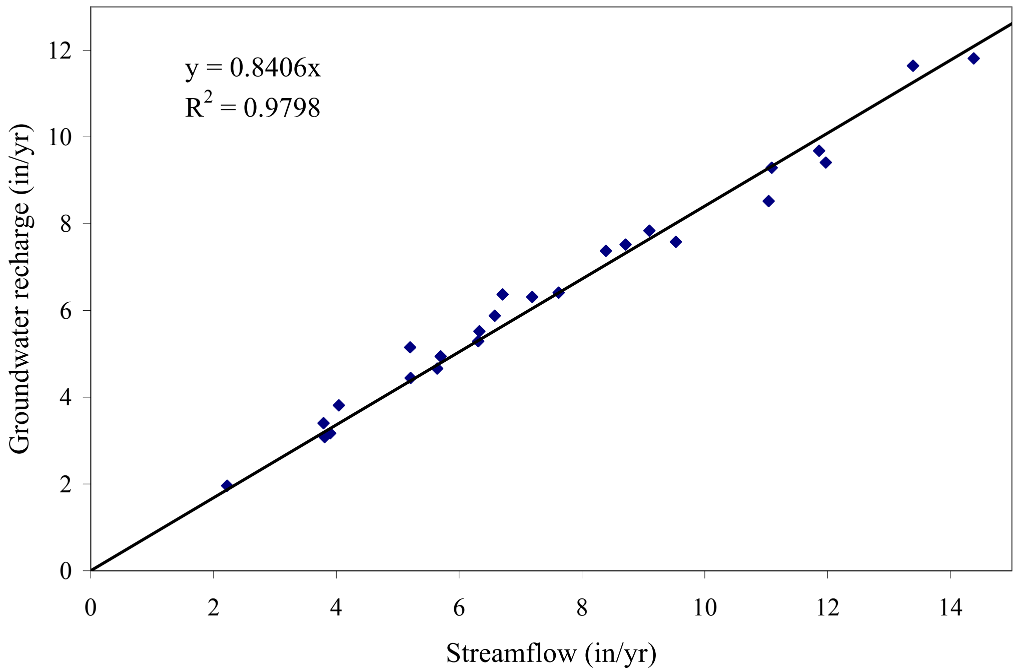


**Figure 2.10: Groundwater recharge estimated by the USGS program RORA vs. streamflow (Erickson and Stefan, 2008).**

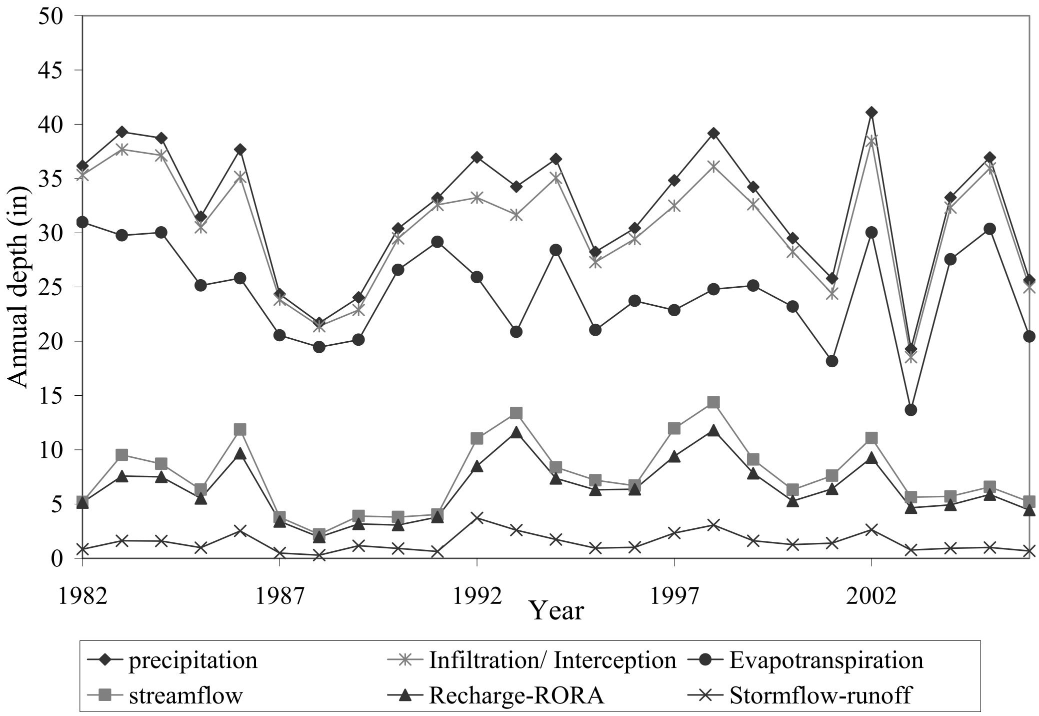


**Figure 2.11: Annual water budget components (1982 to 2006) for the Upper Vermillion River watershed up to the USGS gauging station near Empire, MN (Erickson and Stefan, 2008).**

**Table 2.2: 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 (Erickson and Stefan, 2008).**

| | Precipitation | Stream flow | Recharge (RORA) | Direct runoff | Infiltration/ Interception | 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 |

The average precipitation in the watershed is 32.1 inches/year with about 7.6 inches/year reaching the Vermillion River as either direct runoff (~1.5 in/year) or groundwater discharge (~6.4 in/year). 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 fits the observation that the watershed is composed of mostly well-drained soils. Table 2.2 shows that very little (~5 %) of the annual precipitation becomes direct runoff. The high fraction (94%) of the annual precipitation that infiltrates leads to an excess of water in the soil column that eventually becomes groundwater, which feeds the Vermillion River. On average, approximately 76% of the precipitation in the watershed returns to the atmosphere through evapotranspiration (Table 2.2). This matches average estimates for state-wide evapotranspiration, which is approximately 75% of annual precipitation (Baker et al. 1979).

Natural groundwater recharge in the Upper Vermillion River basin shows a dependence on precipitation (Figure 2.12), but the scatter indicates that recharge is also dependent on other climate parameters. It is noteworthy that Figure 2.12 indicates a minimum (critical) annual precipitation (~11 inches) before groundwater recharge is generated. 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 intercepted and 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.

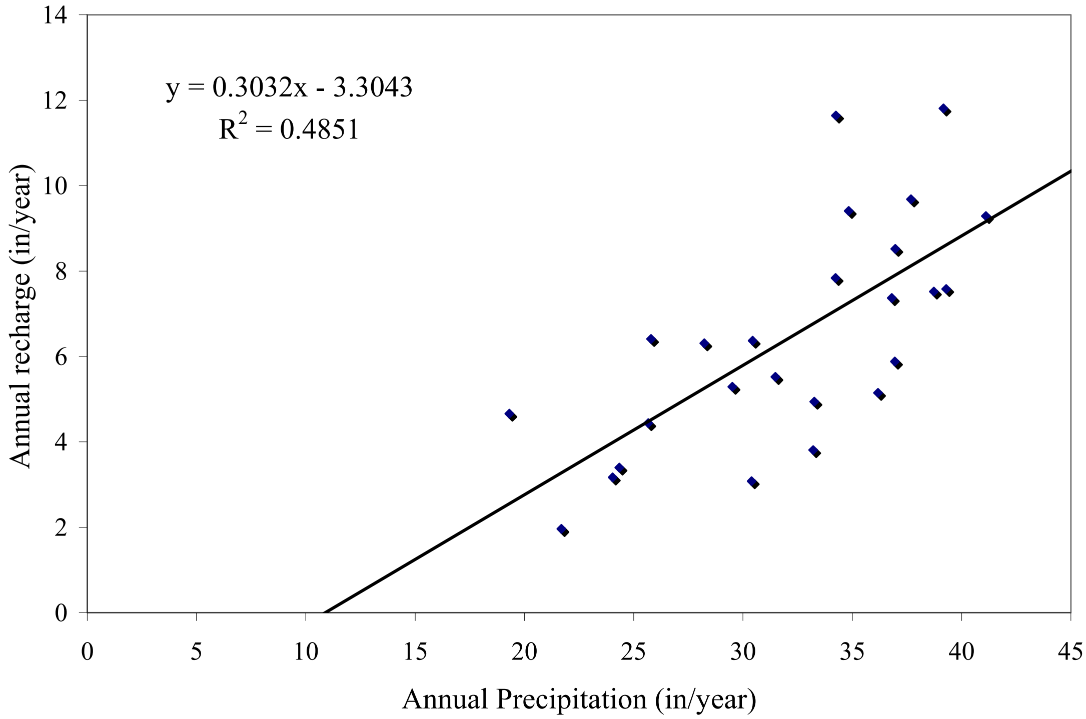


**Figure 2.12 Annual groundwater recharge vs. annual precipitation (Erickson and Stefan, 2008).**

The estimates in Table 2.2 can be used to calibrate or validate a hydrologic model of the Upper Vermillion River watershed. The high dependence of the Vermillion River on groundwater sources makes the river susceptible to the effects of urbanization in the watershed. If a larger portion of the watershed becomes covered by impervious area, and infiltration and groundwater recharge are reduced, less groundwater will be available to feed the Vermillion River. The stream may warm.

# 3. Projecting change in 'natural' groundwater recharge due to urbanization

## 3.1 Methods to estimate groundwater recharge

Groundwater recharge is often the least known but most influential variable in groundwater modeling (Delin et al., 2007). It depends on climate parameters (intensity and duration of rainfall), soil characteristics (permeability, moisture content), root depth, and aquifer depth. Some of these parameters vary significantly with location in a watershed, resulting in significant errors in groundwater recharge estimates.

A variety of methods can be used to estimate groundwater recharge. Scanlon et al. (2002) gives a review of methods for recharge estimation. The methods 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) analyzing temporal water-level fluctuations in wells (Healy and Cook, 2002) or (4) baseflow analysis of streamflow records (Rutledge and Mesko, 1996; Lorenz and Delin, 2007).

Extensive hydrologic models have been formulated to simulate surface water and groundwater interaction. Said et al. (2005) describe such models and their use to estimate groundwater recharge. They include: MIKE SHE, HMS, SWATMOD, MODBRANCH, and FHM. Arnold and Allen (1996) developed a multi-component model called the Soil and Water Assessment Tool (SWAT), which estimates water budget components and tested it for three watersheds in Illinois. The Department of Defense (DoD) developed the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model. It simulates streamflow by modeling surface and subsurface mechanisms in a gridded system (Downer and Ogden, 2004).

Methods of analysis developed-to-date have been used to estimate groundwater recharge for existing conditions to obtain long-term averages. Packaged models, such as SWAT, GSSHA, or MIKE SHE have been developed for wider uses than groundwater recharge estimation and are commonly applied to agricultural watersheds. Few to none of the above models have been used to investigate the effects of landscape changes such as urban development. Two techniques will be used to estimate groundwater recharge response to urbanization: (1) a soil water budget model to investigate the effects of increased imperviousness and (2) a base flow analysis of recorded stream flows by the USGS computer programs RORA and PART (Rutledge, 1998).

## 3.2 Model development

The main objective is to quantify and project the relative change in natural direct groundwater recharge from infiltrated precipitation to a shallow aquifer in a watershed at different levels of urban development. More specifically, the effect of increased imperviousness and changes in surface vegetation on the soil water budget and natural recharge are to be investigated. To accomplish this, three models were developed from well-developed principles and methods, and applied to a tributary of the Vermillion River. A secondary objective is to quantify and project changes in the surficial water budget components including infiltration, evapotranspiration and percolation under different stages of urban development. The latter is the natural, direct groundwater recharge to the shallow aquifer that supplies about 80% of the annual flow in the Vermillion River. A summary of the models, methods, and results is given below; a detailed description can be found in a report by Erickson and Stefan (2007).

Three models were developed using the soil water budget method that tracks soil water throughout the year. The models are called the FAO-SCS, the FAO-GA, and the GA model. Three models instead of one were developed to obtain a broader range of estimates. Each model estimates the four main water budget components: (1) evapotranspiration, (2) infiltration, (3) groundwater recharge, and (4) storage in the soil column. Natural, direct groundwater recharge originates from precipitation. Some precipitation is intercepted by the plant canopy or in depression storage, and some becomes surface runoff that flows overland to streams and wetlands. The remaining water infiltrates into the pores of the permeable soil, where it can be intercepted by the roots of plants and sent back into the atmosphere by transpiration and evaporation (evapotranspiration). The remaining water percolates through the soil column, beyond reach of the root system to the saturated zone or aquifer, becoming groundwater recharge that is stored in the aquifer until it is intercepted by a stream, a lake, a well or another sink.

The basic relationship is the hydrologic water budget. A water budget keeps track of the water transfer processes that occur in the soil column that has a depth equal to the root depth of the vegetation. The water budget and its components (in units of volume per unit area) can be expressed as (Arnold and Allen 1997; Allen et al. 1998)

$$\Delta S_i = I_i + Irr_i - ET_i - R_i + CR_i \qquad [3.1]$$

where $\Delta S_i$ = change in storage in the soil (mm); $I_i$ = infiltration depth (mm), $Irr_i$ = irrigation depth (mm), $ET_i$ = evapotranspiration depth (mm), $R_i$ = groundwater recharge depth (mm), $CR_i$ = water depth attributed to capillary rise (mm). The subscript *i* refers to a given time step. Infiltration depth is the water that infiltrates into the soil during a rain event. Irrigation depth is the infiltration depth if the watering of the soil is artificial (man-made). Evapotranspiration (ET) depth is water used by plants and returned to the atmosphere by evaporation and transpiration. Recharge depth is the water that percolates beyond the root zone, and ultimately reaches the aquifer system. Capillary rise is the water rising from the saturated zone by capillary forces. The amount of water attributed to capillary rise is usually small compared to the other components and will be assumed negligible.

Two methods were used to estimate infiltration: (1) the curve number method developed by the U.S. Department of Agriculture's Soil Conservation Service (SCS) (1973), now the National Resources Conservation Service (NRCS); and (2) the Green-Ampt method (Green and Ampt 1911), developed as an approximate solution of the one-dimensional Richards equation (Richards 1931) for unsteady, unsaturated flow in a porous medium. The FAO-SCS model uses the SCS method to estimate infiltration and the FAO-GA and GA models both use the Green-Ampt method. These infiltration methods were chosen because they are widely accepted methods that are used in many applications, such as SWAT-using the SCS method (Arnold and Allen 1996) and GSSHA-using the Green-Ampt method (Downer and Ogden 2004); the required parameters can be easily estimated; and are discussed in many books and research papers (e.g. Chow et al. 1988; Bedient and Huber 1992; Delleur 1998; Ravi and Williams 1998; Mays 2005).

All three models use the FAO-56 Penman-Monteith (PM) equation developed for the Food and Agriculture Organization of the United Nation (FAO) (Allen et al. 1998) to estimate evapotranspiration (ET). The FAO-56 equation is best suited to this application because it can estimate ET both at an hourly and a daily time scale; the Committee on Irrigation Water Requirements of the American Society of Civil Engineers found that the Penman-Monteith method ranked best when compared to 20 different ET methods tested in different climates (Jensen et al. 1990, Trajkovic 2005). The basic Penman-Monteith method requires extensive weather data that are not usually available. Yoder et al. (2005) therefore tested multiple equations to estimate the required weather variables, using weather variables commonly found at many weather stations, and found the best equations for a 'temperature-modified' FAO-56 PM method.

Two methods for estimating groundwater recharge are used. The FAO-SCS and FAO-GA models use an equation (equation 3.2) derived by rearranging the water budget (equation 3.1) to estimate recharge, and the GA model assumes that the recharge rate is equal to the soil's hydraulic conductivity (equation 3.3). In the first method, it is assumed that the excess water not held in the soil against the force of gravity (i.e. the field capacity of the soil) drains quickly (i.e. on the day of the wetting or rainfall event). Ignoring irrigation ($Irr_i$) and capillary rise ($CR_i$) and using a water depletion parameter to represent the change in storage $\Delta S$, the water budget equation (1) can be solved to estimate recharge (Allen et al. 1998):

$$R_i = I_i - ET_i - D_{w,i-1} \geq 0 \quad [3.2]$$

$D_w$ expresses the water depletion and is defined as the depth (amount) of soil water depleted by plants that is needed to reach field capacity in the soil column. As long as the soil water content in the root zone is below field capacity (i.e., $D_{w,i} > 0$), the soil will not drain and $R_i = 0$.

In the second method, by assuming that the only vertical driving force acting on the soil water is gravity (i.e. no capillary forces), the recharge rate is equal to hydraulic conductivity (K) of the soil. Using an equation for unsaturated hydraulic conductivity by Brooks and Corey (1964), the recharge rate is (Brooks and Corey 1964; Kim et al. 1996):

$$q_p = K(s) = K_s s^{(2+3m)/m} \quad [3.3]$$

where $q_p$ = recharge rate (mm/s); $K$ = unsaturated hydraulic conductivity (mm/s); $K_s$ = saturated hydraulic conductivity (mm/s); $s$ = soil saturation (-); $m$ = Brooks and Corey's pore size distribution index (-). Equation 3.3 is only valid when the soil moisture content is above field capacity since field capacity is defined as the water held in the soil against gravitation forces. The recharge depth ($R_i$) can be estimated by integrating $q_p$ over time.

The basic purpose of the three models is to track soil moisture and estimate each water budget components (equation 3.1) throughout a growing season for each unique soil type and land cover combination present in the Vermillion river watershed. No significant groundwater recharge occurs when the ground is frozen (Walton 1990). For northern climate regions, the models therefore assume that recharge occurs only after the spring thaw and before the winter freeze, i.e. approximately from April through November in the temperate climate of Minnesota. Because the models do not model the entire year, the initial soil moisture content at the spring thaw was assumed to be at field capacity, representing saturation from snowmelt in spring.

The watershed area was broken into soil/land cover combinations by overlaying a land cover map and soil map in a GIS program. The breakdown eliminated some of the error associated with assuming homogenous conditions and taking average values for soil and land cover conditions. The models compute the water budget components for each soil/land cover combination for the given time period using discretized numerical forms of the basic equations. To solve the model equations a Microsoft Excel spreadsheet and macros written in Visual Basic are used to estimate each water budget component (ET, infiltration, and recharge). The change in soil water between each time step was found using a crude Euler method to solve the first-order differential soil moisture equations. The FAO-SCS model solves the water budget at a daily time step and the FAO-GA and GA models solve it at an hourly time step. To obtain a representative value for the water budget components, a weighted average of the land cover/soil cells (taking into account the impervious areas) is computed.

## 3.3 Case Study on sub-watershed

The case study was performed on an un-gauged tributary watershed to the South Creek of the Vermillion River near Lakeville, Minnesota. This sub-watershed has an area of about 6.8 $km^2$ (4.2 $mi^2$) with about 60% undeveloped (i.e. agricultural and natural) land, and about 40% developed (i.e. urban residential and commercial) land. The sub-watershed was selected because it is representative of other developing areas in the Vermillion River watershed.

The soils consist mostly of sandy loams (SL), silty loams (SIL), silty clay loams (SICL), and loams (L) formed by glacial deposits. A small area consists of muck and was ignored and an area of unknown soils covered by urban development was assumed to have the same characteristics as the rest of the watershed. Estimated characteristics of each soil type in the watershed were taken as the average values given by Rawls et al. (1983). These values are considered a first good first estimate (Mays 2005).

To estimate the change in natural groundwater recharge with progressive urbanization over time, four land-use scenarios were developed. The scenarios represent: (1) a pre-development condition referred to as "past" condition, (2) the "present" (2005) condition, (3) a projected "plus 50 years" future condition, and (4) a projected "plus 100 years" fully urbanized future condition. The percentages of land uses for the four scenarios are given in Table 3.1. The levels of development were projected using changes in historic land-uses for Lakeville, MN.

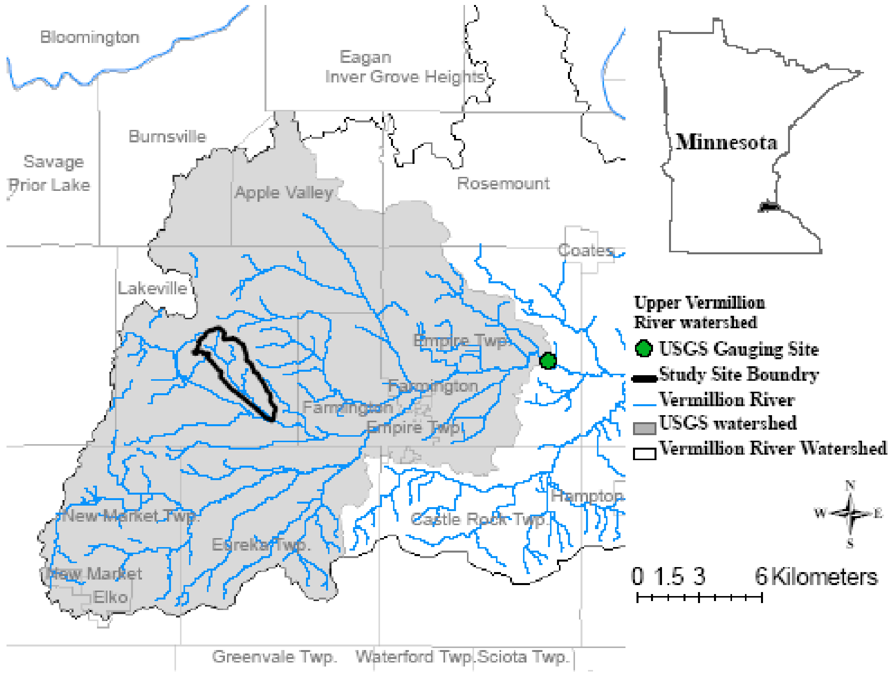


**Figure 3.1: Vermillion River watershed in Minnesota and study area/sub-watershed location (dark contour) (Erickson and Stefan 2007).**

**Table 3.1: Past and future land use scenarios**

| Land-Use Type | Scenario | | | |
|---|---|---|---|---|
| | Past | Present (2005) | Plus 50yrs | Plus 100yrs |
| | Percent (%) of sub-watershed area | | | |
| Agriculture | 50 | 25.1 | 13.2 | 0 |
| Parks/preserves | 0 | 12.7 | 14.6 | 16.5 |
| Industrial | 0 | 1 | 1.1 | 1.1 |
| Institutions | 3 | 8 | 9.2 | 10.3 |
| Multi-family homes | 0 | 7 | 8.6 | 9.9 |
| Retail/offices | 0 | 1.7 | 2.2 | 2.4 |
| Single family homes | 12 | 21 | 23.9 | 25.7 |
| Town-homes | 0 | 1 | 9.2 | 20.8 |
| Undeveloped/natural | 35 | 21.5 | 16.8 | 12 |
| Roads/impervious | 0 | 1 | 1.1 | 1.2 |

Hourly climate data for the water budget model were obtained from the MNDOT weather station near Monticello, Minnesota, about 60 miles from the study site, for 2004 and 2005. The weather station is close enough to the sub-watershed to give representative mean monthly weather. The difference in daily weather between 2004 and 2005 is much larger than the difference between the Monticello station and a station (Farmington) within the Vermillion River watershed in a given year. The root mean square error (RMSE) of the mean daily air temperature between the two climate years is 7.2 °C, where the RMSE between the two sites is 1.9 °C for 2005. All four urbanization scenarios use the same weather data, because the relative change in groundwater recharge, not absolute values, are of interest. It is assumed that both climate years represent weather that could occur in any give year within the sub-watershed. Climate year 2005 had above average annual precipitation (933 mm or 36.7 in) with more total precipitation and higher intensity rainfall events. Climate year 2004 had approximately average annual precipitation (725 mm or 28.5 in).

## 3.4 Effect of urban development on natural recharge

The main goal of the study was to investigate the effect of urban development on direct natural groundwater recharge. Water budget components were computed for two climate years and four land use scenarios by three models. The modeled effects of urban development on groundwater recharge are summarized here. A more detailed description of the results can be found in Erickson and Stefan (2007).

The averages of the water budget components estimated by the three models for the two climate years are given in Table 3.2 as a fraction of annual precipitation. Annual groundwater recharge decreases with urban development according to Table 3.2. This is expected and related to the reduction in infiltration. Groundwater recharge decreases from 20% ±5% of annual precipitation at 4.9% impervious area for the "past" condition to 17% ±5% at 18.3% impervious area for the 2005 "present" condition to 12% ±2% at 36.4% impervious area. That is a 30% to 40% reduction in groundwater recharge with a potentially serious effect on groundwater supply to a coldwater (trout) streams from shallow aquifers.

The estimates of recharge are plotted in Figures 3.2. The mean values from Table 3.2 were linearly connected and extrapolated to 0% at 100% impervious area. It was assumed that from a 100% impervious area no water would infiltrate, there would be no vegetation for evapotranspiration, and no water would be available for groundwater recharge. Most of the values estimated by the three models fall within one standard deviation of the mean (Table 3.2), with the exception of the FAO-SCS 2004 results. This model tended to predict higher values than the rest of the models. The lowest values for groundwater recharge were predicted by the GA model for 2005 (Figure 3.2).

Overall, the case study results show that urbanization decreases all water budget components due to the increase in impervious areas, including ‘natural’ groundwater recharge. However, urbanization of rural lands may have a smaller impact on net groundwater recharge than indicated by this case study because ‘artificial’ recharge from water systems and water uses that come with urbanization, such as leaky pipes, excessive lawn watering, infiltration basins, rain gardens and seepage from storm water detention basins in urban areas can increase infiltration and hence groundwater recharge. ‘Artificial’ groundwater recharge will be investigated in Section 5 of this report.

**Table 3.2: Mean and standard deviations* of normalized water budget components (Erickson and Stefan 2007).**

| Scenario | Infiltration | Actual evapotranspiration | Groundwater recharge |
|---|---|---|---|
| | I | $ET_a$ | R |
| | Fraction of precipitation | | |
| **Past** | | | |
| mean | 0.76 | 0.58 | 0.20 |
| std. dev. | 0.08 | 0.08 | 0.05 |
| **Present** | | | |
| mean | 0.69 | 0.53 | 0.17 |
| std. dev. | 0.08 | 0.07 | 0.05 |
| **Plus 50 Years** | | | |
| mean | 0.63 | 0.50 | 0.14 |
| std. dev. | 0.08 | 0.08 | 0.03 |
| **Plus 100 Years** | | | |
| mean | 0.57 | 0.46 | 0.12 |
| std. dev. | 0.11 | 0.10 | 0.02 |

* of six values obtained by three models for two year (2004 and 2005).

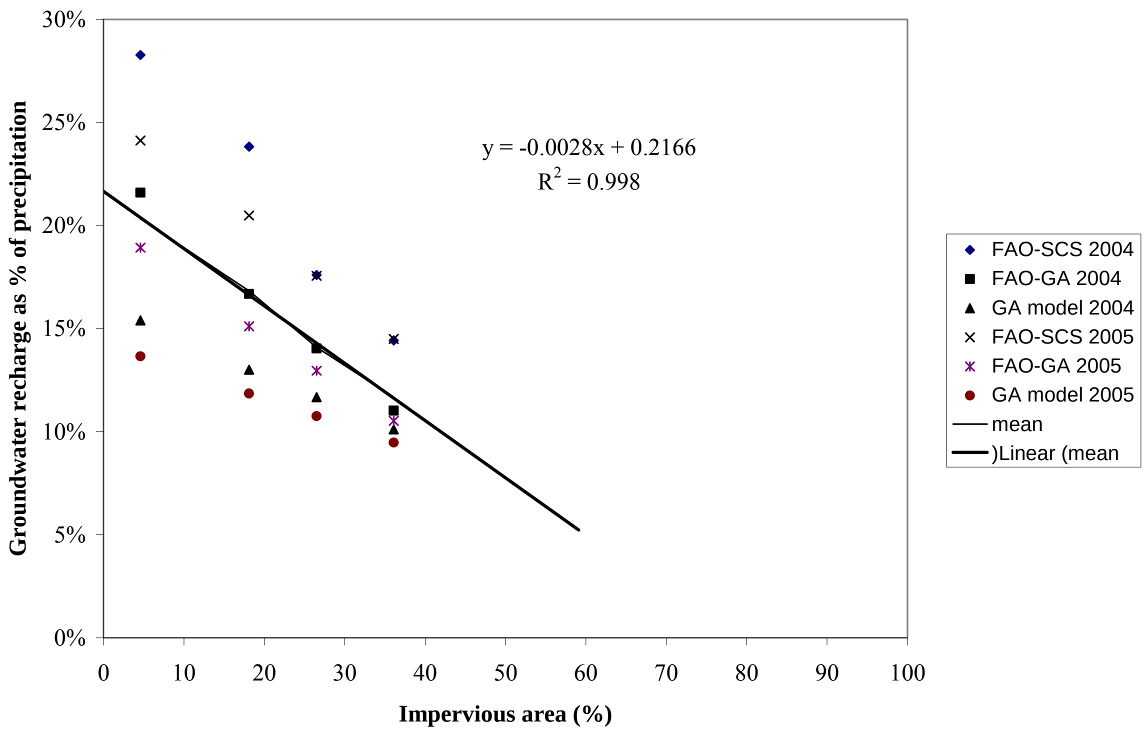


**Figure 3.2: Computed annual groundwater recharge rate (as % of precipitation) vs. impervious area (%) in the Vermillion River sub-watershed (Erickson and Stefan 2007).**

Figure 3.2 was obtained for the sub-watershed, but can be used to estimate the effect of urbanization on natural recharge in the larger, Upper Vermillion River watershed for different stages of development. The findings can be extrapolated because of the similarities between the watersheds. According to 2005 census data, approximately 69% of the Upper Vermillion River watershed is undeveloped (agricultural and natural lands, parks and preserves) and 31% is developed (single-/multi-family homes, commercial, industrial, etc.) compared to 61% undeveloped and 39% developed for the study site watershed. Both watersheds have similar, mostly hydrologic class B soils consisting of various types of loams. Discharge scales linearly or near linearly with drainage area (Dunne and Leopold 1978; Pazzaglia et al. 1998), if the watersheds are similar in all aspects except for size.

The result from the soil water budget modeling given above compare favorably to the results of the streamflow analysis for the USGS gauging site near Empire, MN (Section 2.5). For the average annual precipitation (for the period) of 815 ±152 mm/yr the streamflow analysis gave an annual infiltration/interception of 780 ± 140 mm/yr, annual ET was 625 ± 114.3 mm/yr, and annual groundwater recharge was 163 ± 66 mm/yr (Table 2.2). As percentages of annual precipitation 95.6% of the water infiltrated or was intercepted, 76.6% was evapotranspirated, and 19.9% became groundwater recharge. By comparison the three soil water budget models estimated, on average, 69% for infiltration, 53% for ET and 17% for groundwater recharge (Table 3.2); infiltration and evapotranspiration are substantially underestimated, but groundwater recharge is only off by 3% of rainfall. Some of the discrepancies in infiltration and evapotranspiration can be accounted for. In the stream flow analysis, infiltration was estimated as the difference between annual rainfall and runoff, and this infiltration estimate does include interception and storage of rain (such as depressional storage or detention ponds); infiltration is therefore overestimated. The excess surface storage or intercepted water is also missing in the ET estimate because it returns to the atmosphere through evapotranspiration. The models do not include any surface storage in the infiltration or ET estimates. This can explain some of the differences between infiltration and ET estimates and why the groundwater recharge estimate from the streamflow analysis falls within a standard deviation of the soil water budget model estimates.

The gauged watershed is less developed (31% of 206 $km^2$) than the study site sub-watershed (39% of 6.8 $km^2$). The higher percentage of impervious area in the study site watershed can provide a very reasonable explanation for the differences between the estimates from the stream flow analysis and the three soil water budget models. According to Figure 3.2, an 8% increase in imperviousness is associated with a 2 % decrease in direct natural groundwater recharge.

Overall, the comparison of the annual groundwater recharge estimates in Table 3.2 with estimates from the streamflow analysis in Table 2.2 shows a fair agreement for current watershed conditions. The models used in this study underestimated groundwater recharge compared to estimates from previous studies. The differences were on the order of 3% of average annual rainfall for a recharge estimate of 17% ± 5% of annual rainfall. However, the 8% difference in imperviousness between the study site sub-watershed and the Vermillion River reference watershed, can account for a 2% decrease in direct natural groundwater recharge according to Figure 3.2. Therefore the use of the three models formulated for the projection of groundwater recharge under future urban development conditions, appears justified, because (1) the models apply widely accepted principles and process formulations, and (2) and the comparison with streamflow analysis of groundwater recharge for the Vermillion River watershed as a whole provided assurance that annual groundwater recharge estimates to within 1 to 3% of annual rainfall can be made.

## 3.5 Estimated trends in 'natural' recharge in the Upper Vermillion River watershed.

Figure 3.2 can be used to estimate the 'natural' groundwater recharge in the Upper Vermillion River at different stages of development. A trend line was added to Figure 3.2. This trend line gives an equation for recharge as percentage of annual precipitation as a function of the percentage of impervious area in the watershed.

Using the percentage of impervious area given in Figure 2.8 for the five historical land-use years, the imperviousness for each year between 1984 and 2005 was estimated using linear interpolation (Table 3.3). Applying the equation in Figure 3.2 to the annual imperviousness estimates, the average annual natural recharge was estimated, for an average annual precipitation of 32.1 in/year.

**Table 3.3 Estimated natural recharge in Upper Vermillion River watershed using Figure 3.2**

| Year | Estimated imperviousness % | Estimated natural recharge (in) |
|---|---|---|
| 1984 | 7.60 | 6.28 |
| 1985 | 7.81 | 6.26 |
| 1986 | 8.03 | 6.24 |
| 1987 | 8.25 | 6.22 |
| 1988 | 8.46 | 6.20 |
| 1989 | 8.68 | 6.18 |
| 1990 | 8.90 | 6.16 |
| 1991 | 9.04 | 6.15 |
| 1992 | 9.19 | 6.13 |
| 1993 | 9.33 | 6.12 |
| 1994 | 9.48 | 6.11 |
| 1995 | 9.62 | 6.10 |
| 1996 | 9.77 | 6.08 |
| 1997 | 9.91 | 6.07 |
| 1998 | 10.34 | 6.03 |
| 1999 | 10.77 | 5.99 |
| 2000 | 11.21 | 5.95 |
| 2001 | 11.57 | 5.92 |
| 2002 | 11.93 | 5.89 |
| 2003 | 12.30 | 5.85 |
| 2004 | 12.66 | 5.82 |
| 2005 | 13.03 | 5.79 |
| Watershed averages | | 6.07 |

Table 3.3 shows that the imperviousness decreases natural recharge from 6.28 in/year in 1984 to 5.79 in/year in 2005. These values would be the long-term average natural recharge values and not the actual annual recharge for a specific year. The decrease in recharge from 1984 to 2005 is a reduction of about 0.5 in/yr, using the actual long-term average of 6.4 in/year. This would be a reduction of about 8%. This may not seem significant but imperviousness has only increased by about 5.5% in the same time period.

# 4. Trend analysis of hydrologic parameters

## 4.1 Land use and urbanization effects on trends 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 quantile, 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.

Most studies of trends have focused on long-term trends in streamflow, primarily in agricultural watersheds. Trends are accounted for by changing land management practices through the twentieth century. Few studies have examined the impacts of urbanization on streamflow or base flow.

A trend analysis was first conducted on the streamflow record and base flow estimates (Erickson and Stefan 2008) for the USGS gauging near Empire, MN. The Vermillion River watershed was primarily an agricultural watershed but has experienced a significant shift to urban development. 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.

## 4.2 Evidence of trends in the Upper Vermillion River watershed

To detect trends that would indicate a changing hydrology in the Upper Vermillion River watershed, hydrologic variables were plotted as a time-series (Figure 4.1). The variables plotted 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). Linear regression lines and their equations were added to the plots for the study period from 1982 to 2006. The plots are used to explore (1) if a trends are present, (2) what might cause trends, (3) if trends are due to changes in the hydrology of the watershed, and (4) if trends are due to urbanization of the watershed.

The first sign that the hydrology in the Vermillion River watershed is changing are the trends in precipitation and of streamflow, especially when compared to each other (Figure 4.1a, 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. Had the hydrology of the watershed not changed, a decrease in annual precipitation would be expected to result in a lower streamflow. The opposing trends indicate that a larger percentage of the precipitation must be reaching the stream.

Annual maximum flood flows over the 24 year time period have a slightly decreasing trend. One might expect an increase in maximum flood flow due to urbanization.

The trend line of the 1-day minimum flows is rising significantly. 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, 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 4.1(e) is a time-series plot of the annual groundwater recharge estimated using the USGS program RORA. The linear trend-line indicates that groundwater recharge is increasing,

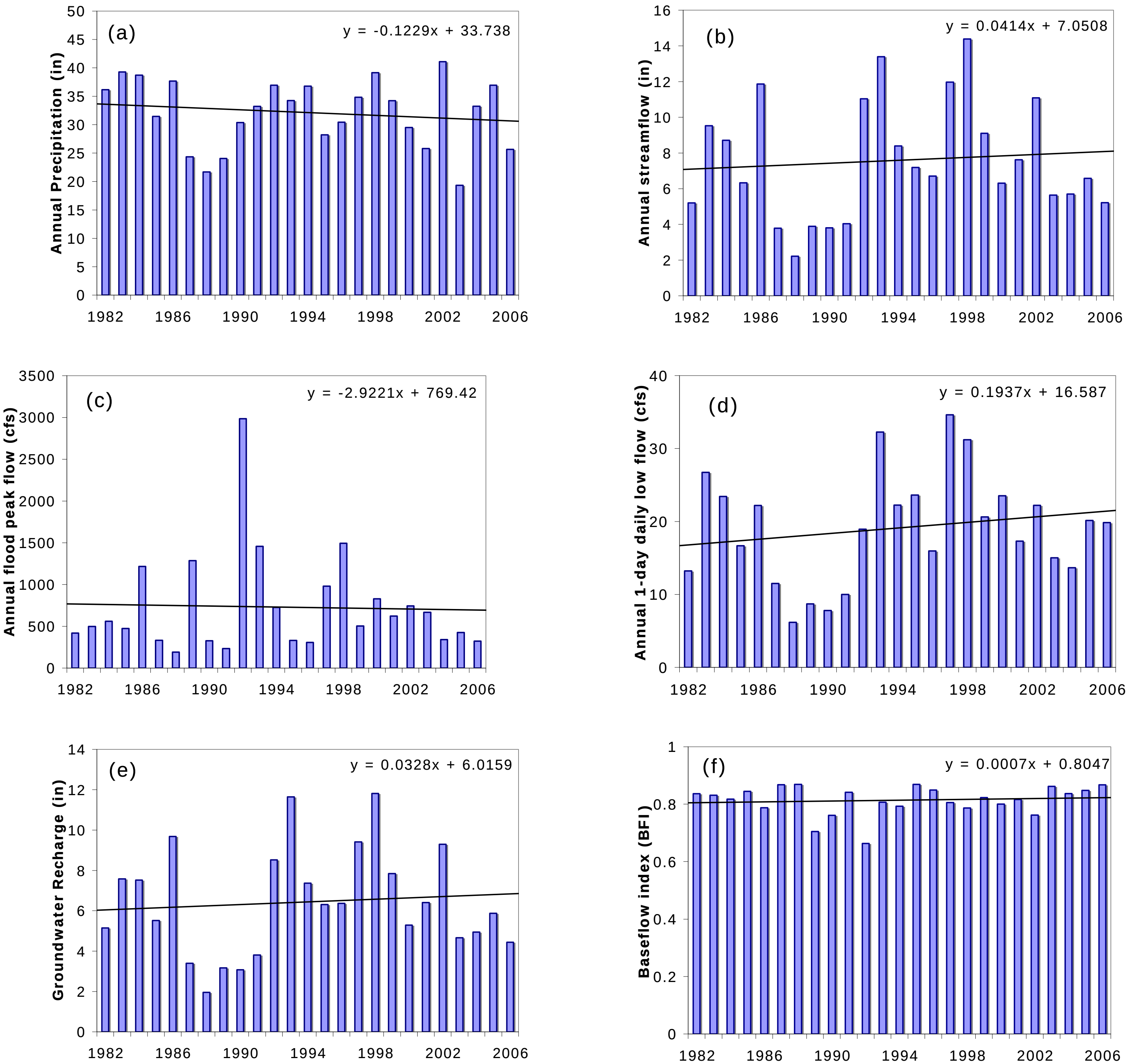


**Figure 4.1 (a) to (f): Trends in the Upper Vermillion River watershed upstream from the USGS gauging site near Empire, MN: (a) annual precipitation (in/yr), (b) annual streamflow (in/yr), (c) annual maximum peak flow (cfs), (d) one-day low flow (cfs), (e) annual groundwater recharge (estimated using RORA) (in/yr), and (f) baseflow (estimated using PART) as fraction of streamflow (Erickson and Stefan 2008)**.

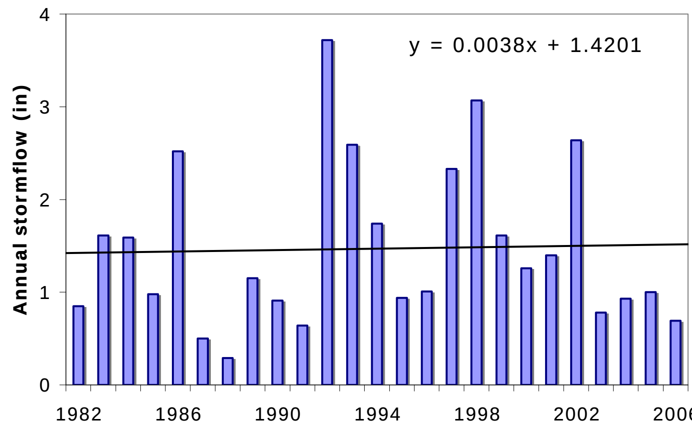


**Figure 4.1 (g): Annual stormflow or direct runoff (in/year) in the Upper Vermillion River watershed upstream from the USGS gauging site near Empire, MN (Erickson and Stefan 2008).**

confirming the trend seen in the low flow plot in Figure 4.1(d). 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 land management practices that cause more of the precipitation to infiltrate and reach the stream through the ground.

Figure 4.1 (g) shows the direct runoff or storm flow as a function of time. The trend line indicates that direct runoff is trending upward slightly.

## 4.3. Statistical significance of trends

The trend lines in Figure 4.1 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 methodology has been summarized in another report (Erickson and Stefan, 2008) . The results, given in the same report can be summarized as follows.

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 4.1. Kendall's τ 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 4.1 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 4.1: Kendall statistics for hydrologic variables in the Upper Vermillion River watershed (Erickson and Stefan 2008).**

| Variable | τ | 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 |

τ = 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 4.1 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 do not 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 4.2.

**Table 4.2: Kendall statistics for selected normalized hydrologic variables in the Upper Vermillion River watershed. Variables have been normalized to precipitation (Erickson and Stefan 2008).**

| 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 |

The normalized hydrologic variables in Table 4.2 do show lower p-values than the p-values in Table 4.1, 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 4.1) has risen to 66% that there is an increasing trend in the percentage of precipitation reaching the stream as streamflow. However, Table 4.2 shows that there are still no statistically significant trends at the 95% confidence level, i.e. all p-values are larger than 0.05.

## 4.4 Discussion of trends

Even though the analysis shows that the null hypothesis cannot be rejected at the 95% confidence interval, trends exist at lower 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.

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 returned 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.

A longer data set than for the 1982 to 2006 time period may be needed to confirm the statistical trends shown in Figure 4.1 and Table 4.1. Interestingly the trends had higher confidence intervals when the hydrologic variables were normalized relative to precipitation. 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, i.e. indicators that urbanization might have affected the watershed.

# 5. Water use and 'artificial' recharge in the Upper Vermillion River watershed.

When an agricultural or natural watershed is urbanized, ground surface covers are altered, water drainage is altered, and water supply systems are installed. In the previous section 3 we have examined the effect of ground surface covers on 'natural' recharge. In this section we shall examine the effect of new water distribution and drainage systems in an urbanized watershed. The effect of infiltration enhancing stormwater management shall be left to another study.

Groundwater recharge due to urbanization may be influenced by water from new water supply and drainage systems which will bw referred to as 'artificial' sources or artificial groundwater recharge as opposed to 'natural' or 'diffuse' recharge starting with infiltration from the land surface.. Urban areas import and use large volumes of water to meet society's need. This water supply comes from surface water bodies or deep aquifers. The potable water used in the Vermillion River watershed is groundwater from deep aquifers like the Prairie du Chien and Jordan aquifers. Used water is carried away in sanitary sewers. Water will percolate through the root zone to the shallow surficial aquifer in the Vermillion river watershed from excessive lawn and crop irrigation or from leaks in municipal water distribution and collection networks and from septic systems in areas without municipal sewers.

We showed in Section 3, based on a study by Erickson and Stefan (2007) that increased imperviousness in the Vermillion River watershed due to urban development would decrease ‘natural’ groundwater recharge. But no statistically significant trends in base flow (groundwater recharge) could be found between 1982 and 2005 even though a significant portion of the watershed had undergone development during that time period (Erickson and Stefan 2008). This contradiction leads us to believe that the decrease in ‘natural” recharge is being replaced by an increase in recharge from ‘artificial’ water sources.

To explore this hypothesis, a water use analysis was conducted. In this analysis we estimated the seasonal use of water for lawn irrigation in cities with municipal water supplies, the pipe leakage in those cities, and septic system drainage for cities and populations without sewage collection networks. From these values the total ‘artificial’ recharge was estimated and compared to simulated decrease in the ‘natural’ recharge to determine the net change in recharge due to urbanization. According to the results of the streamflow analysis, the net change should be very small.

Monthly records of water volumes pumped from wells (Figure 5.1) with permits from the Department of Natural Resources (DNR) were obtained from the Metropolitan Council (METC). The records are from the MN DNR database for the permitted wells. Permits are required for all wells that are withdrawing more than 10,000 gallons of water per day or 1 million gallons per year (MN DNR website). The data set includes all municipal wells and large use private wells for crop and lawn[1] irrigation, dewatering[2] and industrial processing.

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[1] Mainly for golf courses

[2] Dewatering wells used during construction were assumed to have no net effect on recharge since most discharge into the river through the storm water collection network. This flow would be a small fraction of base flow in the streamflow analysis and therefore not skew the recharge estimates.

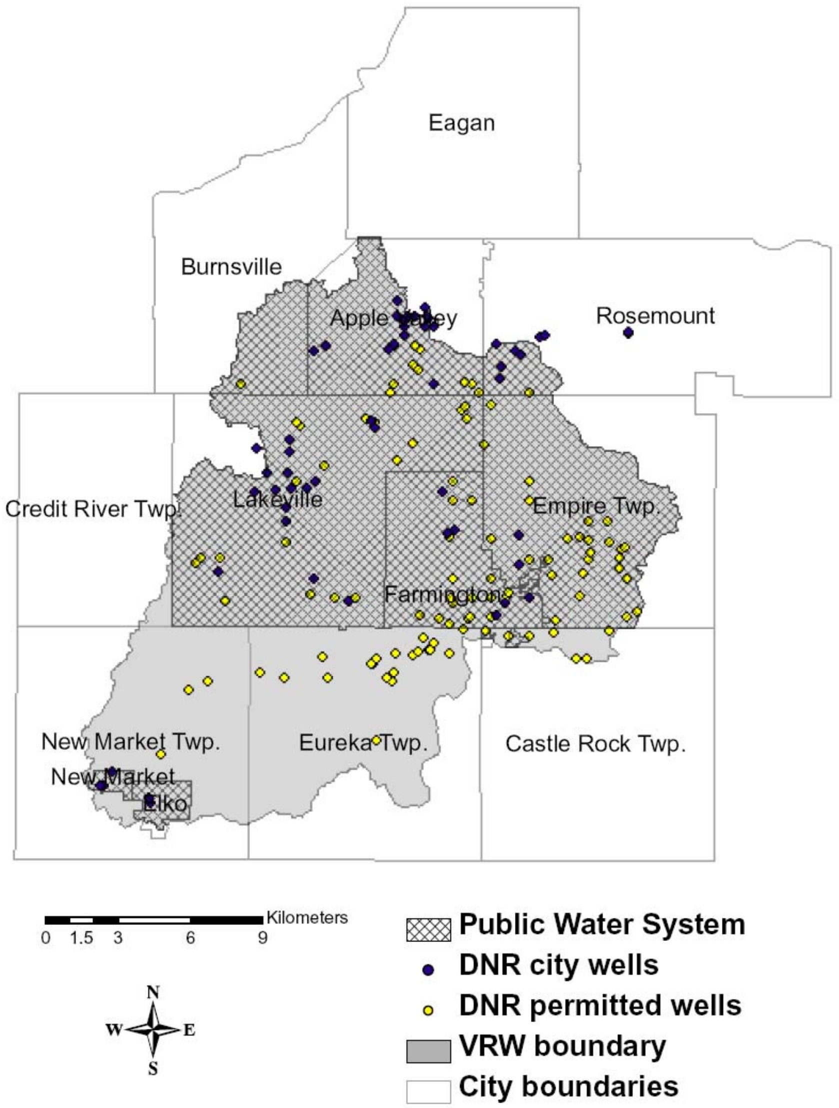


**Figure 5.1 Location of wells in the Upper Vermillion River watershed**

## 5.1 Residential water use in the watershed

The main water source for all municipal water systems in the Upper Vermillion River is groundwater, mostly pumped from the Prairie du Chien and Jordan aquifer systems. The cities within the watershed with public water supplies include: Apple Valley, Burnsville, Eagan, Elko, Empire Township (Twp.), Farmington, Lakeville, New Market, and Rosemount. By analyzing the pumpage record for each municipal water supply, seasonal lawn irrigation and pipe leakage can be estimated (Figure 5.1).

In 2002, the METC investigated the water supply systems of the Twin Cities Metropolitan Area. The resulting regional water demand and planning report (METC 2004) gives data on the number of wells, the percent of population served, the per capita daily use and the percent of accounted/un-metered water use (Table 5.1). These data provide information on the distribution of water in the watershed. The percentage of population served by the public water supply provides information on the percent of population not served and therefore the number of people that have private wells. The same people most likely have private sanitary septic systems. Knowing the population of townships without public water supply networks and daily per capita water use, an estimate of septic system drainage can be obtained.

Unaccounted water is defined as water that was pumped and treated but not sold. Reasons for the apparent loss of water are inaccurate or non-functioning meters, un-metered users such as irrigation of municipal parks or flooding of ice rinks. All water supply networks are prone to leak (Lerner 1986), and most of the unsold water is pipe leakage. The unaccounted water is a good indictor of pipe leakage. Unaccounted water varies from a low of 3.5% of annual water use for Farmington to a high of 32.7% for Elko (Table 5.1). Most of the cities included in the study are only partly in the watershed, with the exception of Farmington (Figure 5.1). However, the percentage of total area of a city within the watershed may not be a good indicator of the percentage of total water use within the area, because water distribution networks can cross the watershed divide;, and most residential areas are not evenly dispersed in a city; the water use records are modified to represent the number of users in the watershed.

**Table 5.1: 2002 Water use statistics for cities in the Vermillion River with public water supply networks**

| City | # of wells | Total population | Population served | % Population served | Residential use gal/cap/day | % Unaccounted water |
|---|---|---|---|---|---|---|
| Apple Valley | 18 | 48360 | 48360 | 100.0 | 82 | 21.8 |
| Burnsville | 16 | 60500 | 59290 | 98.0 | 90 | 4.7 |
| Elko | 2 | 658 | 408 | 62.0 | 101 | 32.7 |
| Empire | 2 | 1638 | 1020 | 62.3 | 100 | 4.7 |
| Farmington | 7 | 16275 | 16275 | 100.0 | 64 | 3.5 |
| Lakeville | 15 | 46453 | 45059 | 97.0 | 84 | 7.0 |
| New Market | 3 | 535 | 306 | 57.2 | na | na |
| Rosemount | 6 | 17603 | 4910 | 27.9 | 65 | 11.6 |

Assuming that a city's residents are the primary users of water, the ratio of residential land use in the watershed to the total residential land use[3] can be used as an estimator for total water use in the watershed. Linear interpolation was used to estimate the ratio of residential area in the watershed to total residential area for years when no land use maps were available. By multiplying this ratio by total annual water use in each city, the water use in the watershed was estimated (Table 5.2). The larger cities tend to have larger annual water uses than the smaller cities, as to be expected. Annual water use in Apple Valley, Burnsville, and Lakeville is on the order of billions of gallons per year whereas Elko, Empire, and New Market use millions of gallons per year. There is much variation in water use between years; this can be due to climate parameters (temperature and precipitation) that influence how much water is used for lawn irrigation. The total annual municipal water use can be found in Table 5.3.

Some of the watershed's population lives in rural areas not served by municipal water. Parts of Elko, Empire, Lakeville, New Market, and Burnsville, and all of Castle Rock, Credit River, Eureka, and New Market townships have small private wells that pump less than one million gallons per year, and do not require a DNR permit.

It is likely people in these townships also have private septic systems. Septic systems can provide large volumes of water to an aquifer because much of the water is drained below the reach of plants. The private wells and septic systems are mostly unregulated and therefore no use records exist. An approximate volume of total water use can be estimated by assuming an annual per capita use and multiplying it by the un-served population or private well users. In townships without municipal water supply, the population with private wells is the population of the township. The per capita water use was estimated by averaging the per capita water use for cities with municipal supplies (Table 5.1) within the watershed. It was estimated to be 84 gallons of water per day per person.

[3] See Appendix C, Table C.1

**Table 5.2: Annual water use in cities with public water supplies.**

| Year | Apple Valley | Burnsville | Elko | Empire | Farmington | Lakeville | New Market | Rosemount |
|---|---|---|---|---|---|---|---|---|
| | MG | MG | MG | MG | MG | MG | MG | MG |
| 1988 | 1834.5 | 2738.8 | 3.0 | 32.9 | 349.0 | 915.5 | 5.9 | 269.0 |
| 1989 | 1587.5 | 2494.1 | 3.3 | 28.4 | 315.0 | 900.0 | 6.3 | 269.5 |
| 1990 | 1531.0 | 2286.8 | 3.3 | 22.6 | 267.0 | 850.9 | 6.9 | 270.2 |
| 1991 | 1598.9 | 2244.7 | 2.9 | 24.0 | 272.3 | 927.9 | 5.9 | 322.6 |
| 1992 | 1751.7 | 2725.5 | 3.0 | 26.1 | 296.3 | 1032.8 | 6.0 | 331.3 |
| 1993 | 1410.3 | 2290.4 | 3.0 | 21.2 | 223.6 | 940.0 | 6.0 | 300.8 |
| 1994 | 1633.8 | 2496.6 | 2.0 | 29.4 | 243.6 | 1087.0 | 5.7 | 352.6 |
| 1995 | 2284.4 | 2353.0 | 2.1 | 27.3 | 289.3 | 1181.4 | 6.4 | 384.6 |
| 1996 | 2029.6 | 2075.6 | 2.1 | 29.5 | 339.4 | 1429.9 | 7.8 | 428.6 |
| 1997 | 1845.0 | 2378.1 | 2.4 | 33.2 | 437.3 | 1322.4 | 6.5 | 405.6 |
| 1998 | 1976.5 | 2507.7 | 3.8 | 35.4 | 381.3 | 1417.3 | 7.1 | 437.5 |
| 1999 | 2019.1 | 2457.9 | 5.3 | 42.3 | 395.8 | 1581.2 | 9.2 | 446.7 |
| 2000 | 2222.0 | 2629.3 | 9.5 | 40.9 | 461.1 | 1892.7 | 12.4 | 536.5 |
| 2001 | 2500.6 | 2750.4 | 13.0 | 46.4 | 517.7 | 1998.1 | 32.1 | 593.6 |
| 2002 | 2154.3 | 2317.2 | 15.0 | 39.0 | 479.3 | 1698.0 | 27.6 | 605.8 |
| 2003 | 2671.5 | 3018.0 | 31.5 | 50.8 | 663.2 | 2183.0 | 47.8 | 769.6 |
| 2004 | 2481.4 | 2690.0 | 35.8 | 53.4 | 589.2 | 2069.7 | 50.5 | 734.9 |
| 2005 | 2358.7 | 2631.9 | 38.3 | 59.7 | 628.3 | 2059.5 | 57.9 | 765.6 |

MG = millions of gallons

The un-served population in cities with municipal water distribution networks can be estimated by assuming that the percentage of served population (Table 5.1) remains constant through the time period. This will give an idea of the un-served population even though in all likeliness the percentage of un-served population might be greater for earlier years because more of the population becomes connected to the water supply as the city develops. This assumption can be made because the number of un-served people in the cities with municipal water is much less than the population of townships with no municipal water supply. The per capita use by people within cities that have municipal water but are not connected to the distribution networks is assumed to be the same as for people who are connected. Total annual water use for people with private wells is given in Table 5.3, along with the estimated total population of served and un-served areas.

**Table 5.3 Estimated annual water use by source: municipal and private wells**

| Year | Estimated population served by municipal wells | Estimated municipal water use (MG) | Estimated population with private wells | Estimate water use from private wells (MG) | Total annual water use in watershed (MG) |
|---|---|---|---|---|---|
| 1988 | 52208 | 2716.1 | 3295 | 109.0 | 2825.1 |
| 1989 | 54255 | 2479.9 | 3359 | 110.8 | 2590.7 |
| 1990 | 56304 | 2320.7 | 3421 | 113.0 | 2433.7 |
| 1991 | 59377 | 2424.6 | 3559 | 117.6 | 2542.2 |
| 1992 | 62473 | 2729.7 | 3699 | 122.6 | 2852.3 |
| 1993 | 65592 | 2299.3 | 3839 | 127.0 | 2426.3 |
| 1994 | 68733 | 2623.4 | 3981 | 131.8 | 2755.1 |
| 1995 | 71897 | 3099.6 | 4123 | 136.6 | 3236.1 |
| 1996 | 75084 | 3157.1 | 4267 | 141.8 | 3298.9 |
| 1997 | 78293 | 3132.8 | 4412 | 146.3 | 3279.1 |
| 1998 | 82011 | 3320.8 | 5628 | 178.3 | 3499.2 |
| 1999 | 85795 | 3553.8 | 6936 | 212.7 | 3766.5 |
| 2000 | 89645 | 4128.7 | 8338 | 250.1 | 4378.8 |
| 2001 | 93240 | 4524.0 | 8728 | 261.6 | 4785.6 |
| 2002 | 97012 | 3943.8 | 9085 | 273.0 | 4216.8 |
| 2003 | 100621 | 5104.8 | 9420 | 284.8 | 5389.6 |
| 2004 | 104415 | 4765.2 | 9833 | 300.5 | 5065.7 |
| 2005 | 108868 | 4744.6 | 10351 | 316.1 | 5060.7 |

The population served by municipal water distribution systems, and the associated annual water supply by municipalities, are much greater than those served by private wells. The difference is more than an order of magnitude (Table 5.3). One could therefore consider ignoring private wells because they account for less than 10% of the total water use in the watershed, but most of this water is returned to the aquifer though septic drainage and may be a substantial source for artificial recharge.

Plotting annual municipal, private, and total water uses as a time series shows that water use has increased substantially over the time period (Figure 5.2). Annual water use has doubled in the watershed between 1988 and 2005, increasing from approximately 2.4 billion gallons/year to approximately 5.0 billion gallons/year. This increase is accounted for by the increase in population and urbanization of the watershed.

Water use for lawn irrigation, pipe leakage from municipal distribution networks, and drainage from septic systems will be estimated separately.

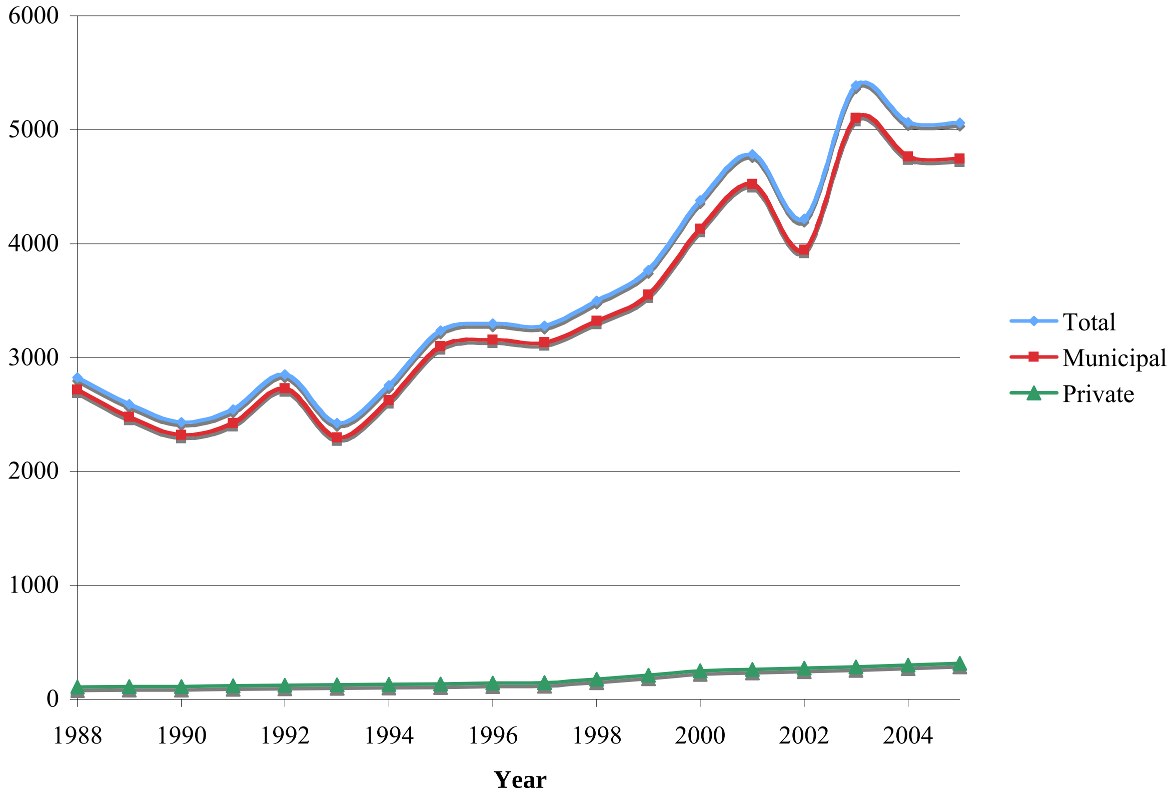


**Figure 5.2: Estimated annual water use in Upper Vermillion River water from 1988 to 2005.**

## 5.2 Crop and Lawn Irrigation

Lawn and crop irrigation can add large volumes of water to the watershed. The excess portion of this water will percolate beyond the root zone and recharge the shallow aquifer. Crop irrigation can be easy to estimate because permitted wells that are used to irrigate fields, require reporting of monthly pumpage. These well records give a good annual estimate of crop irrigation in the watershed (Table 5.4).

Lawn irrigation is harder to estimate. The seasonal distribution of water use shows an increase during the growing season (Figure 5.3). The increase starts in May, peaks usually in July, and declines back to base use in October. This increase in water use follows what would be expected for lawn irrigation.

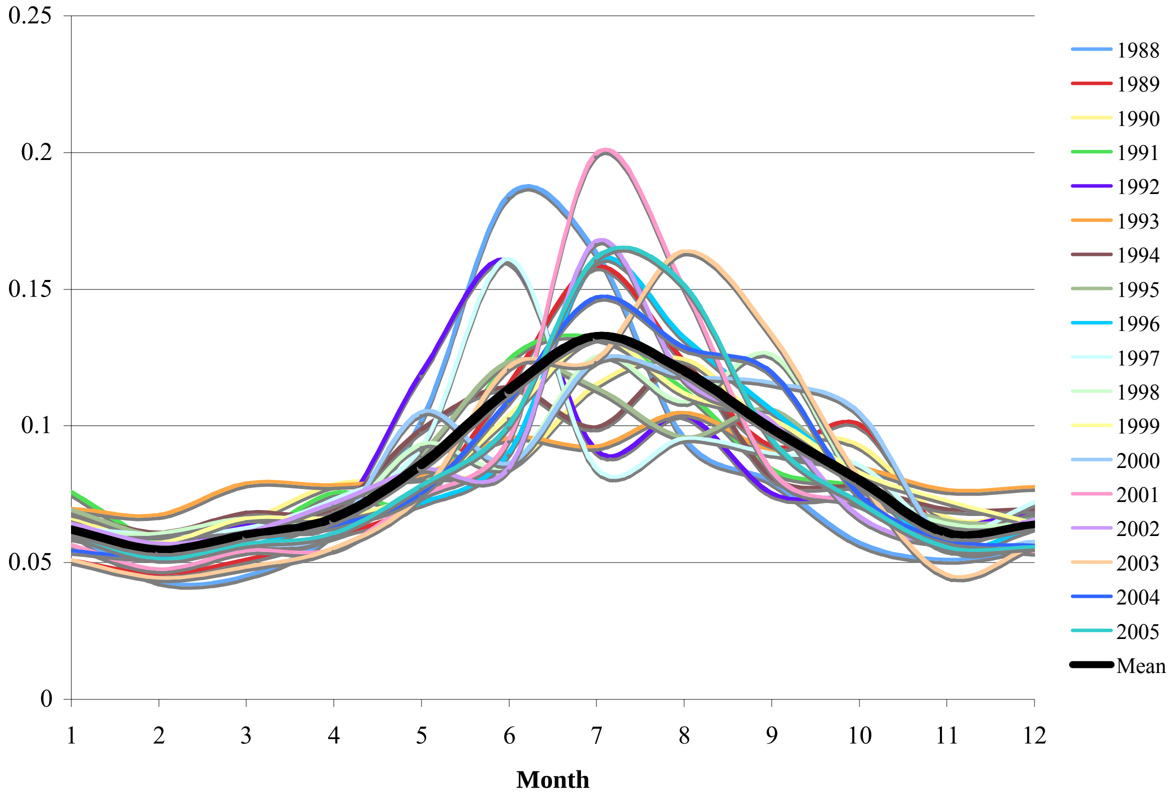


**Figure 5.3: Distribution of annual water use in the Upper Vermillion River watershed.**

The volume of water used for lawn irrigation can be estimated by assuming a base use during the non-growing season months (November to April); the water use above base use is attributed to lawn irrigation. By estimating the base use for each year separately, weather variations between years can be taken into account. Annual estimates of base use and lawn irrigation as a percentage of total annual use are given in Table 5.4. Annual precipitation is also given in Table 5.4 and shows a loose association with annual water use; more water is used in years with less than average precipitation. Estimated volumes of lawn and crop irrigation are also given in Table 5.4 along with a representative irrigation depth[4]. Most of this water will be returned to the atmosphere through evapotranspiration, but a fraction percolates below the root zone and recharges the aquifer. The water depth for lawn irrigation (Table 5.4) is small compared to annual precipitation (Table 5.3) but may be large compared to annual recharge.

[4] Total water volume divided by the area of the watershed (129 sq mi).

**Table 5.4 Watershed irrigation estimates**

| Year | % Base use | % Irrigation | Estimated water use in watershed MG | Estimated lawn irrigation MG | Crop irrigation MG | Irrigation depth in |
|---|---|---|---|---|---|---|
| 1988 | 61.5 | 38.5 | 2716.1 | 1044.6 | 508.9 | 0.69 |
| 1989 | 66.3 | 33.7 | 2479.9 | 835.2 | 298.9 | 0.51 |
| 1990 | 77.7 | 22.3 | 2320.7 | 517.8 | 213.7 | 0.33 |
| 1991 | 76.8 | 23.2 | 2424.6 | 562.6 | 327.4 | 0.40 |
| 1992 | 74.5 | 25.5 | 2729.7 | 695.6 | 177.4 | 0.39 |
| 1993 | 89.0 | 11.0 | 2299.3 | 252.9 | 68.8 | 0.14 |
| 1994 | 80.9 | 19.1 | 2623.4 | 501.0 | 233.0 | 0.33 |
| 1995 | 78.2 | 21.8 | 3099.6 | 676.8 | 348.5 | 0.46 |
| 1996 | 70.2 | 29.8 | 3157.1 | 941.1 | 424.2 | 0.61 |
| 1997 | 76.4 | 23.6 | 3132.8 | 740.0 | 133.0 | 0.39 |
| 1998 | 76.0 | 24.0 | 3320.8 | 796.4 | 294.1 | 0.49 |
| 1999 | 77.8 | 22.2 | 3553.8 | 790.0 | 328.1 | 0.50 |
| 2000 | 68.1 | 31.9 | 4128.7 | 1315.3 | 452.7 | 0.79 |
| 2001 | 64.8 | 35.2 | 4524.0 | 1594.7 | 580.2 | 0.97 |
| 2002 | 73.4 | 26.6 | 3943.8 | 1049.2 | 378.9 | 0.64 |
| 2003 | 58.9 | 41.1 | 5104.8 | 2097.6 | 658.8 | 1.23 |
| 2004 | 67.5 | 32.5 | 4765.2 | 1548.4 | 526.4 | 0.93 |
| 2005 | 67.2 | 32.8 | 4744.6 | 1556.0 | 515.7 | 0.92 |

## 5.3 Pipe leakage and septic system drainage

Pipe leakage and septic system drainage supply additional quantities of water to the aquifer. Most of the leaked or drained water can recharge the aquifer directly because most pipes and septic systems are below the root zone. Simmons and Reynolds (1982) investigated the effects of urbanization on six streams on Long Island, New York. They found that increased storm sewerage and increased sanitary sewerage accounted for most of the reduction in base-flow (from 95 to 20 percent of total annual streamflow). In adjacent, non-urbanized watersheds no such changes in the percentages of streamflow were apparent. Lerner (1986) reports two case studies which showed that pipe leakage can account for as much as 50% of the annual recharge.

Estimates of unaccounted residential water supplies as a percentage of annual residential water use in the Vermillion River watershed were estimated in 2002 (Table 5.1). This unaccounted water could be lost through broken meters, watering of parks, and flooding of ice rinks, but most of it is probably lost by pipe leakage. Pipe leakage would be fairly constant throughout the year, i.e. it would not have much seasonal variation. Assuming that unaccounted water is primarily pipe leakage and is constant with time because all water pipes are below the frost line and leak throughout the year, annual pipe leakage was estimated as a percentage of annual use. This annual use would be part of the base use Using the percentages of unaccounted water in Table 5.1, annual pipe leakage was estimated in Table 5.5. This pipe leakage has an increasing trend from 1988 to 2005 because annual water use increases due to progressive urban development. The public supply leakage increases from approximately 0.14 inches/year to approximately 0.24 inches/year. These water depths are small compared to the annual recharge rate of 6.6 inches/year, but can account for about 5% of annual recharge.

**Table 5.5 Pipe leakage and septic system drainage in the Vermillion River watershed**

| Year | Public supply pipe leakage | | Septic system drainage | | Total leakage |
|---|---|---|---|---|---|
| | MG | depth (in) | MG | depth (in) | (in) |
| 1988 | 329.1 | 0.15 | 109.0 | 0.049 | 0.20 |
| 1989 | 291.8 | 0.13 | 110.8 | 0.049 | 0.18 |
| 1990 | 277.2 | 0.12 | 113.0 | 0.050 | 0.17 |
| 1991 | 289.6 | 0.13 | 117.6 | 0.052 | 0.18 |
| 1992 | 320.8 | 0.14 | 122.6 | 0.055 | 0.20 |
| 1993 | 265.5 | 0.12 | 127.0 | 0.057 | 0.18 |
| 1994 | 305.0 | 0.14 | 131.8 | 0.059 | 0.19 |
| 1995 | 393.3 | 0.18 | 136.6 | 0.061 | 0.24 |
| 1996 | 375.0 | 0.17 | 141.8 | 0.063 | 0.23 |
| 1997 | 352.0 | 0.16 | 146.3 | 0.065 | 0.22 |
| 1998 | 377.8 | 0.17 | 178.3 | 0.080 | 0.25 |
| 1999 | 397.9 | 0.18 | 212.7 | 0.095 | 0.27 |
| 2000 | 453.5 | 0.20 | 250.1 | 0.112 | 0.31 |
| 2001 | 509.1 | 0.23 | 261.6 | 0.117 | 0.34 |
| 2002 | 442.3 | 0.20 | 273.0 | 0.122 | 0.32 |
| 2003 | 567.3 | 0.25 | 284.8 | 0.127 | 0.38 |
| 2004 | 533.5 | 0.24 | 300.5 | 0.134 | 0.37 |
| 2005 | 522.4 | 0.23 | 316.1 | 0.141 | 0.37 |

Septic system drainage is estimated by assuming that all of the water used in residences not connected to sanitary sewers is returned to the grounded by drainage from the septic system. The annual drainage volume and representative depth are also given in Table 5.5. As the population in the watershed increases, septic system drainage rises from approximately 0.05 inches/year to 0.14 inches/year. Total leakage from pipe leakage and septic system drainage is also given in Table 5.5. This total leakage increases (doubles) from about 0.18 inches/year to about 0.38 inches over the time period from 1988 to 2005.

All of these values may seem small but their sum may be enough to supplement the reduction of natural recharge (Table 3.3) due to the urbanization (increased imperviousness) in the watershed. The total artificial recharge in the watershed and its influence on net annual recharge will be discussed next.

## 5.4 Total artificial recharge and its influence on annual recharge.

The sum of total leakage plus a percentage of irrigation gives the total artificial recharge in the watershed (Table 5.6). Assuming that all irrigation water infiltrates and that the fraction (percentage) of irrigation water that become recharge is the same as the fraction (percentage) of water infiltrated from rainfall (in the whole watershed) (Table 2.2) the annual recharge from irrigation can be estimated.

**Table 5.6: Estimated annual artificial recharge in Vermillion River watershed**

| Year | Irrigation depth (in) | Irrigation recharge (in) | Municipal Leakage (in) | Septic drainage (in) | Total artificial recharge (in) |
|---|---|---|---|---|---|
| 1988 | 0.69 | 0.15 | 0.15 | 0.049 | 0.34 |
| 1989 | 0.51 | 0.11 | 0.13 | 0.049 | 0.29 |
| 1990 | 0.33 | 0.07 | 0.12 | 0.050 | 0.24 |
| 1991 | 0.40 | 0.08 | 0.13 | 0.052 | 0.27 |
| 1992 | 0.39 | 0.08 | 0.14 | 0.055 | 0.28 |
| 1993 | 0.14 | 0.03 | 0.12 | 0.057 | 0.21 |
| 1994 | 0.33 | 0.07 | 0.14 | 0.059 | 0.26 |
| 1995 | 0.46 | 0.10 | 0.18 | 0.061 | 0.33 |
| 1996 | 0.61 | 0.13 | 0.17 | 0.063 | 0.36 |
| 1997 | 0.39 | 0.08 | 0.16 | 0.065 | 0.30 |
| 1998 | 0.49 | 0.10 | 0.17 | 0.080 | 0.35 |
| 1999 | 0.50 | 0.10 | 0.18 | 0.095 | 0.38 |
| 2000 | 0.79 | 0.17 | 0.20 | 0.112 | 0.48 |
| 2001 | 0.97 | 0.20 | 0.23 | 0.117 | 0.55 |
| 2002 | 0.64 | 0.13 | 0.20 | 0.122 | 0.45 |
| 2003 | 1.23 | 0.26 | 0.25 | 0.127 | 0.64 |
| 2004 | 0.93 | 0.19 | 0.24 | 0.134 | 0.57 |
| 2005 | 0.92 | 0.19 | 0.23 | 0.141 | 0.57 |

The amount of groundwater recharge from irrigation may be underestimated by this method because the surficial plants may already evapotranspirate near the potential evapotranspiration, and hence a larger portion of the irrigation water may become recharge. The average percent of total infiltrated water that becomes recharge in the watershed is 21% (Erickson and Stefan 2008). Therefore recharge from irrigation is then taken as 21% of the total irrigated water (Table 5.6). The total artificial recharge in the watershed doubles from approximately 0.3 inches/year at the beginning of the time period (1988-2005) to about 0.6 inches/year near the end. This increase in artificial recharge is approximately 10% of the annual recharge estimate (6.4 inches/year). This is only a small fraction of recharge but may be enough to compensate for the decrease in natural recharge due to urbanization. If the reduction in natural recharge due to urbanization follows the analysis in Section 3, and the increase in artificial recharge follows the analysis in Section 5, the combined influence of urbanization on groundwater recharge in the Vermillion River watershed can be understood.

# 6. Net recharge in the Vermillion River

The trend analysis in Section 4 showed that no statistically significant long-term trend existed in the record for base flow in the Vermillion River. Long-term baseflow was assumed to equal to long-term groundwater recharge. The analysis of natural infiltration from rainfall in the Upper Vermillion River Basin (Section 3) showed that an increase in imperviousness due to progressive urbanization has reduced **natural groundwater recharge**. An analysis of infiltration from leaky water supply and drainage systems, lawn irrigation and septic systems in the Upper Vermillion River Basin (Section 5) showed that **artificial groundwater recharge** has increased with urbanization over time.

By summing the reduction in natural recharge with the increase in artificial recharge, the net recharge in the Upper Vermillion River watershed can be found. Table 6.1 summarizes the change in natural recharge due to increased imperviousness (Section 3), the estimated artificial recharge estimated from the water use study (Section 5), and the net recharge in the watershed. A plot of the natural, artificial, and net recharge as a time series (Figure 6.1), shows that natural recharge decreases due to increased imperviousness, artificial recharge increases due to increased population and water use, and net recharge stays relatively constant, which matches the trend analysis in Section 3. The long-term average recharge in the watershed from the base flow analysis (Section 3) is also given in Figure 6.1 to show that the analysis of natural plus artificial recharge gives a result similar to the base flow analysis.

**Table 6.1: Net recharge in the Upper Vermillion River watershed**

| Year | Estimated imperviousness % | Estimated natural recharge (in) | Estimated artificial recharge (in) | Net recharge (in) |
|---|---|---|---|---|
| 1988 | 8.46 | 6.46 | 0.34 | 6.80 |
| 1989 | 8.68 | 6.44 | 0.29 | 6.72 |
| 1990 | 8.90 | 6.41 | 0.24 | 6.66 |
| 1991 | 9.04 | 6.40 | 0.27 | 6.66 |
| 1992 | 9.19 | 6.38 | 0.28 | 6.66 |
| 1993 | 9.33 | 6.37 | 0.21 | 6.57 |
| 1994 | 9.48 | 6.35 | 0.26 | 6.61 |
| 1995 | 9.62 | 6.33 | 0.33 | 6.67 |
| 1996 | 9.77 | 6.32 | 0.36 | 6.68 |
| 1997 | 9.91 | 6.30 | 0.30 | 6.61 |
| 1998 | 10.34 | 6.26 | 0.35 | 6.61 |
| 1999 | 10.77 | 6.21 | 0.38 | 6.59 |
| 2000 | 11.21 | 6.16 | 0.48 | 6.64 |
| 2001 | 11.57 | 6.12 | 0.55 | 6.67 |
| 2002 | 11.93 | 6.08 | 0.45 | 6.53 |
| 2003 | 12.30 | 6.04 | 0.64 | 6.68 |
| 2004 | 12.66 | 6.00 | 0.57 | 6.57 |
| 2005 | 13.03 | 5.96 | 0.57 | 6.53 |
| Watershed averages | | 6.26 | 0.38 | 6.64 |

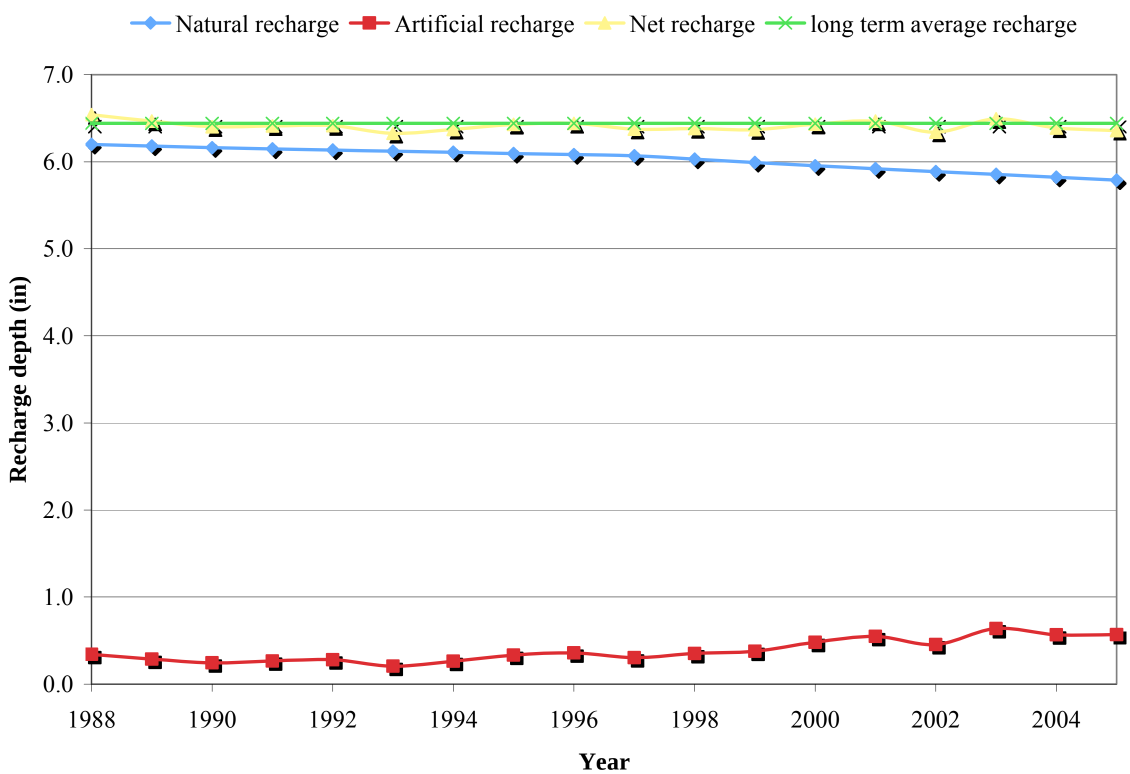


**Figure 6.1: Annual recharge in the Upper Vermillion River.**

Figure 6.1 shows the net annual groundwater recharge rate has hardly changed over two decades of progressive urbanization and illustrates the basis for the lack of a trend (Section 4) in the long-term average recharge.

## 7. Limitations/ Other impacts of urbanization.

This study shows that urban development affects groundwater recharge by decreasing the amount of groundwater recharge from 'natural' sources, i.e. precipitation, but that decrease, in 'natural' recharge, is replaced by an increase in recharge from 'artificial' sources. This study focused on what the authors have considered two main impacts of urban development: (1) the increase in impervious areas, reducing the effective areas available for water to infiltrate into the soil and become 'natural' groundwater recharge, and (2) the increase in 'artificial' recharge stemming from the larger volume of water imported to meet urban needs. These are not the only effects of urbanization that can impact groundwater recharge; several other effects of urbanization can influence groundwater recharge but were not studied. Some of them should at least be mentioned. These 'additional impacts' can either increase or decrease annual groundwater recharge

The impacts of urban development on groundwater recharge can be influenced by methods used to handle stormwater runoff. In the above study we assumed that impervious surface areas are connected to the stormwater sewer network although it is possible that not all impervious areas are connected; the sum of these areas is known as 'disconnected' impervious area. These disconnected impervious areas drain to pervious 'soakways', where it enhances infiltration by adding to the water available for infiltration. For example, stormwater runoff from some residential roofs may drain to pervious lawns and infiltrate into the soil. This added infiltration can enhance groundwater recharge. Even the 'connected' impervious runoff can influence groundwater recharge. Stormwater runoff in urban areas is usually conveyed through a storm sewer pipe network to an outlet. These pipes may leak because of damage or poor seals. If the storm water pipes are above the groundwater table, this leakage can enhance groundwater recharge. Recharge from this type of leakage will be intermittent and will only occur during or shortly after a rainfall event; it can be nearly impossible to measure or estimate, and most likely is much smaller than pipe leakage from water distribution networks because those are under pressure. If the stormwater pipes are below the water table, leakage from the aquifer might drain into the pipes, decreasing overall recharge in the watershed. This can account for large volumes of water because the leakage would be constant as long as the water table is above the pipe. This leakage to the stormwater pipes also would be masked in the baseflow analysis (Erickson and Stefan 2008) because it is constant and cannot be seen in the data. It would be hard to quantify, and expensive to correct this type of leakage.

The installation of best stormwater management practices (BMPs) can enhance groundwater recharge by holding more runoff in the watershed. BMPs such as infiltration basins and rain gardens are designed to enhance infiltration of surface runoff. This enhanced infiltration can increase recharge. Detention ponds, either dry or wet ponds, hold surface runoff, increasing the chance for water to seep into the aquifer. Most of the BMPs increase the potential infiltration in a watershed and ultimately groundwater recharge.

The urban development of natural or agricultural areas can and often does alter the soil substrate during construction and landscaping. Soil movement and compaction during construction, using heavy machinery, can alter the permeability and potential infiltration rates in the soils. Hamilton and Waddington (1999) investigated and compared infiltration rates in 15 residential lawns in central Pennsylvania. They investigated infiltration rates in lawns at different ages (ranging from less than a year old to over 30 years old) and different excavation procedures (including completely excavated, just filled, and left undisturbed). They found infiltration rates ranging from 0.4 to 10 cm/hr, where the youngest (less than a year old) and most disturbed (excavated) lawns had the lowest infiltration rates and the oldest (30 year old lawns) and mostly undisturbed lawns had much higher infiltration rates, near an order of magnitude higher. Soil compaction and its effects on the potential infiltration rates depend on the construction practices used during land development and the age of the development. Soil compaction can have a large effect on groundwater recharge because it can reduce infiltration rates by an order of magnitude, ultimately reducing the soil water available for recharge. This effect of urbanization may be important for groundwater recharge but can be hard, if not impossible, and expensive to quantify at a watershed scale. As the study by Hamilton and Waddington (1999) shows, the reduction of infiltration rates is dependent on the age of the development, meaning over time the infiltration rates can increase back to pre-development levels over time.

In an earlier section of our study we mentionned that septic tank drainage can add to groundwater recharge. On the other hand, research has shown the installation of sanitary sewer systems similar to the previously discussed storm sewer systems, can drastically reduce groundwater recharge (Simmons and Reynolds, 1982). Not considered in our study was pipe leakage from sanitary sewer systems. As for storm sewers, leakage from sanitary sewer systems can either add to recharge if the pipes are above the groundwater table or extract groundwater from a shallow aquifer if the pipes are below the water table. Since flow in sanitary sewer system pipes is usually a gravity driven free surface flow, and not under constant pressure, leakage from these pipes is much less than from water distribution systems that are under pressure. For example, Yang et al. (1999) estimated groundwater recharge in Nottingham, UK, and found that leakage from water distribution systems ranged from 93 to 162 mm/year, but was only 6 to 13 mm/yr for sanitary sewers. The leakage from sanitary sewer systems is much less than that from water distribution networks, but the quality of water leaking from sanitary sewer networks has to be of concern.

Where the urban development occurs can also be of concern. A disproportional level of development in areas of relatively high soil permeability (Figure 2.3) can lower annual infiltration depths, and consequently lower annual recharge depths. The hydrologic components are usually characterized by representative values, although areas with higher or lower recharge rates exist. Development in these areas with higher recharge rates will reduce recharge more than development in areas of low recharge rates. There may be a need to restrict development in the higher permeability areas.

Summarizing this section, there are several factors of urbanization that can influence groundwater recharge. Some are listed above but the list is most likely incomplete. This complexity in urbanization and groundwater recharge is the reason most studies are site specific. Many of the 'impacts' listed in this section may only have a negligible effect when considered alone and compared to the 'impacts' quantified in our study, but taken as a whole, they may have an influence on groundwater recharge and may need further study.

## 8. Conclusions

The sustainability of cold water resources and trout habitat in Minnesota depends on the availability of groundwater. Understanding the effect of urban development on the quantity of groundwater recharge in a watershed with a groundwater-fed stream is therefore important. Conventional thought is that urbanization will decrease groundwater recharge due to the increased imperviousness and stormwater collection networks capturing more surface water runoff. Natural groundwater recharge has in fact been shown to decrease with respect to imperviousness.

However, the decrease in natural groundwater recharge in an urban watershed can be unintentionally replaced by artificial recharge, i.e. infiltation of imported water that has leaked from water supply and sewer pipes, applied as excessive lawn irrigation, and infiltrated from septic system drainage.

A trend analysis on streamflow and baseflow in the Upper Vermillion River watershed showed that no statistically significant trends existed in the record, even though the watershed has seen about 18% of it's area developed over the period of record (1984-2005). The natural recharge in the watershed was shown to decrease by about 8% as imperviousness increased from ~8% to ~13%. This decrease was replaced by an increase in water use and artificial recharge in the watershed. This artificial recharge seemed to cancel the decrease in natural recharge with no significant net effect from urbanization. The quantity of groundwater recharge in the watershed showed no net effect from urbanization.

Even though no net decrease in the quantity of groundwater recharge exists, the quality of the recharged water may have decreased. Large impervious areas (e.g. parking lots) may produce warm surface runoff that may raise subsurface temperatures in shallow aquifers when routed to infiltration basins. Pollutants can enter the aquifer system through pipe leakage and septic system drainage. Water quality was outside the scope of this study.

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# Appendix A: Historic land-use maps of the Upper Vermillion River basin

Table A.1: Land use classification system compared to METC classification systems.

| Reclassified land uses | METC 1984 to 1997 Land use classes | METC 2000 & 2005 Land use classes |
|---|---|---|
| 01-Farmstead | Farmstead | Farmstead |
| 02-Residential | Single Family Residential<br>Multi-Family Residential | Seasonal/Vacation<br>Single Family Detached<br>Single Family Attached<br>Multifamily<br>Manufactured Housing Parks<br>Mixed Use Residential |
| 03-Commercial | Commercial | Retail and Other Commercial<br>Office<br>Mixed Use Commercial |
| 04-Industrial | Industrial<br>Public Industrial | Industrial and Utility<br>Mixed Use Industrial |
| 06-Institutional | Public Semi-Public | Institutional |
| 07-Extractive | Extractive | Extractive |
| 08-Airports | Airports | Airports |
| 09-Highways | Major Four Lane Highways | Major Highways |
| 10-Agriculture | Vacant/Agriculture[1] | Agricultural |
| 11-Natural Areas | Vacant/Agriculture[1]<br>Industrial Parks not Developed<br>Public & Semi-Public Vacant | Undeveloped |
| 12-Green Space | Parks & Recreation Areas | Parks, Recreation, or Preserve<br>Golf Course |
| 20-Water | Open Water Bodies | Water |

[1]Vacant/Agricultural is split into agricultural and vacant

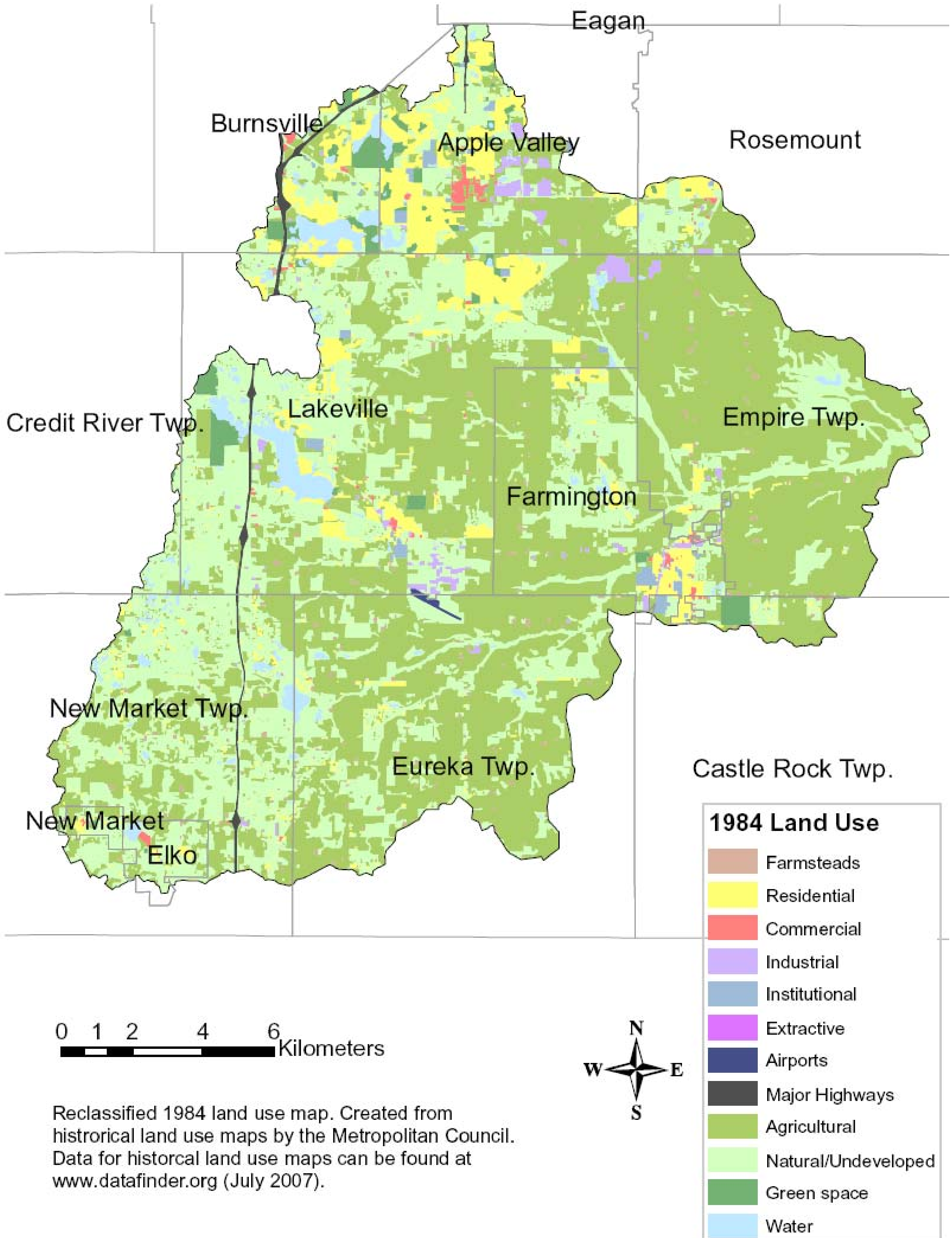


**Figure A.1: 1984 land use map for the Upper Vermillion River watershed.**

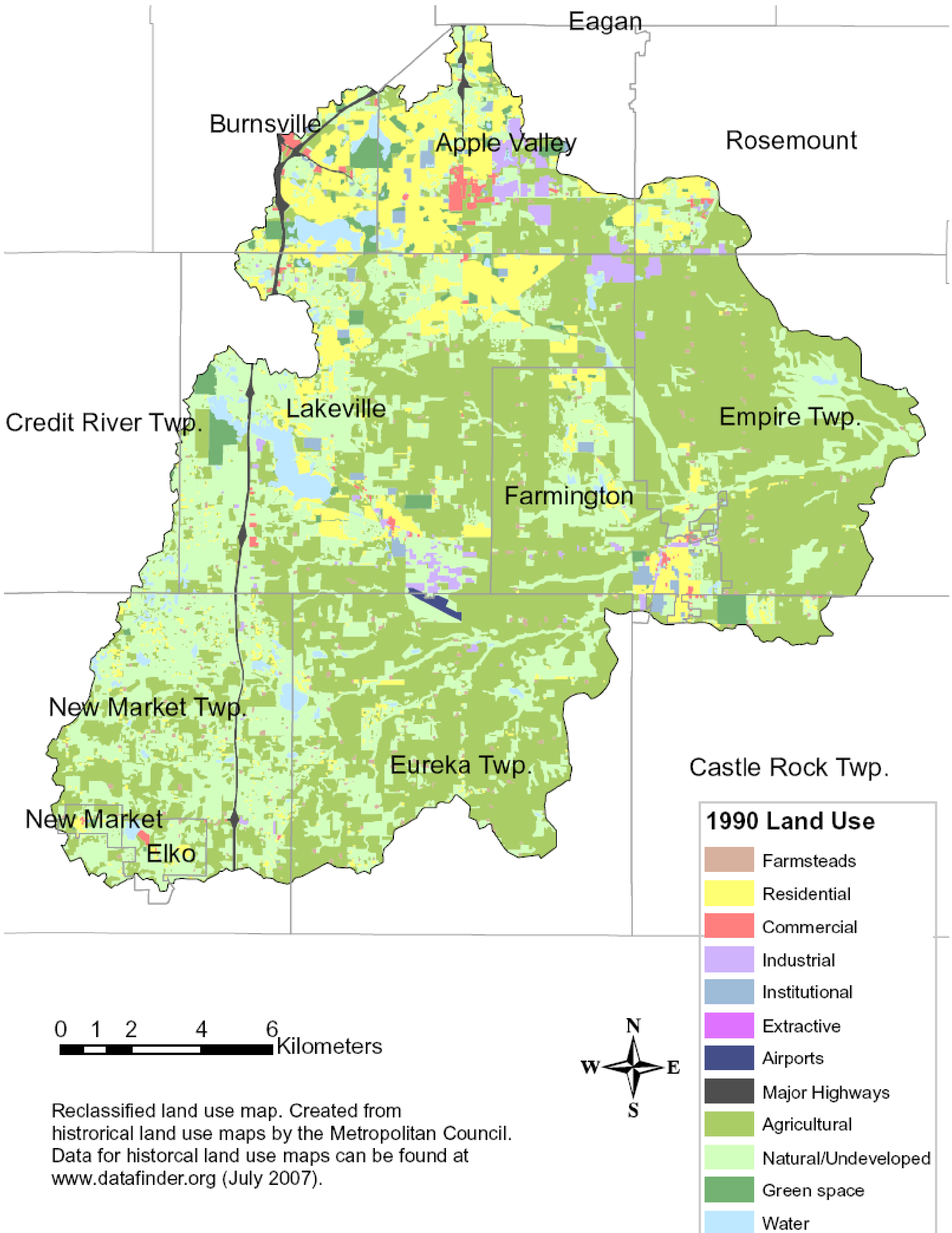


**Figure A.2: 1990 land use map for the Upper Vermillion River watershed.**

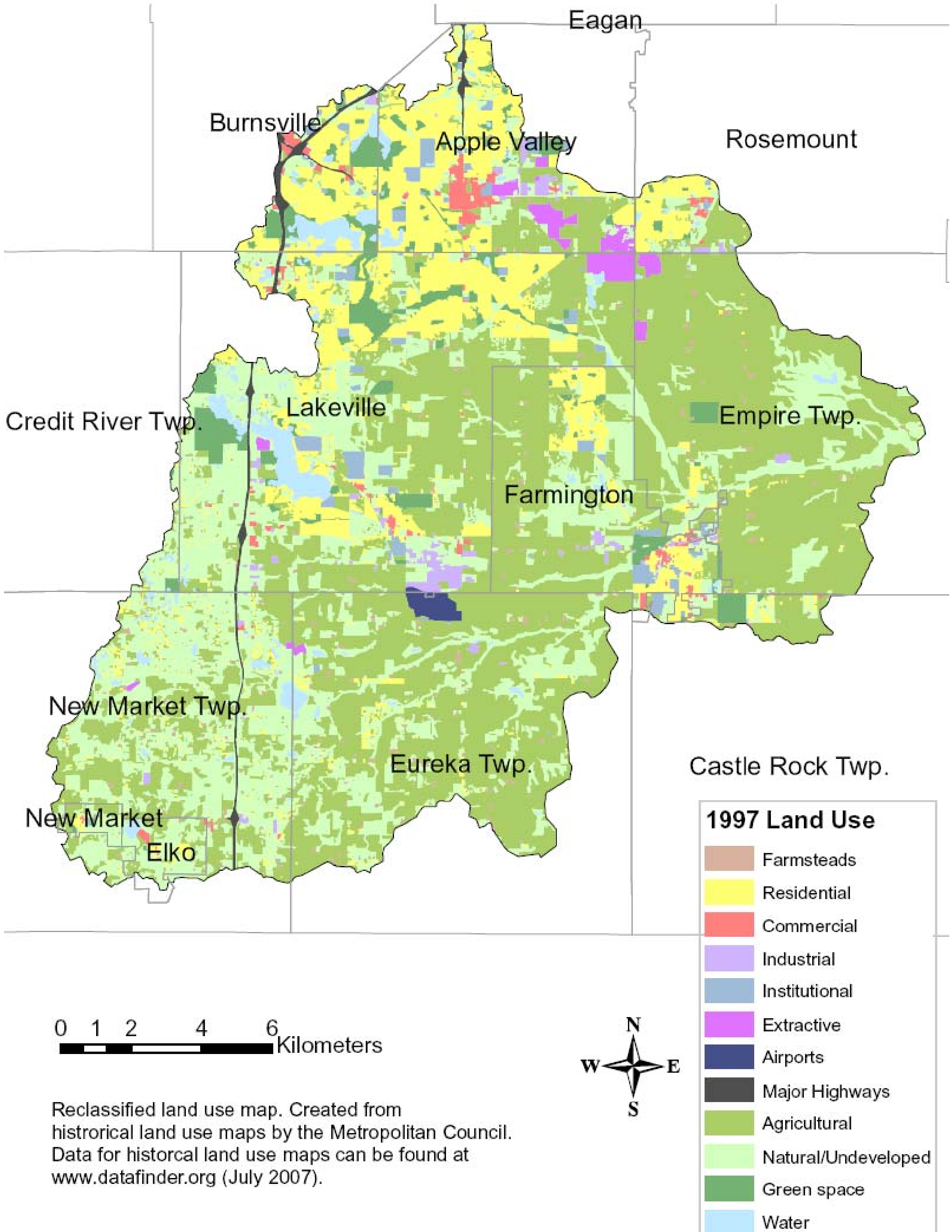


**Figure A.3: 1997 land use map for the Upper Vermillion River watershed.**

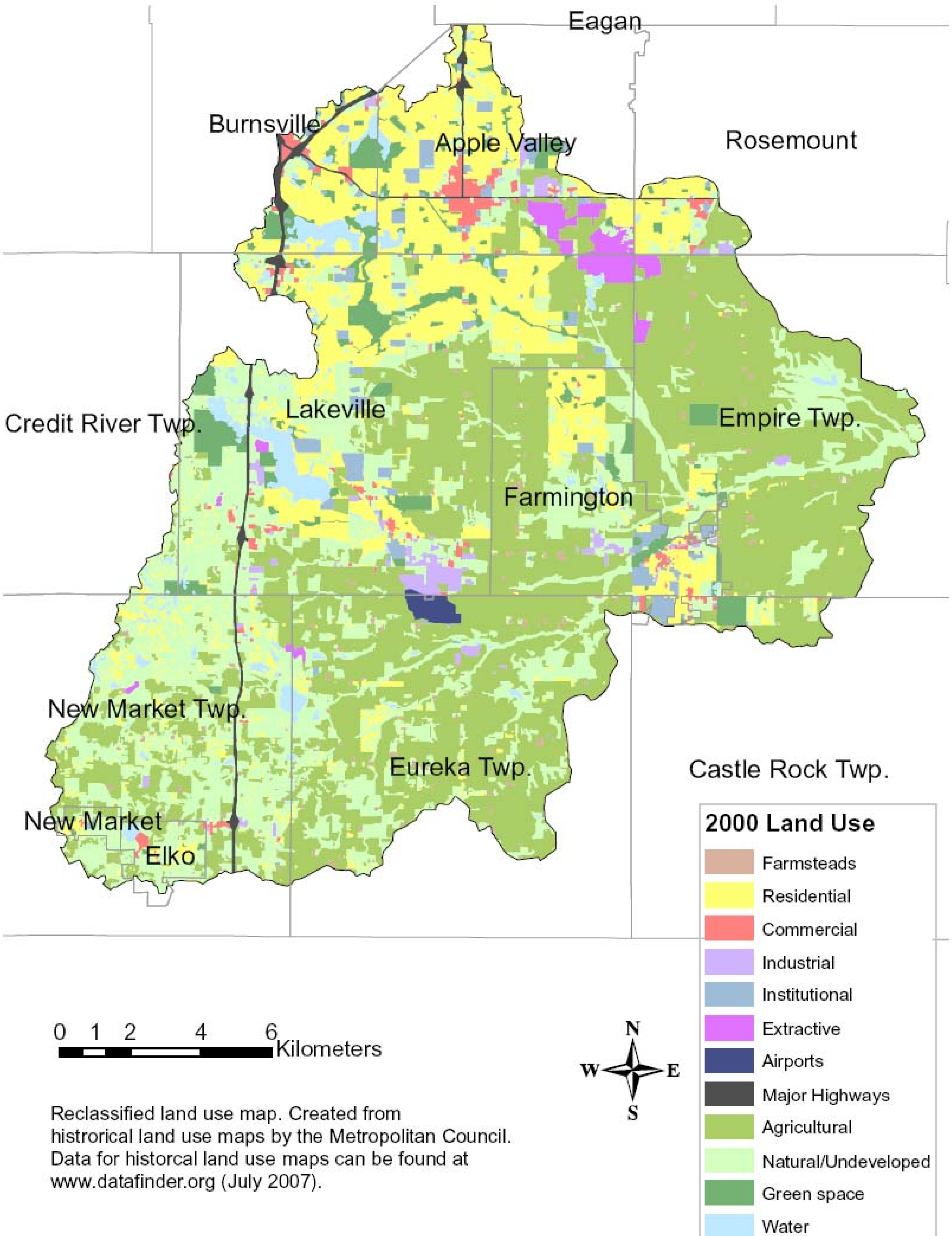


**Figure A.4: 2000 land use map for the Upper Vermillion River watershed.**

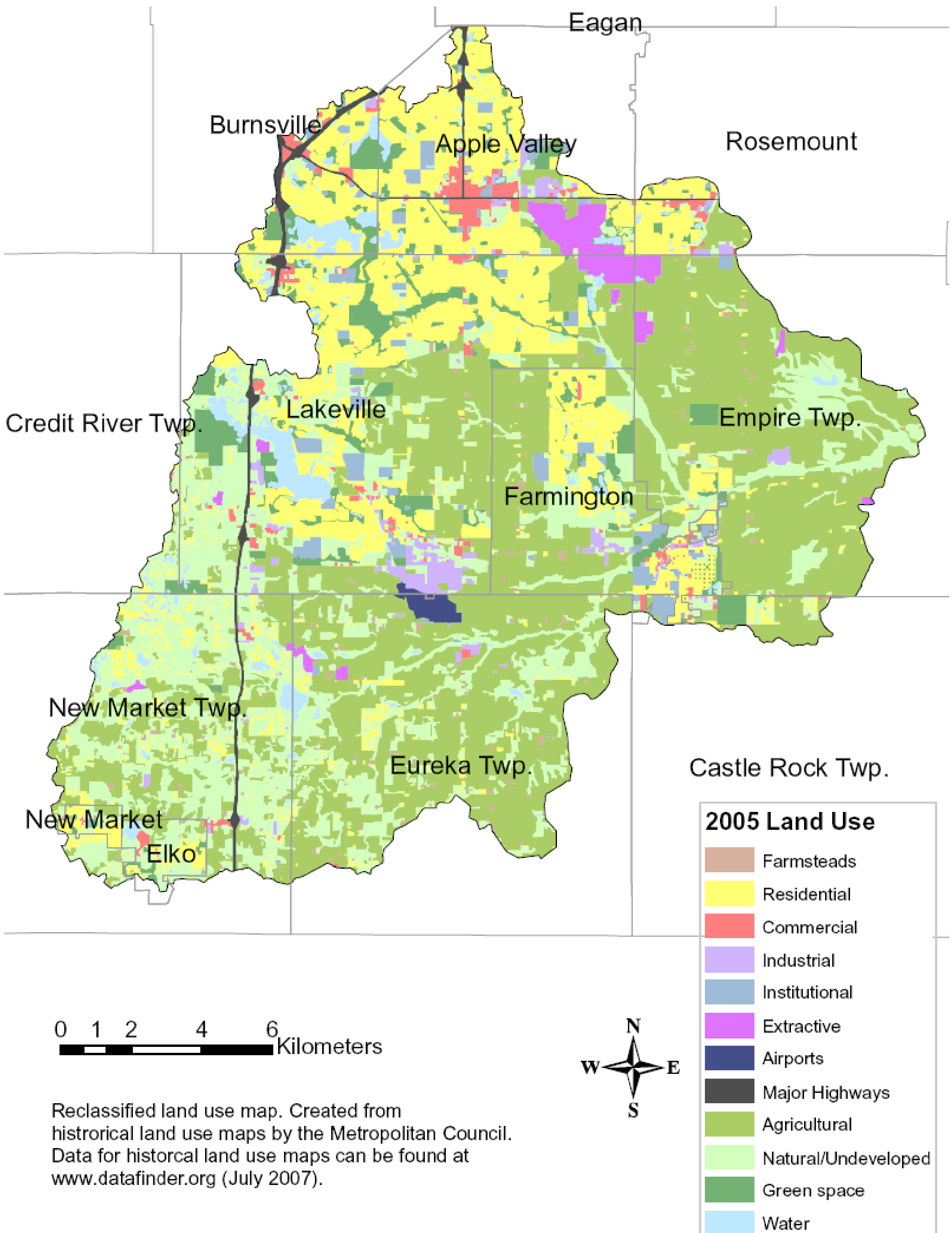


**Figure A.5: 2005 land use map for the Upper Vermillion River watershed.**

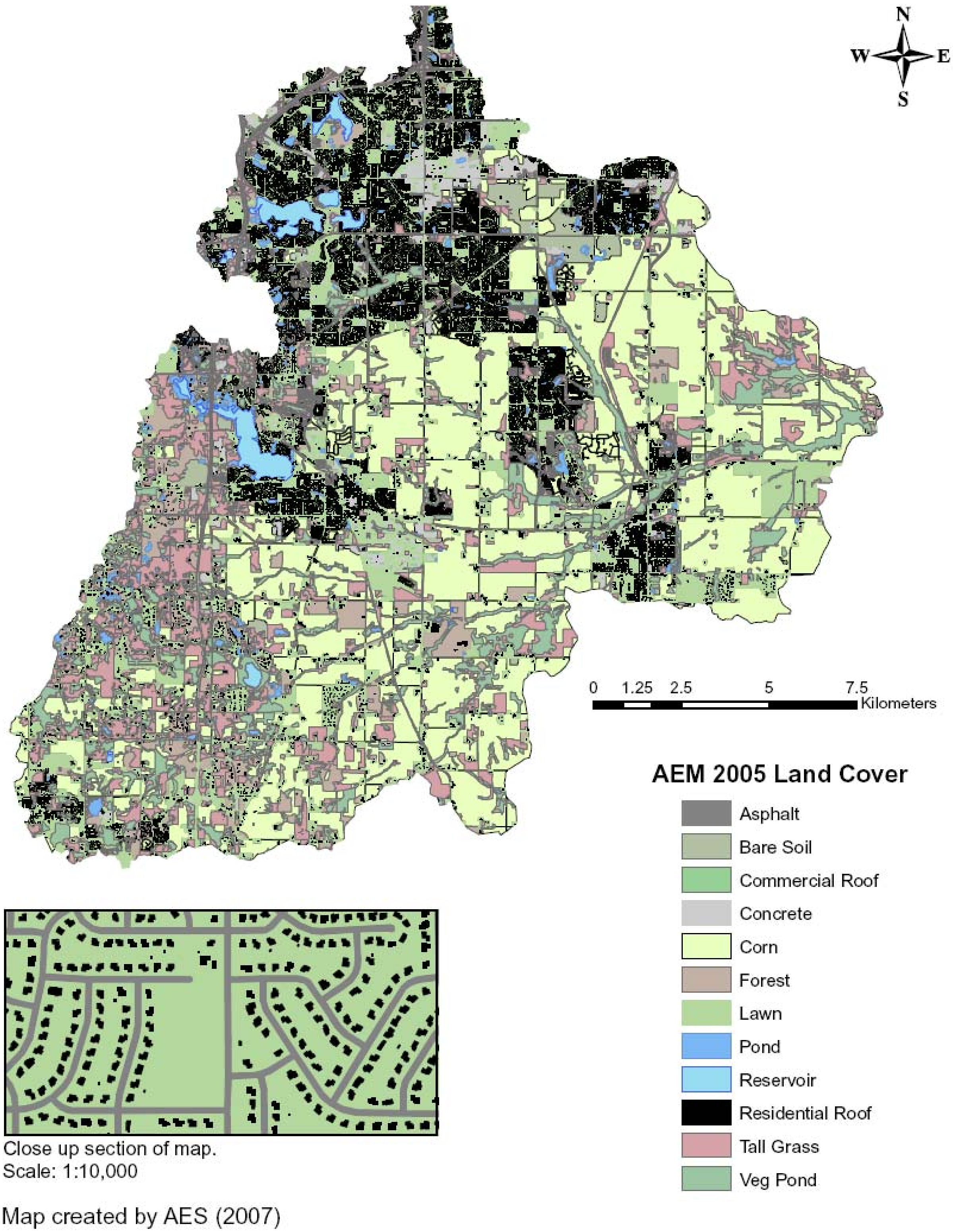


**Figure A.6: AES 2005 Land cover map for the Upper Vermillion River.**

# Appendix B. Components of the Upper Vermillion River basin water budget

Components of the water budget for the Upper Vermillion River watershed can be estimated using streamflow measurements, baseflow estimates, and annual precipitation measurements. The simplest steady-state water budget relationship for the watershed is (Rutledge and Mesko 1996)

$$P = ET + SF \qquad [B.1]$$

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 B.1 implies conservation of the mass of precipitation on a long timescale; precipitation will either leave the watershed as streamflow or be returned to the atmosphere by evapotranspiration. It assumes that long-term storage and leakage to deeper aquifers are negligible. The streamflow $SF$ has two components: 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 $SF$.

$$SF = BF + DR \qquad [B.2]$$

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.

$$I = ET + BF = P - DR \qquad [B.3]$$

Using equations B.1, B.2, and B.3, the water budget components were estimated.

# Appendix C. Residential areas within the Upper Vermillion River basin

**Table C.1 Ratio of residential area within watershed to total residential area (from Metropolitan Council land use maps)**

| City | Percentage of residential area within the watershed | | | | |
|---|---|---|---|---|---|
| | 1984 | 1990 | 1997 | 2000 | 2005 |
| Apple Valley | 61.2 | 58.5 | 57.8 | 58.4 | 60.5 |
| Burnsville | 16.0 | 20.6 | 21.5 | 21.5 | 21.4 |
| Castle Rock | 16.1 | 17.7 | 16.3 | 15.6 | 16.5 |
| Credit River | 1.1 | 2.4 | 2.7 | 3.6 | 3.2 |
| Eagan | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Elko | 95.2 | 90.2 | 94.4 | 95.6 | 93.9 |
| Empire | 67.6 | 66.3 | 71.3 | 70.4 | 74.0 |
| Eureka | 61.7 | 61.6 | 62.1 | 70.0 | 72.3 |
| Farmington | 100.0 | 96.7 | 97.6 | 98.1 | 98.5 |
| Lakeville | 82.0 | 78.8 | 82.8 | 84.9 | 88.4 |
| New Market | 100.0 | 97.7 | 87.8 | 96.8 | 66.6 |
| New Market twp | 51.8 | 52.4 | 55.0 | 68.4 | 73.9 |
| Rosemount | 1.4 | 0.8 | 0.4 | 29.3 | 25.7 |