28

The Impact of Climate Change on Groundwater

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28.1 Introduction

The growing and competing demand for domestic, agricultural, industrial, and recreational water has made clean and safe drinking water a scarce natural resource in many regions of the world. Increasing populations, especially in urban areas, are not only stressing the capacity and sustainability of the existing water supplies, but they are also placing the supplies at a greater risk of contamination. Humans are also affecting the global water resources through climate change. Increases in the atmospheric concentrations of greenhouse gases and aerosols, as well as changes in land use due to deforestation and urbanization already have, and will continue to impact the Earth's climate, and hence the terrestrial hydrologic cycle in the future (IPCC, 2001).

The human impacts on Earth's water resources are not only being felt in developing countries, but they are increasingly, and often dramatically, being noticed in developed nations such as the United States and Canada. Understanding the interaction between the various components of the hydrologic cycle is, therefore, essential for the management of watershed and for ensuring the quality and sustainability of safe and clean drinking water resources.

The surface water and groundwater systems have often been considered as separate due to the pervasive complexity and increased computational effort required by their integration (El-Kadi, 1989). The systems, however, are intrinsically linked through the processes of recharge and discharge, and their interaction constitutes an essential part of the hydrologic cycle.

According to Robins (1998), "the management of both groundwater resources and of individual groundwater sources cannot sensibly be undertaken without some knowledge of recharge: its quantity, its seasonality and, above all, the different routes through the sub-soil and the unsaturated zone by which it can occur". Recharge also plays an important role in the assessment of aquifer vulnerability to contamination. According to Foster (1998) "since the transport of most groundwater contaminants, with the exception of density driven contaminants such as DNAPLs, to saturated aquifers occurs in the aqueous phase as part of the recharge process, assessing aquifer pollution vulnerability is inextricably linked with understanding groundwater recharge mechanisms." Aquifer vulnerability maps can provide valuable guidance to municipal planners and developers regarding land use allocation, well locations, and pumping regulations. This is especially important in areas where the underlying aquifers are exploited extensively for drinking water purposes.

Changes in future climate will alter regional hydrologic cycles and subsequently impact the quantity and quality of regional water resources (Gleick, 1989). While climate change affects surface water resources directly through changes in the major long-term climate variables such as air temperature, precipitation, and evapotranspiration, the relationship between the changing climate variables and groundwater is more complicated and poorly understood. Groundwater resources are related to climate change through the direct interaction with surface water resources, such as lakes and rivers, and indirectly through the recharge process. Therefore, quantifying the impact of climate change on groundwater resources requires not only reliable forecasting of changes in the major climatic variables, but also accurate estimation of groundwater recharge.

Accurate spatial and temporal characterization of groundwater recharge can be difficult, due to its dependence on a multitude of physical factors such as land use and hydrogeological heterogeneity (Lerner et al., 1990). Groundwater recharge can also be significantly impacted by snowmelt and frozen soil conditions in northern climates, and furthermore be complicated by the issue of scale.

It is evident that assessing the impact of climate change on groundwater resources requires a physically based approach for estimating groundwater recharge. The method must not only account for temporal variations in the climatic variables and their impact on the hydrologic cycle, but also consider the spatial variation of surface and subsurface properties across the study area.

Many climate change studies have generally focused on modeling the temporal change in the hydrologic processes and ignored or relied on average spatial characteristics due to model limitations or coarse discretization schemes. This chapter outlines a physically based methodology that can be used to characterize not only the temporal impact, but also the spatial effect of climate change on groundwater recharge. The method is based on the hydrologic software package HELP3 coupled with a geographic information system (GIS). The method is used in an example application to simulate the past conditions and possible future changes in the hydrologic cycle of the Grand River watershed in Ontario, Canada.

28.2 Background

28.2.1 Climate Change

The Earth's energy cycle is driven by short wave radiation from the sun and balanced by the outgoing long wave terrestrial radiation. Any changes in this radiative balance will alter the global hydrologic cycle, and hence, the groundwater recharge as well as the atmospheric and oceanic circulation, thereby resulting in climate change. According to the Intergovernmental Panel on Climate Change (IPCC), the key climate variables impacted by changes in the Earth's energy balance include temperature, precipitation and atmospheric moisture, snow cover, extent of land and sea ice, sea level, patterns in atmospheric and oceanic circulation, and extreme weather and climate events (IPCC, 2001).

The Earth's radiative balance can be affected not only by human impacts, but also by a multitude of natural factors, resulting in both cooling and warming of the climate system. While increases in greenhouse gases, such as carbon dioxide, ozone, methane, and nitrous oxide, reduce the outgoing terrestrial radiation (i.e., heat) to space, thereby resulting in warming of the lower atmosphere and the

Earth's surface, anthropogenic aerosols, such as those derived from fossil fuels and biomass burning, can reflect the incoming solar radiation, leading to cooling of the climate systems (IPCC, 2001). Changes in volcanic activity, the energy output of the sun, and slow variations in the Earth's orbit, not only have, but will also continue to impact the Earth's climate in the future. Climate variations can also occur in the absence of external factors, as a result of complex interactions between the components of the climate system, such as the coupling between the atmosphere and the oceans.

Variations in climate occur across a range of temporal and spatial scales, making both observation and modeling highly uncertain (Goddard et al., 2001). Nevertheless, advanced remote sensing from Earth-observation satellites is providing increasingly detailed images of our current climate, while the growing amount of paleoclimatic core data from trees, sediments, and ice are providing information about the Earth's climate in the distant past. At the same time, the continuing increase in computing power has led to the development of more detailed and sophisticated global climate and general circulation models (GCMs). The interaction between the Earth's orbit, ocean circulation, and atmosphere has contributed to nine glacial episodes in the northern hemisphere over approximately the past 900,000 years. Tarasov and Peltier (2004) integrated a GCM with a glacial model to simulate the evolution of ice coverage over the North American continent. McGuffie and Henderson-Sellers (2001) provide a review of climate modeling over the past 40 years. Significant improvements in hydrological parameterizations and grid resolution have also allowed coupling between the atmospheric circulation and hydrologic surface water models (Stewart et al., 1998; Pitman, 2003).

The greatest uncertainty in future predictions by climate models arises from clouds and their interactions with radiation. Clouds can both absorb and reflect solar radiation and absorb and emit long wave radiation, thereby either cooling or warming the Earth's surface. The variation in the two states is controlled by many factors and is difficult to model. Therefore, clouds represent a significant source of potential error in climate simulations (IPCC, 2001).

Through the co-ordination of researchers from around the world, and after a comprehensive and careful review of a vast number of observational records and results from a number of simple and complex GCM models, the IPCC has arrived at the following general predictions for the global climate during this century (IPCC, 2001):

- The global average surface air temperature is predicted to increase by 1.5 to 4.5°C. Furthermore, it is very likely that nearly all land areas will warm more rapidly than the global average, particularly those at northern high latitudes in the cold season.
- Globally averaged water vapor, evaporation, and precipitation are projected to increase. Both increases and decreases in precipitation are seen at the regional scale.
- Precipitation extremes are projected to increase more than the mean, and the intensity and frequency of extreme precipitation events are projected to increase.
- Ice caps and glaciers will continue their widespread retreat during the 21st century while sea ice and snow cover in the Northern Hemisphere are projected to decrease further.
- The global average sea level is predicted to increase by 0.09 to 0.88 m, with regional variations.

28.2.2 Impact of Climate Change on Water Resources

Various hydrologic models have been used to study the impact of climate change on water resources (e.g., Wilkinson and Cooper, 1993; Gureghian et al., 1994; Cooper et al., 1995; Bobba et al., 1997; Querner, 1997; Rosenberg et al., 1999; Kirshen, 2002). The hydrological effects of climate change are commonly evaluated by estimating the sensitivity of model outputs, such as streamflow hydrographs or soil moisture contents, to hypothetical changes in the magnitude and temporal distribution of model inputs such as precipitation and temperature. In addition to hypothetical perturbations, however, the results inferred from the GCMs have also been used to predict the effects of climate change on regional hydrology.

In one of the early studies, Vaccaro (1992) used a deep percolation model (DPM) to estimate the influence of climate change on recharge variability in a basin in north-western United States. In addition to historical records, climate predictions from the synthetic weather generator WGEN (Richardson and Wright, 1984) and three GCMs were considered along with two different land use conditions. The results of the study indicated that the variability in annual recharge was less under the GCM conditions than using the historic data. The objective of the study was to investigate the degree of variability in climate and its impact on future recharge predictions, and not explicitly to predict the impact of climate change on recharge rates in the basin.

Bouraoui et al. (1999) developed a methodology to disaggregate the outputs of large-scale GCMs for use in hydrologic models. The method was used in conjunction with the runoff and sediment transport model ANSWERS to investigate the impact of doubling CO_2 on groundwater recharge in a watershed in France. The methodology was based on a statistical approach requiring a large number of simulations. The results of the study indicated that recharge would decrease in the basin due to increase in atmospheric CO_2.

Rosenberg et al. (1999) used the GIS-based program HUMUS and the hydrologic model SWAT (Arnold et al., 1998) to study the impact of climate change on the water yield and groundwater recharge of the Ogallala aquifer in the central United States. Three different GCMs were used to predict changes in the future climate due to anticipated changes in temperature and CO_2 concentrations. The study found that recharge was reduced under all scenarios, ranging up to 77%, depending on the simulation conditions.

Kirshen (2002) used MODFLOW to study the impact of global warming on a highly permeable aquifer in the northeastern United States. The lumped hydrologic model HSPF was used to compute streamflows from rainfall, temperature, and potential evapotranspiration, while groundwater recharge was estimated using a separate model based on precipitation and potential evapotranspiration. The sensitivity of the aquifer system to the possible effects of global climate change was simulated by introducing both hypothetical and GCM predicted changes to the input parameters of the HSPF and recharge models, and then running MODFLOW based on the outputs. The results of the study were mixed, showing higher, no different, and significantly lower recharge rates and groundwater elevations, depending on the climate scenario used.

Croley and Luukkonen (2003) studied the impact of climate change on groundwater using a regional scale MODFLOW model of Lansing, Michigan. The results from two separate GCMs were first used in an empirical streamflow model to estimate baseflow rates. The recharge in the regional groundwater model was then adjusted on the basis of the differences in baseflow from the two GCMs. The study used a steady-state approach and hence the transient changes in groundwater levels were not captured in the analysis. The results of the study indicated that the simulated groundwater levels were generally predicted to increase or decrease due to climate change, depending on the GCM used.

Eckhardt and Ulbrich (2003) used a revised version of the SWAT model to investigate the impact of climate change on groundwater recharge and streamflow. The model was applied to a small catchment in Germany. Climate change was simulated by adjusting stomatal conductance and leaf area in the SWAT model as a response to increased CO_2 levels. Four different climate scenarios were considered based on simulations from five different GCMs. The results of the study indicated that more precipitation will fall as rain in winter due to increased temperatures resulting in higher recharge and streamflow in January and February. They also found that the snowmelt increase in recharge in March disappears, while recharge and streamflow were shown to be potentially reduced in the summer months.

Loaiciga (2003) conducted a review of climate change predictions and associated hydrologic consequences and presented the results of a case study of an aquifer in south-central Texas. The study considered a confined karst aquifer that receives recharge only in sections of streams that are hydraulically connected to the underlying water table. The impact of climate change on the indirect recharge was estimated using runoff scaling factors based on the ratio of historical and future streamflows predicted from linked general and regional climate models. The study also considered the impact of changes in pumping rates (i.e., predicted changes in groundwater use) on groundwater resources of the aquifer. The study concluded that the rise in groundwater use associated with predicted growth would pose a higher threat to the aquifer than climate change.

Allen et al. (2004) used Visual MODFLOW to study the impact of climate change in an aquifer in southern British Columbia, Canada. The recharge boundary condition for the groundwater model was estimated using Visual HELP, while rivers were represented using constant heads. Constant recharge was assumed across the domain in a steady-state analysis. The base case recharge analysis was based on synthetic weather generated with WGEN (Richardson and Wright, 1984) using Canadian weather normals (i.e., thirty-year averages) from a nearby weather station as input. Four climate change scenarios were considered based on general predictions for the study area. The average temperature and precipitation were perturbed based on the predictions and were then used in WGEN to generate synthetic records. Average annual recharge rates were then computed for each of the scenarios and applied across the whole domain. Results of the study indicated that there was little change in the overall water table configuration as a result of potential climate change. This is to be expected, however, as constant recharge (i.e., spatially) was assumed across the domain.

Brouyere et al. (2004) investigated the impact of climate change on a chalky groundwater basin in Belgium using the integrated hydrological model MOHISE. The integrated model was composed of three submodels, each for soil, surface water, and groundwater, which were linked through flux boundaries. Three GCMs were used to compute monthly change rates in precipitation and temperature that were then used to adjust the daily historical record to obtain climate change scenarios. The results showed decreases in groundwater levels for two scenarios, while one of the models showed no significant change. Instead of seasonal changes in groundwater levels, a monotonic increase over time was observed. The impact of seasonal variation was likely smoothed out by a thick saturated zone found at their basin.

Understanding the impact of climate change is most crucial for studies concerned with the storage and containment of high-level nuclear waste. Due to the slow decay of nuclear materials, modeling efforts must be concerned with changes in boundary conditions over very long periods of time. However, predictions of climate change are highly uncertain even for shorter periods such as the next century, making the predictions for the next 10,000 to 100,000 years extremely uncertain.

Yucca Mountain in Nevada is being evaluated as a potential site for high-level nuclear waste disposal in the United States. Because the proposed repository is to be located within the deep unsaturated zone, estimating rates of groundwater recharge at the site is critically important (Flint et al., 2002). Gureghian et al. (1994) studied the impact of climate change on the groundwater recharge rate at Yucca Mountain using a quasi-linear form of the Richards' equation. They used two different climatic variation models for temperature and precipitation over the next 10,000 years based on the recommendations by a panel of experts. The results of the study indicate minimal differences between the two climate models on the overall movement of the wetting front.

In summary, climate change will have an impact on future recharge rates and hence on the underlying groundwater resources. The impact may not necessarily be a negative one, as evidenced by some of the investigations. Quantifying the impact is difficult, however, and is subject to uncertainties present in the future climate predictions. Simulations based on general circulation models have yielded mixed and conflicting results, raising questions about their reliability in predicting future hydrologic conditions.

Groundwater recharge is influenced not only by hydrologic processes, but also by the physical characteristics of the land surface and soil profile. Many climate change studies have focused on modeling the temporal changes in the hydrologic processes and ignored the spatial variability of physical properties across the study area. While knowing the average change in recharge and groundwater levels over time is important, these changes will not occur equally over a regional catchment or watershed. Long-term water resource planning requires both spatial and temporal information on groundwater recharge to properly manage not only water use and exploitation, but also land use allocation and development. Studies concerned with climate change should therefore also consider the spatial change in groundwater recharge as a result of future changes in hydrologic processes.

28.2.3 Groundwater Recharge

The word "recharge" has several meanings in the groundwater literature. Generally, it means any water that is added as an input to the system, while discharge is normally considered to be any water that exits the groundwater system. Within the context of this chapter, groundwater recharge is defined as the soil

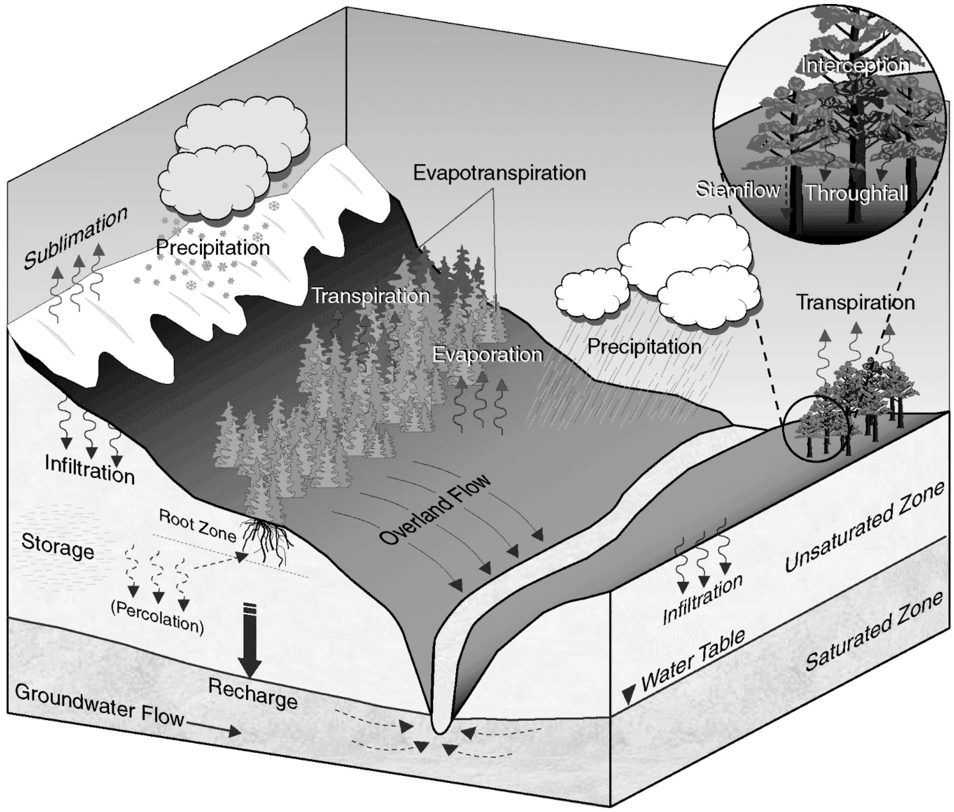

FIGURE 28.1 The hydrologic cycle.

water (from precipitation) in the vadose zone that crosses the water table into the saturated zone. Recharge of deeper confined aquifers can also occur both laterally and vertically through aquitard leakage in the saturated zone (Gerber and Howard, 2000).

Groundwater recharge is part of the vadose zone soil water budget. Figure 28.1 illustrates the main processes. For clarification, infiltration is defined as the volume rate of water flowing into a unit area of soil surface, whereas percolation is the process by which water migrates down through the soil profile in the unsaturated zone. Deep soil water percolation, often referred to as groundwater recharge by soil scientists, is the water that has moved past the evaporative and root zones in the vadose zone and is no longer available to plants.

The driving force for natural recharge is precipitation; however, groundwater recharge may also result from other processes. According to Lerner et al. (1990) groundwater recharge can be divided into three distinct processes:

- *direct recharge*, which is water added to the groundwater system in excess of soil moisture deficits and evapotranspiration by direct vertical percolation of precipitation through the unsaturated zone.
- *localized recharge* is an intermediate form of recharge resulting from the horizontal surface concentration of water in local joints and depressions.
- *indirect recharge* is the flow of water to the water table through the beds of surface water courses, such as rivers and lakes.

As direct recharge due to precipitation forms the highest contribution to the groundwater system in humid climates (Knutssen, 1988), it will receive the main focus in this section. Surface water bodies commonly act as discharge areas rather than recharge areas in humid climates and therefore provide a minor contribution to the overall production of groundwater recharge. However, areas of an aquifer in close proximity to a surface water body, seasonal variations in surface water levels may result in alternating periods of groundwater recharge and discharge. Climate change can impact the levels of the surface water and hence the relative importance of the recharge and discharge.

As shown in the hydrologic cycle in Figure 28.1, precipitation is formed either as rain or snow. Before reaching the ground, however, the vegetation canopy intercepts some of the precipitation, which then either evaporates, or is channeled to the ground via stemflow, or drips directly to the ground as part of throughfall. Depending on the rainfall intensity and ground surface cover, the precipitation reaching the ground surface may then flow overland directly into streams and ditches, or infiltrate into the soil. The infiltrated water then percolates downwards through the vegetative root zone or evaporative zone where a portion of it may be taken up by the plant roots and subsequently transpired through the vegetation canopy. The remaining water will continue percolating deeper into the soil column, eventually becoming groundwater recharge when crossing the water table into the saturated zone. The percolating soil water can also partition into the air phase in the vadose zone through evaporation at any time, depending on the moisture content and distribution in the unsaturated zone.

28.2.4 Factors Affecting Recharge

28.2.4.1 Precipitation

Precipitation is the most important parameter in the groundwater recharge process. It is the driving force in the hydrologic cycle and provides the water that will eventually recharge the groundwater system. Precipitation is effected by climatic factors such as wind and temperature, resulting in a very complex and dynamic distribution. Therefore, determining the amount and rate of precipitation over an area is exceedingly difficult due to the high spatial and temporal variation. Storm events can vary widely in duration, velocity, and intensity, while lower temperatures can result in snowfall or mixed precipitation. Singh (1997) provides a literature review on the effects of rainfall variability across a watershed on streamflow hydrographs. He concludes that the velocity and direction of a storm has a significant impact on the hydrographs and that temporally varying rainfall leads to higher peak flows than constant rainfall. In addition, low intensity rainfall may cause no recharge due to a high rate of evapotranspiration, whereas the same amount in a shorter time period may be sufficient to saturate the soil and cause recharge (Lerner et al., 1990). In arid and semiarid areas, where evaporation dominates the water balance, recharge is determined by the distribution of extreme events in excess of threshold levels (Lloyd, 1986).

In addition to estimation, accurate measurement of precipitation is also very difficult. Point measurements using standard rain gauges, such as weighing, capacitance, tipping-bucket, and optical types, are often used to measure the accumulation of rainfall at a particular location. However, these instruments can be subject to large measurement errors (Habib et al., 2001), and provide poor estimates of the spatial distribution of rainfall over a catchment. Ball and Luk (1998) analyzed the spatial distribution of rainfall over a catchment using several mathematical models in the GIS environment. They showed that all the methods based on spatial extrapolation of point data, such as Theissen polygons, inverse distance weights, kriging, and surface fitting, can result in significant errors in predicted rainfall distributions.

An accurate representation of rainfall is especially difficult in remote areas where the available information is limited. In many cases, synthetic weather generators based on historical weather records and stochastic analysis, such as WGEN (Richardson and Wright, 1984) and MORECS (Hough and Jones, 1998) are often used to generate synthetic weather data and rainfall distributions. However, these methods commonly use the extrapolation methods described by Ball and Luk (1998) and hence are subject to potentially large errors. The use of weather radar to predict precipitation distributions seems promising; however, it is also subject to errors (e.g., due to signal noise) and problems with scale or resolution (Kouwen and Garland, 1989).

In most groundwater modeling applications, rainfall rates are often considered constant spatially, or averaged over time in steady state analyses. Individual storm events are rarely accounted for and monthly or annual averages are commonly used. The assumption of temporally averaged rainfall seems reasonable, at least for shorter time periods, as the fluxes in the vadose zone contributing to recharge are usually much slower than an individual storm. However, rainfall varies considerably even over short distances, and therefore, the spatial variation in precipitation should not be ignored, especially in larger scale modeling studies.

28.2.4.2 Land Use and Cover

The type of land cover can have a significant impact on infiltration, and hence on groundwater recharge. For example, the clearing of native vegetation and replacing it with shallow-rooted annual crops and pastures have resulted in substantial waterlogging and salinity problems in Australia due to increased recharge rates (e.g., Peck, 1978; Williamson, 1990; Walker et al., 2002). Urban areas can also have a profound impact on groundwater recharge by increasing the amount of impervious areas and generally altering the land surface from its natural state (Lerner et al., 1990; Lerner, 2002). However, the most significant impact of urbanization is often its adverse impact on the quality of recharge, rather than on its quantity (Foster, 2001).

The impact of land use changes on groundwater recharge has been the focus of modeling studies. Walker et al. (2002) give a comprehensive review of modeling approaches used in Australia to combat dryland salinity problems. Carmon et al. (1997) and Collin and Melloul (2001) investigated the impact of urbanization and changes in land use types in the context of sustainable groundwater development in Israel. They concluded that measures should be taken to reduce the negative effects of urban development on groundwater quality. Finch (2001) estimated the response of mean annual groundwater recharge to land cover changes in a rural catchment in southern England. He observed that land use changes lead to changes in the recharge pattern, but had no impact on the overall catchment total. Bellot et al. (2001) studied the impact of land use changes on runoff and recharge due to wildfires, afforestation, and land abandonment in Spain. They found that the increase in vegetated land cover has a negative effect on human water availability in semiarid areas, due to decreased aquifer recharge rates. Batelaan et al. (2003) used MODFLOW to study land use changes in Belgium by perturbing recharge rates at selected areas. Their study yielded mixed results.

28.2.4.3 Vegetation

Vegetation reduces recharge by directly interfering with the passage of precipitation from the atmosphere to the water table. The vegetation canopy intercepts a portion of the rainfall, which then either evaporates, or is channeled to the ground through stemflow, or drips directly to the ground as part of throughfall (Le Maitre et al., 1999). Arguably, these processes are very difficult to quantify as they are dependent on a multitude of climatic parameters, such as intensity and duration of rainfall, temperature, wind speed, as well as the physical characteristics of the individual plants (Larcher, 1983). However, they can still have a significant effect on the recharge process as shown by Taniguchi et al. (1996) and Finch (1998).

Perhaps the greatest influence on recharge by vegetation is through evaporation and transpiration. These terms are often lumped together with direct evaporation from the soil and referred to as evapotranspiration. Evapotranspiration is an important component of the water budget with up to 40 to 60% of the annual rainfall being lost through it in humid climates (Knutssen, 1988).

Methods to calculate actual evapotranspiration include the Bowen ratio method, derived from a simplified energy balance, and the eddy correlation method based on the correlation between wind speed and vapor density (e.g., Dingman, 1994). The downside of these models is that they require variables, such as aerodynamic, thermal, and plant specific parameters, which are very difficult to measure in practice. Other methods, such as Penman (1948), Penman-Monteith (Monteith, 1965), Thornthwaite and Mather (1957), and Priestley and Taylor (1972) have been developed to estimate evapotranspiration. However, these models also require many parameters that are derived from ideal conditions. Furthermore, most of these methods estimate potential evapotranspiration, which is not always equal to actual evaporation rates. The Penman–Grindley model (Grindley, 1969) is a widely used and simple soil moisture budgeting and evaporation model, which also allows for the determination of recharge indirectly. Like the other models, however, it can be very sensitive to errors in the input parameters (Finch, 1998).

Plant roots also play an important role in the recharge process. Not only do they enable plants to draw water from deep in the vadose zone (and even from the saturated zone), thereby reducing the amount of percolating water that reaches the water table, but they also create preferential flow paths and channels that aid water flow through the soil profile (Le Maitre et al., 1999). Studies have revealed that in addition to absorption, plant roots can also exude water into the soil in response to gradients in water potential between themselves and the soil (Burgess et al., 1998; Schulze et al., 1998). When root systems span soil layers of different moisture content, water is redistributed by the roots in the direction of the difference in water potential. This hydraulic redistribution of water not only removes excess water from the topsoil and out of the reach of evaporation, shallow-rooted competitors, runoff, and lateral subsurface flow, but it may also increase the capture of mobile nutrients such as nitrogen from the topsoil (Burgess et al., 2001). Although the water stored at depth is unlikely to be significant for drought avoidance by plants, the downward transfer of water to dry soil layers following rain my be important to plant establishment and the reduction of water logging in certain soil types (Burgess et al., 2001).

Both Finch (1998), and Zhang et al. (1999b, 1999c) found that rooting depth, which depends on soil type, available water, and the type of plant, had a significant impact on groundwater recharge rates. The depth of plant root penetration is difficult to measure and can vary significantly even within the same plant community (Canadell et al., 1996; Jackson et al., 1996). Furthermore, only a few roots penetrating deep into the ground can sustain large plant communities (Le Maitre et al., 1999).

Finch (1998) and Zhang et al. (1999b, 1999c) also found that the leaf area index, or the ratio of leaf area to ground cover, has a significant influence on groundwater recharge. Larger leaf areas result in greater interception of precipitation as well as potentially higher transpiration rates leading to decreased groundwater recharge. Although standard methods exist for measuring the leaf area index (Pearcy et al., 1989), these methods are impractical for large areas. The values for leaf area index reported in the literature are also very difficult to apply to many sites due to the high variability of types of vegetation across catchments and watersheds. In addition, the leaf area index not only has high variability between different plants, but it also varies seasonally due to climatic changes.

In summary, the effect of vegetation on recharge can be both positive and negative. Vegetation intercepts rainfall and transpires water obtained from the rooted soil profile; however, it can also facilitate infiltration by reducing overland flow and creating surface storing opportunities. Plant root systems may also increase recharge rates by creating macropores and channels in the soil profile (Le Maitre et al., 1999), and by downward transfer of water due to differences in moisture potentials (Burgess et al., 2001).

28.2.4.4 Urbanization

The water balance of an area can be drastically altered by urbanization. Not only is the recharge rate affected, but the entire climate can also be altered (Lerner et al., 1990). A micro-climate may develop in large urban centers, causing changes in temperature, humidity, wind speed, and air clarity (Hall, 1984). While surface runoff is considerably increased due to increased imperviousness, the amount of direct groundwater recharge due to precipitation is decreased (Burges et al., 1998; Rose and Peters,x 2001). However, most urban centers import their water for consumption from outside sources thereby increasing the amount of water in the area. A portion of this imported water then becomes recharged through septic tanks and leaking sewer and water distribution systems, and over-irrigation of lawns and parks (Lerner et al., 1990; Simmers, 1998; Yang et al., 1999; Foster, 2001; Lerner, 2002). This kind of indirect or man-induced recharge can result in higher recharge rates, or balance the loss of precipitation recharge due to impermeable areas (Lerner, 2002). However, determining the exact spatial and temporal distribution of this indirect recharge is exceedingly complicated and difficult to account for in any modeling efforts (Yang et al., 1999).

In summary, any changes in land cover, whether seasonal changes in vegetation or permanent changes due to urbanization, can impact groundwater recharge by altering the interception, infiltration, surface runoff, evaporation, and transpiration processes.

28.2.4.5 Overland Flow

Overland flow is a rare event in humid climates due to less intensive rainfall, well-developed vegetation, and sufficient infiltration capacity of most soils (Knutssen, 1988). Surface runoff occurs only over short distances or during special events such as intense snowmelt over frozen ground (Johnsson and Lundin, 1991). Furthermore, overland flow only takes place in the discharge areas, which usually occupy only a small part of a catchment (Knutssen, 1988). In areas of high topographic relief, with very low permeability soils such as clays and tills near the ground surface, surface ponding can occur, resulting in overland flow.

AQ: Please provide details in the ref. list for Woolhiser et al. 1996

Overland flow can be estimated using the diffusion wave approximation of the depth-integrated shallow water equations with Manning's equation used for velocity calculations (Woolhiser et al., 1996; VanderKwaak, 1999). Due to small-scale variations in surface slope, the estimation of Manning's roughness coefficients across a catchment is difficult and subject to spatial averaging.

A popular method among surface hydrologists to estimate overland flow is using the Natural Resources Conservation Service (NRCS, formerly the Soil Conservation Service) curve number method (NRCS, 1986). This rainfall-runoff analysis method is based on a simple relationship between precipitation, infiltration, an initial abstraction, which is a function of interception and surface ponding, and an empirical curve number obtained from numerous field experiments. This method is widely applied due to its simplicity (e.g., Colosimo and Mendicino, 1996; Srinivas et al., 1999); however, it only provides estimates of runoff volumes, and ignores any subsurface flow mechanisms.

28.2.4.6 Infiltration and Flow in the Unsaturated Zone

Infiltration is the volume rate of water flowing into a unit area of soil surface. It is generally considered to be one-dimensional in the vertical direction; however, as noted before, local changes in ground cover and near surface permeability can lead to lateral flows. Percolation is the process by which water migrates down through the soil profile, whereas deep soil water percolation is the water that has moved past the evaporative and root zones in the unsaturated zone and is no longer available to plants.

Both infiltration and percolation are very complicated processes as they are governed by such factors as the rate of precipitation, antecedent moisture conditions in the soil, soil hydraulic properties, topography, and others. While infiltration equations (e.g., Green and Ampt, 1911; Horton, 1940; Philip, 1957) simply describe the rate of water movement into the soil at the ground surface, other relationships (e.g., Richards, 1931) are used to describe the percolation of water through the unsaturated zone.

The processes of infiltration and flow in the unsaturated zone have been much studied with many methods derived for their estimation. These processes are examined in detail in other chapters of this book.

28.2.4.7 Soil Properties

The hydraulic properties of the soils in the unsaturated zone are very sensitive to the moisture content and pressure head distributions. A small change in the volumetric water content can often result in a change in the hydraulic conductivity by two or more orders of magnitude (Rushton, 1988). In addition, the soils in the unsaturated zone rarely exhibit homogeneous properties, often consisting of layered sands, silts, and clays, resulting in non-uniform moisture distributions. Instability in the wetting front and subtle changes in the permeability structure can also lead to flow fingering (Kung, 1990; Selker et al., 1992). The fingering process is enhanced by initially dry, layered, coarse-grained systems (Sililo and Tellam, 2000); however, the antecedent moisture contents prevalent in the field in humid climates will generally inhibit its occurrence.

The unpredictable occurrence of preferred pathways, due to plant roots, cracks, and fissures, in even relatively homogeneous materials furthermore complicates the hydraulic characterization of soils in the unsaturated zone (Simmers, 1990). Large variations in recharge can also occur even across uniform soils due to topography, resulting in depression focused recharge (e.g., Freeze and Banner, 1970; Winter, 1983; Schuh et al., 1993).

28.2.4.8 Temperature

In northern climates, subzero temperatures result in snow accumulations in winter time, as well as frost formation in the near surface soil layers due to pore water freezing. Furthermore, in northern Canada, the layer of frost remains in the ground throughout the entire year and is referred to as permafrost. The presence of both a snowpack and a frozen soil layer will clearly have a significant impact on the recharge process.

Similar to rainfall, the spatial and temporal distribution of snow accumulation is very complex, and even further complicated by its high sensitivity to temperature and wind velocities (i.e., drifting) (Deng et al., 1994). Snowpack melting is a fairly well-understood process and is primarily based on the energy balance at the air–snow interface, and on the physical characteristics of the snowpack (Harms and Chanasyk, 1998). However, the presence and extent of the frost layer influences the amount and distribution of the infiltrating snowmelt. Snowmelt or rain located in one portion of a watershed may be redistributed by either surface runoff or interflow on top of the frozen soil layer depending on the topography (Johnsson and Lundin, 1991).

As the soil frost layer develops, the water in the soil pores freezes. The growing ice constricts or blocks the infiltrating water, thereby increasing the tortuosity and producing a net reduction in hydraulic conductivity and infiltration rates (Kane and Stein, 1983; Granger et al., 1984; Black and Miller, 1990). Infiltration rates can also vary depending on the initial soil water content before freezing (Engelmark, 1988).

The depth of the frozen soil layer is dependent on several factors such as temperature, the duration of freezing temperatures, snow depth at the ground surface, and initial soil water content (Daniel and Staricka, 2000). The porosity of the frozen soil may also change due to expansion caused by ice formation. The freeze–thaw process can also create large, temporary fractures resulting in higher hydraulic conductivities as the ice melts (Johnsson and Lundin, 1991). As shown by Jyrkama (1999), during and immediately after thawing of the frozen soil layer in the spring, rapid infiltration of the accumulated snowmelt can create a transient groundwater mound, resulting in significant recharge to the water table.

Therefore, due to the complex interaction of all the above processes, modeling unsaturated zone flow in a seasonally (or permanently) frozen environment is very challenging.

28.2.5 Recharge Estimation Methods

The link between climate change and groundwater is the precipitation recharge at the land surface and the recharge and discharge that occurs at surface water bodies. Reviews on the unsaturated zone flow processes and methods to quantify groundwater recharge rates from precipitation can be found in texts by Lerner et al. (1990) and Stephens (1996). In addition, Simmers (1988) and Sharma (1989) provide several examples on how these methods have been applied in many field studies. An overview of estimation problems and developments in groundwater recharge are also given by Simmers (1998) and the special theme issue of the *Hydrogeology Journal* (vol. 10, 2002). It should be noted that much of the literature and the associated methods have been developed for estimating recharge in arid and semiarid areas, where recharge plays both an economically and environmentally critical role.

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Lerner et al. (1990) highlight five main methods of estimating direct recharge from precipitation:

- direct measurement
- empirical methods
- water budget methods
- Darcian approaches
- tracers.

Other methods include, for example, plane of zero flux, temperature and electromagnetic methods, baseflow separation, remote sensing, and inverse groundwater modeling (Stephens, 1996). A brief discussion of these and other additional methods is presented in the following sections.

28.2.5.1 Field (or Direct) Techniques

The most common and practical instrument to measure recharge directly is with a lysimeter. A lysimeter is a block of soil instrumented such that all the parameters in the water budget can be quantified, with the recharge flux being either measured directly at the bottom (e.g., Lerner et al., 1990), or estimated based on the changes in the block weight (Kirkham et al., 1984; Yang et al., 2000). The inherent problems with lysimeters are that they are difficult and expensive to construct and only provide a point or an average value of recharge for the materials within the block. Soil disturbance is also a problem, as well as leaks and other failures resulting in potentially erroneous measurements. The major difficulty with weighing lysimeters is in measuring small weight changes in relation to the large and heavy soil mass.

As an example, Fayer et al. (1996) used three lysimeters, in conjunction with other methods, to estimate recharge rates at the Hanford nuclear waste site in the United States. They measured drainage from the bottom of each instrument over several years to estimate an average annual recharge rate. The lysimeters were of different depths and filled with soils typical of their surroundings. The main problem with their measurements, however, was that the instruments were too shallow (i.e., within or above the root or evaporative zone). Therefore, in spite of the long measurement period used, the collected drainage may have overestimated the actual recharge rates in the area. To avoid problems with the larger size instruments, Holder et al. (1991) developed a special wick pan lysimeter, also called the passive capillary sampler (PCAPS). The PCAPS is generally constructed from a small sealed bucket and instrumented with a wetted fiberglass wick that acts as a hanging water column and develops suction in the soil water depending on the flux. Louie et al. (2000) used a number of PCAPS and found them to perform satisfactorily under various field conditions.

The matric potential and water content measurements using tensiometers and time-domain reflectometry (TDR) can also be used in the field to estimate hydraulic gradients and storage changes in the vadose zone. As a pulse of infiltrated water moves through the unsaturated zone, a plane of zero flux, that is, where the hydraulic gradient is zero, may develop as the water above the plane moves upward due to evapotranspiration while below the plane, water moves downward due to gravity (e.g., Scanlon et al., 2002). Water below the zero flux plane will therefore become recharged, and the amount or rate can be calculated by monitoring the change in water content below the plane. However, this requires extensive monitoring in the field and is therefore unfeasible for large areas. Furthermore, the location of the zero flux plane changes with time and only applies to a pulse of infiltrated water. Therefore, the method breaks down when there is a downward hydraulic gradient due to a continuous precipitation event (Stephens, 1996).

Temperature and electromagnetic methods have been developed based on the fact that surface waters and groundwaters have different temperatures and chemical compositions. The rate of recharge can be estimated based on measured borehole temperature profiles (Taniguchi, 2002) or through soil temperature measurements (Taniguchi and Sharma, 1993). Electromagnetic methods are mostly used for reconnaissance investigations to screen sites where more quantitative methods for recharge could be applied (Cook and Kitty, 1992). Similarly, remote sensing, such as Landsat imagery (Salama et al., 1994) or InSAR analysis of ERS-1 and ERS-2 images (Lu and Danskin, 2001) have been used to distinguish regions of recharge and discharge over larger areas.

28.2.5.2 Empirical Methods

Recharge rates have been estimated by correlating precipitation with recharge using an empirical relationship often based on regression (e.g., Sinha and Sharma, 1988; Shade and Nichols, 1996; Yang et al., 1999; Nichols and Verry, 2001; Xu and van Tonder, 2001; Chen et al., 2002) or stochastic analysis (Wu et al., 1997; Gau and Liu, 2000). Although these methods may be adequate for the particular study area and purpose, they are not applicable to other areas. Expressing recharge as a function of precipitation has no physical basis, as all the unsaturated zone processes described in the previous section are completely ignored.

Methods have also been developed to quantify groundwater recharge based on the analysis of the recession curve in the streamflow hydrographs (e.g., Rorabaugh, 1964; Chapman, 1999; Wittenberg and

Sivapalan, 1999; Arnold et al., 2000). It is assumed that the recession part of the hydrograph represents primarily groundwater discharge to the river as a direct result of precipitation recharge to the aquifer. Erskine and Papaioannou (1997) further developed a relationship called the aquifer response rate based on maximum permissible abstraction and minimum flow requirements for a river.

Halford and Mayer (2000) studied various hydrograph separation techniques and concluded that baseflow is frequently not equivalent to groundwater discharge because other hydrologic phenomena can significantly affect stream discharge during the recession periods. Drainage from bank storage, wetlands, surface water bodies, soils, and snowpacks also decreases exponentially during recession periods, and along with evapotranspiration, were shown to affect the stream discharge more than groundwater discharge during the recession periods. These methods have obvious limitations, therefore, and at best only provide an approximation of the overall volume of groundwater recharge over a selected time period.

28.2.5.3 Water Budget Methods

Soil water budget methods are based on a soil moisture balance whereby all the components of the water balance equation are estimated with groundwater recharge being the residual (also see Figure 28.1)

$$R = P - ET \pm O \pm \Delta S \tag{28.1}$$

where R is the recharge, P is precipitation, ET is actual evapotranspiration, O is the lateral surface runoff in and out of the area, and ΔS represents the change in water storage in the unsaturated zone. Assuming a unit cross-sectional area, each process can be described as a rate or a flux. As indicated, water is added or depleted from the soil storage with any excess becoming groundwater recharge.

Due to the difficulty in accurately estimating each of the processes, propagation of errors in the water budget method can result in large uncertainty in the calculated recharge. Furthermore, this method ignores the movement of moisture, that is, percolation, through the unsaturated zone, and therefore fails to account for the time it takes for the infiltrated water to reach the water table. Recharge is assumed to occur instantaneously as water is released from soil storage. Therefore, the temporal recharge pattern or the timing of recharge is difficult to capture with this method. The water budget method has been used to calculate average recharge rates in various situations (e.g., Bekesi and McConchie, 1999; Srinivas et al., 1999; Finch, 2001; Chapman and Malone, 2002).

28.2.5.4 Darcian Approaches

Water movement in the unsaturated zone can be modeled based on Darcy's equation and conservation of mass (Richards, 1931). The strength of this method is that it is physically based, however, in addition to the uncertainty in the antecedent moisture conditions and heterogeneities of the soil column, the high nonlinearity between the hydraulic conductivity, pressure head, and water content in the unsaturated zone pose several difficulties in its application. This method is therefore computationally intensive and requires detailed information about the hydraulic characteristics of the unsaturated zone. These inherent difficulties are compounded by the potential presence of root channels and other fissures, which may dominate the recharge process. However, accounting for the moisture movement through the unsaturated zone explicitly provides a robust method of estimating groundwater recharge (assuming errors in the input data can be minimized).

28.2.5.5 Tracers

A host of environmental tracers have been used to estimate groundwater recharge. These include tritium and chlorine-36, chloride, carbon-14, chlorofluorocarbons, and stable isotopes such as deuterium, and ^{18}O. These methods require the measurement of a concentration profile in the soil column, which provides information about water movement in the unsaturated zone. Recharge is then estimated based on a tracer mass balance, total water content analysis, or numerical modeling. These methods usually assume piston displacement and result in an estimate of either a long-term average recharge rate or a total volume of recharge (e.g., Allison, 1988; Scanlon et al., 2002).

28.2.5.6 Inverse Groundwater Modeling

Recharge is commonly used purely as a calibration parameter in many groundwater modeling studies (e.g., Martin and Frind, 1998; Bonomi and Cavallin, 1999; Javed and Bonnell, 1999; Varni and Usunoff, 1999; Ella et al., 2002). Therefore, the resultant recharge pattern can potentially be used to quantify recharge rates in the area. Zoning of recharge into equivalent areas is often used to reduce the total number of calibration parameters.

The concepts of inverse calibration and zoning are based on earlier conceptual models (e.g., Toth, 1963; Freeze and Witherspoon, 1968; Winter, 1978, 1983) where the specific recharge and discharge zones emerge naturally as a response to geologic or topographic conditions. The distribution of recharge can therefore be delineated with the knowledge of the depth of the water table and the underlying hydraulic conductivity distribution, while the rate of recharge can furthermore be estimated using the Darcy equation. Stoertz and Bradbury (1989) and Levine and Salvucci (1999) used this approach with numerical groundwater flow modeling to delineate recharge areas and rates.

Using the same concept, Lin and Anderson (2003) developed a recharge and discharge mapping procedure based on pattern recognition and image analysis. Similar to Stoertz and Bradbury (1989) their method is based on a mass balance calculation performed using MODFLOW, and therefore is critically dependent on the accuracy of the water table interpolation. Zoning is used to smooth out the results as "it is not practical to work with numerous grid specific rates in a parameter estimation code, nor are the individual values expected to be very accurate" (Lin and Anderson, 2003). Scale is also a major problem with this method as the resolution of the hydraulic gradient between adjacent model cells decreases with finer grid spacing. As the method ignores all the physically based processes in the hydrologic cycle contributing to recharge, and only considers parameters used in the groundwater flow model, Lin and Anderson (2003) admit that the method may result in unreasonable estimates of groundwater recharge, for example, recharge greater than precipitation.

The main problem with inverse groundwater model calibration is that it relies entirely on the accuracy of the groundwater flow model which often has great uncertainty associated with it due to limitations in the input data. Small changes in the calculated hydraulic conductivity field, for example, can result in potentially large variations in the recharge estimates. Furthermore, because hydraulic conductivity ranges over several orders of magnitude, estimated recharge rates are highly uncertain. The results are also non-unique because the same distribution of hydraulic heads can be produced with a range of recharge rates, as long as the ratio of recharge to hydraulic conductivity remains the same (Scanlon et al., 2002). This approach, therefore, ignores all the physical processes in the hydrologic cycle and disregards the dynamic interaction between the surface water and groundwater systems.

28.2.5.7 Combined Modeling

Groundwater recharge has also been estimated by using a mixed approach, based on a combination of the water budget methods and the Darcy equation. The problem with the Darcian approach alone is that it lacks the description of many of the important hydrologic processes. It simply calculates the movement of water through the soil column based on limited boundary conditions. Using the water budget method first to estimate important processes such as surface runoff, evapotranspiration, and snowmelt, for example, and then calculating percolation through the unsaturated zone using the Darcy equation, will preserve the hydrologic moisture balance and allow recharge to be quantified in both space and time.

This approach is also well suited to the investigation of the impact of land use and climate changes on groundwater recharge. The various weather input parameters, such as precipitation and temperature, can be perturbed according to predicted changes in the future climate, while the ground surface properties, such as runoff potential and rooting depths, can be modified due to expected changes in land use.

Examples of combined models include Bauer and Vaccaro (1987), UNSAT-H (Fayer and Jones, 1990), TOPOG_IRM (Dawes and Hatton, 1993), PRZM-2 (Mullins et al., 1993), HELP3 (Schroeder et al., 1994), Sandstrom (1995), ANSWERS (Bouraoui and Dillaha, 1996), PERFECT (Abbs and Littleboy, 1998), SWAT (Arnold et al., 1998), and WAVES (Zhang and Dawes, 1998). The rate of recharge in each model is simulated using a combination of various vegetation, climate, and hydrologic models.

28.2.6 Recharge in Groundwater Modeling

28.2.6.1 Introduction

Groundwater models are employed for numerous hydrologic investigation purposes such as vulnerability assessments, remediation designs, and water quantity estimations. Most often, however, they are used in groundwater quality studies dealing with the increasing number of emerging groundwater contamination problems. Groundwater models are applied across various scales, from very small scale flow analyses (e.g., Srinivas et al., 1999; Ella et al., 2002), to the regional, or even national scale groundwater flow studies (e.g., Brodie, 1999; Varni and Usunoff, 1999; Vermulst and De Lange, 1999). Both steady-state and transient modeling strategies are employed, depending on the extent and nature of the particular problem.

Whereas fully saturated models, such as the United States Geological Survey (USGS) modular finite-difference groundwater model MODFLOW (McDonald and Harbaugh, 1996), only simulate groundwater flow below the water table, variably saturated models that depict flow in the unsaturated zone also exist, and are used in some instances (e.g., Freeze, 1971; Huyakorn et al., 1986; Deng et al., 1994; Therrien and Sudicky, 1996). Infiltration at the ground surface is used as the top boundary condition in variably saturated models, while groundwater recharge is calculated explicitly as part of the flow solution. Although subsurface fluid flow (both air and water) is therefore modeled as a continuum, this approach is still limited by the scaling problem. The highly nonlinear relationships between water content, pressure head, and unsaturated hydraulic conductivity requires very fine discretization, limiting the application to smaller areas due to increased computational costs.

In addition to added input data, variably saturated models also need to account for the near surface hydrologic processes such as infiltration, evapotranspiration, frost penetration, and snowmelt that influence not only the top boundary condition, but also the upper few meters of the unsaturated zone. Fully saturated groundwater models, on the other hand, only require the specification of the recharge boundary condition at the water table and are therefore more commonly used in most groundwater modeling investigations.

Variably saturated flow is described by the Richards' equation, while transient three-dimensional saturated groundwater flow in heterogeneous anisotropic porous media is expressed as (Bear, 1972)

$$\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial h}{\partial x_j}\right) + Q = S_s\frac{\partial h}{\partial t} \tag{28.2}$$

where K_{ij} is the hydraulic conductivity tensor, h is the hydraulic head, Q represents sources or sinks, and S_s is the specific storage. As fully saturated models only describe groundwater flow below the water table, the specification of either the location of the water table (Dirichlet — Type I) or the recharge flux (Neumann — Type II) is required as the top or upper boundary. Depending on the model, the flow equations are commonly solved either by the finite difference method, for example, MODFLOW (McDonald and Harbaugh, 1996), or the finite element method, for example, WATFLOW (Molson et al., 1992).

As the exact location of the phreatic surface is often difficult to determine, and small errors in its location may potentially lead to large errors in groundwater fluxes, the recharge flux is often specified as the upper boundary condition. However, due to the many difficulties in recharge estimation, as alluded to earlier, the recharge boundary condition is commonly used purely as a calibration parameter to improve the model fit (e.g., Martin and Frind, 1998; Bonomi and Cavallin, 1999; Varni and Usunoff, 1999). Where information about precipitation is available, a fraction of it is also often assigned as the recharge boundary condition (Kennett-Smith et al., 1996; Brodie, 1999). The concept of the recharge spreading layer (RSL) has also been proposed to redistribute recharge from areas of low permeability to areas of relatively high permeability (Therrien and Sudicky, 1996; Martin and Frind, 1998; Beckers and Frind, 2000). Although these assumptions may be reasonable for the long-term simulation of a regional groundwater flow system or flow in a deep confined aquifer, a physically based and more accurate description of the recharge boundary condition is required for studies involving climate change, where the detailed knowledge of the spatial and temporal variation of the recharge is imperative.

28.2.6.2 Coupled Models

To obtain a more physically based recharge boundary condition for saturated groundwater models, several researchers have adopted a coupled approach (Chiew et al., 1992; Prathapar et al., 1994; Fayer et al., 1996; Beverly et al., 1999; Srinivas et al., 1999; Vermulst and De Lange, 1999; Zhang et al., 1999a; Sophocleous and Perkins, 2000; Batelaan and De Smedt, 2001; Ruud et al., 2001; Coppola et al., 2002). Groundwater recharge is estimated separately, using methods described Section 28.2.5, and the results are then used as a boundary condition in a saturated groundwater flow model. While most, if not all, of the methods presented in Section 28.2.5 have been used in groundwater modeling studies, the following discussion will focus on combined vadose zone–water budget modeling, as it provides the most versatile and physically based means of estimating the recharge boundary condition.

Chiew et al. (1992) developed a coupled approach based on the rainfall-runoff model HYDROLOG and the finite element groundwater flow model AQUIFEM-N to estimate regional groundwater recharge rates. The surface hydrologic model was used to calculate daily recharge rates, which were then summed over a month and input into the groundwater flow model as the recharge flux boundary condition. While their methodology may provide improved results as calibration is conducted against both streamflow and potentiometric head data, there are still many shortcomings and limitations in their approach. First, they divided their catchment into ten sub-areas based on drainage divides, rather than into areas with similar hydrologic characteristics. This resulted in spatially averaged values being used for each sub-area in the recharge analysis. Second, the rainfall-runoff model HYDROLOG completely ignores flow in the unsaturated zone and is simply calibrated against streamflow hydrographs with recharge estimated as a result. Even though the analysis is conducted based on daily precipitation records, the combination of ignoring the unsaturated zone and using average parameters to represent each sub-area results in an averaged estimate of recharge for a given sub-area. This is clearly shown in their simulated groundwater levels, which fail to match the transient variations observed in the groundwater flow field resulting from significant recharge events.

Prathapar et al. (1994) developed a soil water and groundwater simulation model SWAGSIM to estimate water table fluctuations in extensively irrigated regions. They calculated daily recharge at the water table based on an analytical solution to the Richards' equation and added it to a two-dimensional finite difference groundwater flow model through the source/sink term. The main problems with their model include the simplification of important hydrologic processes, the requirement of homogeneous and isotropic conditions for the analytical solution, and the two-dimensional nature of the groundwater flow model (essentially assumes a one-layer system with assigned transmissivities and specific yields). Therefore, their model is only applicable to very simple systems.

Using a geographic information system (GIS), Fayer et al. (1996) estimated the spatial distribution of recharge with four different methods for their groundwater study at the Hanford nuclear waste site in the United States. They used a combination of field techniques such as lysimeters, water content measurements, and tracer studies in conjunction with numerical modeling (UNSAT-H) to generate a temporally averaged recharge boundary condition map for their groundwater flow model of the study area. The use of the GIS aided significantly in the analysis by allowing the identification of all possible combinations of soil type and vegetation in the area that could be assigned an appropriate estimate of recharge. The inclusion of field studies provided additional confidence to the unsaturated zone modeling results. However, the resulting recharge map only depicts average annual recharge rates and neglects to provide information regarding the change of recharge over time. The results from the groundwater model were not discussed.

Due to data limitations required by more physically based models, Beverly et al. (1999) developed a simple unsaturated module SMILE to provide recharge estimates to MODFLOW. Their model accounts for overland flow and evaporation from both the unsaturated and saturated zones and recharge is calculated based on either a matrix or crack flow approximation, or an empirical Darcy approach. The two models are again linked through the recharge boundary condition; however, their approach also allows for groundwater discharge, due to heads in excess of the ground surface, to be distributed in overland flow and reinfiltrated in the subsequent time steps. This dynamic linking seems very attractive with a small computational burden due to the simplicity of the model; however, the process descriptions are overly simplified and may lead to significant errors in the results.

Srinivas et al. (1999) used the water budget method to calculate monthly recharge rates for their nested squares groundwater flow model NEWSAM of a small fractured granitic aquifer in India. They used the SCS curve number method to calculate an average curve number for the watershed and applied the water balance method on a monthly basis to estimate recharge. The estimated temporal recharge pattern was then coupled to the groundwater flow model through the boundary condition. Their results showed the importance of including temporally varying recharge in groundwater flow modeling to capture the temporal fluctuations observed at the water table. However, their model consistently over predicted the observed water levels by a wide margin, although it seemed to capture the timing of changes in the flow field. Using the water budget method across the entire watershed leads to spatial averaging, which may account for the problems in their simulated data. As mentioned previously, the water budget method ignores percolation through the unsaturated zone resulting in average results.

VanderKwaak (1999) discusses several coupled surface–subsurface models in his work; however, the coupling in the models is accomplished by matching boundary conditions at the land surface interface.

Vermulst and De Lange (1999) used a GIS interface to link the unsaturated flow model MOZART and the analytic element groundwater flow model NAGROM to aid in national groundwater policy analysis in the Netherlands. As their models operated at different spatial and temporal scales, they coupled them through the Cauchy boundary condition using up- and down-scaling procedures. The models were run sequentially until a steady state was obtained. Although recharge was averaged both spatially and temporally, their model provides a valuable tool for policy decisions at the national scale. However, the model has limited potential for groundwater quality studies of point source contamination.

To simulate catchment scale responses under different land management options in the context of salinity control, Zhang et al. (1999a) used a distributed parameter ecohydrological model TOPOG-IRM to estimate soil moisture and groundwater recharge rates. The model accounts explicitly for the spatial distribution of topography, soil characteristics, and vegetation properties and predicts the dynamic interactions within the soil–vegetation–atmosphere system. It also uses the Richards' equation to simulate water movement in the unsaturated zone and links soil and canopy processes with catchment topography. Evapotranspiration is based on a Penman–Monteith type approach, with transpiration based on a canopy resistance model. The model uses daily climate variables such as precipitation, temperature, vapor pressure deficit, and solar radiation to estimate the recharge rate at the bottom of the soil column. Their model, therefore, seems to offer a very sophisticated approach for estimating groundwater recharge.

Using the results from the recharge analysis, Zhang et al. (1999a) also used MODFLOW to simulate groundwater flow in their catchment. The simulated water levels, however, failed to match the temporal variations in the observed data. This was likely not caused by problems in the recharge analysis, but by the simplicity of the groundwater flow model. Due to the lack of soil information in the study area, they assumed homogeneous conditions across the entire site. Furthermore, the calculated recharge was only approximately 5% of the annual rainfall in the area, resulting in a very small recharge boundary flux.

Sophocleous and Perkins (2000) combined the semi-distributed agricultural watershed model SWAT (Arnold et al., 1998) with MODFLOW to study conjunctive water use and management scenarios in three watersheds in Kansas. They developed a linking routine where the results from SWAT were distributed or averaged over the groundwater model grid and passed as inputs into MODFLOW at each MODFLOW time step. They also utilized GIS to aid in parameterization of hydrologic variables using overlaying and averaging operations. They calibrated the model against actual streamflows and groundwater levels in three watersheds and found reasonable agreement between the simulated and observed results. In addition to allowing calibration to multiple targets, the main advantage of their method is in the flexible modular linking approach that allows other watershed models to be used in place of SWAT. The main shortcoming, however, is that the linked model is based on the HRU concept resulting in averaging of important parameters. Mean sub-basin responses are first estimated by averaging the mean results from each of the HRUs within the sub-basin, and then distributed over the underlying groundwater model grid. The inputs to the groundwater model are therefore not only averaged temporally, but spatially as well.

Batelaan and De Smedt (2001) developed a GIS-based methodology to provide recharge estimates for regional groundwater modeling. Their model, WetSpass, estimates recharge on a raster cell basis using a simplified water balance formulation. They used the results of the recharge analysis as boundary conditions in MODFLOW to study the effect of land use changes on groundwater discharge in a catchment in Belgium (Batelaan et al., 2003). While their method may provide reasonable estimates of average annual recharge rates at the regional scale, it is unsuitable for small temporal and spatial scales. One of the main drawbacks of the method is the coarseness of the raster approach, which requires average parameter values to be used for each raster cell. However, the central weakness of their method is the crude water balance, which employs simple empirical relationships to describe important hydrologic processes, with recharge estimated as the residual.

Ruud et al. (2001) used a similar GIS-based approach in their coupled groundwater and surface water flow model at the basin scale. They linked a surface water model, a land–atmosphere interface and unsaturated zone model, and a groundwater flow model (MODFLOW) in GIS to evaluate conjunctive use alternatives and their impacts on groundwater resources in response to land use demands and potential changes to surface water deliveries in their study area. Monthly rates of recharge were calculated from the surface water models and input as the recharge flux boundary condition in MODFLOW. The main weakness in their approach is that the modeling is conducted at a very large scale leading to spatial averaging of important processes and parameters. Furthermore, they used the water budget method (and a quasi-hydraulic model) to compute the recharge rates at the water table which ignores or simplifies the impact of the unsaturated zone soil column.

As part of a groundwater flow study in New Jersey, Coppola et al. (2002) developed a fuzzy-rule based approach to estimate monthly recharge rates for the groundwater flow model. Instead of estimating recharge using a physically based description of hydrologic processes, they employed a fuzzy-rule based approach relating monthly groundwater recharge to mean monthly air temperature, monthly precipitation, and the previous month's total streamflow. They used the method to estimate monthly basin wide recharge values during transient calibration of the groundwater flow model. Similar to other empirical approaches, however, their method is only a statistical tool and lacks physical basis. Furthermore, at best, it can only estimate average basin wide values as the analysis is based on monthly streamflow totals from the basin.

In summary, various types of coupled models have been developed for different purposes and applications. The approaches portray various degrees of sophistication, from the rigorous numerical treatment of many hydrologic processes, to simple water budget or empirical models. Regardless of the many obvious weaknesses present in many of the models, these methods provide a more versatile and practical way to estimate groundwater recharge than the more expensive and intensive field methods. Physically based method are especially useful, as they not only provide current estimates of recharge, but they can also be used to study the impact of changes in the physical processes, for example, in temperature and precipitation due to climate change, on recharge distribution and rates.

28.2.6.3 Integrated Models

To overcome the problems inherent in the coupled approaches, several researchers have attempted to model the entire hydrologic system as a whole. The basic design of the integrated surface–subsurface modeling approach was first outlined by Freeze and Harlan (1969). Yan and Smith (1994) proposed a framework for an integrated approach based on integrating a surface water management model SFWMM with MODFLOW. Although the idea of integrating existing and widely used models sounds appealing, their approach, however, suffers from many simplifying assumptions common with the coupled methods. Furthermore, besides the proposed framework, details of model development and applications have not been found in literature to date.

Using the GIS, Xiao et al. (1996) developed a raster-based spatially and temporally continuous surface–subsurface hydrologic flow model. The model is based on a dynamic linkage between precipitation, surface flow, infiltration, and subsurface flow submodels and uses simple physical relationships instead of the more rigorous higher order transient differential equations. The processes of interception and evapotranspiration are ignored due to sparse vegetation and the assumption that evapotranspiration rates would be low during a rainfall event due to high humidity. The equations are solved sequentially, and the percolation of water through the unsaturated zone is ignored. The model was applied to a large watershed in northern Alaska to simulate the system response to a single rainfall event. In addition to the inherent problems with a simplified model, the lack of evapotranspiration, snow pack, and snowmelt processes limit the application of the model to simple systems.

Querner (1997) developed a physically based groundwater and surface water model MOGROW and used it to investigate the effects of human interventions and natural factors on groundwater recharge at the regional scale in the Netherlands (Querner, 2000). The model combines a variably saturated finite element groundwater flow model SIMGRO with a surface water model SIMWAT. Although advertised as an integrated model, the two models operate at different time steps and are linked through the surface boundary condition. Furthermore, the flow in the unsaturated zone is modeled with a pseudo-steady-state approach with empirical parameters introduced for surface runoff, perched water tables, and preferential flow. Results from their study indicate that the model may be suitable for long-term assessments of changes in the groundwater flow field due to changes in land use, groundwater abstractions, and meteorological conditions.

VanderKwaak (1999) developed a fully integrated surface water and groundwater model that rigorously considers the flow and transport processes on the land surface and in the variably saturated, dual-continua subsurface. The two-dimensional diffusion wave equation is used to describe the shallow surface water flow, while groundwater flow is described using the three-dimensional form of the Richards' equation. The linkage between the surface and subsurface systems is through first-order, physically based flux relationships or through continuity assumptions. The entire system of equations is also solved simultaneously resulting in a truly integrated model. The weakness of the model, however, is that it ignores important hydrologic processes such as interception and evapotranspiration, which can account for significant losses in long-term flow simulations. Snowmelt processes are also ignored, limiting the application of the model to warmer climates or short-term simulations. Parameterization and the scaling problem between the surface and subsurface processes furthermore restrict the application of the model to smaller areas with small variations in properties or characteristics (VanderKwaak and Sudicky, 2000).

Montgomery Watson (1993) has also created an Integrated Groundwater Surface Water Model (IGSM) based on a quasi three-dimensional finite element approach. The major components of the hydrologic cycle simulated by the model include rainfall, runoff, groundwater recharge, pumping, consumptive use, evaporation, subsurface flows, and seawater intrusion.

> Integration of groundwater and surface water flows is carried out using a soil mixture accounting and unsaturated flow model. This, combined with runoff and soil percolation, allows for full interaction between surface and groundwater. Water quality simulation is also included which can track a contaminant through the processes of advection, dispersion, and dissolution
>
> (Futter 1995).

The model has been applied in basin management studies in California, Florida, and Colorado. Due to its increasing popularity, LaBolle et al. (2003) conducted a comprehensive review of the underlying assumptions and mathematical formulations present in the IGSM model. In addition to using empirical land use and vadose zone models to compute net percolation or recharge to the water table, they found that "the model fails to properly couple and simultaneously solve groundwater and surface water models with appropriate mass balance and head convergence under reasonable conditions" (LaBolle et al., 2003). They further concluded that due to instabilities and errors caused by some of the algorithms in the model, the model results may produce misleading predictions and interpretations that may influence planning and management decisions.

HydroGeoLogic (2002) developed an integrated hydrologic modeling system MODHMS based on the USGS MODFLOW model. They added modules for three-dimensional flow in the unsaturated zone using the Richards' equation, two-dimensional overland flow using the diffusion wave approximation, and flow through a network of one-dimensional channels or pipes using the diffusion wave approximation with Priesmann Slot conceptualization for pressurized flow in pipes. The model is fully compatible with GIS and provides an interface with ArcView for accessing and analyzing spatially distributed input parameters. The model has been applied to various problems, such as groundwater interaction with rivers and saltwater intrusion analysis. Due to the lack of published data, however, a more detailed description of the model cannot be given here.

Graham and Refsgaard (2001) give a descriptive overview of the fully distributed hydrologic model MIKE-SHE, which is an extension of the original Systeme Hydrologique Europeen (SHE) code (Abbott et al., 1986). They assert that "MIKE-SHE is one of the only distributed, physically based, fully integrated surface water/groundwater models available today." The model includes descriptions for many of the important hydrologic processes, including snowmelt, with well-known non-empirical equations used to represent the physical processes in the different parts of the hydrologic cycle (Graham and Refsgaard, 2001). The model and its earlier versions have been around for quite some time and therefore have been applied to numerous hydrologic problems. One of the weaknesses of the model includes the strictly one-dimensional flow assumption in the unsaturated zone and sheet flow approximation of overland flow. Furthermore, as with any of the integrated hydrologic models, the central problem is with parameterization and increased computational requirements due to rigorous mathematical equations as well as coupling, or integration, of processes that take place on vastly different spatial and temporal scales.

Singh and Woolhiser (2002) give a comprehensive review of hydrologic models reported in literature over the years. While most of the models listed in their paper deal only with surface water hydrology, references to more comprehensive models are also included.

In the end, the problem comes down to the purpose and scope of the model, and its associated conceptual model. As Reddi and Danda (1994) pointed out, "while simple lumped parameter models may be adequate in regional groundwater quantity studies on homogeneous soil domains, models addressing multidimensionality and spatial heterogeneity are necessary in groundwater quality studies, such as remediation designs at contaminated sites." Therefore, depending on the objectives and purpose of the model, the use of steady-state or average parameters may very well be appropriate. However, this does not imply that using average values, especially across many spatial or temporal scales, results in an accurate model. Parameter sampling and modeling must be done at the appropriate scale to accurately describe the processes that the model intends to simulate.

28.3 A Case Study: Recharge Analysis of the Grand River Watershed

28.3.1 Introduction

The Grand River watershed is located in south-western Ontario, draining an area of nearly 7000 km^2 into Lake Erie. The location of the watershed is shown in Figure 28.2. The main tributary is approximately 290 km in length with an elevation differential of about 362 m from its source to the mouth. The landscape of the watershed has mainly been shaped by the last period of glaciation, resulting in highly variable soils and topography. The southern part of the watershed consists of low permeability lacustrine clay deposits and low topographic relief. The central part is formed mostly of higher permeability sand and gravel kame moraines with moderately high relief, while the northern portion of the watershed is comprised of lower permeability till plains with varying surface relief (Holysh et al., 2000).

FIGURE 28.2 Location of the Grand River watershed.

Although 90% of the watershed is classified as rural, the watershed contains some of the fastest growing urban areas in Ontario, such as the cities of Kitchener, Waterloo, Cambridge, and Guelph. Not only is increasing urbanization stressing the existing water supply, but it is also placing the supply at a greater risk of contamination. There is growing concern about the environmental impact of such rapid urbanization and the ability of the river and groundwater systems to meet the rising demand for water. The recent and continuing drought conditions in southern Ontario have also placed an additional stress on the hydrology and water resources of the watershed.

The objective of this study is to assess the spatial and temporal distribution of groundwater recharge in the Grand River watershed and to estimate the impact that climate change may have on groundwater recharge, evapotranspiration, and runoff. Approximately 80% of the population in the watershed derive their drinking water from groundwater. Therefore, quantifying the input to the groundwater system is critical for developing an effective groundwater management strategy that will ensure an adequate and clean supply of drinking water, now and in the future.

28.3.2 Input Data

Numerical modeling at the regional watershed scale, such as the Grand River, involves the handling of large amounts of input and output data. A geographic information system (GIS) is ideally suited for this purpose as it provides an integrated platform to manage, analyze, and display model parameters and results. Due to the large volume of temporally varying climate data (e.g., daily precipitation, temperature, and solar radiation), a separate relational database management system (RDBMS) was also utilized in this work to facilitate data organization and storage.

The physically based hydrologic model HELP3 was used to calculate the spatially varying daily groundwater recharge rates for the watershed. The model was linked to ArcView GIS and the database management system (MS Access) using simple Visual Basic and ArcView Avenue scripts. Details of the methodology can be found in Jyrkama et al. (2002). HELP3 was chosen mainly because it was readily available and easy to use. Furthermore, HELP3 simulates all of the important hydrologic processes in the water budget, including the effects of snowmelt and freezing temperatures. Following is a summary of the input data used in the model.

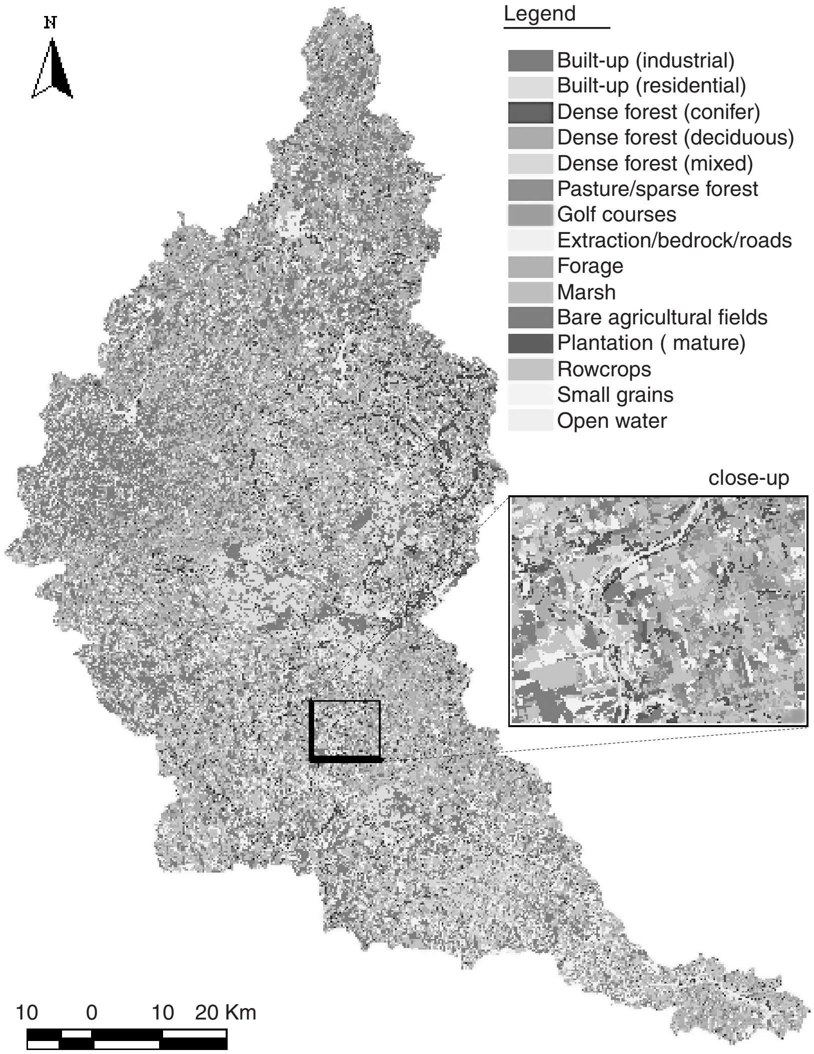

FIGURE 28.3 Land use/land cover (LULC) map.

28.3.2.1 Land Use/Land Cover Data

Digital land use and land cover (LULC) data for the Grand River watershed were obtained using 1999 satellite imagery from the Landsat 7 thematic mapper. As shown in Figure 28.3, the raster LULC coverage is based on a 25-m grid with 15 unique field descriptors.

28.3.2.2 Soil Data

The surface soil information in Figure 28.4, was assembled from various regional soil surveys conducted in the watershed. All the information was obtained from the Canadian Soil Information System (CANSIS) website in digital form. However, several difficulties were encountered during the construction of the soil map and the associated database for the watershed.

The Grand River watershed spans a number of different counties and municipalities, each with its own soil survey and database, as shown in Table 28.1 and Figure 28.2. Due to differences in scales and mapping methods, relatively minor to severe discontinuities and overlaps existed between adjacent soil map sheets. Therefore, to generate a continuous soil map for the entire watershed, these gaps and overlaps needed to

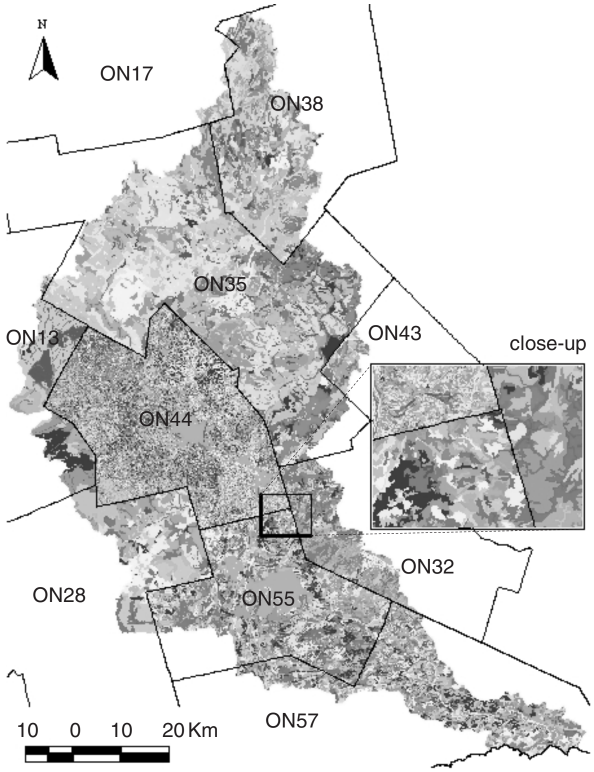

FIGURE 28.4 Soil surveys and soil map.

TABLE 28.1 Soil Surveys in the Grand River Watershed

Survey	County	Scale	Year
ON13	Perth	63360	1975
ON17	Grey	63360	1981
ON28	Oxford	63360	1961
ON32	Wentworth	63360	1965
ON35	Wellington	63360	1963
ON38	Dufferin	63360	1963
ON43	Halton	63360	1971
ON44	Waterloo	20000	1971
ON55	Brant	25000	1989
ON57	Haldimand-Norfolk	25000	1984

AQ: Please clarify the entries below scale represents area, if so please specify unit

be corrected. It was assumed that newer maps and maps with finer scales were more accurate and therefore were used to fill gaps (by extending edge polygons), and to trim the surrounding map sheets.

There were a total of 723 unique soil types identified in the watershed. In addition to physical and chemical details, the associated soil database also contained information on soil type, number of layers, layer depths, and soil texture classifications.

28.3.2.3 Vegetation Data

Plant roots can have a significant impact on recharge as they remove infiltrated water from the soil. However, the determination of plant root penetration and subsequently the evaporative zone depth are very difficult tasks. In this study, the average evaporative zone depths (based on the combination of soils and land cover types) were estimated using the guidelines given in the recharge methodology developed by the New Jersey Geological Survey (NJGS) (Charles et al., 1993).

HELP3 also requires a value for the maximum leaf area index (LAI) to calculate transpiration rates for the vegetative cover. Following the guidelines in HELP3, where the LAI ranges from 0 for bare ground to 5.0 for maximum vegetal leaf coverage, the values for LAI were assigned based on the LULC data. For example, the maximum LAI for bare agricultural fields was assumed to be 0, and for golf courses 2.0.

28.3.2.4 Weather Data

Due to its large size, the weather varies significantly across the Grand River watershed. Actual daily precipitation and temperature records from January 1960 to December 1999 were obtained from the Grand River Conservation Authority (GRCA) for the watershed. The data were based on point observations at various locations within (as well as outside) the watershed that were then used to represent the weather patterns within 13 subregions, or zones of uniform meteorology (ZUM) shown in Figure 28.5. The built-in weather generator in HELP3 was then used to generate daily synthetic solar radiation values for each ZUM as a function of latitude, precipitation, and temperature. A preliminary study revealed, however, that these subregions were still quite large resulting in discontinuities in recharge along their boundaries. Therefore, a new method based on an interpolation algorithm was developed.

The Grand River watershed was divided into 293 smaller sub-basins, also shown in Figure 28.5, each with its distinct values of daily precipitation, temperature, and solar radiation. The values were interpolated using the inverse distance squared (IDS) algorithm as

$$P^{\mathrm{SUB}} = \frac{\sum_{i=1}^{13} P_i^{\mathrm{ZUM}}/d_i^2}{\sum_{i=1}^{13} 1/d_i^2} \tag{28.3}$$

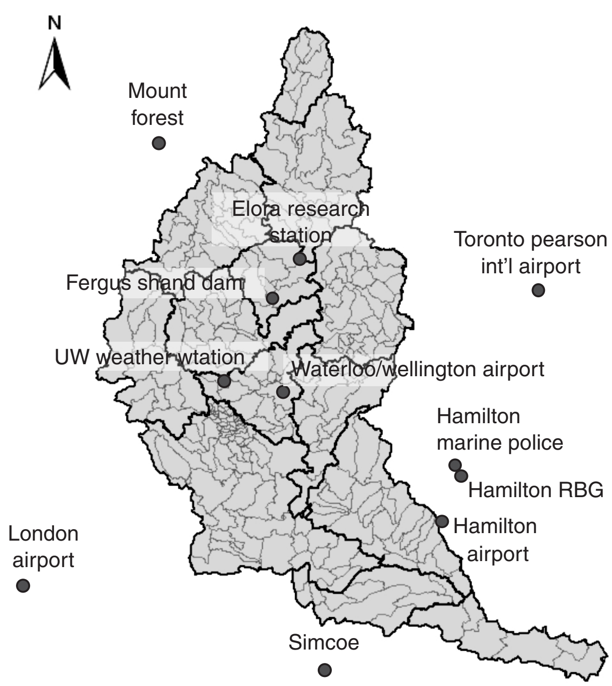

FIGURE 28.5 Zones of uniform meteorology (ZUM), sub-basins, and location of relative humidity and average wind speed observations.

where P is the daily precipitation, temperature, or solar radiation, and d is the distance from the centroid of each ZUM to the centroid of each sub-basin. This provided a much smoother transition of weather data across the entire watershed, while still honouring the original observations.

The average quarterly relative humidities and average annual wind speeds were obtained from Environment Canada as well as the University of Waterloo weather station for various locations in and around the watershed, as shown in Figure 28.5. As before, the inverse distance squared weighting scheme was then used to estimate values for each of the 293 sub-basins.

The dates for the start and end of growing season were estimated using guidelines provided in HELP3 (Schroeder et al., 1994). The values were estimated for each ZUM, therefore, constant growing season dates were assumed for each sub-basin within each of the ZUM areas. Growing season starting dates varied from May 2nd to May 6th, while the ending dates ranged from October 7th to October 12th.

28.3.3 Methodology

As mentioned previously, the methodology was based on the work by Jyrkama et al. (2002), therefore, only a brief description is given in the following. Figure 28.6 illustrates a schematic diagram of the method. First, the LULC and soil maps were overlaid in the GIS to produce a combination map. These combinations were then used to determine vegetation data such as evaporative zone depths, as well as curve numbers used by HELP3 in the recharge analysis. HELP3 was then run daily from January 1960 to December 1999 for each of the unique combinations within each of the 293 sub-basin using the interpolated weather data for each sub-basin. This resulted in a total of approximately 47,000 unique combinations of LULC, soil,

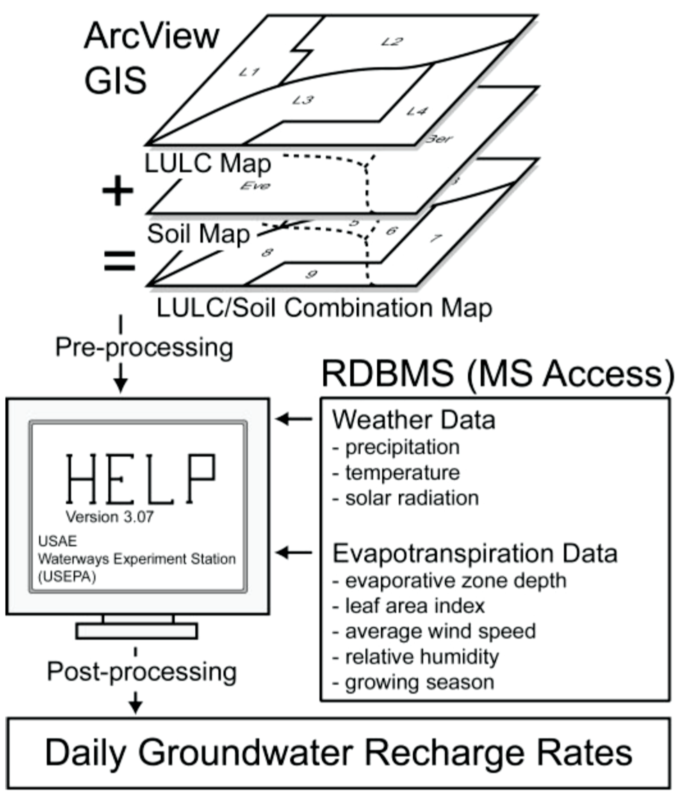

FIGURE 28.6 Methodology for estimating groundwater recharge. (After Jyrkama, M.I., Sykes, J.F., and Normani, S.D. 2002. *Ground Water*, 40, 638–648.)

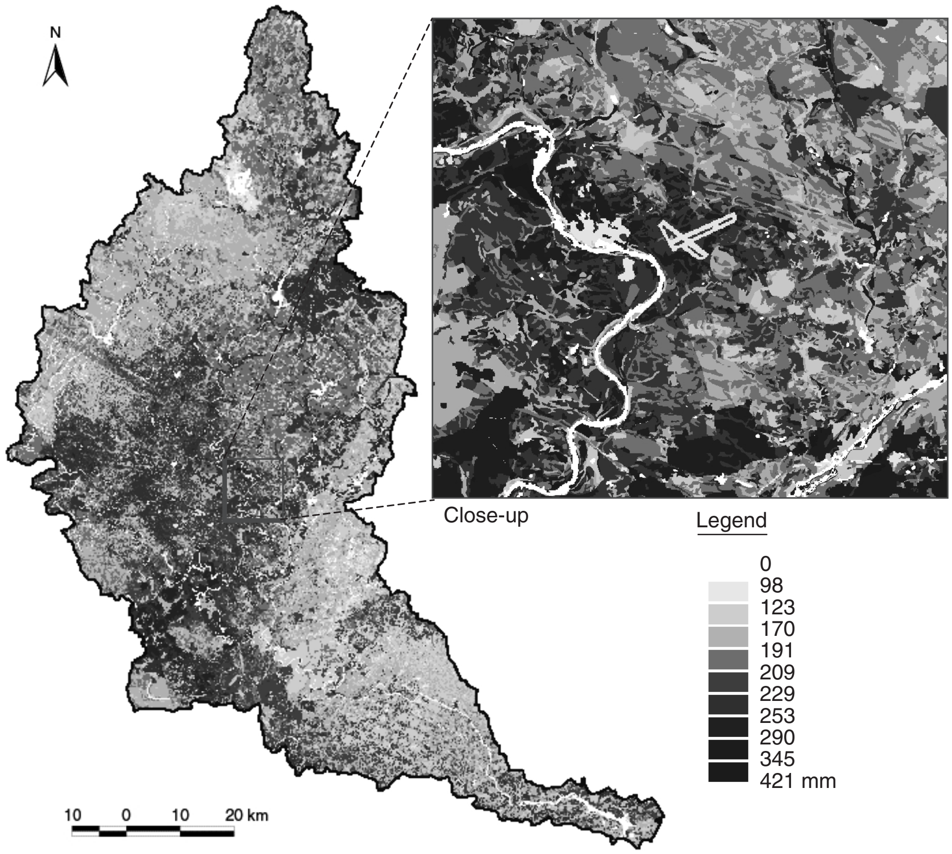

FIGURE 28.7 Average annual recharge for the Grand River watershed (mm/yr).

and weather data (i.e., ~47,000 HELP3 simulation runs). Areas classified as open water were ignored in the recharge analysis.

28.3.4 Results

Figure 28.7 shows the average annual recharge rates obtained from the HELP3 analysis for the Grand River watershed. Figure 28.8 illustrates the histogram of the same distribution. The average annual groundwater recharge in the watershed is approximately 200 mm/yr, which is approximately one-fifth of the average annual precipitation (950 mm/yr). As shown in Figure 28.7, recharge varies considerably across the watershed, responding directly to variations in land use and the hydraulic characteristics of the underlying soils.

As discussed previously, areas of high recharge may indicate areas where the underlying aquifers are subjected to increased vulnerability from contamination. This may have significant implications on land use planning near the urban areas, where existing lands are rapidly being converted into residential subdivisions and industrial areas.

The recharge rates also vary considerably over time, as shown by the monthly rates in Figure 28.9. Due to warmer temperatures in December 1992, most of the precipitation is able to infiltrate and become groundwater recharge, while during the much colder period in December 1998, most of the precipitation occurs as snow over frozen ground resulting in negligible recharge rates across the watershed.

As shown in Figure 28.9a, there is also considerable variation in recharge rates across the watershed. This variation is not only due to the variations in the land cover and soils, as discussed previously, but

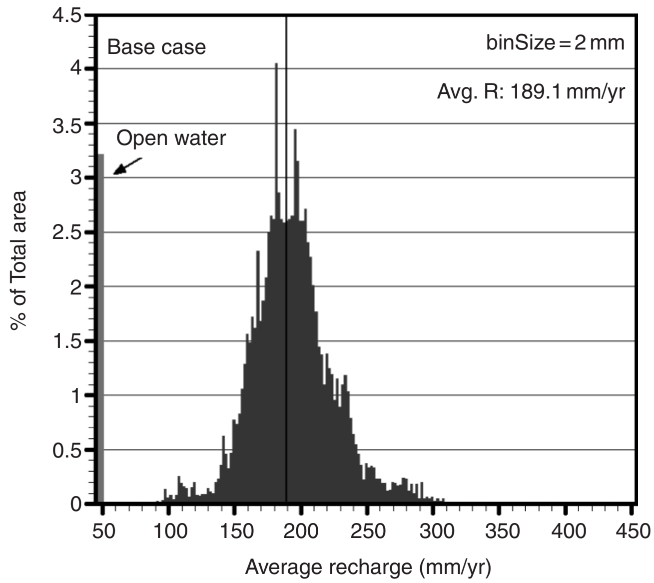

FIGURE 28.8 Recharge histogram.

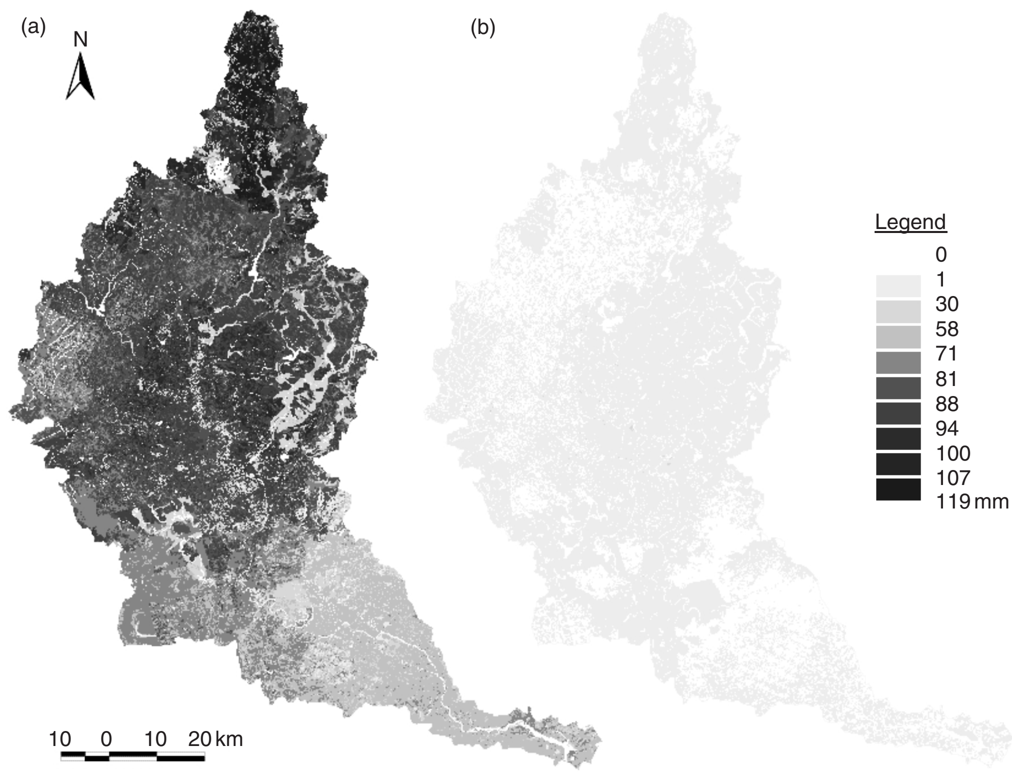

FIGURE 28.9 Monthly recharge rates for (a) December 1992 and (b) December 1998 (mm/month).

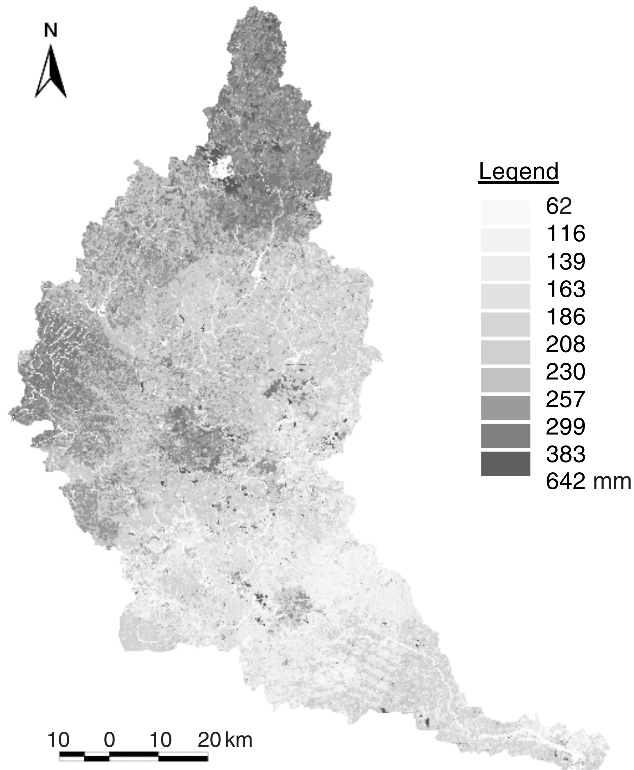

FIGURE 28.10 Average annual surface runoff (mm/yr).

also as a response to variations in climatic conditions across the watershed. Contrary to what might be expected, the northern portion of the watershed has considerably higher recharge rates in December 1992 than the southern end. This is explained by lower precipitation rates and unusually cool temperatures prevalent in the southern part of the watershed at the time.

The physically based recharge methodology also provides estimates of evapotranspiration and surface runoff, shown in Figure 28.10 and Figure 28.11, respectively, which can be used in an assessment of the watershed's overall water budget. As expected, both evapotranspiration and surface runoff vary considerably across the watershed, responding directly to variations in the land cover and soils. The northern portion of the watershed has significantly higher surface runoff rates, as expected, due to the presence of low permeability tilly soils.

Approximately 210 mm of annual precipitation is subjected to overland flow while approximately 510 mm is evapotranspired by the vegetation in the watershed on an annual basis. Evapotranspiration, therefore, constitutes the largest portion of the watersheds' overall water budget.

As demonstrated by the above results, the methodology can potentially be used to assess the impact of climate change and changes in land use due to urbanization. The results further prove the applicability of the methodology across various scales, that is, from the small sub-basin level analysis to the regional watershed scale.

28.3.4.1 Impact of Climate Change

As discussed previously, climate change has the potential to significantly impact and alter the key processes in the Earth's water and energy cycles. Specific evidence from a wide variety of General Circulation (GC) and other climate models predict increases in the globally averaged surface air temperature, water vapor, evaporation, and precipitation. The intensity and frequency of extreme events is also projected to grow

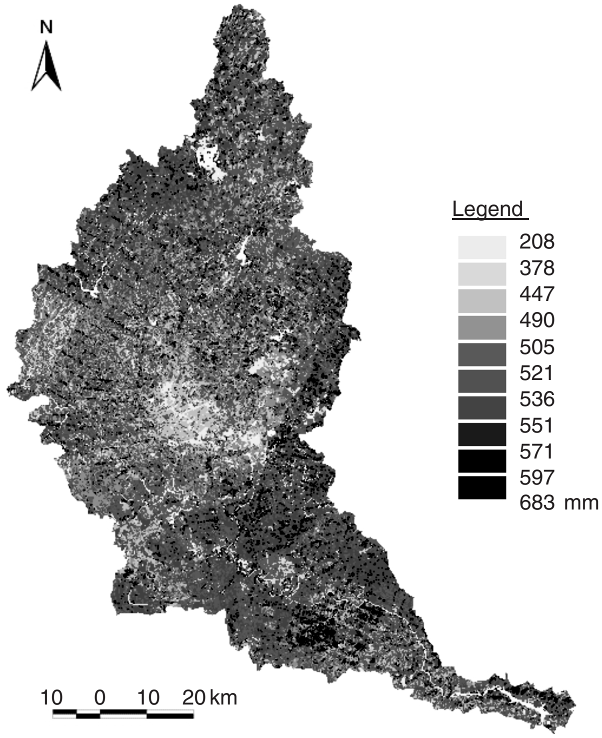

FIGURE 28.11 Average annual evapotranspiration (mm/yr).

(IPCC, 2001). Understanding the impact of these potential changes in the hydrologic cycle is essential for ensuring the quality and sustainability of water resources in the Grand River watershed.

The impact of climate change was modeled by perturbing the HELP3 model input parameters using predicted changes in the climate of the Grand River watershed. In addition to global changes, the IPCC reported the following general predictions for the regional climate in north-eastern North America over the next 100 years (IPCC, 2001):

- precipitation is projected to increase with an average change between 5 and 20% in the winter
- precipitation extremes are projected to increase more than the mean with higher intensities and higher frequency of extreme events
- greater than average warming in both summer and winter temperatures
- a possible reduction in incoming solar radiation due to increases in greenhouse gases.

Using the actual historical weather data as a reference for the Grand River study area, several scenarios were constructed to simulate the impact of climate change on the hydrologic cycle in the future. These scenarios are shown in Table 28.2.

All of the simulation parameters were scaled over the length of the study period. That is, they were assumed to increase linearly over time. For example, the temperature change of $+0.016°$C/yr corresponds to a predicted increase of 1.6°C in 100 years, or to a daily increase of approximately 4.4×10^{-5}°C. The changes in precipitation intensity were simulated using

$$\Delta x = \frac{\sum_{i=1}^{N} P \cdot \delta}{\sum_{i=1}^{N} iP} \tag{28.4}$$

TABLE 28.2 Climate Change Simulation Scenarios

Case	Description
Base	Actual daily temperature, precipitation, and simulated solar radiation
1	Precipitation +5% for Dec, Jan, and Feb
2	Precipitation +20% for Dec, Jan, and Feb
3	Precipitation +20% for all months
4	Temperature +0.016°C/yr
5	Temperature +0.070°C/yr
6	Solar radiation 2% for all months
7	Combination of Cases 1, 5, and 6
8	Combination of Cases 3, 5, and 6

and

$$P_i^{cc} = P_i(1 + i\Delta x) \tag{28.5}$$

where P is the actual daily precipitation on day i, P^{cc} is the new daily precipitation due to climate change, Δx is the calculated change in daily precipitation, δ is the percent change in the average precipitation, and N is the total number of days in the study.

Figure 28.12 presents the cumulative differences in surface runoff, evapotranspiration, and recharge between all the cases and the Base Case scenario, for the Grand River watershed, averaged spatially over the study area. As shown, changing the precipitation (Case 1 to Case 3) has the highest influence on the hydrologic cycle, while solar radiation (Case 6) has a minimal impact. Groundwater recharge is predicted to increase under all scenarios, while evapotranspiration increases in all cases, except when incoming solar radiation is reduced (Case 6).

Figure 28.12a illustrates that, as expected, surface runoff increases with increasing precipitation. Furthermore, increasing the precipitation rate will generally increase all three hydrologic parameters as there is more water available in the system. Increasing temperature, however, has both a negative and positive impact on the hydrologic processes.

As demonstrated by Case 4 and Case 5 in Figure 28.12a for the Grand River watershed, temperature has a significant influence on the runoff process. The cumulative surface runoff decreases with increasing temperature mainly due to a reduced period of ground frost. Due to warmer winter temperatures, less water is stored in the snowpack and more water is able to infiltrate into the ground thereby reducing runoff and increasing groundwater recharge. This effect is less pronounced for more southerly study areas where the average winter temperatures are generally higher. At the watershed scale, climate change has the highest relative impact on groundwater recharge resulting in a 53% increase over 40 years, while surface runoff and evapotranspiration increase by 10% and 12%, respectively, over the same time period.

The temporal variabilities in the hydrologic processes are further demonstrated using the results from Case 8. Figure 28.13 shows the spatially averaged monthly differences for Case 8 and Base Case for the Grand River watershed. The increase in temperature and precipitation intensity over time is directly reflected in the hydrologic processes.

Figure 28.14 shows the same results for each month. As shown in Figure 28.14 for the Grand River watershed, it is evident that there is a significant reduction in the average runoff in the spring (e.g., April) as the springmelt is shifted into the winter months due to warmer temperatures. The amount of runoff is consequently increased during January, February, and March as moisture is released from the snowpack (as opposed to being stored or accumulated).

Groundwater recharge also increases significantly during the winter months as more water is able to infiltrate into the ground. Evapotranspiration rates are increased for the study area during the summer months due to higher temperatures and increased amount of available water.

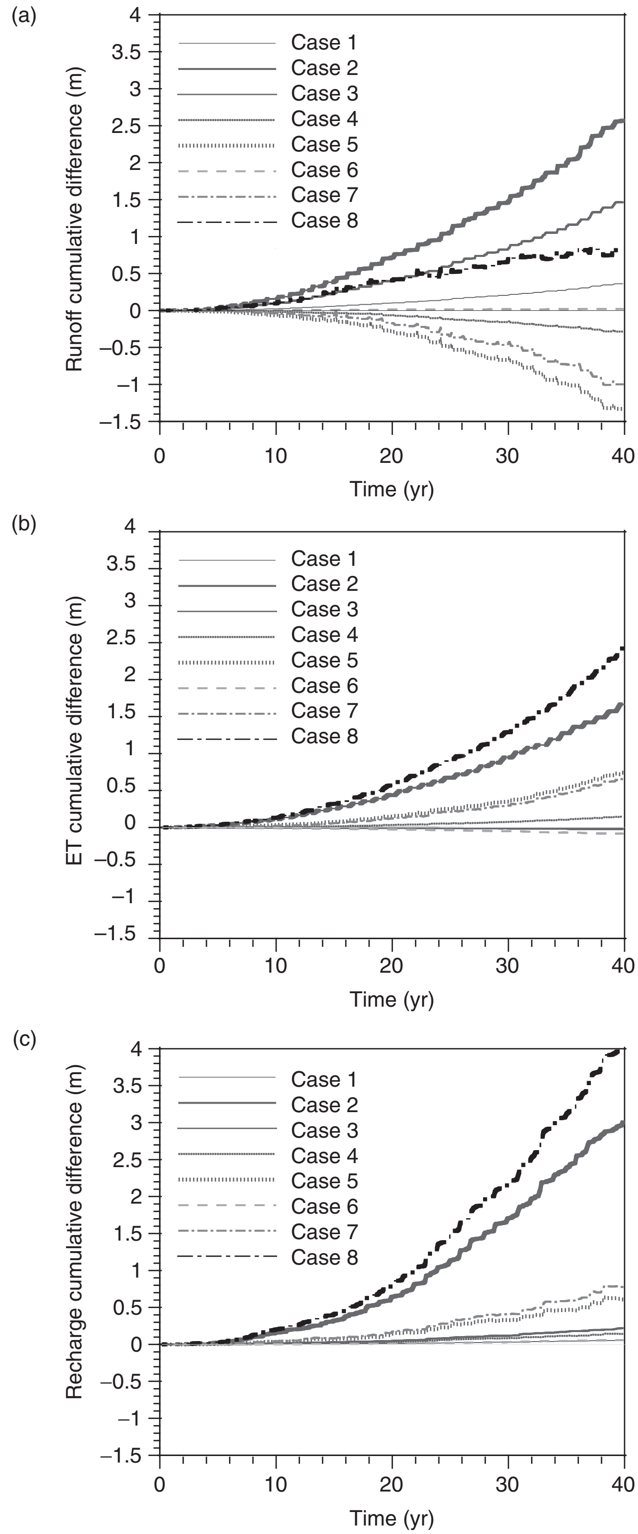

FIGURE 28.12 Cumulative differences between the climate change scenarios and the Base Case for (a) surface runoff, (b) evapotranspiration, and (c) groundwater recharge.

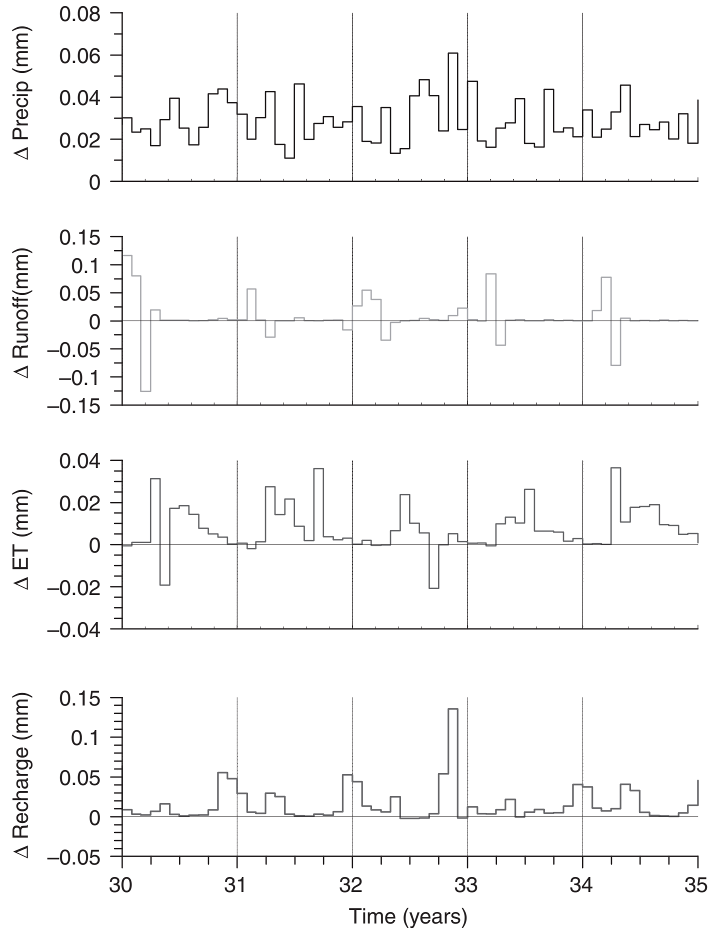

FIGURE 28.13 Monthly differences in precipitation, surface runoff, evapotranspiration, and groundwater recharge between Case 8 and the Base Case for a selected time period.

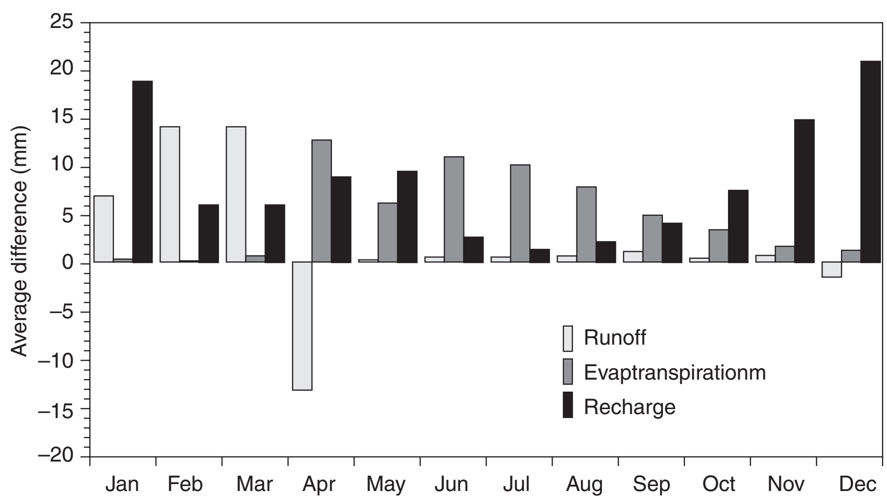

FIGURE 28.14 Average differences for each month between Case 8 and the Base Case.

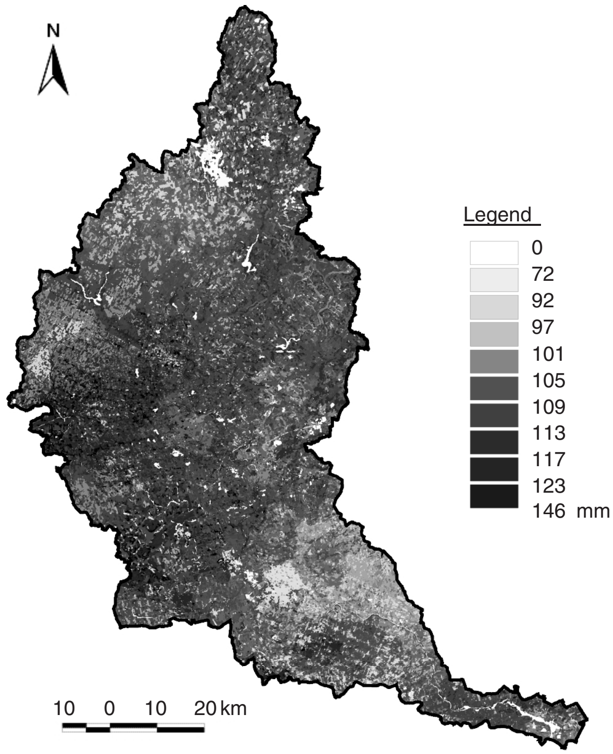

FIGURE 28.15 Average annual change in recharge between Case 8 and the Base Case.

Figure 28.15 shows the temporally averaged groundwater recharge rates for the Grand River watershed for the Base Case and Case 8. As illustrated, there is an overall increase in the recharge rate across the areas due to climate change. The average rate is predicted to increase by approximately 100 mm/yr from 189 mm/yr to 289 mm/yr over the 40-year study period for the Grand River watershed.

Unlike the significant reduction in recharge rates as predicted by Rosenberg et al. (1999) for the Ogallala aquifer in the United States, the results of this study predicted increased recharge rates for the study area due to climate change. The reason for the contrasting results is not only due to the temperature impacts in cooler climates, but also due to differences in the input data. Rosenberg et al. (1999) only included predicted changes in temperature and CO_2 concentrations in their simulations. As shown by the results for the Grand River watershed study area, increased precipitation has a significant influence on the estimated recharge rates.

Land use changes due to potential increases in urbanization, especially in the Grand River watershed, will also impact the hydrologic processes beyond the possible effects of climate change. The predicted increases in overall groundwater recharge due to climate change will, therefore, not necessarily guarantee sustainability in the future because human impacts, such as increased pumping, also exert a major influence in the aquifer system and can lead to depletion of the drinking water resources.

In conclusion, understanding the impact of potential changes in the hydrologic cycle due to climate change is essential for ensuring the quality and sustainability of our water resources in the future. The results of the study demonstrate the benefit of using the developed recharge methodology to address these issues.

28.3.5 Conclusions

Estimating groundwater recharge is critical for developing an effective watershed management strategy that will ensure the protection of the fresh water resources of the watershed. The physically based hydrologic model HELP3 was integrated with ArcView GIS to estimate spatially distributed daily groundwater recharge rates for the Grand River watershed over a period of 40 years, from January 1960 to December 1999. The use of the GIS and a relational database management system (RDBMS) was essential due to the large volume of data required for numerical modeling of watershed processes at the regional scale.

The results of the study indicated that on average, only one-fifth of the overall precipitation in the watershed contributes to direct groundwater recharge, with an average recharge rate of approximately 200 mm/yr. In addition to quantifying the temporal distribution and amount of recharge, the results also identify areas of varying recharge potential. As the transport of most groundwater contaminants to saturated aquifers occurs in the aqueous phase as part of the recharge process, areas of high recharge may indicate areas where the underlying aquifers are subjected to increased vulnerability from surface contamination. This may have significant implications on land use planning, especially near urban areas. The developed recharge methodology also provides estimates of evapotranspiration and surface runoff, which may be used in estimating the watershed's overall water budget.

The results also demonstrate the applicability of the methodology across various scales. The method can easily be applied to hydrologic analyses, for example, due to climate change, at the regional watershed scale, or a detailed evaluation of the impact of land use changes at the much smaller sub-basin scale.

28.4 Chapter Summary

Climate change can directly affect the water balance of a surface water system; the impact on the groundwater system is indirect and is influenced through the spatially and temporally varying recharge and discharge boundary conditions that link the groundwater system to the surface water system. Recharge can occur as a result of precipitation events while both recharge and discharge can occur at surface water bodies. Assessing the impact of climate change on groundwater systems will generally require physically based models of these boundary conditions. Alternatively, fully integrated or coupled surface water and groundwater models can be used to assess climate change impact. Regardless of the modeling methodology used, it is essential that an assessment include the evaluation of historical conditions. For some groundwater systems, the spatial and temporal variation in historical groundwater recharge and discharge rates may be greater than the perturbation caused by climate change. In this chapter, the model HELP3 has been used as a simple tool to assess both the historical recharge and the impact of climate change for the Grand River Ontario watershed. For engineers and scientists, the value of the tool lies in the model's ready availability and its easy-to-use database. However, there are many other physically based models that are suitable for the assessment of the impact on groundwater of climate change. This chapter has reviewed many of these models and analyses.

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