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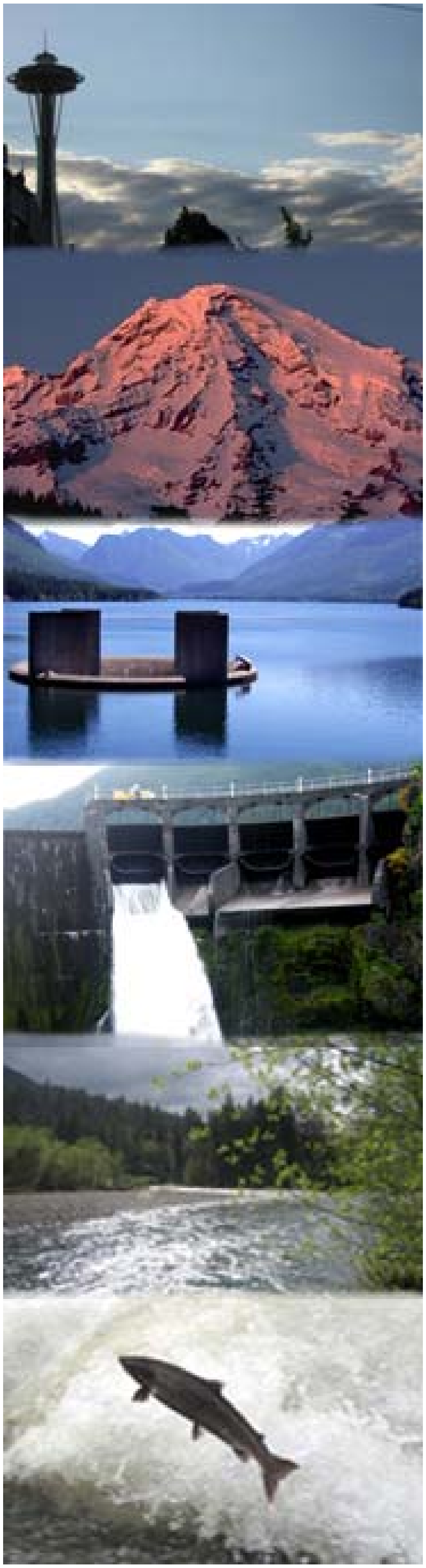

Technical Memorandum #8:

Impacts of Climate Change on Groundwater Resources:

A Literature Review

Prepared for:

Climate Change Technical Committee

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Executive Summary

During the last decade, the number of studies devoted to evaluating the impacts of climate change on water resources has grown dramatically. Climate change is predicted to change patterns of temperature and precipitation, and these will significantly alter hydrologic systems that are influenced by snowmelt processes. One anticipated impact, although less studied, is on groundwater levels due to changes in the rate of recharge.

The Puget Sound region has been a leader in evaluating the impacts of climate change on water resources. This report summarizes past research of the impacts of climate change on groundwater that may be relevant to the Puget Sound region. The literature review overviews groundwater processes, groundwater in the Puget Sound, and the eight most relevant studies completed in the United States and Canada investigating the impacts of climate change on groundwater resources. This is followed by a concise list of recommendations and "next steps" that can be taken in the region. These recommendations provide guidelines and suggestions for how to effectively evaluate the potential impacts of climate change on groundwater resources in the Puget Sound region.

Groundwater/climate change interactions have been evaluated over a broad range of geographical and climatological regions. Each study site has unique characteristics and the methods used in each study are unique. No widely accepted study approach or groundwater model has emerged as the only protocol for investigating the impacts of climate change on groundwater resources. As a result of the vast differences between study sites and approaches, results vary significantly from study to study.

The literature review indicates that a wide range of groundwater impacts could result from climate change. Some studies indicate negative impacts to groundwater recharge related to climate change, while other studies predict increased groundwater recharge. In general, results suggest that changes in precipitation, caused by different emissions of greenhouse gases in the future, influence the amount of recharge. However, in some situations, local conditions, such as evapotranspiration, surface water exchanges, and changes to groundwater pumping, are more significant to groundwater systems than changes in climate. While results vary from study to study, many studies indicate the relative importance of hydraulic conductivity to rivers and changes in river flows to groundwater levels. Unfortunately, because of the unique nature of the Puget Sound Lowlands aquifer system, there are no published results directly applicable to the Puget Sound. Furthermore, the majority of the studies cited in this report were completed in semi-arid to arid climates, many of which have dissimilar rainfall-recharge patterns than that of the Puget Sound Lowlands.

Past studies of the Puget Sound Lowlands aquifer system do offer promise and a framework for evaluating the potential impacts of climate change on groundwater. Although no past study specifically evaluated the impacts of climate change on groundwater resources in this region, they offer details into the type of aquifers located in the region, as well as the models that have been used to model groundwater recharge. For many regions that have been extensively studied in other portions of the US and Canada, it appears the effects of population growth and increased groundwater pumping often dominate the predicted impacts of climate change on groundwater.

The report concludes with some general recommendations for approaches, climate scenarios and models that can be used to evaluate the effects of climate change on groundwater recharge in the Puget Sound Lowlands. The suggestions provided are, by no means, comprehensive nor do they imply that there is only one correct method that can be applied to this region. There are three basic approaches to evaluate the effects of climate change on groundwater: a detailed study approach, a general overview study approach, and semi-detailed study approach. The approach taken depends on several factors including: the data available, the budget available, the level of detail required, and the decision framework that will use this information. Likewise, two different groundwater models are discussed in detail: Deep Percolation Model (DPM) and MODFLOW or its Window's based version, Visual MODFLOW. DPM is a groundwater recharge model, and MODFLOW, from which the majority of groundwater work has been done, is a saturated zone groundwater model. The type of model chosen is directly dependent upon the approach taken. Finally it is recommended that incorporation of output from Global Circulation Models into regional groundwater impact studies should follow the methodology created by the committee and make use of referenced literature to ensure proper treatment of model uncertainty and climate impacts.

Table of Contents

List of Figures

List of Tables

Technical Memorandum #8:
Impacts of Climate Change on Groundwater Resources: A Literature Review

1. Introduction

1.1. Climate Change and Groundwater

The study of climate change on water resources has expanded during the last decade. Predicted changes in temperature and precipitation due to climate change are expected to significantly alter hydrologic systems. One expected impact of climate change will be on groundwater levels due to changes in the rate of recharge. While the majority of water resources related climate change research has focused on surface water hydrology, only a small portion has been focused on the potential impacts to aquifers. However, in recent years, numerous studies on climate change impacts on groundwater recharge throughout the United States and Canada have been published. Most recently, several studies have been conducted in British Columbia and Ontario, Canada; Eastern Massachusetts; Texas and other locations throughout North America. Some studies addressed the integration of surface water and groundwater as they looked at climate change impacts.

This paper accesses the potential impacts of climate change on groundwater by means of a literature review. The paper's goal is neither to provide a comprehensive evaluation on groundwater in Puget Sound, nor to define the potential susceptibility of Puget Sound aquifers to climate change impacts. Rather, the report provides a review of the "lessons learned" by other studies and provides a framework for the approach a more comprehensive study might take.

1.2. Regional Interest in the Effects of Climate Change on Groundwater Resources

As a response to predicted climate change, King County and other agencies throughout Puget Sound are investigating the possible impacts to water resources. Considerable work has been done evaluating the potential impacts of regional climate change on water supply and demand throughout the Puget Sound, possible impacts on fish habitat, and the projected changes in frequency and intensity of flooding events, among other things.

While significant evaluations of the effects of climate change on surface water resources in King County have been performed, to date, limited work has focused on the effects of climate change on groundwater resources. As approximately 30 percent of King County's population relies on groundwater for drinking water, it is important to investigate the potential impacts of climate change on groundwater resources. As a preliminary step, this study reviews climate change studies related to groundwater throughout North America, focusing on the United States and Canada. These studies provide guidance to the regional planning process as it creates the framework to evaluate the potential effects of climate change on the region's water resources. It is also important to evaluate which investigations have study sites with aquifers and climates similar to that of the Puget Sound. To clearly compare other study areas to the Puget Sound, the location of studies, types of aquifers and the different models used will all be highlighted.

2. Groundwater

2.1. Groundwater and the Hydrologic Cycle

The process of water percolating into the ground is known as groundwater recharge. Groundwater recharge is driven by precipitation. Depending on several factors (including rainfall intensity, temperature and ground surface cover) precipitation can be subjected to interception, evaporation, surface runoff and infiltration into the soil. After infiltration, the water can be taken-up by the plant roots to be transpired or continue downward through the soil column, eventually crossing into the saturated zone and becoming groundwater recharge (Figure 1).

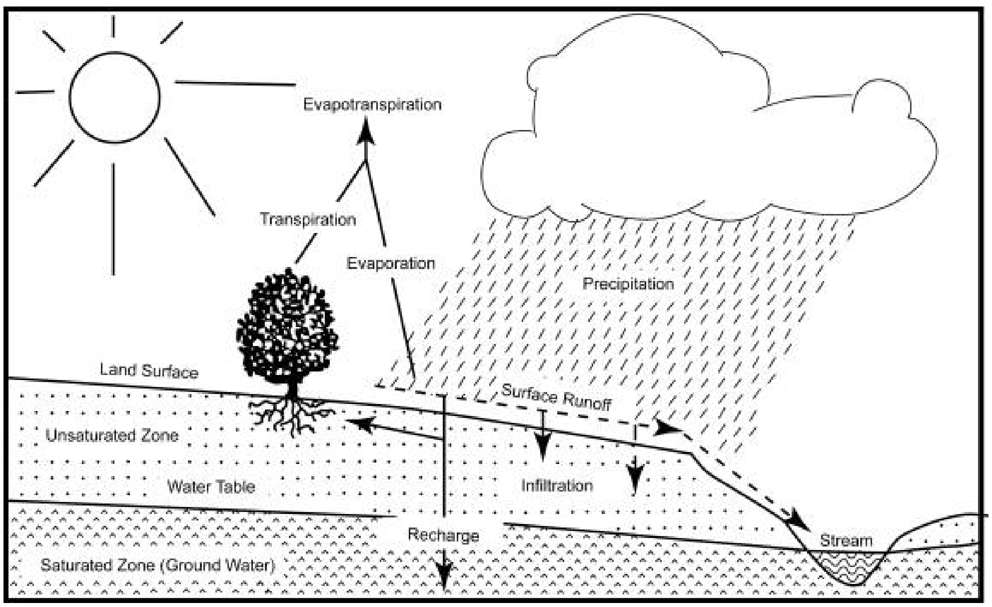

Figure 1: Process of Groundwater Recharge

Numerous parameters affect groundwater recharge. Precipitation can be affected by wind and temperature. Through the processes of interception and transpiration, vegetation also affects groundwater recharge. Recharge is further influenced by plant roots, which not only utilize soil moisture, but can cause cracks and fissures in the soil creating preferential flow paths. All of these factors can be very difficult to quantify, as they themselves are dependent on climatic factors such as rainfall intensity and duration, temperature, and plant characteristics (Jyrkama et al., 2007).

2.1.1 Groundwater Recharge

A groundwater system is a collection of hydraulically connected aquifers served by a common recharge area. Shallow groundwater systems are recharged by local rainfall. Progressively deeper groundwater systems are recharged by progressively wider areas. Unlike surface watersheds, groundwater systems act more like storage reservoirs than conveyance pipelines. They can be viewed as deep pools within a surface water body that are fully connected to, but only partially participating in stream flow (Freeze and Cherry, 1979; Fetter, 1994)).

Percolation, or recharge into the saturated zone, is controlled by hydraulic properties of soils that are governed, in part, by moisture content and pressure head distributions. Small changes in volumetric water content can potentially change the hydraulic conductivity by several orders of magnitude. Moreover, soils in the unsaturated zone are rarely homogeneous in nature. This is further complicated by preferential flow paths that exist due to cracks, fissures or roots. Even in uniform soils, topography can have a major influence in groundwater recharge, potentially resulting in large variations in recharge within a small area.

The time required to change the level of groundwater lengthens with the flow path from the point of recharge into the reservoir to point of discharge out of the reservoir. Shallow groundwater travel time from point of recharge to point of discharge ranges from days to months. Deep groundwater travel time ranges from years to centuries (or even millennia in eastern Washington deep basalt aquifers) (Toth, 1963, 1999).

The rate of annual recharge and discharge in groundwater systems reflects the combined seasonal variation and long-term trends in precipitation, which consequentially affects the storage volumes of groundwater systems. Groundwater levels (i.e., storage) in shallow groundwater systems typically fluctuate by several to tens of feet annually reflecting rapid filling and draining of the groundwater reservoir depending on the rainfall pattern, water withdrawals and the degree of hydraulic continuity with a surface water body (Freeze and Cherry, 1979; Fetter, 1994).

Another factor that influences recharge is the presence of snowpack and /or a frozen soil layer. Like rainfall, the spatial and temporal accumulation of snow is very complex. Snow accumulation is affected by the topography; presence of buildings, trees or other objects; and the wind patterns and velocities. Frost layers also influence the rate and distribution of infiltrating snowmelt (Johnsson and Lundin, 1991; Black and Miller, 1990).

Lastly, the rate of recharge can be significantly influenced by urbanization. Impervious cover, over-irrigated lawns and parks, and leakage from water distribution systems can all affect the local and regional rate of recharge (Lerner, 2002). Impermeable paving, stormwater drainage, and large scale groundwater withdrawal reduce groundwater recharge and storage at rates significantly greater than natural influences on storage. Urban stream depletion and water level declines in groundwater supply aquifers clearly indicate the greater effect of land use on groundwater levels than climate variability.

2.1.2. Estimating Groundwater Recharge

To simulate groundwater recharge, a physically-based approach is needed. This is typically accomplished by modeling the interaction between all of the important processes in the hydrologic cycle such as infiltration, surface runoff, evapotranspiration, snowmelt, and groundwater level variations (Jyrkama et al., 2007).

A basic equation for creating groundwater balance is:

Equation 1: $R_i + S_i + I_g = E_T + T_p + S_e + O_g + \Delta W$

Where:

R_i = recharge from infiltration,
S_i = influent recharge from rivers,
I_g = inflow from other basins,
E_T = evapotranspiration,
T_p = draft from groundwater,
S_e = effluent recharge to rivers,
O_g = outflow to other basins, and
ΔW = change in groundwater storage.

Assessing climate change impacts on groundwater further complicates a complex process. A method is required that accounts for not only temporal variations in climatic variables and their impact on the hydrologic cycle, but also the spatial variation of surface and subsurface properties throughout the study site.

2.2. Groundwater in Puget Sound

The Puget Sound Lowland region encompasses approximately 16,200 mi^2, of which about 2,500 mi^2 is saltwater. Approximately 5,700 mi^2 is underlain by the Puget Sound Lowland aquifer system. The Puget Sound Lowland Aquifer system is part of a larger aquifer system called the Puget-Willamette Trough regional aquifer system, which underlies a basin that extends from the Canadian border through Washington and into Central Oregon (Vaccaro, 1992). Figure 2 details the Puget-Willamette Trough regional aquifer system and Figure 3 highlights the glacial extent in the Pacific Northwest.

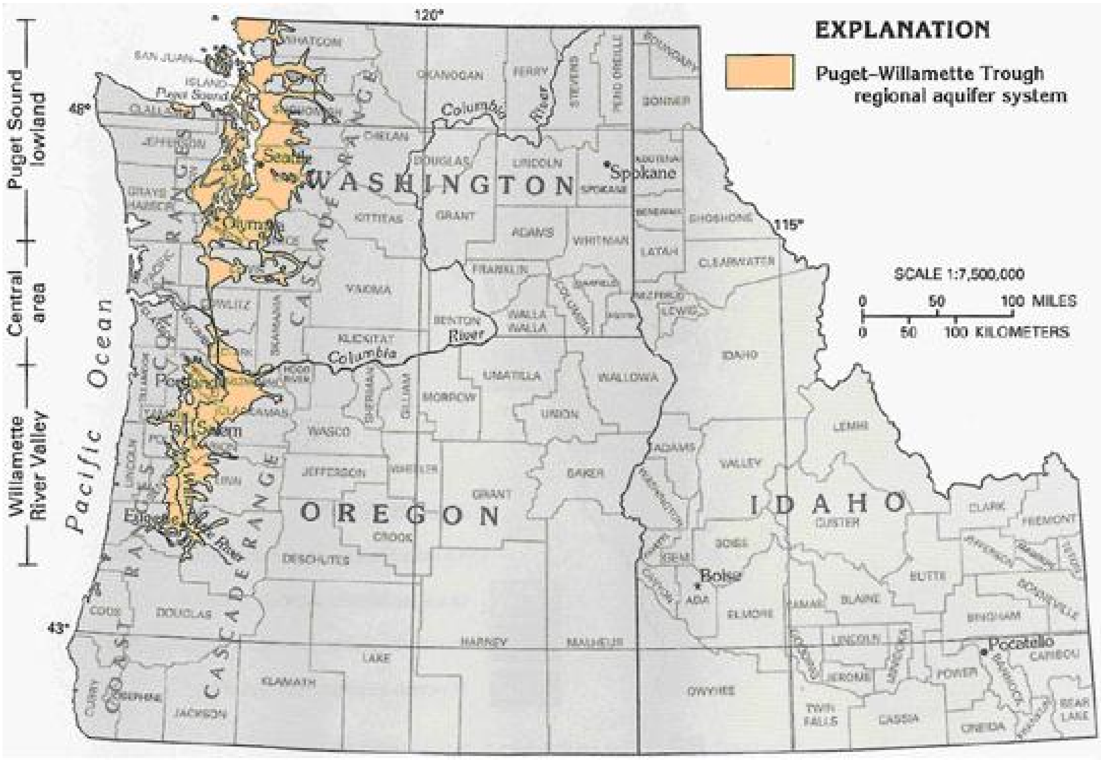

Figure 2: Puget-Willamette Trough regional aquifer system
(Adapted from: USGS, Groundwater Atlas of the United States. 2005)

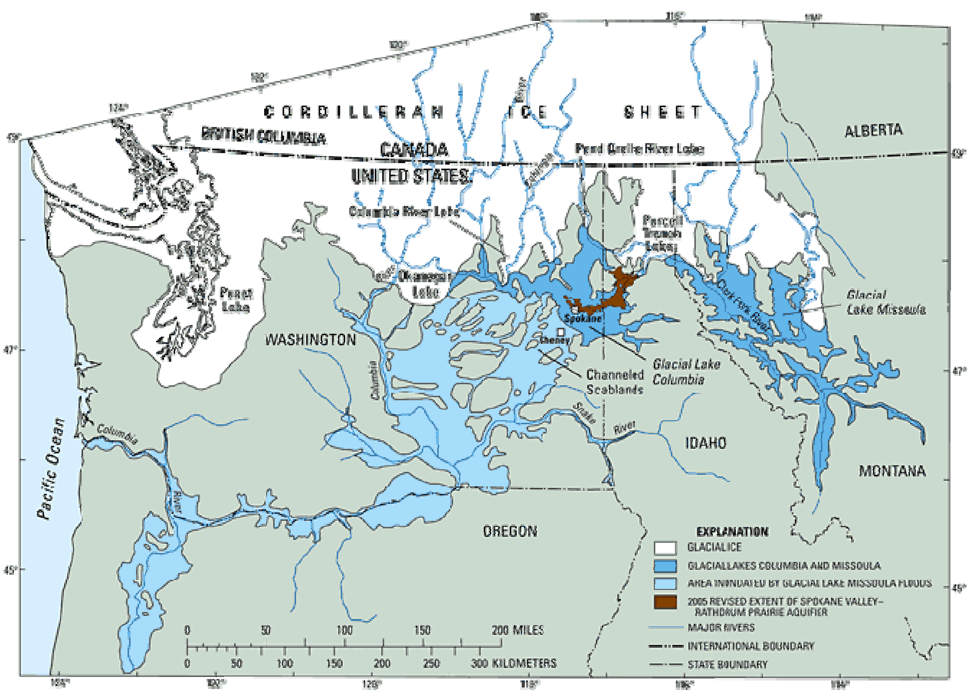

Figure 3: Glacial Extent in the Pacific Northwest

The lithology of the Puget Sound Lowland aquifer system is highly complex and variable. The aquifer system is comprised primarily of Quaternary alluvial, glacial, and interglacial unconsolidated sediment. These sediments are predominately Quaternary river alluvium, till, recessional and advance outwash, and other interglacial sediment and can be as thick as 3,000 feet near Seattle, Washington. The upper 200 to 300 feet of the unconsolidated deposits is composed of sand and gravel deposited during the last glaciation and is considered the most productive aquifer.

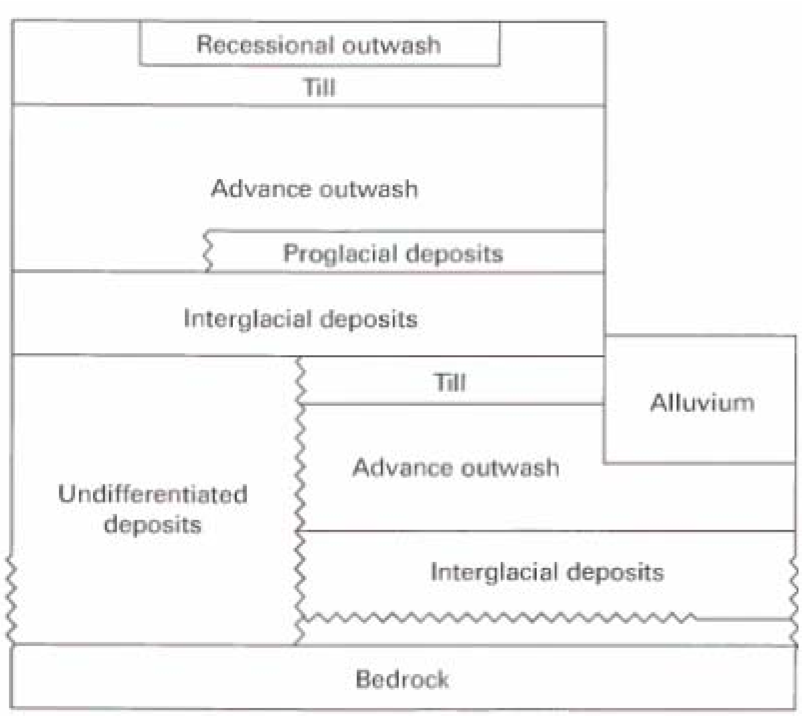

Figure 4: Ideal Sequence of Puget Sound Lowland Aquifer System

The U.S. Geological Survey (USGS) divides the Quaternary sediment in the Puget Sound Lowland into aquifers and confining beds depending on whether they are predominately coarse grained or fine grained and their mode of origin. The following describes how each is classified:

- These uppermost, coarse-grained deposits are considered to be one hydrogeologic unit, which generally consists of advance or recessional outwash. They can be very localized or centralized.
- Another geological unit, present at the land surface in the large river valleys, consists of alluvial deposits and can be quite extensive. Depending on grain-size, these units can be classified as poor aquifers if overall grain size is fine or productive if more coarse-grained materials are present.
- Interglacial and proglacial deposits are fine-grained and classified as confining units.
- Fine-grained, cemented tills are classified as semi-confining units. Oftentimes, these deposits overlie and/or underlie interglacial sediment. In which case, they are often included in the interglacial hydrologeologic units.

- Coarse-grained sands are defined as aquifers.
- Beyond 200 to 500 ft below land surface, deposits are undifferentiated unless deep well information is available. In which case, they can be differentiated between predominately coarse-grained and fine-grained.

The extent of the hydrogeologic units within the Puget Sound Lowlands is highly variable, both locally and regionally. The hydrogeologic units range in both extent and depth throughout the region. Localized recessional outwash deposits average approximately 10 ft in thickness; however, in a few areas outwash deposits are as thick as 150 ft. Similarly, the thickness of the upper till, which blankets much of the Puget Sound Lowland, also varies considerably, ranging from 20 ft to 40 ft on average to as great as 125 ft in some locations. Below the till, coarse-grained deposits, averaging between 40 ft and 50 ft, can reach as deep as 400 ft; however, a depth of 150 ft to 200 ft is more common. Fine-grained deposits consisting of glacial till or silt-clay underlie the coarse-grained deposits and average 40 ft to 65 ft in thickness. Again, however, their thickness has been known to exceed 150 ft in some areas. In general, the total extent of the above described aquifer system extends from 200 ft to 500 ft in depth.

The lithology of the deeper deposits in the Puget Sounds Lowlands is generally unknown. According to the USGS, there are 23,000 wells located in the Puget Sound Lowlands, of which less than 50 percent are more than 100 ft deep and only 360 wells are more than 500 ft deep. Therefore the deep deposits in the Puget Sound Lowland cannot be adequately described.

Groundwater movement is predominately controlled by topography and the geometry of the groundwater system. In general, the configuration of the water table and the uppermost aquifer parallels that of the surface. Regional groundwater movement is typically from topographic highs to topographic lows, which are usually stream drainages or saltwater bodies. Groundwater movement is generally horizontal in the aquifers and vertical in the confining units.

The lateral groundwater movement is a function of both hydraulic conductivity and lateral hydraulic gradients. In the upper aquifers, lateral gradients range from 30–60 ft/mi and in the deeper aquifers, they range from 5 – 10 ft/mi. Lateral hydraulic conductivity of the glacial aquifers ranges from 30 to 550 ft/d, and the conductivity of the coarse-grained alluvium ranges between 100 and 200 ft/d.

Seasonal water fluctuations in the uppermost aquifer range from about 4 to 10 ft and are generally less than 4 ft in the deeper aquifers. In general, shallow wells show a rapid response to recharge during winter precipitation, while deeper wells show a lag time of 1 to 3 months. Depending on location, tides can also affect groundwater levels.

Groundwater recharge varies temporally and spatially due to the distribution of precipitation, topography, soil permeability, land use cover, and geology. Estimated recharge varies from 10 percent to 100 percent of precipitation; the low estimates are for areas of till cover and the high estimates are for areas of coarse-grained recessional outwash cover.

While groundwater recharge into the upper aquifer can be estimated fairly readily, the quantity of groundwater that enters the deep aquifer is difficult to determine and has only been estimated through water-budget or numerical groundwater modeling techniques. Estimates of deep aquifer recharge in the Puget Sound Lowlands range from 3 ft^3/s on Whidbey Island (1989) to 34 ft^3/s on Gig Harbor peninsula (1982) and 37 ft^3/s of Vashon Island (2005).

Groundwater-surface water interaction varies throughout the region. In 1999, the Washington State Department of Ecology published a report entitled, "Estimated Baseflow Characteristics of Selected Washington Rivers and Streams." This study, intended to provide information on the hydrologic interactions between groundwater and surface water within Washington State, utilized 582 discharge records from the U.S. Geological Survey (USGS) National Water Information System and a USGS hydrograph separation software program called HYSEP to perform statistical analysis for baseflows throughout the state. Results indicated, that on average groundwater discharge represented approximately 68% of total annual streamflow for the stations modeled, and estimates for groundwater contributions for the months of July, August, September and October were 86%, 86%, 77%, and 69% respectively. It should be noted that these values are state-wide values, and any attempt to apply these numbers at a local scale would be inappropriate.

3. Groundwater and Climate Change Impact Studies

Although the peer-reviewed literature evaluating the impacts of climate change on groundwater resources is limited, there has been important research performed. This section highlights eight studies in which groundwater and climate change impacts have been assessed. These studies are throughout the United States and Canada. The most notable studies are of the Grand Forks aquifer in B.C. Canada (Scibek and Allen, 2006; Allen et al., 2006) and on the Edwards aquifer in Texas (Loáiciga, 2003; Loáiciga et al., 2000). Other studies have been conducted on the Ogallala aquifer, the Ellensburg Basin in Washington, and the "Ponds" aquifer in Eastern Massachusetts, for example. Table 1 presents an overview of the studies. This summary is followed by details of each study, organized by geographical area.

Table 1: Comparison of Studies Evaluating the Impacts of Climate Change on Groundwater Resources

Date	Authors	Study Site	Site Description	Aquifer Description	Models	General Circulation Model(s) (GCMs)	Climate Change Scenarios	Variables Investigated	GW metrics and Results
2004, 2006	Allen et al.	Grand Forks Aquifer, south central B.C., Canada	Located in the mountainous valley of Kettle R.; semi-arid climate; groundwater used extensively for irrigation and domestic use	Highly productive, alluvial (sand & gravel), unconfined	MODFLOW, HELP	CGCM1	1961 – 99 present; 2010 – 39; 2040 – 69; 2070 – 99	1. Changes in recharge 2. Changes in river stage	1. Water table levels changed minimally with change in recharge levels (ranges from: -.025m to 0.05m) 2. Water table levels were significantly influenced by changes in river stage (ranges from: -2.10m to 3.45m)
2003	Croley II and Luukkonen	Saginaw Aquifer, Lansing, Michigan	Located in the south central part of the Lower Peninsula of Michigan	A composite of sandstones of Pennsylvanian age, typically ranges in thickness from 100 to 350 feet in areas where this unit is used for drinking water supply.	GLERL hydrologic modeling system, MODFLOW	CCCMA, Hadley	2030	2 climate change scenarios based on GCM emissions and predicted increased pumping demands. In general the CCCMA scenario predicts a warmer, dryer future than does the Hadley scenario.	Groundwater levels declined under the CCCMA scenario and increased under the Hadley scenario.
2007	Jykrama and Sykes	Grand River Watershed, Ontario	Located in south-western, Ontario, draining an area of almost 7,000 km^2 into Lake Erie	Highly variable soils and topography, ranging from low permeability lacustrine clay deposits and low topographic relief to higher permeability sand and gravel kame moraines with moderately high relief.	HELP3	N/A – Used IPCC 3rd Assess. Report	Looked at change over 40 years using 8 scenarios, all with increasing precipitatio n and temperature	1. Precipitation and temperature 2. Spatial variation of surface and subsurface properties including soil type and vegetation data	1. Recharge increased with increasing precipitation and temperature 2. Recharge varied considerably due to spatial variation in land use and underlying soils.

Date	Authors	Study Site	Site Description	Aquifer Description	Models	General Circulation Model(s) (GCMs)	Climate Change Scenarios	Variables Investigated	GW metrics and Results
2002	Kirshen	Eastern Massachusetts	28 km^2; referred to as the "Ponds"	Highly permeable, unconfined stratified drift aquifer	MODFLOW	N/A	2030, 2100	Temperature and precipitation due to mean and 20 year drought climate change scenarios for both 2030 and 2100.	Annual recharge stays the same or improves slightly under mean conditions for both 2030 and 2100. Annual recharge is significantly reduced for both 2030 and 2100 under 20 year drought conditions.
2000, 2003	Loaiciga	Edwards Aquifer, Texas	Located in south-central Texas; total area is 15,650 km^2; primary source of drinking water for the area;	Karst aquifer; one of the most productive regional aquifers in the US; groundwater recharge occurs through stream seepage within recharge area.	GWSIM IV	N/A	2xCO_2	1. 2xCO_2 climate warming scenario 2. 2050 use do to population increase	1. Spring flows increase with 2xCO_2 climate scenario 2. Spring flows decrease with population increase. Population increase has a greater effect than 2xCO_2 climate warming scenario
1999	Rosenberg et al.	Ogallala Aquifer	One of the world's largest aquifers; underlies portions of 8 states; provides water for 20% of irrigated land in US	Not uniform in its stratigraphy, recharge rate or withdrawals	HUMUS	GISS, UKTR, BMRC	+1°C, +2.5°C, +5.0°C	3 GCMs applied at 3 levels of global mean temperatures (a surrogate for time) and at 3 levels of CO_2 concentration in order to estimate the impacts of direct CO_2 effects on photosynthesis and evapotranspiration	Under all scenarios recharge was decreased.

Date	Authors	Study Site	Site Description	Aquifer Description	Models	General Circulation Model(s) (GCMs)	Climate Change Scenarios	Variables Investigated	GW metrics and Results
1991	Vaccaro	Ellensburg Basin, WA	Located in the semi-arid region of the Columbia Plateau	N/A	DPM	GISS, OSU, GFDL	AVE-GCM MAX-GCM	2 scenarios evaluated: the average of 3 GCMs and a maximum water deficit scenario	Recharge for pre-development, native plant conditions under an average GCM climate change scenario is increased while recharge under 1980's conditions for irrigated agricultural crops is reduced. Under maximum GCM climate change scenario, recharge for both land-use scenarios is reduced.
2005	Zhu et al.	Upper Sacramento Valley, Lower Sacramento Valley and Bay Delta, San Joaquin and South Bay, Tulare Basin, Southern California		N/A	CALVIN, CVSGM	Hadley, PCM	12 total climate change scenarios	The potential effects of climate change on California water supply were evaluated by investigating predicted changes in rim inflows, groundwater, local runoff, reservoir evaporation.	Water availability for nine of the twelve scenarios decreased; however, for the HadCM2 scenarios, water availability increased throughout the year.

3.1. British Columbia, Canada

Allen et al. (2004) have performed some of the most extensive research on the impacts of climate change on groundwater. The authors have conducted numerous studies evaluating the effects of climate change on the Grand Forks Aquifer, in south-central British Columbia, Canada. Allen et al. (2004) evaluated the effects of groundwater levels to river stage and recharge. Scibek and Allen (2006) investigated the modeled impacts of predicted climate change on recharge and groundwater levels. Other studies completed by the authors include a comparison of modeled responses of two-high permeability, unconfined aquifers to predicted climate change and an evaluation of groundwater-surface water interaction under climate change scenarios. Due to the similarity of each of the four studies, this review focuses on the sensitivity analysis of the Grand Forks aquifer and the modeled impacts of climate change on the aquifer.

3.1.1 Groundwater and climate change: a sensitivity analysis for the Grand Forks aquifer, southern British Columbia, Canada

Allen et al. (2004) studied the sensitivity of an aquifer to changes in recharge and river stage in the Grand Forks aquifer. The results indicated that changes in river-stage elevation of the Kettle and Granby Rivers, which flow through the valley, have a much larger impact than variations in recharge to the aquifer under different climate-change scenarios, modeled under steady-state conditions.

This study attempted to identify the potential impacts of climate change on groundwater of the Grand Forks aquifer, a surficial, unconfined aquifer located in south-central BC, Canada. The aquifer is a highly productive, alluvial aquifer, consisting predominately of sand and gravel. The region is semiarid; groundwater constitutes approximately 22% of the drinking water in BC and is used for agriculture in many regions of the province. The main drainage features in the Grand Forks area include two rivers.

The authors assessed two main parameters potentially affected by climate change impacts to groundwater levels: recharge and river stage/discharge. This was accomplished by calibrating a flow model and conducting sensitivity analysis by varying both recharge and river stage/discharge and calculating the differences in water levels.

The authors developed a three-dimensional groundwater flow model for the Grand Forks aquifer to facilitate a comparison of well captured zones defined using numerical modeling and analytical techniques. The authors used Visual MODFLOW, a groundwater flow model that solves the groundwater flow equation using block-centered finite-difference method. Visual MODFLOW can simulate flow in a quasi-3D manner, and both steady-state and transient conditions can be modeled, as well as water-balance calculations (using Zone Budget) and particle tracking (using MODPATH).

Modeling Results

Recharge Analysis

To estimate recharge based on available precipitation and temperature records and anticipated changes to these values, the authors utilized the computer code UnSat Suite and its subprogram

Visual HELP. Visual HELP, a more user-friendly interface for the program HELP, a program approved by the US EPA for designing landfills, enables the modeler to generate estimates of recharge using a weather generator and properties of aquifer column.

The authors varied the amount of recharge to the system by varying precipitation and evaporation according to the General Circulation Model (GCM) values for precipitation and temperature. In reality, this increase in precipitation and evaporation is coupled with river-stage elevation. However, to conduct a controlled sensitivity analysis, the authors varied two independent variables: recharge and river-stage elevation.

The authors used the model HELP to conduct the climate sensitivity analysis by using four scenarios generated by various GCMs. The four scenarios include:

- Low temperature/low precipitation
- Low temperature/high precipitation
- High temperature/low precipitation
- High temperature/high precipitation

The two extreme recharge values (high temperature/low precipitation and low temperature/high precipitation) were then put into Visual MODFLOW in order to determine the impact on the groundwater system. The results of the climate sensitivity modeling indicate that there is very little difference in either the general appearance of the water-level contours or the hydrogeology of the valley compared to the current recharge model. There is a very small (0.05m) increase in water level under the high-recharge scenario and a very low (-0.025m) decrease in water level under the low-recharge scenario.

River Stage

The model incorporated specified head boundaries relating to projected impacts of climate change. Using this method it was determined that these specified heads play a dominant role on the hydrogeology of the aquifer. Furthermore, their role affects the overall water balance much more than recharge due to changes in precipitation and evaporation. Simulated flows 20 and 50% greater than peak flow levels correlated with 2.72 and 3.45 m increases in water-table levels, respectively.

3.1.2 Modeled Impacts of Predicted Climate Change on Recharge and Groundwater Levels

Scibek and Allen (2006) developed a method for linking climate models and groundwater models in a systematic manner. The Grand Forks aquifer in south central British Columbia was used as the study site, and climate change scenarios from the Canadian Global Coupled Model 1 (CGCM1) were downscaled to local conditions using Statistical Downscaling Model (SDSM). The factors were then extracted and applied in LARS-WG stochastic weather generator. The outputs of this model were inputs for the groundwater recharge model, HELP. Finally, MODFLOW was used to simulate four climate scenarios - present, 2010 – 2039, 2040 – 2069, and 2070 – 2099. Groundwater levels for the modeled climate scenarios were then compared to present levels. Results indicated that the effects of spatial distribution of recharge on groundwater levels, was much greater than that of temporal variation in recharge. Predicted future climate scenarios resulted in more recharge to the unconfined Grand Forks aquifer for the spring and summer seasons; however, due to the dominant interactions between river stage and groundwater levels (as shown in their previous study), the overall effect of recharge on the water balance was small.

Spatial Modeling of Recharge

The authors presented a method to generate spatially distributed and temporally varying recharge zones using a GIS model linked to the one-dimensional U.S. Environmental Protection Agency's Hydrologic Evaluation of Landfill Performance model, HELP. The approach depends on high-resolution GIS maps for defining recharge zones, which the authors then linked to MODFLOW model grids by developing a specific code to link Visual MODFLOW 3.1.84 to Arc GIS 8.13. The authors highlighted that their method differs from that of previous distributed recharge methods in that they also estimated the distribution of vertical saturated hydraulic conductivity in the unsaturated zone and the thickness of the unsaturated zone. Sixty-four recharge zones for the study site were determined based on combinations of soil permeability, vertical hydraulic conductivity and water depth.

The authors then evaluated sensitivity of modeled recharge in the HELP model to input parameters. Results indicated that the type of stand grass, wilting point, field capacity and initial moisture content had very little effect on output results (<5%). Soil thickness and porosity of percolation layer had a moderate effect. Recharge was most sensitive to depth to water table (depth of unsaturated zone), soil permeability, and for vertical hydraulic conductivity of the unsaturated zone. These effects were found to be seasonal and most pronounced in early summer.

In the previous study by Allen et al. (2004), a uniform annual recharge value for the Grand Forks aquifer of 135.5 mm/year (approximately 27% of precipitation) was used. However, according to the results of this study, mean annual recharge varies across the 64 recharge zones, ranging from less than 30 mm/yr to over 120 mm/yr.

Climate Change Scenarios and Predicted Recharge

Under the predicted climate change scenarios, recharge was predicted to increase in all recharge zones, under all climate-change scenarios. The 2010 – 2039 climate scenario predictions indicated a 2 to 7% increase in historical mean annual recharge. The 2040 – 2069 climate scenario had a predicted 11 to 25% increase from historical mean annual recharge. Recharge values for each climate period were implemented into Visual MODFLOW in order to quantify the effect of changes in recharge on groundwater levels in the aquifer.

Modeling Results

Sensitivity to Recharge Distribution

The authors investigated the sensitivity of the HELP model by evaluating two scenarios. The first scenario had spatially distributed mean annual recharge as the recharge input, and the second had temporally variable recharge rates with one uniform recharge zone. Results indicate that spatial distribution of recharge representation in the model has more significant impact on the water balance than does the temporal representation of recharge.

Climate Change Impacts on Groundwater Levels
Under future climate scenarios, recharge was slightly lower in the late winter and was greatly increased in the late spring and summer. However, in this aquifer, effects of changing recharge due to climate change on groundwater levels was found to be very small compared to changes in timing of snowmelt events in the Kettle River. Because the groundwater system and the Kettle River are so hydraulically connected, shifts in the hydrographs had greater impacts on groundwater levels compared to that of changing recharge. It should be noted that this may not be the case for aquifers where surface water and groundwater are not as highly connected.

3.2. Ontario, Canada

Jyrkama and Sikes (2007) evaluated the potential impacts of climate change on groundwater recharge for the Grand River watershed using a hydrologic model (HELP3). The results indicated that the overall groundwater recharge is projected to increase as a result of climate change. While global warming may result in increased evapotranspiration rates, the projected increase in intensity and frequency of precipitation for the area will contribute significantly to the surface runoff. Projected warmer winters will reduce the extent of groundwater frost and shift the spring melt to earlier in the season, allowing more water to infiltrate into the ground (Figure 5).

Figure 5: Grand River Watershed, Ontario, Canada.
(Taken from: Jyrkama and Sykes (2007))

The authors used a physically based approach to assess the climate change impacts on estimating groundwater recharge. The authors noted that this method must consider both temporal variations in climatic variables as well as spatial variation of surface and subsurface properties across the study area. The primary objective of the paper was to present a methodology to quantify the spatial effect of potential climate change on groundwater recharge. The method was based on the hydrologic software package HELP3 coupled with a geographic information system (GIS). This method was applied to Grand River watershed in Ontario, Canada, which contains highly variable soils and topography ranging from low permeability lacustrine clay deposits and low topographic relief to higher permeability sand and gravel kame moraines with moderately high relief.

HELP3, a quasi-two dimensional, deterministic routing model for computing water balances was chosen because it is readily available and easy to use. It simulates the important processes in the hydrologic cycle, including the effects of snowmelt and freezing temperatures. It simulates the daily movement of water into the ground, and accounts for precipitation, surface storage, runoff, evapotranspiration, vegetative interception and growth, unsaturated flow, and temperature effects (Schreoder et al., 1994). When HELP3 was compared to other modeling approaches for the eastern United States; even without calibration, the model was in closest agreement with direct recharge measurements (Risser et al., 2005).

Spatial Modeling with HELP3

This paper's primary contribution was to model the effects of spatially distributed parameters. This is somewhat different than similar studies done by Scibek and Allen (2006), which incorporated the concept of zoning or averaging for a 50-m raster grid. This concept of zoning is commonly used in modeling; however, when using averaging or lumping approaches, the authors argued that one loses the important information resulting in possibly erroneous analysis. Because of its one-dimensional nature and relative simplicity, the HELP3 model can include all available spatially and temporally distributed input parameters into the analysis.

Climate Change Scenarios

The impact of climate change was modeled by perturbing the HELP3 model input parameters using IPCC 2001 projections for the Grand River watershed over the next 100 years (IPCC, 2001). For the watershed, the general predictions from the 2001 report were:

- Projected increase in precipitation with an average change between 5% and 20% in the winter,
- Increased precipitation extremes,
- Greater than average warming in both summer and winter, and
- Possible reduction of incoming solar radiation due to increased greenhouse gases.

Eight scenarios were devised based on these projections and were scaled over a 40-year study assuming yearly linearly change. Results showing cumulative differences in surface runoff, evapotranspiration, and recharge between all scenarios and the "Base Case" scenario, averaged spatially over the entire watershed were given. Nine different climate change scenarios are used and the results summarized (Table 2, Figure 6). The results suggested that changing precipitation has the highest influence on the hydrologic cycle, while solar radiation had minimal impact. Under all scenarios, groundwater recharge was predicted to increase. Evapotranspiration was predicted to increase in all scenarios, except for scenario 6 where incoming solar radiation was reduced. Furthermore, surface runoff was increased with increasing precipitation; however, increasing temperature has both negative and positive effects on the hydrologic process.

Table 2: Climate Change Simulation Scenarios
(Modified from: Jyrkama and Sykes (2007))

Scenario	Description
Base Case	Actual historical daily temp., precip., and simulated solar radiation for the past 40 years
1	Precipitation +5% for December, January, and February
2	Precipitation +20% for December, January, and February
3	Precipitation +20% for all months
4	Temperature +0.016 °C/year
5	Temperature +0.070 °C/year
6	Solar radiation +2% for all months
7	Combination of Scenarios 1, 5, and 6
8	Combination of Scenarios 3, 5, and 6

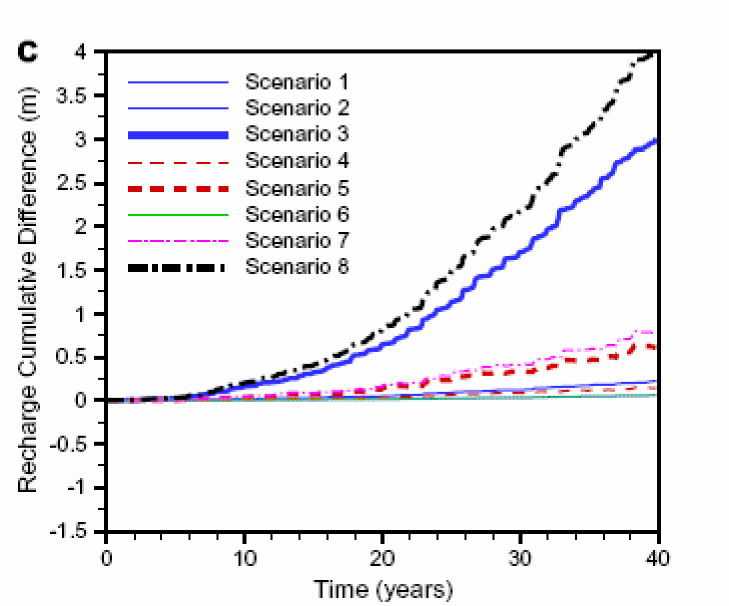

Figure 6: Cumulative Difference Between Climate Change Scenarios and Base Case for Groundwater Recharge.
Taken from: Jyrkama and Sykes (2007)

Comparing the results of the combined scenarios (7 & 8), the relative overall impact of climate change ranges from -12% to 10% for surface runoff, 3% to 12% for evapotranspiration, and 10% to 53% for groundwater recharge.

The authors then estimated the spatial impact of climate change on groundwater recharge in the basin and determined that there is a non-uniform impact across the basin, where some areas will be subject to greater changes in recharge rates than others. The degree of impact is directly related to groundwater levels, characteristics of the groundwater surface, and the nature of the underlying soils.

3.3. Eastern Massachusetts

Kirshen (2002) analyzed the potential impacts of climate change on a highly permeable, unconfined aquifer located in Eastern Massachusetts for the years 2030 and 2100 under average and 20-year drought conditions. Results vary for each climate change scenario, ranging from slightly higher annual recharge and groundwater elevations to significantly less annual recharge and groundwater elevations.

The study area is 28 square kilometers, consists of sorted and layered sand, gravel, silt, and clay, and is underlain in most parts by a stratified drift aquifer. The area climate is humid, receiving an annual precipitation of approximately 1,040 mm. The surface waters and aquifer are hydraulically connected; in fact, most of the surface flows in the area come from the groundwater (Figure 7).

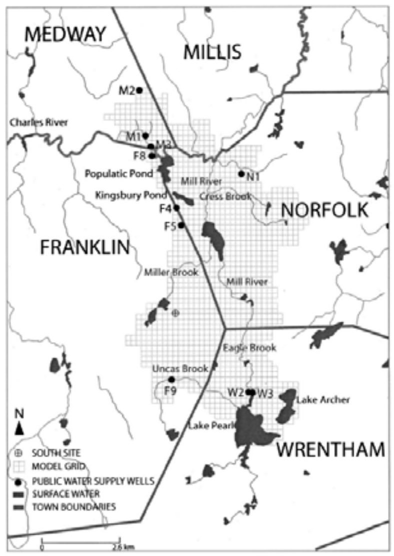

Figure 7: Ponds Study Site,
Eastern Massachusetts.
Taken from: Kirshen, 2002.

Model Application

The finite difference, three dimensional groundwater model (MODFLOW) was used in this study, due to its ability to replicate the dominant hydrologic processes in the area. Inputs into the model include: hydraulic parameters describing each cell, recharge, streamflows, and well withdrawals and characteristics. Outputs of the model include: transient groundwater elevations in each cell, surface water flows, elevations, and groundwater interactions for modeled streams and rivers. The model HSPF, (Hydrologic Simulation Program- FORTRAN), was used to provide historic streamflow estimates for MODFLOW. Field data, however limited by space and time, were used for calibration and verification of MODFLOW for the study area.

Modeling the Possible Impacts of Climate Change

To compare the possible impacts of global warming, the impacts of present water withdrawals under present mean annual precipitation and an extreme low value of precipitation (20-year drought condition) were determined. Then, two 2030 mean scenarios were chosen, one which assumed a 1°C increase in annual average temperature, and one which assumed a 1°C increase in annual average temperature (S1) and 10% increase in annual average precipitation (S2). The temperature and precipitation changes were chosen due to their likeness with several GCM scenarios. Based on the U.S. National Assessment recommendations, results were taken from the Canadian Climate Center (CCC) and used as the basis for the mean and drought conditions for year 2100. For the 2030 extreme conditions event, a 20-year drought condition (annual precipitation at a nonexceedance probability at the 5 percentile level) was used.

Results

Results indicated that for the 2030 mean climate conditions, impacts on groundwater elevation and recharge may not be significant or may even be beneficial. For 2100 mean climate conditions, the impacts were sensitive to actual evapotranspiration estimates and could be positive or negative. Drought scenarios for 2030 and 2100 resulted in neutral or harmful effects on groundwater elevation and recharge. Each of the climate scenarios had differing impacts on water supply potential. Detailed results are shown below in Table 3.

Table 3: Summary of Climate Change Scenarios
Taken from: Kirshen (2002)

Scenario	Annual precipitation (mm)	Average monthly temperature (°C)	Annual PET (mm)	Annual AET (mm)	Annual recharge (million cubic meters)
		(a) Mean conditions			
Present climate	1,073	9.4	846	488	12.96
		Degree change	Percent change[a]		
2030 climate[b]					
S1	1,073	1	+3.1	499	12.96
S2	1,127	1	+3.1	507	13.94
2100 CCC climate[c]	1,153	4.8	+9.3	531,607	13.94,12.27
		(b) 20 year drought (Dgt)			
Present climate	747	0	0	422	7.00
2030 climate[d]					
SL1	721	1	+3.1	422	6.50
SL2	757	1	+3.1	432	7.00
2100 CCC Climate[e]	719	4.8	+9.3	434,496	6.45,5.16

[a](Scenario-Base)/Base × 100.

[b]S1 is sensitivity run with 1°C annual temperature increase and present mean annual precipitation. S2 is sensitivity run with 1°C annual temperature increase and 10% increase in present annual precipitation.

[c]2100 mean climate scenario from Canadian Climate Center (CCC) with two values of AET.

[d]SL1 is sensitivity run with 1°C annual temperature increase and 20 year drought resulting from increase of 10% in coefficient of variation. SL2 is sensitivity run with 1°C annual temperature increase and 20 year drought resulting from increase of 10% in present annual precipitation and increase of 10% in annual coefficient of variation.

[e]2100 drought climate scenario from Canadian Climate Center (CCC) adjusted for 30% increase in annual coefficient of variation with two values of AET.

The future assumptions used in the study are important and impacted the results. They included that: 1) there would be no increases in water demands from the aquifer, 2) there would not be further losses in recharge because of more impervious surfaces, and 3) the expected increased intensity of precipitation events in the future would not significantly change recharge mechanisms.

3.4 Ogallala Aquifer

This paper evaluated the potential effects of climate change on the sustainability of the Ogallala Aquifer as a source of water for irrigation and other purposes in the region (Rosenberg et al., 1999). The Hydrologic Unit Model of the U.S. (HUMUS) was applied to the Missouri and Arkansas-White-Red water regions that overlie the aquifer by applying three general circulation models (GISS, UKTR and BMRC) under varying climate change scenarios. The authors simulated the changes that may be induced in water yields (runoff plus lateral flow) and groundwater recharge. As a surrogate for time, each GCM was applied to HUMUS at three levels of global mean temperature (GMT) to represent increasing severity of climate change. To estimate the impacts of direct CO_2 effects on photosynthesis and evapotranspiration, HUMUS was also run at three levels of atmospheric CO_2 concentrations. In the Missouri River Basin, the UKTR and GISS GCMs projected increased precipitation in the Missouri River basin, and hence increased water yields; however, the BMRC GCM projects significant decreases in precipitation resulting in decreased water yields. In the Arkansas basin, projected precipitation declines under the BMRC projections are even greater, resulting in sharp water yield losses, while the GISS and UKTR projections led to only moderate losses in the water yield in the Arkansas basin. Under all three GCM models and severities of climate change, recharge was reduced.

Background of Ogallala Aquifer

The Ogallala Aquifer, which underlies approximately 450,000 km^2 of the states of South Dakota, Wyoming, Colorado, Nebraska, Kansas, Oklahoma, Texas and New Mexico, is the largest aquifer in North America (Figure 3.4.1). Approximately 30% of all groundwater used for irrigation in the United States (Dugan and Sharpe, 1996) comes from the Ogallala Aquifer, and in 1990, irrigation accounted for approximately 96% of the 20.4 billion cubic meters of water withdrawn from the aquifer. The Ogallala aquifer in not uniform in its stratigraphy or its recharge rate. The withdrawals vary from region to region, as does the potential for recharge.

Figure 8: The Ogallala Aquifer (shown in gray)

Methods

Three GCMs were selected to represent a broad range of climate change outcomes for the United States: the Goddard Institute for Space Studies (GISS) model, the United Kingdom

Meteorological Office transient model (UKTR), and the Australian Bureau of Meteorology Research Center (BMRC) model. This study evaluated the effects of mild to very severe climate change consistent with credible emissions futures by using GMTs of 1.0, 2.5 and 5.0°C. GMTs may also be used as a surrogate of time, increasing with a strengthening greenhouse effect. The three GCM models projected warming for the basins of the Missouri and the Arkansas-White-Red rivers; however, they differed with regard to precipitation. These differences in precipitation projections predominated in determining the different hydrologic outcomes for the region. A summary of the changes in precipitation is given in Tables 4 and 5.

Table 4: Projected Precipitation Changes under Three Different GCM Models.

	Basin	
	Missouri basin	**Arkansas-White-Red basin**
GISS	20% increased monthly precipitation in late spring and late summer; little difference throughout remainder of year	Nearly unchanged precipitation except in Aug. and Sep. when precipitation is approximately 20% higher than baseline
UKTR	Increases as great as 60% in first half of year; decreases from Aug. to Nov.	Early year decreases from Jan. through May and late year decreases
BMRC	Reduced precipitation throughout the year except in Mar.; reductions as great as 60% in July	Precipitation is reduced in all months

Table 5: Simulated percent change from baseline precipitation by GCM and GMT.
(Adapted from: Rosenberg et al. (1999))

Basin	Missouri			Arkansas-White-Red		
GCM	GISS	UKTR	BMRC	GISS	UKTR	BMRC
GMT (C)	(Baseline = 506 mm)			(Baseline = 776 mm)		
1.0	2	3	-3	0	0	-6
2.5	6	8	-8	1	-1	-14
5.0	11	16	-16	2	-3	-28

The authors also simulated the "CO_2 fertilization effect" by running each climate change scenario at three levels of CO_2 – 365, 560 and 750 ppm. The CO_2 fertilization effect occurs from reduced water usage in C3 and C4 plants due to increased CO_2 concentrations. Therefore, in this paper there were inherent contradictions in the matrix of scenarios, such that, for example, no climate change could be associated with elevated CO_2 levels (e.g. 560 or 750 ppm) or strong climate change (e.g. GMT = 5°C) with current CO_2 levels. Thus, for this paper, the total number of scenarios applied is: 3 GCMs x 4 GMTs x 3 [CO_2] – 6 (only 1 baseline calculation is required for each level of [CO_2] regardless of the number of scenarios tested) = 30.

Hydrologic Analysis

The authors used the model HUMUS to evaluate the impacts of climate change on water resources. HUMUS is a GIS-based system that provides the input data necessary to operate the Soil Water Assessment Tool (SWAT). HUMUS maps the outputs to various scales. The subbasin water balance is represented by four storage volumes: snow, soil profile (0-2 m), shallow aquifer (2-20 m), and deep aquifer (> 20 m). The percolation component of SWAT uses a storage routing technique to predict flow through each soil layer when field capacity is exceeded where percolation from the bottom of the soil profile recharges the shallow aquifer. In addition to percolation into the shallow aquifer, SWAT simulates groundwater recharge by channel transmission losses that recharge the shallow aquifer.

For this study, HUMUS modeled the sub-basins of the Missouri and Arkansas-White-Red basins where each sub-basin is approximately 3,000 square km in size. Each sub-basin was treated as if it were comprised of a single soil type, land use, and vegetative cover under a uniform climate. Using HUMUS, the 30 climate x [CO_2] scenarios were then applied to each of the sub-basins. The results of the water yields for each of the sub-basins were then aggregated up to the larger basin scales (Missouri and Arkansas-White-Red basins, respectively).

Results

Under all GCM scenarios, recharge is reduced in both the Missouri and Arkansas-White-Red basins. Table 3.4.3 illustrates the percent change of recharge from baseline as a function of climate change scenario (GCM), severity of change (GMT), and atmospheric CO_2 concentration.

Table 6: Percent change in recharge from baseline as a function of climate change scenario (GCM), severity of change (GMT) and atmospheric CO_2 concentration [CO_2].
(Adapted from: Rosenberg et al. (1999))

	GCM	GISS			UKTR			BMRC		
	[CO_2]	365	560	750	365	560	750	365	560	750
Missouri Basin (baseline recharge = 61 mm)										
GMT (C)	0	0	-1	-1	0	-1	-1	0	-1	-1
	1.0	-10	-10	-10	-14	-14	-13	-17	-17	-17
	2.5	-21	-21	-20	-26	-26	-25	-35	-35	-35
	5.0	-33	-33	-32	-40	-39	-38	-55	-55	-54
Arkansas-White-Red Basin (baseline recharge = 47 mm)										
GMT (C)	0	0	3	8	0	3	8	0	3	8
	1.0	-13	-10	-5	-20	-17	-12	-25	-22	-17
	2.5	-26	-23	-18	-39	-36	-32	-51	-49	-45
	5.0	-39	-36	-32	-59	-56	-51	-77	-75	-72

3.5 Lansing, Michigan

This study (Croley and Luukkonen, 2003), conducted by USGS and NOAA at the Great Lakes Environmental Research Laboratory (GLERL), evaluated the potential impacts of selected climate change projections on groundwater levels in the Saginaw Aquifer, Lansing, Michigan. Using climate projections from the Canadian Climate Centre and the Hadley Centre for 20 years centered around 2030, results indicated the groundwater levels rose in the Saginaw Aquifer under Hadley simulations and declined under the Canadian Climate Center simulations.

Study

In this study, streamflow was calculated with GLERL's hydrologic modeling system by using the CCCMA and the Hadley meteorology estimates for a 1961 through 1990 reference period for

20 years centered around 2030 under a changed climate. The Canadian Centre for Climate Modeling Analysis and the United Kingdom Hadley Centre for Climate Prediction and Research provided monthly mean data from GCM runs with transient carbon dioxide content and sulfate aerosol concentrations. In general, the Hadley GCM scenario was wetter and colder than the CCCMA GCM scenario. Both scenarios are warmer than current conditions.

Study Site

The Saginaw Aquifer is the primary source of water for residents and businesses in the Tri-county region, Michigan. The aquifer is a composite of sandstones of Pennsylvanian age, typically ranging in thickness from 100 to 350 feet in areas where it is used for drinking water supply. The Saginaw Aquifer is largely recharged by leakage from glacial deposits. For this study the aquifer was assumed to be impermeable. Figure 9, below highlights the active model area of the Saginaw Aquifer in the Tri-County region.

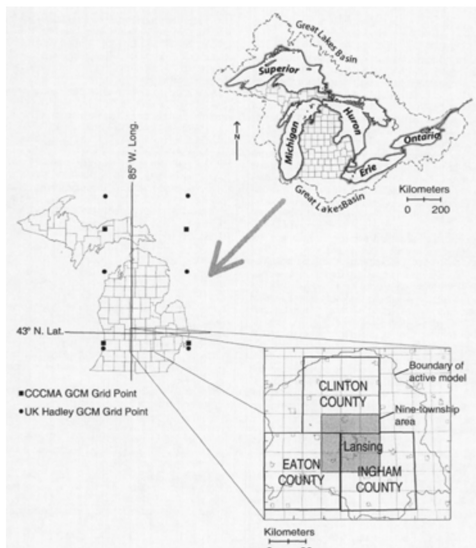

Figure 9: Active Model Area of the Saginaw Aquifer.
(Adapted from: Croley and Luukonen (2003).)

Groundwater withdrawals in the aquifer have increased from 1.75 m^3/s (39.9 Mgal/d) in 1992 to 1.86 m^3/s (42.4 Mgal/d) in 1997, approximately a 1.3 percent increase per year. Water withdrawals for 2030 are projected to be 3.16 m^3/s (72.2 Mgal/d) based on anticipated changes in population. These numbers do not include potential changes in recharge due to climate change.

Development of Recharge Estimates

In this study, the groundwater flow component is considered to be the base flow component, which is associated with groundwater flow into the stream. The authors use the method developed by Rutledge (1998) to calculate baseflow based on antecedent recession, which is applied over a long period of record to obtain records for mean rate of groundwater flow into the stream. Using the GLERL hydrologic simulation system, streamflow was simulated and the Rutledge method was used to compute simulated base flows for the base case meteorology and for the CCCMA and Hadley adjusted meteorologies. Changes in base flow represented changes in the amount of water available for recharge to, or discharge from, the groundwater system. The CCCMA and Hadley GCM climate meteorologies were applied to the years 1954 to 1995 to compare the reference conditions to determine whether historical base flow would increase or decrease due to GCM climate estimates. Results indicated that for the CCCMA GCM meteorology for historical climate, changed climate and reference estimates resulted in baseflow conditions of -19.7 +/- 4.7 percent, while results for the Hadley GCM meteorology was a changed climate and reference estimates of base flow of 4.1 +/- 3.3 percent.

Groundwater Flow Model

MODFLOW was used to simulate the regional, steady-state response of the Saginaw aquifer to major groundwater withdrawals in the region surrounding Lansing, Michigan. The authors divided the region into variably spaced grid cells consisting of two layers, with the upper layer of the model representing glacial deposits and the lower layer representing the Saginaw aquifer. In the model, water enters the glacial deposits as recharge from precipitation and moves to the stream or to the aquifer in response to hydraulic gradients. Groundwater exited the model at streams or wells. No flow boundaries were defined at drainage and groundwater divides, and the rivers were modeled as constant heads. The authors assume that the horizontal flow of water in the glacial deposits was controlled by the hydraulic conductivity of the unconsolidated materials, and the vertical flow of water between the glacial deposits and the Saginaw aquifer was controlled by the vertical hydraulic conductivity in the glacial deposits. It should be noted that this method does not capture transient changes in groundwater conditions at seasonal, monthly or daily timescales.

Results

Model simulations using the 19.7 percent decrease in baseflow to streams predicted by the CCCMA GCM resulted in declines in groundwater levels from reference conditions. These changes in groundwater levels further declined with projected future demands. Results indicated that under for 2030 pumping rates, the Saginaw aquifer declined 0.3 to 2.3 m (1 to 7.6 ft) from the reference condition. Model simulations using the 4.1 percent increase in baseflow to streams predicted by the Hadley GCM resulted in inclines in groundwater levels from reference conditions. These changes in groundwater levels were offset by higher projected future demands. Results for 2030 pumping rates indicated that the Saginaw aquifer increased 0.1 to 0.3 m (0.3 to 1.0 ft) from the reference condition.

3.6 Texas

Loáiciga (2003) focuses on regional aquifer systems and on the methods used to link large-scale climate change processes to groundwater recharge and groundwater flow in a warmer climate. The paper introduces a methodology to calculate the effects of climate change and population growth on hydrologic response. The Edwards Aquifer of Texas, one of the largest freshwater aquifers in the U.S., illustrates a specific procedure for assessing the potential impacts of warming climate and changes in groundwater use on regional scale aquifer systems. In the Edwards Aquifer, spring flow is important as it is a direct measure of water available for pumping; i.e., as spring flows decrease, there is less water available for pumping of municipal and agricultural needs. Results indicate that climate change increases spring flow in the Edwards aquifer relative to the base condition, while the year-2050 groundwater use scenario reduces flow relative to the base condition. The combined effect of climate change and year-2050 groundwater use is a significant decrease in spring flow compared to the base condition indicating that the primary threat to groundwater use in the Edwards aquifer comes from the rise in groundwater use associated with predicted growth. Climate change, in fact, would increase spring flow in the study area.

Climate Change and Regional Groundwater Systems

Climate change impacts groundwater systems through changes in aquifer recharge. Groundwater recharge is determined by surface-water/groundwater conditions and vadose zone hydrologic balances. The authors highlight the need to determine the effect of climate change on groundwater recharge, the changes in precipitation, evapotranspiration, infiltration, and various component of total runoff including overland flow, interflow and baseflow, as well as changes in water storages. The author argued that the best way to do this is by the implementation of a continuous-time hydrologic simulation model that integrates land-atmosphere interactions and subsurface processes.

The author further highlighted the fact that groundwater recharge occurs by two main mechanisms: 1) spatially distributed recharge to the aquifer system to the vadose zone and 2) seepage from streambeds and lake bottoms overlying aquifers. Local conditions determine the relative contributions of each component to the groundwater recharge. When stream recharge is the dominant mechanism of aquifer recharge, the problem can be simplified. Linked GCM-RCM simulations can be used to generate streamflow scaling factors of Q_{2xco2}/Q_{1xco2} and then used to generate $2xCO_2$ groundwater recharge directly. Using the following set of equations the author demonstrated a simple method for estimating the groundwater recharge under $2xCO_2$ conditions:

Equation 2: $R_{historical} = Q_u + Q_I - Q_D$

Where Q_u and Q_D are stream flows measured in the uppermost and lowermost channel cross sections in the recharge zone, respectively. Q_I is the streamflow contribution generated within the recharge zone itself. The right-hand side of equation above can be scaled up by the runoff-scaling factors applicable to the area of interest. The $2xCO_2$ aquifer recharge is given by:

Equation 3: $R_{2xCO2} = \frac{Q_{2xCO2}}{Q_{1xCO2}} R_{historical}$

Where $R_{historical}$ can be monthly or annually recharge.

Steps to assess climate-change forcing on aquifer systems

The author illustrated a step-by-step approach for analyzing climate change impacts in aquifer systems. The steps are as follows:

1. Create or choose climate change scenarios
2. Estimate the groundwater recharge under the climate-change scenario

The simplest method of doing this is to specify the groundwater recharge as a fraction of precipitation. This is best suited for groundwater simulations with annual time steps. For shorter time steps the previous equation can be used. Alternatively, estimated groundwater recharge can be used to drive a groundwater simulation model such as MODFLOW or a coupled groundwater/transport model such as Visual MODFLOW.

Study Site

The Edwards aquifer, located in Texas, is one of the most productive regional aquifers in the United States, as it is the primary source of water (agricultural and municipal) in south-central Texas (Figure 10). The aquifer is contained within nine river basins. It is comprised of two hydrogeologic regions: a recharge region and a freshwater, confined, groundwater flow zone. The total aquifer surface is 15,650 km^2 divided into 2,820 km^2 and 12,830 km^2 of recharge and confined (discharge) areas, respectively. Groundwater recharge occurs almost exclusively as stream seepage within the recharge area. The two largest and most prominent springs are the Comal and the San Marcos.

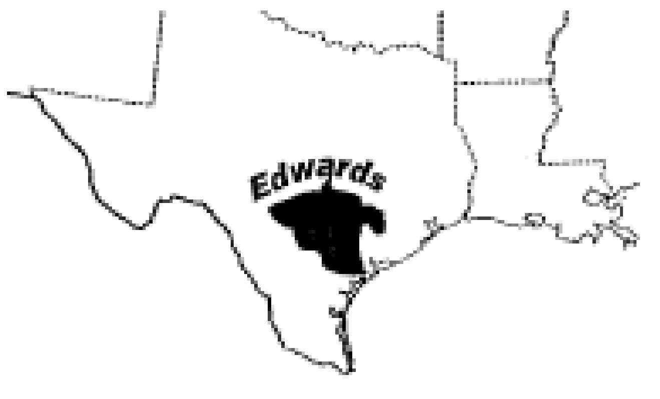

Figure 10: Edwards Aquifer, Texas
(Taken from Loáiciga (2003).)

Spring-flow Vulnerability to Groundwater Pumping in a 2xCO_2 Climate

Using a finite-difference, groundwater-transport model (GWSIM IV), specifically developed for and calibrated to the Edwards Aquifer, the author simulated groundwater levels and spring flow. The unique spring flow conditions in the Edwards aquifer have created diverse aquatic ecosystems, which in turn, support unique habitat. Several species living in ecosystems are listed as endangered, and as such, protection of these species is central to management of the aquifer system including spring flow levels. The climate change simulations considered the scaling of historical dry and average climate to a warmer (2xCO_2) climate. The author considered a wide range of pumping rates in the simulation of the Edwards Aquifer under an "average climate" 2xCO_2 forcing based on scaling historical aquifer recharge in a period of average recharge. Annual pumping varied from 0 to 0.784×10^9 m^3, with the latter being projected groundwater use by the year 2050.

Loáiciga demonstrated the effects of groundwater pumping under average climate 2xCO_2 and dry-climate 2xCO_2 conditions on two of the largest springs in the Edwards Aquifer. Results indicated that under average conditions the aquifer had a long-term estimated yield close to that projected for 2050; however under dry conditions the maximum annual pumping rate could only be between 0 and 0.2×10^9 m^3/yr, much lower than the projected pumping rate for 2050.

Climate and Groundwater Use Effects on Hydrologic Response

Next, Loaiciga evaluated the hydrologic response of groundwater to both groundwater use and climate, where change in groundwater use is caused by population growth and/or economic development. This is estimated in the following equation:

Equation 4: $\Delta Z = \frac{\partial f}{\partial W}\Delta W + \frac{\partial f}{\partial C}\Delta C$

Where ΔZ represents the change in hydrologic response, ΔW represents the change in groundwater use, and ΔC represents climate change. The first term on the right-hand side of the equation denotes the change in hydrologic response caused by a change in the human use of groundwater while climate is constant, and the second term on the right-hand side of the equation represents the change in hydrologic response caused by climate change while groundwater use remains constant.

Results for both springs illustrated that climate change increased spring flow relative to base conditions, while year-2050 groundwater use reduced spring flow relative to base conditions. The combined effect of projected groundwater use and climate change was a net reduction in spring flow. Therefore, results indicated that the primary threat to groundwater flow in the Edwards Aquifer comes from the projected rise in groundwater use associated with population increase, and not climate change, which is, in fact, projected to increase groundwater flow in the aquifer. It should be noted that although the trend was the same for both springs, the magnitude of impact was quite different.

3.7 Ellensburg Basin, Washington

Vaccaro (1991) evaluates the sensitivity of groundwater recharge estimates to observed, synthetic and projected climate change scenarios for the Ellensburg basin, located in west-central Washington on the Columbia plateau. The recharge is estimated for pre-development conditions (native plant communities) and 1980's conditions (irrigated crops) using a recharge-estimation model, Deep Percolation Model (DPM). The results are compared to a previous study, based on climatological data for three weather stations for the 22-year period (1956-1977).

The recharge-estimation model, Deep Percolation Model (DPM), is operated under predevelopment and current land use conditions for the years 1901 through 1987 using three sets of climatological data: historical climatological data and two sets of climatological data based on three GCMs. Results indicate that recharge for pre-development conditions under an average GCM climate change scenario is increased while recharge under current, 1980's conditions for irrigated agricultural crops is reduced under the average GCM climate change scenario. Under the maximum GCM climate change scenario, recharge for both land-use scenarios (predevelopment, native plants and 1980's irrigated agriculture) is reduced.

Study Area

Approximately 362 mi^2 of the Ellensburg basin are included in the study site. Elevations range from approximately 1,500 ft to 3,000 ft, and in general the 2,000 ft contour line defines the transition from the flat-lying lowlands and the uplands and mountains. Average annual precipitation ranges from approximately 7 in to 25 in. Pre-development land cover is estimated as predominately sagebrush. Under current conditions, there is approximately 193 mi^2 of irrigated croplands. Surface-water application to the cropland was assumed constant for this study; an estimate of 17.42 in/yr was used.

Climate Variability and Projected Climatic Changes

This study uses three methods to investigate the sensitivity of groundwater recharge estimates to climate variability and projected climate change. Historical records are used to analyze the effects of observed climate variability on recharge estimates, the results of which are assumed to represent a range of recharge values that can be expected to occur in the future. However, problems exist with this method, including: the length of historical record, lack of information on the probability of reoccurrence of the historical climate, and the potential effects of global warming, among others.

Climatic change projections are based on the doubling of CO_2 calculated by GCMs. Average values from three GCMs (the Goddard Institute for Space Studies model (GISS), the Geophysical Fluid Dynamics Laboratory model (GFDL), and the Oregon State University model (OSU)) are used and applied to the observed daily data for each month of the 87-year record to modify the historical record for two scenarios. The first simulation is based on the average change projected from the three models (AVE-GCM), and the second method is based on the model run that predicted the maximum water-deficit effect.

Eighty-seven years of climatological data were generated using a stochastic daily-weather generation model. The model uses parameters that were based on the 1928-37 drought period to investigate the possible long-term effects of a persistent drought.

Groundwater Recharge Estimates for 1901-1987 from Projected Climate Records

Results from the AVE-GCM scenarios for pre-development conditions indicate that changes in recharge are less than 10%. However, for the AVE-GCM scenarios under current land-use conditions, results indicate that recharge is about 16% less than historical recharge suggesting that current land-use is more sensitive to AVE-GCM projected changes in climate due to the assumed irrigation water that was applied for the 1980's land-use conditions. This, combined with increased temperatures, resulted in more AET during summer months translating into less recharge. In fact, for all but two of the averaging periods chosen, the recharge estimates for the 1980' climate conditions under AVE-GCM simulations result in less recharge than the average for the 1928-1937 drought period historical record and equal to the historically simulated 1928-1937 period. Moreover, results for the MAX-GCM 1980's recharge estimates for all averaging periods was less than the historical estimates.

3.8 California

Zhu et al. (2005) estimates the impacts of climate warming on California water availability. Spatially disaggregated estimates of over 131 streamflow, groundwater, and reservoir evaporation monthly time series were created for twelve future climate scenarios for a 72-year period. Results indicate that even under scenarios with increased precipitation, less water would be available because of the current storage system's inability to catch increased winter streamflow in compensation for reduced summer runoff. Within the study, groundwater inflows are specifically evaluated. Results of which indicate that under the HadCM2 general circulation model for all three GCM periods, groundwater inflows increased. Alternatively, groundwater inflows decreased with the PCM model for all three GCM periods.

There have been numerous studies of the potential impacts of climate change on streamflows in California (e.g. Lettenmaier and Gan, 1990; Lettenmaier and Sheer, 1991; Gleick and Chalecki, 1999); however, there has been less research conducted on the effects to groundwater systems in the state. This paper provides a very general study over a large region in California. Five index basins chosen for evaluation are:

- Upper Sacramento Valley
- Lower Sacramento Valley and Bay Delta
- San Joaquin and South Bay
- Tulare Basin
- Southern California

Two GCM projections, based on 1% per year increases in CO_2 relative to late 20th Century CO_2 conditions, were used for three projected future periods (2010 to 2039; 2050 to 2069; and 2080 to 2099) to generate six future climate scenarios. The two GCM projections used were the Hadley Centre Model, which represents relatively warm/wet scenarios and NCAR's PCM Model, which represents relatively warm/dry scenarios. Six additional scenarios were chosen to comprehensively explore the possibility of changes that may occur as a result of climate change. The twelve climate scenarios used in this study are shown below:

- 1.5°C temperature increase and 0 percent precipitation increase (1.5 T; O% P).
- 1.5°C temperature increase and 9 percent precipitation increase (1.5 T; 9% P).
- 3.0°C temperature increase and 0 percent precipitation increase (3.0 T; 0% P).
- 3.0°C temperature increase and 18 percent precipitation increase (3.0 T; 18% P).
- 5.0°C temperature increase and 0 percent precipitation increase (5.0 T; 0% P).
- 5.0°C temperature increase and 30 percent precipitation increase (5.0 T; 30%P).
- HadCM2025 (1.4 T; 26% P).
- HadCM2065 (2.4 T; 32% P).
- HadCM2090 (3.3 T; 62% P).
- PCM2025 (0.4 T; -2% P).
- PCM2065 (1.5 T; -12% P).
- PCM2090 (2.3 T; -26% P).

The hydrologic components considered in this study are: rim inflows into the Central Valley from the surrounding mountains, groundwater, local runoff, and reservoir evaporation; however, the groundwater portion is the focus of this evaluation.

Climate change impacts on groundwater inflows and local runoff

To estimate the climate change impacts on groundwater inflows and local runoff, precipitation changes are partitioned into deep percolation and local runoff for each groundwater subbasin.

These changes are then added to corresponding historical groundwater and local runoff time series. It should be noted the unsaturated layer water balance and changes in stream-aquifer exchanges are not considered in this study.

To best represent the nonlinear historical relationship between monthly deep percolation and precipitation volumes for each groundwater subbasin, a cubic regression equation is used. These empirical equations are based on the Central Valley Ground and Surface Water Model (CVSGM) simulated data over the 1922 to 1990 period (USBR, 1997). Using its empirical equation based on precipitation changes for each climate change scenario, deep percolation changes are then estimated for each groundwater subbasin. For the six GCM scenarios, spatially and temporally varied monthly precipitation change ratios are used, and for the six other scenarios, the specified spatially and temporally uniform precipitation changes were applied for each month.

Central Valley Ground and Surface Water Model

In CVGSM, groundwater recharge (excluding operational deliveries to agricultural and urban demand areas) for each groundwater subbasin can be represented by:

Equation 5: $GW = DP + SA + BF + SS + LS + AR$

Where:

DP - deep percolation of precipitation, in billion of cubic meters (bcm) per month
SA - gains from streams, in (bcm) per month,
BF - gains from boundary flows (from outside the CVGSM modeled area), in (bcm) per month,
SS - gain in the subbasin from subsurface flows across basin boundaries, in (bcm) per month,
LS - seepage from lakes and bedrock in (bcm) per month,, and
AR - seepage from canals and artificial recharge, in (bcm) per month,

Changes in groundwater inflows are estimated by assuming all components of groundwater inflows are unchanged except for deep percolation from changes in rainfall. This can be shown as:

Equation 6: $GW^P = GW + \Delta DP$

Where GW^P is the change groundwater inflow for the groundwater subbasin and ΔDP is the change in deep percolation.

Results for groundwater inflows

The CALVIN model has 28 groundwater inflows; however, due to limited data, seven groundwater basins outside of the central valley were not studied. For all three GCM periods, groundwater inflows increased with the HadCM2 scenarios and decreased with the PCM scenarios. Since infiltration capacity limits deep percolation, most increased precipitation contributes to direct local runoff.

Results for Statewide Water Supply Availability
These results were combined with results for local runoff, reservoir evaporation and rim inflows (all evaluated in the article) in order to generate results for statewide water supply availability for each of the twelve climate scenarios. Results indicate that, on average, water availability for nine of the twelve scenarios decreased; however, for the HadCM2 scenarios, water availability increased throughout the year.

4.0 Comparison of Studies to Puget Sound Region. Can Comparisons Be Made?

Although this report presents the results of a number of different studies that investigate the potential impact of climate change on groundwater resources, it is clear that no study to date has focused on the Puget Sound or a region similar to the Puget Sound. Furthermore, the majority of the studies cited were completed in semi-arid climates that are very different to the Puget Sound. The study site with the most similar climatological and geological conditions to that of the Puget Sound Lowlands is that of the "Ponds" region in Eastern Massachusetts. The "Ponds" study site is located in a humid region, and is a stratified drift aquifer, consisting of sorted and layered sand, gravel, silt, and clay, that was deposited by glacial meltwater streams. For insight into how one might approach evaluating the impacts of climate change on groundwater resources, this is arguably the most relevant study to date.

In the Puget Sound Region, previous groundwater studies also provide insightful and useful information. Although no studies have been published in peer reviewed literature investigating the impacts of climate change on groundwater resources in the Puget Sound, there have been modeling studies on the aquifer systems that provide insight as to appropriate models for regional groundwater. The most notable study conducted in recent years was completed by Bauer and Mastin (1997). In this study, the authors used the Deep Percolation Model (DPM) to evaluate the direct recharge from precipitation through glacial till in three small catchments in the Puget Sound Lowlands. Because DPM was originally developed for eastern Washington, the authors modified the code to better incorporate the physical and geological features of the Lowlands, and this code is available today upon request from USGS (Vaccaro, 2007). Again in 2001, Bidlake and Payne (2001) used DPM to assess recharge from precipitation at a naval submarine base in Kitsap County, Washington.

5. Recommendations

Peer-reviewed articles concerning groundwater and climate change have been applied to a wide range of settings and these methodology and models used can serve as a guideline for future modeling studies in the Puget Sound region. These methodologies can incorporate the climatic impacted future scenarios created by the Climate Change Technical Committee as input to ensure consistency with on-going studies. This report concludes with some general recommendations for approaches, climate scenarios and models that can be used to evaluate the effects of climate change on groundwater recharge in the Puget Sound Lowlands. This is not an extensive or comprehensive set of suggestions, nor does it imply that there is only one correct method that can be applied to this region.

5.1 Approach

There are three basic approaches to evaluate the effects of climate change on groundwater. The appropriate approach depends on several factors including: the data available, the budget available, the level of detail required, and the decision framework that this information will support. The following section is a description of three possible approaches that can be taken to evaluate the effects of climate change on groundwater supply in the Puget Sound region.

5.1.1. Detailed Study

The first approach is a detailed study on a small number of selected watersheds that have available extensive data available including groundwater data, streamflow data, geological data and climate data. For this approach there are two options that are available. The first would be to use an integrated surface water – groundwater model to assess the impacts of climate change within a watershed. Alternatively, two types of models would potentially be necessary: a comprehensive groundwater model and surface water hydrology model that includes water diversions and returns and detailed surface/groundwater interactions. These models, driven by future climate scenarios developed for the region, could forecast the impacts of climate change on groundwater flows and levels. The resources required to develop such models would be considerable, depending upon the watershed chosen and the availability of past groundwater studies and data. The models would provide information at a highly refined level appropriate for inclusion in a detailed decision framework. The users would have to be cognizant of the uncertainties associated with the climate forecasts and the groundwater model to properly incorporate the results into appropriate decision-making.

5.1.2. General Overview Study

The second approach is to model groundwater recharge at a much lower level of detail and resolution, acknowledging that there is not sufficient groundwater data available (nor is there currently plans for collecting such data) to create a region-wide groundwater model. This approach would provide general information for situations in which such information might help inform a decision. Because the information would be general in nature, less basic data would be required. In some situations, this approach could provide useful information relative to anticipated trends in groundwater levels and availability, although it would likely not be sufficient for decision making at a detailed watershed scale. It is not clear whether such a model would be superior to simplified analytical estimates made by a groundwater hydrologist (Steve Nelson, personal communication, 2007). This approach would be less costly, but its application would require careful appreciation of its limitations in decision-making. Such consideration would be necessary to prevent misinterpretation or improper interpretation of the results.

5.1.3. Semi-detailed Study

The third option is to use a model to measure groundwater recharge at specified watersheds in the region. This option, while much less extensive than a detailed study, would provide estimates of groundwater recharge due to precipitation at specific sites. It would give much more realistic results for groundwater recharge due to precipitation at specific sites than would a general overview study. This approach, which has not been used to evaluate the effects of climate change on groundwater recharge in the region, has been used by the USGS on at least two specific occasions to model groundwater recharge at specific sites in the region (Bauer and Mastin, 1997; Bidlake and Payne, 2001). Again, care is in needed in interpreting the overall impacts of climate change on surface and groundwater if this approach was taken.

5.2. Groundwater Models

Depending on the purposes of the study, two types of models could be used. The first type of model needed is a model that evaluates recharge due to precipitation. Although numerous models have been used in the peer-reviewed literature, the Deep Percolation Model, or DPM, has been most extensively used in this region. DPM was developed in 1987 at the USGS by Bauer and Vaccaro. It was originally developed for eastern Washington, a semiarid region, but has since been modified for use in western Washington (Vaccaro, 2007). It is a daily water budget model for estimating groundwater recharge, where deep percolation is calculated as precipitation minus evapotranspiration minus direct runoff minus the change in soil moisture in the root zone.

The other useful model suggested is a groundwater flow model that can evaluate streamflow-groundwater interaction and boundary conditions. The most commonly used and well-known model in this category is MODFLOW or its Windows based companion, Visual MODFLOW. MODFLOW is a three-dimensional finite-difference groundwater model that was developed by the USGS and first published in 1984 (McDonald and Harbaugh, 1988). Visual MODFLOW is the commercially available version of MODFLOW and is not an open-source model. Visual MODFLOW simulates flow in a quasi-3D manner, and both steady-state and transient conditions can be modeled, as well as water-balance calculations (using Zone Budget) and particle tracking (using MODPATH). The model shares many of the features of MODFLOW although it is considered to be more user-friendly, and it provides some checks on unit compatibility.

5.3. Climate Scenarios and Methodology

The Climate Change Technical Committee has created Technical Memoranda that detail methodologies for including climate impacts into water resources planning. Incorporation of output from Global Circulation Models into regional groundwater impact studies should follow the methodology created by the committee and make use of referenced literature to ensure proper treatment of model uncertainty and climate impacts.

Datasets are now available locally for estimation of potential climate impacts. Both the Climate Impacts Group (CIG) and researchers working with the Climate Change Technical Committee have developed rich datasets that can be accessed freely via the internet. Although the data differ in spatial and temporal resolution, both datasets contain output from multiple GCMs downscaled to a local grid of one-eighth of a degree.

6. Conclusions

In the past decade, there have been numerous studies conducted evaluating the effects of climate change on groundwater resources throughout the United States and Canada. The most notable studies have been conducted in British Columbia, Canada; however, other studies have been completed in parts of Texas, eastern Massachusetts, California, and eastern Washington, as well as other places throughout North America. Unfortunately, because of the unique nature of the Puget Sound Lowlands aquifer system, there is no region that has been studied that is exactly similar to this region. Furthermore, the majority of the studies cited in this report were completed in semi-arid climates, dissimilar to that of the Puget Sound.

This report evaluates peer-reviewed studies relating to groundwater and climate change throughout Canada and the United States. The geography, physical features of the aquifer systems, climate and models used for each study are all investigated. In Section 4 previous studies are compared with potential studies of the Puget Sound Lowlands. Results of the review indicate that a wide range of groundwater impacts could result from climate change with some studies projecting negative impacts to groundwater recharge related to climate change and others predicting an increase in groundwater recharge. While the conclusions of each study vary, there are some general themes represented in several of the studies:

1) Increases in precipitation, projected for some regions by some GCM emission scenarios, influence the amount of recharge; however, in some situations, evapotranspiration, surface water exchanges, and changes to pumping are significant and have an off-setting influence on the groundwater system,

2) If changes in seasonal runoff directly translate to recharge, the projected changes in climate have minor impacts on deep aquifer recharge; however, this is highly site specific and there is no evidence to suggest that pattern or intensity of rainfall will not have an impact on deep groundwater recharge, and

3) Hydraulic conductivity and other site specific characteristics will continue to be important in calculating the relationships between flows in rivers and changes in groundwater levels.

In Section 5, recommendations are made for the Puget Sound region. These recommendations are not extensive or meant to be exclusive; however, they do provide some guidance as to possible steps that can be taken in this region to further evaluate the impacts of climate change on groundwater resources.

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8. Appendices

8.1 Overview of Groundwater Models Used in Studies

8.2.1. MODFLOW

MODFLOW is a three-dimensional finite-difference groundwater model that was developed by the USGS and first published in 1984 (McDonald and Harbaugh, 1988). MODFLOW has continually evolved since then with the development of several new packages. It is used for simulating common features in groundwater systems. Because of its ability to simulate a wide variety of systems, its extensive publicly available documentation, and its rigorous USGS peer review, MODFLOW has become the most widely used groundwater flow model in the world (Scientific Software Group, 1998).

As stated by the USGS, the following is a list of reasons for the widespread use and popularity of MODFLOW (USGS, 1997).

- The finite-difference method used by MODFLOW is relatively easy to understand and apply to a wide variety of real-world conditions.
- MODFLOW works on many different computer systems ranging from personal computers to super computers.
- MODFLOW can be applied as a one-dimensional, two-dimensional, or quasi-or full three-dimensional model.
- Each simulation feature of MODFLOW has been extensively tested.
- Data input instructions and theory are well documented.
- The modular program design of MODFLOW allows for new simulation features to be added with relative ease.
- A wide variety of computer programs written by the USGS, other federal agencies, and private companies are available to analyze field data and construct input data sets for MODFLOW.
- A wide variety of programs are available to read output from MODFLOW and graphically present model results in ways that are easily understood.
- MODFLOW has been accepted in many court cases in the United States as a legitimate approach to analysis of ground-water systems.

Steady-state and transient flow can be simulated in unconfined aquifers, confined aquifers, and confining units. A variety of features and processes such as rivers, streams, drains, springs, reservoirs, wells, evapotranspiration, and recharge from precipitation and irrigation also can be simulated. MODFLOW simulates ground-water flow in aquifer systems using the finite-difference method. In this method, an aquifer system is divided into rectangular blocks by a grid. The grid of blocks is organized by rows, columns, and layers, and each block is commonly called a "cell." For each cell there are several inputs that the user must specify including aquifer properties and information relating to wells, rivers, and other inflow and outflow features of the cell. MODFLOW uses the input data to construct a set of solutions that consists of head of every cell in the aquifer system at intervals called "time steps." In addition to water levels, MODFLOW also calculates the water budget for the system.

8.2.2 Visual MODFLOW

Visual MODFLOW is a commercially available groundwater flow model that solves the groundwater flow equation using block-centered finite-difference method. Unlike its predecessor, the USGS MODFLOW, it is not an open-source model. Visual MODFLOW simulates flow in a quasi-3D manner, and both steady-state and transient conditions can be modeled, as well as water-balance calculations (using Zone Budget) and particle tracking (using MODPATH). It shares many of the features of MODFLOW although it is considered to be more user friendly and it provides some checks on unit compatibility.

8.2.3. Deep Percolation Model

The Deep Percolation Model, or DPM, was developed in 1987 at the USGS by Bauer and Vaccaro. It was originally developed for eastern Washington, a semiarid region, but has since been modified for use in western Washington. It is a daily water budget model for estimating groundwater recharge, where deep percolation is calculated as precipitation minus evapotranspiration minus direct runoff minus the change in soil moisture in the root zone. Using DPM, all of the fluxes of water into and out of and changes in volume extending from the top of the foliage to bottom of the root zone are accounted for. For cases where unsaturated zones exist between the bottom of the root zone and the water table, the water flux out of the root zone is assumed to move vertically downward, recharging the saturated material below the water table.

While the water-budget method is conceptually simple, it can be difficult to implement due to temporal variations in the climate and spatial variations in soils, subsoils and vegetation that can exist within small areas. In order to account for these variations, DPM is usually applied at small, homogeneous catchments. The water budget is calculated on a daily basis; the results of which are summed over a multi-year period.

As previously mentioned, daily water-budget calculations are made for a number of land segments, or cells. For each cell, the following equation is applied at a daily time-step for a volume that extends from the top of the foliage to the bottom of the root zone:

Equation 8.1: $R = P - SE - PT - SRO - EI - (\pm SNO \pm SM \pm IS) \pm DS$

Where

R	=	deep percolation (recharge),
P	=	precipitation,
SE	=	soil evaporation,
PT	=	plant transpiration,
SRO	=	surface runoff,
EI	=	evaporation of intercepted water,
SUB	=	snow sublimation,
$\pm SNO$	=	change in snowpack,

$\pm SM$ = change in soil water in the root or soil zone,
$\pm IS$ = change in intercepted moisture storage, and
$\pm DS$ = deficit or surplus

Basic inputs into the model include daily minimum and maximum temperatures measured at one or more locations within the model and daily stream discharge from one gage. Algorithms are used to provide best estimates for weather variables within each cell. Similarly, daily precipitation and maximum and minimum temperatures are estimated for each cell, using distance-weighted methods, from data from nearby weather stations.

8.2.4 HELP/HELP3

HELP is a quasi-two dimensional, US EPA model used for predicting landfill hydrologic processes; however, HELP can also be used to estimate groundwater recharge rates. It simulates the daily movement of water into the ground, and accounts for precipitation, surface storage, runoff, evapotranspiration, vegetative interception and growth, unsaturated flow, and temperature effects (Schreoder et al., 1994). HELP requires the following input:

- Weather: precipitation, solar radiation, temperature, and evapotranspiration
- Soil parameters: porosity, field capacity, wilting point, and hydraulic conductivity
- Engineering design data: liners, leachate, runoff collection systems, and surface slope

HELP uses numerical-solution techniques to account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, and various engineering parameters. The natural water balance components that the program simulates include precipitation, interception of rainwater by leaves, evaporation by leaves, surface runoff, evaporation from soil, plant transpiration, snow accumulation and melting, and percolation of water through the soil profile.

The profile structure, initial moisture content, runoff, weather generator, and evapotranspiration must all be input into the model before beginning a model run. The structure can be multi-layered, consisting of a combination of natural (soil) and artificial materials (e.g. waste, geomembranes). Initial water content is specified before running simulations; these values can be user-specified or computed by the model. For runoff calculations, the area over which runoff can occur and the type of vegetation is specified. The rainfall-runoff processes in HELP are modeled using the USDA soil conservation curve-number method (USDA, 1986), and allows the user to adjust the runoff calculation to a variety of soil types and land management practices. Three different types of meteorological data must be provided as daily values: (1) precipitation, (2) solar radiation, and (3) mean air temperature. HELP also requires sets of parameters to simulate evapotranspiration. HELP uses these data to:

1. Calculate the volume of water flowing into the layered sequence, and simulate surface runoff, evaporation, vegetation growth and transpiration, and infiltration during warm periods.
2. Simulate surface storage, snowmelt, runoff, and infiltration during cool periods.

Daily data can be imported from a weather-data file for a particular meteorological station, or synthetically generated using the Weather Generator.

HELP model uses a multi-level procedure for calculating values for evaporation from snow, soil, and leaves, as well as transpiration based on type of vegetation. The parameters that require the user's input include: (1) evaporative zone depth, (2) maximum leaf-area index, (3) growing season start and end day, (4) average wind speed, and (5) quarterly relative humidity.

8.2.5. GWSIM IV

GWSIM IV is an updated version of GWSIM, a two-dimensional, finite-difference, groundwater model originally developed by Prickett and Longquist in 1971. GWSIM IV was updated in 1983 by Knowles and is specifically used for the Edwards Aquifer. Input data into the model include historical monthly pumping, recharge and beginning head levels. These are divided into appropriate cell locations. Outputs from the model include monthly springflows, ending head levels for each cell over the aquifer, and mass balance.

GWSIM IV is broken into grid cells and distinguishes among no-flow boundary cells, outcrop or recharge-zone cells, and artesian cells.