Predicted Impacts of Climate Change on Groundwater Resources of Washington State

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For more information contact:

Publications Coordinator
Environmental Assessment Program
P.O. Box 47600, Olympia, WA 98504-7600
Phone: (360) 407-6764

Washington State Department of Ecology - www.ecy.wa.gov

Headquarters, Olympia	(360) 407-6000
Northwest Regional Office, Bellevue	(425) 649-7000
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Cover photo: Mount Shuksan in the North Cascades National Park, from Hannegan Peak, Washington. Photo by Mark Henderson.

Predicted Impacts of Climate Change on Groundwater Resources of Washington State

by

Charles F. Pitz, Licensed Hydrogeologist

Environmental Assessment Program
Washington State Department of Ecology
Olympia, Washington 98504-7710

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Purpose of the Report

The purpose of this project was to evaluate how global climate change may impact or alter groundwater conditions in the coming decades. To support the analysis, recent scientific literature was distilled and synthesized. Where possible, I have attempted to describe recurrent or common themes in the available research, determine how the predicted changes might specifically manifest themselves in Washington State, and clarify uncertainties in the predictions. Based on the project findings, I also present recommendations for monitoring and assessment actions the Washington State Department of Ecology (Ecology) could undertake to prepare for and adapt to the changes that are predicted for state groundwater resources.

Acknowledgements

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Executive Summary

Purpose and Scope of Work

This report summarizes findings from an evaluation of how global climate change may impact groundwater resources in Washington State in the coming decades. Recent scientific literature was reviewed and synthesized to support the evaluation. Based on this analysis, recommendations are presented to help our state prepare for, and adapt to, the climate-related changes that are predicted for groundwater.

Although out of sight, groundwater is a highly valuable natural resource for Washington's citizens, economy, and environment. Throughout the state, groundwater provides a major source of water supply, sustains streamflows and wetland functions during biologically critical periods of the year, and helps to buffer the impact of short-term droughts.

Despite groundwater's importance, research into the likely impacts of climate change on Washington aquifer systems has lagged far behind surface water impact analyses. The lack of a comprehensive review of potential climate change impacts on groundwater conditions represents an important gap in our ability to respond to the challenges that lie ahead. This report represents an initial step to help fill that gap.

Climate Change Impacts on Groundwater Resources

Global-scale climate changes are unfolding at very rapid rates in comparison to historical patterns, and are expected to have far-reaching consequences for Washington's water resources. As an integral component of the hydrologic cycle, groundwater will not be immune to these changes. It is particularly important to understand that future groundwater responses to climate change will be superimposed on top of widespread and alarming problems with overdraft and groundwater quality that already exist in Washington. Climate change has the potential to magnify or accelerate these longstanding stresses. Concurrent with a predicted rise in demand for additional groundwater supply (driven by human population growth and diminishing summer streamflows), climate change is likely to greatly compound the challenge of sustainably managing state groundwater resources.

Absolute predictions of climate impacts on groundwater have a high level of uncertainty, and more research and field data are needed on this topic. Changes in local meteorological conditions related to global climate change can cascade a highly complex series of hydrologic-system responses over long timescales that are difficult to accurately model. Nonetheless, new technical tools are becoming available to help highlight the relative sensitivity of aquifers to the range of potential environmental changes predicted for the future. These tools clarify sources of uncertainty in the predictions, and greatly improve our understanding of the mechanisms and feedback loops most likely to alter state groundwater conditions.

Climate-driven changes in groundwater conditions and processes are predicted to play out most clearly in two key settings in Washington: (1) in arid and semi-arid areas where aquifer recharge rates are low and demand for groundwater for irrigation supply is high, and (2) in areas where snowpack melt plays a large role in groundwater recharge. While climate-related changes to groundwater recharge, storage, and baseflow discharge are all probable, the specific causes for the changes, and the nature and degree of the impact, will be a function of local conditions and water management choices.

Climate-driven changes in temperature and precipitation rates are likely to *directly* alter some important aspects of groundwater hydrology in Washington (particularly the timing and temperature of baseflow discharge to streams). Current research, however, suggests that stresses brought about by *indirect* societal-feedback responses to a warming climate are likely to pose the highest risk to the resource.

Climate Change and Water Management Choices

Of particular concern is the potential for a large, climate-driven increase in groundwater pumping. Significant decreases in summertime surface water availability and increases in water demand are predicted for the state in response to climate change. State aquifers are likely to be viewed as an important alternative supply to surface water, as we work to develop our response to these new stresses. However, if a substantial increase in the net volume of groundwater withdrawal is used to address these problems, there are likely to be strong and undesirable effects on groundwater storage, baseflow discharge to streams and rivers, groundwater-dependent aquatic ecosystems, and coastal aquifer water quality. Future water management decisions regarding groundwater use will play a dominant role in dictating the extent of climate impact on state aquifers and streams.

A summary of the key technical findings and recommendations from this evaluation are presented below.

Key Findings

1. Methods and considerations for evaluating climate change impacts on groundwater resources

- The technical methods for evaluating climate change impacts on groundwater have grown more sophisticated over time, but there is still a high degree of uncertainty in absolute response predictions.
- The preferred technical approach for developing predictions of groundwater response to climate change relies on the use of a series of linked numerical computer models. Long-term forecasts of future air temperature and precipitation conditions derived from large-scale atmospheric models are first scaled-down to a regional or local level. The downscaled climate values are used as an input boundary condition for a numerical model(s) of surface and subsurface water flow. This approach allows researchers to quantitatively estimate how a groundwater system is likely to respond to a predicted future climate scenario. The prediction uncertainty from this linked-model approach comes primarily from uncertainty in the initial large-scale climate forecasts used to force the model response.

- Studies of groundwater response to climate change are best used to highlight the relative sensitivity of aquifers to the potential range of meteorological changes predicted for the future. The findings from such studies can (1) improve our understanding of the mechanisms and feedback loops that are most likely to drive changes in groundwater conditions and (2) help define the possible groundwater-related climate impact outcomes our state is likely to face in the coming decades.
- To accurately predict the impact of climate change on groundwater conditions, it is critical to account for changes in groundwater use that may be an *indirect* societal-feedback response to a warming climate. Best estimates of anticipated changes in groundwater pumping or agricultural practices that are likely to occur in response to climate change need to be incorporated into future modeling analyses in order to provide credible predictions.

2. Climate change impacts on groundwater recharge and storage

- Although there is uncertainty in the absolute predictions of *direct* climate impacts on future groundwater recharge rates and storage volumes in the Pacific Northwest (PNW), the available research suggests that changes in the timing (and perhaps location) of recharge are more likely than large changes in average annual recharge amount. Direct climate-driven changes in long-term recharge rates (and therefore related groundwater storage conditions) are likely to be modest in comparison to natural variability.
- Areas of the PNW where snowpack and snowmelt play a large role in groundwater recharge are the most likely to see direct changes in recharge processes and rates.
- Driven by human population growth and declining summer streamflows, the potential for increases in groundwater pumping as an *indirect* response to climate change could have large consequences for state groundwater storage conditions. The indirect impact of pumping would likely far outweigh the direct consequences of climate-driven meteorological changes. Arid and semi-arid settings heavily reliant on snowmelt runoff for irrigation supply are the most at risk for pumping-related groundwater storage losses. The impacts of pumping on groundwater storage will likely unfold over significantly shorter timeframes than direct climate effects.

3. Climate change impacts on groundwater/surface-water interactions and baseflow discharge

- Changes in patterns of flow between the surface and subsurface may be among the earliest and most noticeable *direct* groundwater-related consequences of climate change.
- In response to climate-driven changes in snowmelt and recharge dynamics, there may be important shifts in the timing of groundwater discharge to some PNW streams, potentially leading to reductions in baseflow discharge during the latter half of the summer.
- The *indirect* impacts of climate change, most importantly the significant potential for an increase in groundwater pumping, could lead to large reductions in natural groundwater discharge in many settings, even if there are only modest changes to natural recharge.

- Hydrogeologic setting plays a key role in determining the streamflow recession and baseflow characteristics of a watershed, which can, in turn, significantly influence streamflow sensitivity to climate change, and regulate late-summer surface flow rates.

4. Climate change impacts on groundwater quality

- Research on climate change impacts on groundwater quality is limited, and predictions have a high degree of uncertainty.
- The *indirect* impacts of climate change are more likely to drive groundwater quality problems than direct impacts.
- Published studies on this topic suggest that climate change is likely to result in increased rates of leaching of soluble contaminants such as nitrate.

5. Climate change impacts on groundwater temperature

- Contrary to commonly held assumptions, recent research suggests that groundwater temperatures may be more sensitive to climate warming than previously thought.
- Warmer groundwater temperatures could have significant, negative consequences on groundwater-dependent aquatic habitats. Groundwater discharge may not buffer stream temperatures as much as assumed in the past.
- Modeling studies of stream-temperature sensitivity to climate warming should account for the potential for a substantial increase in groundwater-discharge temperatures in the future.

6. Impacts of sea-level rise on groundwater

- Although climate-driven changes in sea-level position would increase the potential for sea-water intrusion into coastal aquifers, poorly managed near-shore groundwater pumping is likely to continue to be the dominant factor driving intrusion in most coastal communities. Increases in near-shore pumping rates in response to climate change could further impact coastline areas that have a demonstrated sensitivity to saltwater intrusion.
- The direct impacts of sea-level rise (saltwater intrusion and saltwater inundation) on groundwater are likely to be largest in settings with very low topographic relief and very low hydraulic gradients between freshwater and marine water (<0.001). In Washington, coastal aquifers south of Point Grenville are the most likely to experience future problems from sea-level rise.

Recommendations

- Preventing further groundwater storage losses, and the hydrologic, biologic, and surface water quality consequences associated with such losses, should be a critical priority for state water managers in the coming years.
- Water resource managers responsible for overseeing the sustainability of Washington State aquifers will need to account for a range of possible hydrologic responses to climate change in their decision-making and water-allocation planning.

- The changes and stresses facing state aquifers in the future, and the high level of uncertainty in predicting the absolute responses to those pressures, highlight the need for a rigorous, long-term, reliably-funded, and strategic groundwater monitoring program for Washington State.
- The highest priority information-need for groundwater is accurate data about state groundwater storage status and trends, with a particular focus on how groundwater pumping is affecting state aquifers. Improved monitoring of statewide groundwater storage changes will not only provide the information required to make defensible and informed choices about water supply, but will also help scientists track and forecast closely-related changes in recharge and baseflow discharge (hydrologic processes that are intimately connected to storage).

Technical recommendations

In light of the findings of this evaluation, the following summary recommendations are offered.

Data consolidation

- Continue consolidating and standardizing Ecology-related groundwater monitoring information:
    - Use the groundwater module of Ecology's Environmental Information Management data system (EIM-Groundwater) to centrally manage all groundwater data collected by all Ecology programs conducting or overseeing field monitoring.
    - Adopt agency-wide minimum data quality standards for all groundwater monitoring measurements and samples collected by Ecology employees.
    - Require all external organizations collecting groundwater monitoring data using state funding to meet Ecology data quality standards and import the monitoring information to the EIM-Groundwater system.

State groundwater monitoring council

- Establish and fund a state groundwater monitoring council to improve data sharing, standardize data quality, and leverage existing monitoring efforts to the maximum extent possible. Include representatives from Ecology, U.S. Geological Survey, Washington Dept. of Agriculture, Washington Dept. of Natural Resources, Washington Dept. of Health, and local agencies or organizations conducting ongoing groundwater monitoring at the basin or sub-basin scale:
    - Use the groundwater monitoring council to identify and prioritize monitoring gaps.
    - Develop cooperative agreements for use of external-agency (non-Ecology) groundwater data for statewide assessment purposes.
    - Expand the function of the EIM-Groundwater system to allow import of groundwater monitoring data collected by Washington State government agencies other than Ecology. Encourage the use of the EIM-Groundwater system as the central groundwater data management tool for all state agencies.

Groundwater monitoring and assessment

- Establish a permanent, formal state monitoring and assessment program to track groundwater storage changes and trends. Dedicate long-term funding and staff to the program activities.
    - In cooperation with external partners participating on the monitoring council, collect, synthesize, and assess groundwater water-level data across Washington to support ongoing evaluation of state aquifer storage conditions. Focus monitoring primarily in areas that have shown long-term water level declines or are experiencing an increase in net groundwater pumping.
    - Assemble, collect, and assess groundwater-usage data to support interpretation of groundwater storage changes.
    - As appropriate, incorporate long-term ambient monitoring data for key groundwater quality parameters of concern (nitrate, chloride, and temperature) to track trends in large-scale water quality conditions over time.
    - On an annual basis, report the findings of the storage and water quality status-and-trends assessment to the public and the state legislature.
- Support the development and ongoing operation of the USGS Washington Climate Response Network to track baseline conditions for groundwater storage changes in areas away from pumping effects.
- As a follow-up to Pitz and Sinclair's 1999 analysis, assess and continue to track long-term trends in baseflow discharge across Washington using existing streamflow data records. Use the findings from the groundwater storage assessment to inform the baseflow analysis and help forecast baseflow conditions in future years.

Modeling and remote sensing

- Continue to support efforts to apply and improve numerical models to forecast climate change impacts on groundwater in Washington. Due to the potentially very long timeframes required for a change in climate condition to be fully manifested in larger scale, multi-layer aquifer systems, models will be an important supplemental tool to empirical field measurements.
    - Use, or where necessary update, existing numerical models of state aquifer flow systems to test climate change impacts on groundwater storage and baseflow discharge. Models that are designed to closely couple groundwater and surface-water processes are the most likely to provide accurate predictions of groundwater stress response to climate change.
    - In cooperation with water managers, hydrologists, agricultural economists, and policy makers, develop or refine forecasts for future state pumping and irrigation scenarios. Incorporate representation of these forecasts into all modeling analyses conducted to assess future climate change impact on groundwater.
- Explore the use of emerging remote-sensing tools to improve tracking of large-scale changes in state groundwater storage conditions.

Background

In tandem with observations of rising greenhouse gas concentrations in the atmosphere, scientists have reported that significant changes in global temperatures and atmospheric circulation patterns have occurred across the earth over the past 50 or more years. Even more profound modifications of climate and planetary ice cover, and associated shifts in sea-level position and seasonal weather patterns, are predicted through at least the end of the 21st century (IPCC, 2013; Melillo et al., 2014; Blunden and Arndt, 2015).

Global-scale atmospheric changes are unfolding at very rapid timescales in comparison to historical patterns, and are directly affecting environmental conditions in Washington State (Snover et al., 2013; Dalton et al., 2013; Mauger et al., 2015; Georgakakos et al., 2014; Mote et al., 2014; Mote and Salathé, 2010; Salathé et al., 2014). These changes are causing important shifts in regional hydrologic processes (Barnett et al., 2008; Dettinger et al., 2015a), which are expected to have far-reaching consequences for both state water resource supply and management, and for aquatic ecosystem function.

Snover et al. (2013) and Mote et al. (2014) presented observations describing how the Pacific Northwest (PNW) hydroclimatology has changed over the past 100+ years:

- Average temperatures have risen by +0.7°C (+1.3°F) since 1895.
- The frost-free season is now 35 days (±6 days) longer than it was in 1895.
- Annual snowpack has shown an overall decline (~20%) in the Washington Cascades since the mid-20th century, and the spring snowmelt season is occurring up to 30 days earlier.
- The peak of spring runoff is occurring earlier in the year for many snowmelt-driven streams across the state.

These authors also provided sobering projections of changes expected in the coming decades for the PNW[1], including:

- Average annual temperatures are predicted to rise between +1.1 and +4.7°C (+2.0 and +8.5°F) by the 2050s, with the largest increases in the summer.
- April 1 snowpack is predicted to continue to decrease by a minimum of -38% to -46% by the 2040s, and the average elevation of the rain-snow transition zone will rise.
- Even though comparatively small changes are predicted for annual precipitation amounts (particularly in comparison to natural variability), the number of days with more than 1 inch of rain (i.e., intense rainfall events) are predicted to increase by as much as +13%.
- Shifts in seasonal precipitation amounts are predicted, with models forecasting generally drier summers (up to a -30% reduction in summer rainfall) and wetter winters (up to a +7% rise in winter precipitation).

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[1] Mauger et al., 2015 present more recent climate projections specifically for conditions in the Puget Sound basin. Although the statistics vary slightly from previous regional forecasts, their findings essentially match the predicted patterns of change described earlier.

- In response to reductions in glacial area and mountain snowpack, and changes in precipitation form and timing (mid-elevation areas becoming increasingly rain-dominated), many streams and rivers driven by snowmelt will experience a continued shift in peak flow to earlier in the year. There will be significant reductions in minimum summertime flows.
- Sea level is predicted to rise along Washington State coastlines by at least +10 to +142 cm (+4 to +56 inches) by 2100[2].

The hydrologic cycle is directly affected by (and can rapidly respond to) changes in climatic conditions. As regional temperatures and precipitation patterns evolve in response to planetary warming, it is critical to anticipate the likely stresses and modifications that could be imposed on water budgets and water fluxes, both above *and* below the ground surface. Developing best estimates of what lies ahead will help ensure a sustainable supply of water for our homes, livelihoods, and natural environment in the future.

Thanks to important contributions by scientists at the University of Washington's Climate Impacts Group (CIG), the U.S. Geological Survey (USGS), and many other institutions, there is a strong body of technical studies predicting how climate change is likely to impact state surface-water resources (e.g., Elsner et al., 2010; Snover et al., 2013; Mastin, 2008; Markstrom et al., 2012; Safeeq et al., 2013; Safeeq et al., 2014a; Stewart et al., 2005; Hamlet et al., 2013; Tohver et al., 2013; Salathé et al., 2014; Mantua et al., 2010; Voss and Mastin, 2012; Brekke et al., 2009). Despite the critical role it plays for water supply and ecosystem support, research into the potential impacts of climate change on *groundwater* in the PNW has been significantly more limited.

Groundwater is an integral component of the hydrologic cycle, frequently in close interconnection with surface-water features and, itself, sensitive to long-term changes in both precipitation and temperature. Groundwater is also a highly valuable natural resource for Washington's citizens, economy, and environment. Among other functions, state aquifers:

- Provide a major source of water supply for human consumption, agriculture, and industry (Lane and Welch, 2015).
- Help to sustain streamflows and wetland functions (often during the most critical biological season) (Pitz and Sinclair, 1999).
- Buffer the impact of short-term droughts[3].

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[2] Readers should note that newly published research suggests that longer term global sea level rise of a significantly greater magnitude than previously predicted (up to ~16-30 ft rise; 5-9 m) is possible, based on analysis of paleoclimatic data, and climate modeling evaluations. Technical debate on these findings is still ongoing (see Hansen et al., 2015). Additional research has also suggested that sea level declines may be possible along specific portions of the Washington coastline (e.g., the northwestern coast of the Olympic Peninsula) due to tectonic uplift (Snover et al., 2013).

[3] See for example: http://www.ecy.wa.gov/programs/wr/cro/yrb-emer-drought-auth.html; Washington RCW 43.83B.410

As the PNW population grows, and access to unallocated surface-water supply shrinks, demand for additional freshwater, particularly groundwater, is likely to increase significantly through at least the first half of the 21st century (Brown et al., 2013; Foti et al., 2012; Green et al., 2011; WDOE, 2011; WOFM, 2014; Lindsey et al., 2013).

Most of the recent climate change impact reports for Washington State include only limited mention of groundwater. When groundwater is discussed, it is often associated with suggestions that state aquifers may provide an alternative, mitigating supply of water as summer stream flows decline (CIG, 2009; WDOE, 2012; Dalton et al., 2013). The out-of-sight nature of groundwater can lead to the false assumption that state aquifers will largely be immune from the effect of climate change and/or can serve as a large-scale supply of new water. However, a growing body of literature suggests climate change could introduce significant new pressure on an already challenged and diminishing resource. The lack of a comprehensive evaluation of predicted groundwater behavior and vulnerability to climate change represents an important gap in Washington's ability to prepare for the challenges that lie ahead.

Groundwater is already a highly stressed resource in Washington State, and state aquifers have not been managed in the past in a sustainable manner. In addition to existing large-scale concerns regarding degraded groundwater quality (Carey and Cummings, 2012; Ryker and Frans, 2000; USEPA, 2013), there is a growing recognition of alarming trends in groundwater overdraft throughout many arid and semi-arid areas of eastern Washington (Burns et al., 2012; Vaccaro et al., 2015; Lindsey et al., 2013; PBAC, 2014; Konikow, 2013). The information reviewed during this project suggests that climate change has the potential to greatly compound and even accelerate these existing concerns.

In late 2007, a subcommittee of the CIG published a limited literature review on the impacts of climate change on groundwater resources, with an emphasis on the Puget Sound area (Alexander and Palmer, 2007). Since then, technical research and modeling analyses on how groundwater systems are predicted to respond to changes in global and regional climate have advanced significantly. The focus of the current effort was to assemble and evaluate the recent scientific literature on this topic to help inform state water managers and technical staff of the nature and scope of the changes to anticipate for state groundwater.

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Guidelines for the Evaluation

Focus on Recent Research

To provide a framework for this evaluation, and account for the rapid developments in climate change research, I evaluated peer-reviewed technical articles or reports that were published between 2008 and early 2016. This timeframe is intended to highlight information that has become available since publication of the 2007 Alexander and Palmer review.

The methods for examining this question have evolved rapidly and are becoming increasingly sophisticated over time. In addition, significant advances have been made in the spatial resolution and predictive capability of the global- and regional-scale atmospheric circulation models used as a basis for climate impact studies. In response, I have incorporated few findings from papers prior to 2008. In certain cases, the approaches and findings described by papers published even as recently as the late 2000s may no longer be considered accurate by some, but these references have nonetheless been included here for the sake of completeness.

Focus the Evaluation on Washington State

The primary geographic focus of this analysis is on climate change impacts on groundwater within the boundary of Washington State. In reality, a very limited number of technical papers or reports have been published since 2008 that address this question specifically for Washington. For certain subtopics (for example, groundwater quality impacts of climate change; groundwater impacts of sea-level rise), no journal papers were found that address state-specific analyses. As a result, my evaluation incorporates the findings from a variety of additional papers that may address study areas outside of Washington, predict impacts at larger scales, or examine climate impacts on groundwater using theoretical approaches.

Since the response of watershed hydrology to climate change is ultimately dictated by the unique combination of local-scale meteorological and physiographic conditions, I prioritized the findings of the work incorporated into the evaluation in a hierarchical order. Research studies specific to Washington State received highest priority. These were followed in order by publications for the PNW at large, North America, study areas outside of North America, and finally, papers that address climate impacts on groundwater at a global scale. While specific predictions of groundwater response to climate change for areas outside the state may not always apply to Washington, recurrent themes and lessons learned can support the findings presented here. Papers describing areas outside of the PNW can also potentially serve as analogues for specific regions of our state.

Provide Annotated Summaries for Select Research Papers

Appendix A contains annotated summaries of many of the papers reviewed during this effort for readers interested in learning more about the details of specific technical studies. Since 2008 there have also been a number of broad survey papers or reports published that provide valuable high-level discussions of predicted climate change impacts on groundwater (Dragoni and Sukhija, 2008; Bovolo et al., 2009; Loaiciga, 2009; Doll, 2009; Kundzewicz and Döll, 2009;

Earman and Dettinger, 2011; Green et al., 2011; Zhou et al., 2010; Triedel et al., 2012; WRF, 2012; Taylor et al., 2013; Famiglietti, 2014; Klove et al., 2014; Pike et al., 2010; Chang and Jung, 2010; Georgakakos et al., 2014; Gurdak et al., 2009; Bloomfield et al., 2013; Clifton et al., 2010; Franssen, 2009; UNESCO, 2008; Meixner et al., 2016). Synopses of these papers have not been included in Appendix A, but important concepts have been incorporated throughout the findings presented here.

Include Evaluation of Climate Change Impacts on Groundwater/Surface-Water Interactions

Although groundwater is the central focus of this evaluation, the close interconnection between groundwater and surface-water resources cannot be ignored. Over the course of the past five years, research on the hydrologic impacts of climate change has increasingly recognized that responses of groundwater systems will likely have a significant bearing on downgradient surface flows and water quality, and vice versa. In this context, I have included findings from papers that discuss how changes in groundwater discharge processes, and the hydrogeologic conditions of a watershed, are predicted to affect streamflows, spring flows, and surface-water temperatures in the PNW.

Focus on Building a Technical Understanding of the Problem

This evaluation is focused on gaining a better technical understanding of the mechanics of groundwater response to global climate change, and on identifying the new *consequences and vulnerabilities* that these changes may impose on state water resources. The report does not discuss groundwater management or policy solutions, or propose groundwater-related adaptation strategies (such as engineered aquifer storage and recovery systems) that might help the state respond to climate-driven water shortages. The importance of the role of monitoring climate-related changes in state aquifers as they unfold is, however, highlighted in the recommendations section.

Summary of Findings

1. Methods and Considerations for Evaluating Climate Change Impacts on Groundwater Resources

Key Findings

- The technical methods for evaluating climate change impacts on groundwater have grown more sophisticated over time, but there is still a high degree of uncertainty in absolute response predictions.
- The preferred technical approach for developing predictions of groundwater response to climate change relies on the use of a series of linked numerical computer models. Long-term forecasts of future air temperature and precipitation conditions derived from large-scale atmospheric models are first scaled-down to a regional or local level. The downscaled climate values are used as an input boundary condition for a numerical model(s) of surface and subsurface water flow. This approach allows researchers to quantitatively estimate how a groundwater system is likely to respond to a predicted future climate scenario. The prediction uncertainty from this linked model approach comes primarily from uncertainty in the initial large-scale climate forecasts used to force the model response.
- Studies of groundwater response to climate change are best used to highlight the relative sensitivity of aquifers to the potential range of meteorological changes predicted for the future. The findings from such studies can (1) improve our understanding of the mechanisms and feedback loops that are most likely to drive changes in groundwater conditions, and (2) help define the possible groundwater-related climate impact outcomes our state is likely to face in the coming decades.
- To accurately predict the impact of climate change on groundwater conditions, it is critical to account for changes in groundwater use that may be an *indirect* societal-feedback response to a warming climate. Best estimates of anticipated changes in groundwater pumping or agricultural practices that are likely to occur in response to climate change need to be incorporated into future modeling analyses in order to provide credible predictions.

Developing accurate predictions of how groundwater resources are likely to respond to climate change is among the most challenging technical problems in groundwater science today. Studies of climate impact on groundwater can require the integration of expertise over a wide range of technical disciplines, including meteorology and climatology, remote-sensing analysis, statistical analysis, and numerical modeling of fluid (and energy) movement both above and below the ground surface. In many cases, such evaluations also require access to very large, spatially and temporally distributed data sets that quantify climatic, landscape, and subsurface conditions.

Since groundwater systems are highly variable in their hydrogeologic setting and hydraulic characteristics, each aquifer system will respond to climate change in a unique and complex way, requiring careful consideration of spatial scale when evaluating climate impact. Impact predictions must be made at the multi-decadal to even century-long timescale, and must attempt to distinguish predicted changes in groundwater conditions that are due to long-term climate change from those that are related to human-activity or natural climatic cycles [e.g., the El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO)](Gurdak et al., 2009; Green et al., 2011; Bredehoeft, 2011; Loaciga, 2009; Kuss and Gurdak, 2014).

Climate response analyses are additionally challenged by the need to not only accurately predict the hydrologic impact of the *direct* changes that do occur in the climate (e.g., changes in temperature, precipitation, and ET rates), but to also properly anticipate how the many *indirect* changes and feedback loops that arise in response to that climate will alter hydrologic processes (e.g., *natural* changes in vegetation cover or wildfire frequency; *anthropogenic responses* in land use, farming practices, and groundwater extraction). Indirect feedback responses can potentially amplify the impact of meteorological changes on groundwater systems and significantly alter groundwater recharge, storage, and discharge conditions.

The central goal of most of these evaluations is to develop accurate predictions of how recharge rates may change in the future (i.e., changes in timing, location, and amount of recharge). Given the complexity and cost of measuring recharge over the long term (even in the absence of climate change), it is one of the least-monitored and least well-understood physical parameters in groundwater hydrology. In most cases, recharge is either calculated directly by water-budget modeling methods (e.g., using the HELP, DPM, PRMS, SWAP, or VIC models), or estimated as a residual value during groundwater flow model calibration.

Attempts to model the impact of climate change on recharge are complicated by the fact that recharge rates do not show a linear relationship to changes in precipitation; a complex set of terrestrial controls *filter* or modify how changes in meteorological conditions ultimately manifest changes in subsurface infiltration (Healy, 2010; Georgakakos, 2014). In addition, experience has shown that even when numerical hydrologic models are well-calibrated to current conditions, they frequently fail to provide accurate estimates of future outcomes (even in the absence of rapid climate shifts).

The combined challenges described above suggest that predictions of impacts of global-scale atmospheric changes on local-scale groundwater processes are likely to have a high degree of uncertainty (Earman and Dettinger, 2011).

While a variety of technical methods for predicting climate impacts on groundwater have been used over the past 8-10 years, most of the studies reviewed adopted one of four major approaches described in more detail below:

1. Using *empirical relationships* identified between historical climate and groundwater monitoring records as an analogue for future groundwater responses to climate change,
2. Using *analytical models* to theoretically examine groundwater response(s) to changes in climate or sea-level position,
3. Applying a domain-wide *change factor* to an existing groundwater flow model to evaluate the sensitivity of a groundwater system to a different climate regime, or

4. Using meteorological conditions from global- or regional-scale atmospheric circulation models as forcing input values for basin-scale water balance and flow models (referred to here as the *top-down linked modeling* approach).

Empirical Approach

Evaluating the historical record to gain insight into how groundwater recharge, aquifer storage, and baseflow discharge have responded in the past to significant longer-term changes in climate is a least commonly used approach in the literature reviewed (e.g., Allen, 2010; Liu et al., 2013; Safeeq et al., 2013; Stoll et al., 2011b). While the historical record can reveal correlations between distinct climate patterns or cycles and a subsequent groundwater process response, there are a number of potential downsides to the "past as an analogue for the future" concept.

The expectation that anthropogenically-driven climate change will unfold over a century or longer, the long timeframes necessary for complete groundwater response to those changes, and the need to account for natural decadal-scale climate cycles such as the PDO, all suggest that very long record sets are required for this type of analysis. Such record sets may be available for some Washington rivers and streams, but long-term, continuous groundwater monitoring data sets are significantly more limited (particularly in areas of aquifer systems that could be the most likely to show early, easily-attributed response to direct changes in climate).

Perhaps even more importantly, the past might not accurately reflect how the hydrologic cycle is likely to respond to the non-stationary (and likely non-linear) climatic conditions anticipated to unfold through the end of the 21st century (Hirsch, 2011; Milly et al., 2008; Milly et al., 2015). For example, there may not be an equivalent in the historical climatic record that reflects the longer-term changes that many researchers predict in precipitation intensity (a meteorological factor that can play a significant role in groundwater recharge). The historical record may also lack a precedent for the *cumulative* impacts of the long-term shifts in climate and hydrology anticipated in the future.

Using the historical record to predict future response also assumes that many of the non-meteorological factors that influence groundwater dynamics will largely be the same in the future as they were in the past. However, the significant changes in these variables that have occurred in Washington State in recent decades (population growth, land-use and land-cover change, expansion of groundwater pumping) largely violate that assumption. In addition, as many authors have noted, development of reliable predictions of groundwater responses to climate change requires accurate representation of the wide range of anthropogenic feedback or adaptation responses that are likely to occur as the climate warms (e.g., changes in irrigation practices, acceleration of aquifer pumping). These types of feedback responses may be missing or unquantifiable in historical records, suggesting that past aquifer response to a specific change in precipitation or temperature may simply not accurately represent how the future will unfold.

Analytical Modeling

The use of theoretical analyses of groundwater response to climate change has mostly been applied to the question of sea-level rise. For example, authors such as Werner and Simmons (2009), Webb and Howard (2011), and Ferguson and Gleeson (2012) have used various analytical models to run sensitivity analyses on which hydrologic factors (e.g., recharge rate, effective porosity, aquifer dimensions, hydraulic gradient) have the greatest effect on how (and which) aquifers respond to sea-level change. Although this technique can help to identify settings that are likely to be the most vulnerable to changes in sea-level position, the use of idealized algorithms for modeling (e.g., assuming isotropy and homogeneity in aquifer properties, or steady state horizontal flow) prohibits the use of such tools for the development of absolute predictions for any specific setting.

Applying Climate “Change Factors” to Numerical Flow Models

Several evaluations specific to climate change impacts on Washington State groundwater have used a “change factor” approach to examine how an aquifer system might respond to a theoretical shift in climate regime. This approach typically involves testing system response to the modification of a single boundary condition in a numerical model of groundwater flow. For example, after building and calibrating current-condition groundwater flow models for two western Washington aquifer systems, Johnson and Savoca (2011; Skagit River Basin), and Johnson et al. (2011; Chambers-Clover Creek watershed) ran additional steady-state model scenarios to test the groundwater response to a domain-wide reduction in annual recharge (in both cases: -20%). These types of model parameter change factors were intended to evaluate aquifer sensitivity to a possibly drier future. They were not, however, based on a specific climate change prediction for the study areas in question. In many cases this approach may fail to fully account for the feedback loops that can arise when there is a significant shift in a major hydrologic variable.

Top-down Linked Modeling

In the past decade, researchers have increasingly relied on the use of a linked modeling approach to the problem – i.e., using a suite of mathematically-coupled numerical models to develop “top-down” evaluations of future groundwater response to specific global- or regional-scale climate model predictions. With this approach, the output values from one model serve as boundary-condition input values for a subsequent model, through the entire hydrologic cycle. While the technical methods and level of complexity vary widely from study to study, most of these studies follow a similar, step-wise process:

1. Future temperature and precipitation predictions from a larger-scale atmospheric circulation model, based on an accepted global carbon emission scenario, are downscaled (spatially refined) to the basin or sub-basin scale.
2. The downscaled meteorological predictions are used as inputs for a numerical water/energy budget model to estimate surface and near-surface hydrologic response to the predicted change in climate. This model step is used to partition predicted precipitation between runoff, evapotranspiration (ET), infiltration, interflow, and recharge, as a function of climate and landscape conditions.
3. The predicted future groundwater recharge estimates are in turn used to define forcing boundary conditions for a numerical model of subsurface flow. Modern modeling studies track the return of that subsurface flow back to the surface to maintain mass conservation.

As study of the hydrologic impacts of climate change has evolved, researchers have increasingly recognized that a linked numerical modeling approach is the best method for capturing (and revealing insights into) the highly complex interactions and feedback loops inherent to the problem. Each step in this process, however, requires important decisions about data handling and model choice, and can introduce additional uncertainty into the predictions. For example:

- What specific atmospheric circulation model(s) should be used?
- What future carbon emission scenario(s) should be used?
- What timeframe should be used for prediction?
- What method should be used to downscale the climate data?
- Are spatially and temporally distributed climate data values required?
- What modeling approach should be used to estimate near-surface soil-water-energy flux and recharge rate?
- What modeling approach should be used to characterize groundwater flow?
- How should groundwater and surface water be integrated numerically?
- Should a transient or steady state model condition be used?
- How should indirect anthropogenic feedback responses be represented?

Studies using linked models have become increasingly sophisticated over time. Earlier efforts typically derived future climate predictions from only one or two global-scale general circulation models (GCM) based on a single carbon emission scenario, applied simple change factors to stochastic weather generators (in part to help represent historical fluctuations in meteorological conditions), and modeled surface and subsurface water flow processes in an uncoupled manner (i.e., where surface hydrologic processes are compartmentalized or mathematically separated from subsurface processes, potentially ignoring mass conservation between domains; for example, see Huntington and Niswonger, 2012 for further discussion).

Over time, researchers have adopted more advanced (and resource-intensive) methods of data processing and model integration. A set of best practices has been proposed for linked modeling efforts intended to evaluate climate impacts on groundwater resources (Holman et al., 2012). For instance, to account for the wide variation and uncertainty in global-scale predictions of future temperature and precipitation, many authors now rely on climate data derived from suites of multiple GCM/carbon emission scenario model combinations. A recent U.S. Bureau of Reclamation groundwater modeling analysis, for example, used meteorological predictions from a suite of 112 GCM scenarios, ultimately categorized into broad climate-outcome prediction classes (e.g., greater warming/drier climate, less warming/wetter climate, median condition; USBR, 2014).

A number of papers have raised concern about the larger errors introduced into climate impact predictions by the geostatistical downscaling procedures used by many researchers to apply global climate forecasts to a local scale hydrologic analysis. These procedures rely on developing a statistical relationship between atmospheric variables predicted by GCMs (typically 500 km x 500 km grid spacing) and local meteorological conditions (Holman et al., 2009; Holman et al., 2012; Scibek et al., 2008; Smerdon et al., 2010; Allen et al., 2010a; Stoll et al., 2011a; Toews et al., 2009). As technical advances have been made in climate science, dynamical downscaling techniques have been adopted to produce higher-resolution, regional-scale circulation models (RCM; typically 50 km x 50 km grid spacing) that simulate weather physics at a scale better suited for hydrologic modeling. Regional scale dynamical models use output from GCMs as boundary condition input to a more finely-spaced climate model grid to improve numerical representation of local topographic and storm effects. These higher-resolution tools have improved the accuracy of the initial meteorological predictions used to feed models of water and energy flux between soil, vegetation, and the atmosphere (e.g., Li et al., 2015).

Procedures for modeling recharge processes and rates have also grown in sophistication. Earlier studies, for example, relied on software such as the USEPA's HELP model. More authors (e.g., Huntington and Niswonger, 2012; USBR, 2014; Frans et al., 2011; Vaccaro et al., 2015) are now adopting advanced basin-scale, distributed water-energy budget models such as PRMS or DPM. These models can improve representation of the complex interconnections between the large number of factors that affect soil moisture, ET, and recharge responses to climate across a watershed (e.g., topography, elevation, meteorological variables, soil properties, vegetation, water table depth, snowpack and soil freeze/thaw processes, hydrogeologic setting, water use efficiency of plants, diffuse vs. focused recharge phenomenon). In addition to using a stochastic weather generator to produce a range of GCM meteorological predictions for modeling, Ng et al. (2010) applied a probabilistic (Monte Carlo) approach to account for uncertainties in the key landscape variables such as vegetation and soil properties that control recharge. The use of these advanced modeling approaches has allowed the development of more accurate, spatially- and temporally-distributed estimates of recharge for use as input to subsurface flow models.

To improve the calibration of stream discharge predictions in response to climate change, some researchers have modified land-surface hydrologic models such as the VIC, DHSVM or SWAT programs to simulate groundwater infiltration and return flow processes (e.g., Liang et al. 2003; Pfannerstill et al., 2013). Jin and Sridhar (2012), for example, developed predictions of potential climate-driven changes in recharge in the Spokane Valley-Rathdrum Prairie Aquifer system using the SWAT model. A number of authors, however, have observed important limitations in the predictions produced by such modeling tools in settings where groundwater and surface-water interactions or deep groundwater storage play a large role in watershed hydrology (Liu et al., 2013; Safeeq et al., 2014a; Safeeq et al., 2014b; Maxwell and Kollet, 2008; Wenger et al., 2010).

Recently, authors have increasingly adopted fully-integrated numerical models (e.g., GSFLOW, ParFlow, HydroGeoSphere, or MIKE-SHE) that explicitly couple surface and subsurface flow mathematically, and represent saturated-zone fluid movement using three-dimensional finite element or finite difference equations. Such integrated approaches are allowing an improved understanding of important feedback loops between the surface-water and groundwater environments key to many settings (Huntington and Niswonger, 2012; Kollet and Maxwell, 2008, Ferguson and Maxwell, 2010; Ferguson and Maxwell, 2012; Stoll et al., 2011a; Kidmose et al., 2013; Van Roosmalen et al., 2009; Goderniaux et al., 2010; Surfleet and Tullos, 2013; Maxwell and Kollet, 2008; Sultana and Coulibaly, 2010).

Over time, many researchers have also come to understand the critical role *indirect* climate feedback responses can play in developing accurate predictions of groundwater response to climate change (e.g., vegetation and crop water demand responses to higher temperatures and ET rates, increased summer demand for water supply, land use changes, changes in irrigation practices and length of growing season). As a result, authors such as Stoll et al. (2011b), Allen (2009), Toews and Allen (2009b), USBR (2014), Van Roosmalen et al. (2009), and many others have incorporated representations of future indirect climate responses into their modeling analyses. Additional modeling tools such as the ModFlow Farm Process model, for example, have been used to modify model pumping rates to represent future increases in crop water demand under warmer, drier growing-season conditions (e.g., Hanson et al., 2012).

Despite the technical advances that have been achieved, nearly all authors acknowledge the high degree of uncertainty that remains in the predictions derived from linked models (e.g., Scibek et al., 2008; Allen, 2009; Allen et al., 2010a; Vaccaro et al., 2015; Jin and Sridhar, 2012; Markstrom et al., 2012; Barron et al., 2010; Van Roosmalen et al., 2009; Stoll et al. 2011b; Ng, 2010; Hanson et al., 2012; Crosbie et al., 2010; Zhou et al., 2010; Surfleet and Tullos, 2013). In some cases the changes predicted in groundwater conditions are smaller than the cumulative uncertainty estimate for the model result (Pike et al., 2010).

This uncertainty arises from a variety of sources, including the high degree of compounded or *cascading* error that results when using a linked series of models, and the large amount of guesswork that can be involved when attempting to predict anthropogenic or socioeconomic reactions to significant changes in climate. In addition, no matter how sophisticated the modeling approach, current linked modeling studies do not account for all of the possible changes likely to result from global-scale shifts in atmospheric patterns (e.g., modifications to recharge rate that may result from changes in forest structure or vegetation community caused by increased wildfire or CO_2 increases). Linked models also rarely mathematically account for the extreme hydrologic events likely to occur with climate change (Kidmose et al., 2013).

Crosbie et al. (2011), Kidmose et al. (2013) and Ducharne et al. (2010) each systematically evaluated the sources of error in linked modeling studies and concluded that the choice of GCM/carbon emission scenario for determining future meteorological conditions is consistently the largest source of prediction uncertainty. This uncertainty is driven not only by the technical complexity of mathematically modeling the whole earth carbon/climate system, but also the difficulty of accurately predicting how humankind will ultimately choose to respond to the challenge of climate change (i.e.: will we allow carbon emissions to continue to grow at the same pace observed during the late 20th century and early 21st century?). The uncertainty associated with predicting human response to climate change was followed in decreasing scale by errors introduced by the choice of data downscaling method, and finally errors introduced by how surface and subsurface properties and flow processes are mathematically represented.

The accuracy of all models of the hydrologic impact of climate change, no matter how well they are assembled, are also limited by the inability to calibrate to a future condition. Hydrologic models of surface and subsurface flow are typically calibrated to comparatively short duration data sets of historic or current conditions. It is then assumed that the modeled system will behave in a predictable manner in the future under a new and different (potentially non-stationary) long-term stress. The temporal scale of the models used to develop climate impact predictions on groundwater may also limit the accuracy of the forecasts; no model reviewed during this evaluation provided predictions beyond the end of the 21st century. For larger aquifer systems with very long groundwater travel times, the timeframes necessary to express the maximum direct impacts of climate change on groundwater storage and discharge conditions at the end of a regional flow path may be well beyond that date.

Ultimately, most authors conclude that the highest value of numerical modeling efforts is not in producing predictions of absolute responses of hydrologic systems to climate change, but rather in shedding light on relative responses and sensitivity of aquifers to the array of meteorological changes predicted by GCMs. This approach improves our understanding of the mechanisms and feedback loops that are most likely to drive change in groundwater conditions. It also defines the range of possible climate impact outcomes our state is likely to face in the coming years. In this light, the sections below focus on describing the larger-scale or relative process changes predicted by the majority of researchers. Quantitative details about the absolute changes predicted in the future for specific study areas can be found for many of the report references in the annotated bibliography accompanying this report (Appendix A).

2. Climate Change Impacts on Groundwater Recharge and Storage

Key Findings

- Although there is uncertainty in the absolute predictions of *direct* climate impacts on future groundwater recharge rates and storage volumes in the PNW, the available research suggests that changes in the timing (and perhaps location) of recharge are more likely than large changes in average annual recharge amount. Direct climate-driven changes in long-term recharge rates (and therefore related groundwater storage conditions) are likely to be modest in comparison to natural variability.
- Areas of the PNW where snowpack and snowmelt play a large role in groundwater recharge are the most likely to see direct changes in recharge processes and rates.
- Driven by human population growth and declining summer streamflows, the potential for increases in groundwater pumping as an *indirect* response to climate change could have large consequences for state groundwater storage conditions. The indirect impact of pumping would likely far outweigh the direct consequences of climate-driven meteorological changes. Arid and semi-arid settings heavily reliant on snowmelt runoff for irrigation supply are the most at risk for pumping-related groundwater storage losses. The impacts of pumping on groundwater storage will likely unfold over significantly shorter timeframes than direct climate effects.

Introduction

A principle topic addressed in studies of climate impacts on groundwater conditions is how recharge will be modified in the future. Developing predictions of how recharge rates may change in response to a warming climate lays a foundation for gaining insight into closely-associated (and perhaps even more pressing) questions about how aquifer storage and discharge[4] may change.

Quantifying groundwater recharge is a challenging technical problem, even in the absence of long-term modifications to climate. Field measurement and modeling of recharge can be resource-intensive, and require expertise in a broad spectrum of technical disciplines. Monitoring programs that directly measure recharge responses to climate variability are rare in the high-elevation mountain settings where a significant percentage of western U.S. recharge occurs (Earman and Dettinger, 2008). In addition, the majority of water-level monitoring that is conducted in PNW to track changes in groundwater storage (a potential indirect method of estimating climate-driven changes in recharge) is focused in areas where groundwater pumping

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[4] Potential impacts of climate change on groundwater discharge patterns are discussed separately in the next section.

exerts a significant effect on aquifer water levels. These pumping impacts can effectively mask recharge changes driven by climate alone.[5]

The hydrologic process of recharge is influenced by the interaction of a wide variety of factors, and highly complex feedback loops between these variables can lead to non-linear responses in recharge rates to changes in precipitation or ET (McCallum et al., 2010; Ng et al., 2010). Land-use and land-cover, soil column and vadose zone permeability conditions, topography, water table position, antecedent soil moisture, snowpack, frozen ground, and water management activities can all play a role, in combination with meteorological variables, in modifying recharge rates. Absolute changes in recharge at any given location in the future will be driven by the unique combination of all of these factors at the local scale (Earman and Dettinger, 2011; Healy, 2010; Klove et al., 2014; Georgakakos et al., 2014).

Accurately accounting for all of these variables when developing spatially and temporally distributed predictions of future recharge is complicated by the large seasonal-, annual-, and decadal-scale cycles that occur naturally in climate and recharge rates (Kuss and Gurdak, 2014; Bredehoeft, 2011; Healy, 2010). These variations are expected to continue into the future and are likely to be greater in magnitude than the predicted long-term changes in precipitation rates in the PNW. Depending on their sign direction, natural climate cycles (as well as anthropogenic factors) can alternatively amplify or weaken the modifications to recharge specifically brought about by global climate change (Melillo et al., 2014; Georgakakos et al., 2014; Earman and Dettinger, 2011; Klove et al., 2014).

Precipitation is a primary driver of recharge rate, particularly in water-limited areas like much of eastern Washington, and longer-term reductions in precipitation would logically lead to long-term reductions in recharge (and subsequently storage). However, current climate model predictions for the PNW do not foresee large changes in average annual precipitation (Dalton et al., 2013). Instead, climate change is more likely to modify the timing, form, intensity, and perhaps location of precipitation. Evapotranspiration (ET) rates, another primary control on recharge (particularly in heat-energy-limited settings like much of western WA), is anticipated to increase in the coming decades, although the largest ET changes are expected to occur in the summertime when recharge rates are already naturally limited.

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[5] The development and long-term operation of the USGS climate response water-level monitoring network (CRN) will be a key component of understanding recharge and storage responses to climate change in Washington State in the future. This network is comprised of monitoring wells that are largely installed in shallow aquifers in locations that are minimally affected by anthropogenic influences. The Washington State component of this larger national network currently includes wells in 6 out of the 10 climate sub-regions designated for the state. The USGS Washington Water Science Center is currently seeking funding for an expansion of the network to the remaining climate sub-regions of the state, and conversion of all stations to real-time telemetry capability (Long, 2015). For more information see: http://groundwaterwatch.usgs.gov/NetMapT1L2.asp?ncd=crn&sc=53.

Together with predicted increases in temperature, these changes are expected to lead to key modifications in Washington's hydroclimate:

- Wet areas will become wetter.
- Dry areas will become drier.
- Less precipitation will fall in the form of snow (Dettinger et al., 2015b).
- Precipitation rates will increase during the winter and decrease during the summer.
- Storm intensity will increase.

Each of these factors can, in turn, alter the timing, amount, and location of groundwater recharge. Ignoring anthropogenic influences, each change to recharge volume will be balanced by a combination of changes in groundwater storage and natural discharge. The relative ratios of change in storage and discharge will be a function of the local hydrogeologic conditions. The sensitivity of a specific aquifer system to recharge fluctuations, and the lag times required for downgradient storage responses to those changes, are dependent on a variety of factors, including the volumetric scale and hydraulic properties of the affected aquifer system (Georgakakos et al., 2014; Safeeq et al., 2014a; Waibel et al., 2013).

Direct climate change impacts on groundwater recharge and storage

Although predictions of future recharge changes in the PNW have a significant level of uncertainty, the current research suggests that changes in the timing (and possibly location) of recharge are potentially more likely than large changes in annual recharge volumes (Toews and Allen, 2009a; Toews and Allen, 2009b; Allen et al., 2010a; Frans et al., 2011; Jin and Shridhar, 2012; Markstrom et al., 2012; Mastin and Josberger, 2014; USBR, 2014; Liu et al., 2013; Safeeq et al., 2013; Safeeq et al., 2014a; Waibel et al., 2013; Waibel, 2011; Huntington and Niswonger, 2012; Pangle et al., 2014; Meixner et al., 2016).

The available literature indicates that the largest direct impacts on recharge rates in the PNW are likely to occur in settings where snowpacks are vulnerable to climate change. In many mountainous areas of the western U.S., a large percentage of groundwater recharge is derived from snowmelt. Therefore the climate-related changes that are predicted to occur to snowpack conditions in the future are likely to have a great effect on infiltration processes in these areas (Melillo et al., 2014; Georgakakos et al., 2014; Earman and Dettinger, 2011; Earman and Dettinger, 2008).

Snowmelt is generally a more efficient generator of recharge than rainfall, therefore a shift from snow to rain could in some cases result in lower recharge-to-precipitation ratios (all other factors held equal) (Earman and Dettinger, 2011). In comparison to rainfall, snow can hold and slowly release precipitation stored up from multiple storm cycles. The sustained release of a larger water volume at the end of the cold season from snow can help to overcome ET and soil-water tension demands that can otherwise prevent infiltration during individual rainstorm events. The insulating effect of snowpack can raise soil temperatures, reducing the extent of frozen ground that might otherwise reject infiltration (Mastin and Josberger, 2014). The higher land surface albedo conditions created by snow cover can also reduce overall rates of ET, leading to more recharge.

Rain events, by contrast, often deliver precipitation to the land surface at more intense rates over shorter timeframes than snowfall. This can increase the probability that the arrival of precipitation at the land surface will exceed the soil infiltration capacity, resulting in a greater degree of overland runoff. Coupled with the predicted increase in wintertime precipitation in the PNW (coming more often in the form of rain), these changes will likely increase runoff during this period of the year in many settings in the PNW (depending on local soil infiltration capacities).

In Washington State even modest levels of warming are expected to cause large areal reductions in snowpack in the future, most notably mid-elevation areas in the Olympic and Cascade Mountains, where the moderating influence of Pacific marine weather patterns create a ‘warm’ snowpack (i.e., snowfall frequently occurring close to freezing temperatures). Interior areas of the state like the central Columbia Basin and the Walla Walla area, by contrast, tend to have “cold” snowpack (i.e., lower maximum daily temperatures and winter conditions less affected by the moderating effect of a marine climate) that will be less likely to undergo significant changes as the climate warms (Safeeq et al 2013; Dettinger and Culberson, 2008; Snover et al., 2013; Earman and Dettinger, 2011).

While some scientists have suggested that the processes and changes described above could lead to significant reductions in the amount of groundwater recharge that occurs in the future, this evaluation did not find a clear consensus in the technical literature that this will be the case in the PNW. Earman and Dettinger (2011), in fact, have noted that snowmelt-related reductions in recharge rates in high elevation settings could simply cause the additional runoff to infiltrate at a point lower in watersheds. This spatial redistribution would shift where recharge occurs but would not necessarily result in large volumetric changes in total infiltration and storage at the aquifer system scale. It is also important to remember that in many settings, the process of mountain recharge is limited not by ET or precipitation conditions, but rather the hydraulic characteristics of the vadose zone.

A number of the papers reviewed for this project found that the greatest direct impact of climate change on recharge in the PNW is likely to be a shift in seasonal rates (e.g., Markstrom et al., 2012; Mastin and Josberger, 2014; Waibel, 2011; Waibel et al., 2013; Chang et al., 2010; Safeeq et al., 2013, Allen et al., 2010a; Mayer and Naman, 2011). This change would be directly related to shifts in wet season precipitation, the shift of peak snowmelt to earlier in the spring, and rising ET and reduced precipitation in the late spring and early summer. The predicted modifications in recharge timing are closely associated with the timing shifts expected to also occur in surface runoff and baseflow discharge in many PNW watersheds.

Markstrom et al. (2012), for example, used downscaled meteorological data forecasts from a suite of GCMs as input to a deterministic watershed model (PRMS) to test the hydrologic response to climate change in the Naches Basin on the eastern slopes of the central Cascades. The modeling results predict that as temperatures rise in the coming century, snowfall will increasingly shift to rain, and peak snowmelt will occur earlier in the water year. Precipitation rates are also predicted to undergo significant changes from a seasonal perspective. The largest increases in precipitation will occur in the winter, and the largest decreases will occur in the summer. Analysis of the model water budget under future conditions indicates that while *annual* recharge rates are likely to show negligible change out to the year 2090, there is the potential for notable shifts in *seasonal* recharge rates (more recharge between November and February, and less recharge during the spring and early summer).

Mastin and Josberger (2014) used the PRMS model to examine how climate-driven changes in frozen ground conditions would impact recharge in the upper Crab Creek watershed of the Columbia Plateau. They found that although the extent of frozen ground is likely to decrease locally in the coming century (removing a barrier to snowmelt infiltration), and wintertime precipitation is expected to increase, net annual recharge rates would not change significantly. This is explained by the counterbalancing effect of changes in other hydrologic patterns. For example, while wintertime (Dec/Jan) recharge rates were forecast to increase, spring recharge rates (Mar) were predicted to decrease at approximately the same scale. In this analysis, the predicted increases in precipitation were also largely canceled out by long-term increases in ET rates within the watershed, resulting in only a small overall increase in water year recharge.

Waibel (2011) and Waibel et al. (2013) forecast similar hydrologic process shifts for the Deschutes River Basin in central Oregon. These studies predict that future decreases in groundwater recharge during the early spring (up to -60%) related to large reductions in snowmelt are likely to be counteracted by increases in fall and winter recharge (up to +100%) related to increases in wet-season precipitation. In this case, the strong spring recharge peak related to the freshet would effectively be replaced over time with a more sustained, lower-intensity recharge season between November and May. Although the timing of the recharge season is forecast to occur earlier in the water year, the net change in annual recharge magnitude was predicted to be relatively modest. Waibel et al., 2013 also showed that the climate change factors that lead to temporal changes in recharge would also lead to associated spatial redistribution of recharge, with more infiltration occurring in high elevation settings during the wet season where precipitation increasingly falls as rain rather than snow.

While the absolute changes predicted by the various modeling analyses reviewed are unique to the geologic setting, the results show that climate-driven shifts in seasonal precipitation, ET, and snowmelt can cause large timing changes in basin recharge dynamics, even though annual recharge and precipitation rates remain similar to current conditions.

In the future, the largest seasonal increases in PNW temperature and ET are expected to occur during the summer, when many areas of the state are already experiencing a moisture deficit, and recharge is already low to nonexistent (Smerdon et al., 2010). This suggests that a warming climate could have a comparatively limited impact on groundwater recharge rates during the summer. By contrast, during the winter, the expected increases in precipitation rate would be occurring during a period when cooler temperatures can limit the role of ET in influencing infiltration. On balance, the additional winter precipitation is likely to either effectively be canceled by the concurrent rise in ET or possibly even drive a small increase in net annual recharge (Meixner et al., 2016). There is little evidence that the direct impacts of climate change will drive a large reduction in annual groundwater recharge rates (and corresponding groundwater storage volumes) in Washington.

Natural recharge rates in humid areas of the state that are already rain-dominated (e.g., warmer, lower-elevation areas of western Washington) are unlikely to experience the large direct shifts in recharge dynamics predicted in snow-dominated areas. In fact, it is possible that in lower-elevation geologic settings where higher permeability deposits are present at the land surface (e.g., portions of the Puget Sound lowland mantled by recessional outwash), annual recharge and groundwater storage could increase in response to increases in wet season precipitation rates when ET conditions are at their lowest.

Some authors have suggested that natural recharge rates may be sensitive to future changes in episodic storm intensity (Crosbie et al., 2013; Ng et al., 2010; Klove et al., 2014; Taylor et al., 2013; Georgakakos et al., 2014). In some settings, more intense storms may produce precipitation rates that rapidly exceed soil infiltration capacities, leading to more runoff and less recharge. However, in arid and semi-arid environments, deep infiltration is often associated with periods of high-intensity rainfall that generates focused recharge beneath ephemeral surface water bodies (Ng et al., 2010). This would suggest that natural recharge rates could increase in some settings of the state in response to the more intense storm events predicted in the future. At this time, the role of storm intensity in modifying natural recharge rates (or spatial distribution) is not well understood.

Groundwater storage responses to direct climate-driven changes in precipitation and recharge rates are likely to be slower than surface-water responses. Aquifers generally have comparatively greater temporal stability to changes in climate. As a result, short-term, higher-frequency variations in recharge can be effectively filtered out at the aquifer scale (NRC, 2004; Healy, 2010; Bredehoeft, 2011; Waibel et al., 2013). These factors, coupled with the relatively modest magnitude of the long-term changes predicted for recharge, may make it difficult to distinguish storage changes due to natural climate variability or anthropogenic impacts vs. the direct influence of global scale climate change (Loaiciga, 2009; Kuss and Gurdak, 2014, Bredehoeft, 2011; Taylor et al., 2013).

Direct climate-related storage responses in aquifers that serve as sources of water supply are likely to be sensitive to: (1) the volumetric scale and hydraulic properties of the aquifer, (2) the depth of the aquifer, and (3) the length of the flow path between the point of recharge and the supply well. In very large and/or deep aquifer systems, very long periods of time may be required for direct climate-driven changes in recharge to be expressed as a storage change in a well downgradient from the recharge zone, and the response may be diffused upon arrival at the well. Storage conditions in smaller aquifers with shorter flow paths (often present in higher elevation settings) are likely to be the most sensitive to direct changes in recharge.

Indirect climate change impacts on groundwater recharge and storage

Although the *direct* impacts of climate change are not projected to lead to large changes in groundwater recharge rates and storage volumes, many researchers suggest that *indirect anthropogenic* responses to a warmer climate may have far-reaching ramifications for groundwater supply. The changes in groundwater conditions brought about by indirect impacts could also unfold on far shorter timescales than those prompted by the direct effect of climate change (Georgakakos et al., 2014; Earman and Dettinger, 2011).

One of the primary concerns identified during this evaluation is the potential for an increase in groundwater pumping as an indirect response to climate change. Such an increase could have large near- and long-term consequences for state groundwater storage (and discharge) conditions.

Many researchers predict a significant rise in demand for groundwater as the global climate warms (e.g., Loaiciga, 2009; Taylor et al., 2013; Georgakakos et al., 2014; Earman and Dettinger, 2011 Foti et al., 2012; Brown et al., 2013; Allen, 2009; Ficklin et al., 2010). In Washington, this demand is expected to be driven by:

- A reduction in available surface-water supply during the summer (due to significant long-term declines in mountain snowpack and earlier peak runoff, Mote et al., 2014),
- A large rise in irrigation demand (in response to a longer growing season and higher ET rates),
- The increased potential for sustained summer droughts, and
- Continued growth in the state human population (WOFM, 2014).

Since surface-water supplies in Washington are already fully allocated in many basins, the rise in demand may lead water users to seek an alternative source of water supply. This additional demand would mostly occur during the warm season when surface-water availability is most restricted and need for water is greatest. It is possible that increased pumping from state aquifers, with their large storage capacity and perceived resilience to climate change (relative to surface water), could be seen as a way to meet a significant proportion of the new demand.[6]

Mote et al. (2014) concluded that some water-limited agricultural areas of Washington that already depend heavily on irrigation from snowmelt-dominated streams will be among the most vulnerable to future water shortages. For example, they reported that the odds a junior water right holder in the Yakima Basin will be restricted to only 75% of their annual water allotment could increase by 80% by the year 2080. Basins in western Washington that rely heavily on snowmelt for water supply (e.g., the Dungeness), or already have strong competition for water (e.g., the Skagit) are also likely to experience increasing stress on available supply as our regional climate warms.

Restrictions on groundwater pumping by water regulators to protect instream flows, future improvements in irrigation efficiency, and implementation of adaption technologies such as aquifer storage and recovery (ASR) systems[7], may help to mitigate stress on aquifers in the

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[6] The 2015 water year provided a case study of how the future may unfold; with near normal precipitation, but significantly reduced winter snowpack, summer surface flows across Washington State were severely reduced. The warm, dry spring and summer that followed the s*now drought* further stressed the remaining water supplies, and increased crop water demand. As in previous drought years, in 2015 water managers restricted access to surface water by junior water rights holders. In the Yakima Basin, regulators allowed a number of emergency wells to be activated (or allowed existing wells to be deepened), to provide additional supply.

[7] ASR systems are typically designed to capture and store winter runoff in the subsurface for later use during periods of high demand and low precipitation.

coming years. If there is, nonetheless, a significant net increase in groundwater pumping across Washington, the related changes to aquifer storage and natural discharge could pose significant risks and costs[8] to state water supply and aquatic ecosystems.

A number of recent studies highlight the importance of accounting for indirect anthropogenic feedback responses when developing predictions of climate change impacts on groundwater (Ferguson and Maxwell, 2012; Ferguson and Maxwell, 2010; Kollet and Maxwell, 2008; Stoll, 2011a, Stoll, 2011b; Sheng, 2013; Earman and Dettinger, 2011; Green, 2011; Loaiciga, 2009; Taylor et al., 2013; Toews and Allen, 2009b; Vaccaro et al., 2015). These analyses suggest that aquifers may not be buffered from climate change influences to the degree commonly assumed, due to the stress posed by indirect climate impacts.

Hanson et al. (2012), for example, used a coupled numerical model to examine climate impacts on groundwater conditions in the semi-arid, irrigated Central Valley of California. These authors predict that as the basin's climate changes in the coming decades, reductions in surface runoff and rising crop water demand will lead to a shift to a largely groundwater-dominated irrigation economy. Coupled with sustained summer droughts, this shift (represented by the authors as a 3.5X increase in groundwater pumping across the model domain) is predicted to lead to large reductions in future groundwater storage in the valley aquifer system (causing up to 10's of meters of water level decline). The depletion in storage volume caused by pumping far exceeded model-predicted volumetric changes in recharge related to direct climate impacts (~+4% change from historic conditions).

In many areas of Washington, particularly east of the Cascades where precipitation rates are limited and ET demands are high, groundwater pumping can far exceed annual rates of natural recharge. For example, annual recharge rates are quite low to the deeper basalt aquifers that provide the bulk of agricultural, municipal, and industrial supply for the Columbia Basin. In many cases the water pumped from these systems was emplaced thousands or even tens of thousands of years ago (CBGWMA, 2009; Vaccaro et al., 2015). The long-term imbalance between rates of recharge and extraction has already led to large reductions in groundwater storage over more than 10,000 mi^2 of eastern Washington. In response, water levels have declined by more than 300 feet in some of the area's deeper basalt aquifers (Burns et al., 2012).[9] Future increases in groundwater pumpage in these areas would worsen this imbalance, and in the coming decades could far outweigh the comparatively modest changes in natural recharge and storage that are projected to occur from direct climate effects.

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[8] Groundwater level declines driven by over-pumping can lead to significant increases in the cost of drilling new wells or deepening existing wells to obtain required yield. As depth to water increases, the pumping cost to bring water to the surface also increases. If energy prices rise in the future, or water levels decline too much, pumping could become prohibitively expensive for some water users.

[9] Storage has simultaneously increased in shallow unconsolidated aquifers receiving high rates of return flow from imported surface-water used for irrigation.

Vaccaro et al. (2015) used a calibrated numerical model of the Columbia River Basin aquifer system to illustrate the considerable effect that pumping increases that occur in response to climate change could have on groundwater storage conditions in the future. Using GCM predictions of changes in meteorological conditions as input to a hydrologic model, the authors estimated there will be an increase in the basin crop PET rate of at least 13% above current conditions by the year 2050 (considered by the authors to be a conservative estimate). To test the potential impact of this additional water demand, they ran a model scenario in which irrigation-related groundwater pumping across the model domain was increased by a corresponding 13%. The model results indicate that, if allowed, this comparatively modest rate of additional pumping would cause at least 5 million acre feet of additional reduction in groundwater storage in the basin's basalt aquifers by the year 2050. The strong response of the model to these pumping modifications, which are *above and beyond* the storage reductions that could occur if *current* pumping rates continue, highlights the importance of accounting for possible anthropogenic responses to climate change.

These findings are echoed in a modeling analysis conducted for the Hood River Basin in north-central Oregon by the U.S. Bureau of Reclamation (USBR, 2014). While the authors of this study observed only modest changes in groundwater recharge rates or storage conditions due to the direct changes in future climate (<3 feet of head increase during the winter), they predicted very significant changes in storage (and baseflow) in response to projected climate-related pumping increases. To test the impact of additional groundwater demand, the authors increased the pumping rate in irrigated areas of the model domain. The pumping increase was set to an amount equivalent to 50% of the summer streamflow reduction predicted to occur in the basin in response to climate-driven changes in high-elevation snowpack (replacing surface water that had previously been available for irrigation). The modeling results under this scenario indicated 30-year average groundwater head losses of up to 50+ feet in the aquifer system (depending on climate condition and density of pumping wells).

In conducting an analysis of climate impacts on groundwater conditions in the southern Great Plains, Ferguson and Maxwell (2012) compared relative aquifer response to changes caused by direct climate effects vs. the changes exerted on the system by water management activities (groundwater pumping and irrigation). They found that while the predicted impacts of these separate factors in this setting were essentially equivalent in magnitude, the *spatial* distribution of the direct and indirect impacts showed significant differences.

In the PNW, it is possible that the *direct* effect of climate change on groundwater conditions will largely manifest in higher elevation areas where temperature changes alter snowmelt-driven recharge processes, while the *indirect* effects of climate change will likely be focused in the lower portions of watersheds where groundwater pumping (and irrigation) is concentrated. While the changes in higher elevation recharge could take many decades or even centuries to impact storage conditions in deep aquifers, the effects of climate-related increases in pumping could be immediate.

While groundwater extraction poses a significant concern in the future, an increase in the amount of irrigation water applied to agricultural fields during the growing season could potentially simultaneously result in an increase in return flow rates to shallow portions of aquifer systems (depending on crop type and irrigation efficiency; e.g., Ficklin et al., 2010; Toews and Allen, 2009b; Hanson et al., 2012). An increase in the irrigation water applied to crops could be a response to higher temperatures and ET rates, longer growing seasons, an increase in the number of crop cycles per season, or changes in crop type (Li and Merchant, 2013). More return flow could lead to an increase in storage in surficial aquifers similar to what has occurred over the past 50+ years across large areas of the central Columbia Basin. Climate-related reductions in irrigation or return flow (due to limited availability of supply, improvements in irrigation efficiency, lining of leaky canals, CO_2-related increases in crop water use efficiency and growth rates, temperature-related abandonment of crops) could by contrast result in reductions in recharge to the water table (Ficklin et al., 2010).

In urban and suburban areas, it is possible that increasing rates of winter precipitation and more intense storm events will prompt the expansion of stormwater control infrastructure, redirecting heavy winter precipitation to the subsurface in order to protect surface-water quality and control flooding. The net result of this indirect response to climate change could be an overall increase in the rate of recharge to underlying aquifer systems. Frans et al. (2011) noted that the indirect impacts of urban growth, with an accompanying expansion in the amount of impervious surface area is likely to have a larger effect on recharge rates to the aquifer system of the rapidly developing Bainbridge Island community than the direct effects of climate change.

In addition to the indirect impacts potentially caused by an increase in groundwater pumping, there are other non-anthropogenic indirect effects of climate change that may have important consequences for groundwater recharge. For example, the forest ecosystems in the higher elevation terrain of the PNW are predicted to undergo significant structural modifications in the coming century due to climate-driven changes in temperature, pest populations, and wildfire frequency and extent (Littell et al., 2010; Barbero et al., 2015; CIG, 2009). While such changes have the potential to alter energy and moisture transfer at the land surface (Ferguson and Maxwell, 2012; Kollet and Maxwell, 2008; Pike et al., 2010), to date no research has been conducted on how climate-related modifications in PNW forest species composition could affect mountain recharge processes.

Barron et al. (2010) noted the importance of accounting for changes in the natural landscape in response to climate change, finding that as a regional climate regime changes, major changes in the vegetation structure of a watershed can occur, which in turn can alter recharge rates. Recent research also predicts a high likelihood for a significant expansion in wildfire intensity and areal impact in the PNW (Yue et al., 2013; Barbero et al., 2015), potentially leading to major changes in plant communities and soil hydraulic characteristics in mountain front settings that serve as important recharge areas for regional scale aquifers.

3. Climate Change Impacts on Groundwater/Surface-Water Interactions and Baseflow Discharge

Key Findings

- Changes in patterns of flow between the surface and the subsurface may be among the earliest and most noticeable *direct* groundwater-related consequences of climate change.
- In response to climate-driven changes in snowmelt and recharge dynamics, there may be important shifts in the timing of groundwater discharge to some PNW streams, potentially leading to reductions in baseflow discharge during the latter half of the summer.
- The *indirect* impacts of climate change, most importantly the significant potential for an increase in groundwater pumping, could lead to large reductions in natural groundwater discharge in many settings, even if there are only modest changes to natural recharge.
- Hydrogeologic setting plays a key role in determining the streamflow recession and baseflow characteristics of a watershed, which can, in turn, significantly influence streamflow sensitivity to climate change, and regulate late-summer surface flow rates.

In most settings, groundwater and surface-water systems are closely interconnected components of the larger hydrologic cycle, often exchanging water back and forth throughout the seasons through the processes of baseflow discharge and surface-water infiltration (Winter et al., 1998). This suggests that modifications to a groundwater system due to climate change will have potentially important consequences for hydraulically connected surface-water resources, and vice versa.

The uppermost zones of groundwater systems (i.e., the surficial or *water table* aquifers) are simultaneously the portion most sensitive to long-term changes in meteorological conditions *and* the location where the majority of groundwater/surface-water exchange occurs. As a result, alterations in patterns of flow between the surface and the subsurface may be among the earliest and most noticeable groundwater-related consequences of climate change. Some authors have suggested that predicted changes in baseflow contributions to surface water may in fact be one of the most vulnerable aspects of direct groundwater response to a warming climate (Earman and Dettinger, 2011).

Although this evaluation is focused primarily on evaluating the likely impact of climate change specifically on aquifer conditions in Washington, this section presents some of the important recent findings of how predicted changes in groundwater baseflow discharge processes are expected to impact surface flows. I have also included discussion in this section regarding recent research that highlights the important role that geologic setting can play in dictating the relative hydrologic sensitivity of different surface watersheds to climate change.

Several authors have noted that the impact of climate change on groundwater recharge and storage is not necessarily manifested, in turn, as a one-to-one proportional change in groundwater discharge (e.g., Earman and Dettinger, 2011; Huntington and Niswonger, 2012). For example, Earman and Dettinger describe the important influence that the saturated thickness of an aquifer can have on the groundwater discharge response to climate-caused changes in upgradient aquifer conditions (Figure 1).

In settings where the saturated thickness of an aquifer is not significantly greater than the depth of an overlying stream, an example reduction in groundwater storage of 5% can result in a proportional 5% reduction in the amount of baseflow discharge to the stream, still leaving a significant groundwater contribution to surface flow (Figure 1A, B, C). However, in many settings the saturated thickness of an aquifer is considerably greater than the stream depth. For these systems, a 5% change in groundwater storage related to climate change could lead to a total loss of groundwater inflow to the stream (Figure 1D, E, F). This is due to the fact that storage losses are largely manifested in the uppermost portions of an aquifer. The storage reduction in this example can lower the regional water table below the base of the streambed, completely eliminating discharge from the aquifer (and in the process, potentially reversing the vertical hydraulic gradient between the stream and groundwater, leading to stream *losses*).

While groundwater inflow to streams occurs throughout the year, it is the summer period when the role of baseflow is most socially and environmentally pivotal; predicted climate-related changes to summertime baseflow rates are most often the central focus of the available research on this topic. This is because groundwater inputs serve an essential role in sustaining flows in many streams (and related springs) during the summer when precipitation and surface runoff are typically limited. Groundwater baseflow contributions regularly comprise more than 75% of the total daily discharge rate in many unregulated Washington State streams and rivers during the biologically critical July, August, and September period (Pitz and Sinclair, 1999). Given that the majority of recent climate studies predict reductions in summertime snowmelt contributions to many streams, improving our understanding of concurrent changes expected in baseflow processes is becoming all the more essential.

Even modest summertime reductions in baseflow contributions to surface waters could have very important impacts on the quality of aquatic habitats in our state (Klove et al., 2014). In addition to sustaining volumetric flow rates critical to aquatic organisms, groundwater inputs to surface water bodies can (Winter et al., 1998; Pitz and Sinclair, 1999; Brown et al., 2007; Klove et al., 2014; Yeakley et al., 2014):

- Support fish passage and habitat connectivity during the dry season,
- Help to stabilize surface-water temperatures during both the winter and the summer,
- Provide thermal refugia for fish,
- Dilute undesirable solute concentrations in streams and rivers, and
- Sustain wetlands and associated plant and animal communities.

Reductions in streamflows (and spring flows) due to climate-driven declines in aquifer discharge could also have far-reaching consequences for surface-water-dependent irrigation and municipal water supplies.

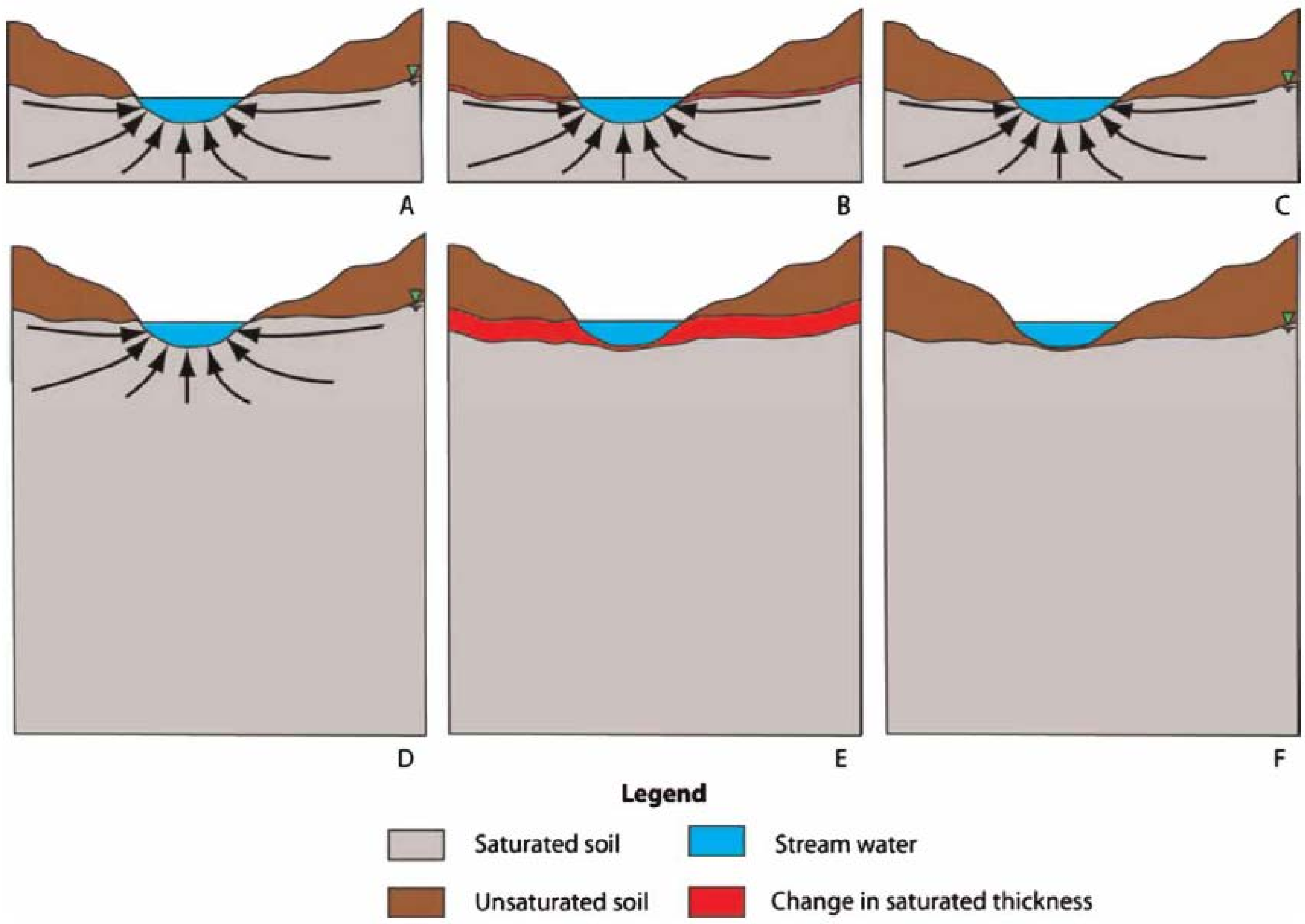

Figure 1. Conceptual model of the effect of a 5% change in groundwater storage on aquifer discharge to a stream, as a function of saturated thickness (from Earman and Dettinger, 2011).

Direct climate change impacts on groundwater discharge timing

A number of the papers reviewed for this project discuss how climate change is predicted to directly modify groundwater discharge patterns (e.g., Allen, 2009; Allen et al., 2010a; Huntington and Niswonger, 2012; Markstrom et al., 2012; Earman and Dettinger, 2011; Hanson et al., 2012; Kurylyk et al., 2014b; Klove et al., 2014; Kundzewicz and Döll, 2009; Pike et al., 2010; Scibeck et al., 2008; Taylor et al., 2013; Waibel, 2011; Waibel et al., 2013; Chang et al., 2010; Mayer and Naman, 2011; Chang and Jung, 2010). The explanations of the specific hydrologic mechanisms and feedback loops that bring about these changes vary between studies (as do the specific predicted outcomes). Nonetheless, many recent authors share the conclusion that significant changes in the *timing* of discharge may be more likely than large changes in the total annual *amount* of discharge. Changes in groundwater discharge to the surface are likely to occur in the PNW despite only modest predicted changes in annual precipitation and recharge rates.[10]

As discussed earlier, the peak periods for snowmelt, runoff, and aquifer recharge are all predicted to shift in mid- to higher-elevation settings to an earlier point in the water year. While net rates of annual natural recharge will not necessarily change significantly, modeling analyses have shown that the changes in the timing of these processes can combine to alter downgradient discharge cycles. The specific changes are likely to be a function of local conditions, and could be influenced by, among other factors, the length of the groundwater flow path (Waibel et al., 2013), the hydrogeologic setting (Safeeq et al., 2014a; Mayer and Naman, 2011; Tague et al., 2008), and shifts in the seasonal character of stream stage and bank storage (Scibek et al., 2008; Huntington and Niswonger, 2012).

In settings where these changes occur, there is likely to be a corresponding shift in the timing of peak groundwater discharge to earlier in the year[11]; in essence, the affected aquifers are predicted to drain earlier in the year in comparison to historical patterns. This timing shift would cause a reduction in baseflow discharge during the most critical point in the summer dry season, exacerbating the climate-driven reductions in spring/summer melt runoff also predicted by many researchers.

While only a limited number of Washington-specific studies of these changes have been published, a review of the literature suggests that mid- to high-elevation streams on the northern and eastern slopes of the Olympic Mountains, streams near and to the east of the crest of the Cascade Mountains, and streams in the water-limited, arid to semi-arid portion of north-central Washington are likely to be the most vulnerable to these changes in discharge timing (Markstrom et al., 2012; Waibel, 2011; Safeeq et al., 2014a; Scibek et al., 2008; Toews and Allen, 2009b; Mastin, 2008; Allen, 2009).

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[10] Huntington and Niswonger (2012) in fact highlight the point that reductions in summertime baseflow to many snowmelt-dominated mountain streams in the western US are likely to occur *even if* long-term average annual precipitation and groundwater recharge rates are projected to increase.

[11] Most modeling analyses suggest a shift on the order of approximately 1 to 3 months earlier in the year.

Markstrom et al. (2012), for example, predict that by the end of the 21st century in the Naches Basin (eastern slopes of the Washington Cascades), there will be a seasonal increase in baseflow during the December to March period (up to ~18 ft^3/sec increase), and a seasonal reduction in baseflow from May through August (up to ~15 ft^3/sec decrease), with a small overall increase in the annual baseflow rate. Waibel et al. (2013) predict direct summertime baseflow reductions in the upper Deschutes basin of central Oregon of between -0.3 to -17.2% by the 2080s, and up to a +27.5% increase in wintertime baseflow. In that setting, the changes would be dependent on the position of the stream in the watershed, with the highest rates of baseflow reduction occurring in high elevation, low-order streams.

Lower elevation streams that are already rain-dominated (e.g., streams in the Puget Sound lowland, the Chehalis Basin) are not predicted to experience the same baseflow timing changes that are predicted for currently snow-dominated areas; the hydrologic mechanisms that control recharge in these areas are not likely to be altered to the same degree. Increases in recharge rates would lead to increased storage, particularly in surficial aquifers, which in turn would increase baseflow to local streams.

Groundwater discharge to the surface is also likely to be affected in areas where actual reductions in annual recharge rates occur in the future, even if winter precipitation rates increase (possibly due to rejection of intense or prolonged rainfall). At the aquifer scale, the cumulative effect of even small decreases in infiltration rates caused by climate change during the peak recharge season could result in comparatively large volumetric reductions in groundwater storage, inevitably leading to declines in discharge to downgradient surface-water interfaces.

Johnson and Savoca (2011) and Johnson et al. (2011) both applied a climate-related “change factor” to a calibrated numerical flow model of a groundwater system in western Washington to test the possible impact of a warming climate on hydrologic conditions (Lower Skagit basin and Chambers-Clover Creek watershed, respectively). For both models, the annual model recharge rate was reduced by 20% to characterize steady-state system response to a potentially drier future.

Both studies showed significant impacts to study area groundwater/surface-water exchange under the recharge parameter modification. In the lower Skagit basin, the reduction in recharge led to a nearly one-to-one reduction in discharge to streams (~18,000 acre-ft/yr; ~25 ft^3/sec).

The tested reduction in recharge for the Chambers-Clover Creek area had even more significant consequences for interactions between the groundwater system and surface water bodies. In this case, a recharge decline of 20% would cause a large *reversal* in the direction of net water exchange in the study area (existing condition scenario: >17,000 acre-ft/yr of groundwater discharge *to* streams and lakes; reduced recharge scenario: ~23,000 acre-ft/yr *loss* of surface water to the groundwater system, with an additional 5 acre-ft/yr loss of flow to springs, and a reduction of groundwater discharge to Puget Sound).

While these scenarios are not necessarily representative of the long-term changes that are predicted for the Puget Sound lowland at large, they do illustrate the sizable effect that climate-change-induced recharge modifications can have on the transfer of water between the surface and the subsurface. The increasing likelihood of extended drought cycles related to climate change in the PNW (Melillo et al., 2014) also highlights the value of this type of analysis.

Predicted summertime reductions in precipitation and increases in ET rates in the PNW are not expected to play a large role in directly modifying groundwater discharge rates, since natural recharge rates are typically negligible during this time of the year already. It is possible, however, that temperature- and ET-driven increases in water uptake by riparian corridor phreatophytes could reduce groundwater inputs to surface water locally. Although not extensively studied, climate-related reductions in surface discharge rates may, in reverse, have a direct impact on underlying groundwater storage conditions in settings where an aquifer system is routinely or periodically recharged by streambed infiltration.

Indirect climate change impacts on groundwater discharge

While many studies focus on how summer baseflows may change in response to direct climate-driven shifts in the hydrologic cycle, other authors have highlighted the critical role that *indirect* impacts of climate change are likely to play in altering groundwater/surface-water exchange (i.e., changes in groundwater pumping rates, changes in irrigation practices, land use/land cover modifications). Many authors, in fact, predict that anthropogenic responses to climate change are likely to play at least as large a role in altering groundwater/surface-water interactions as direct meteorological impacts themselves. Unlike the effect of direct climate impacts on groundwater discharge, indirect impacts are not necessarily limited to specific areas of the state or periods of the water year.

Of greatest concern is the likelihood for an increase in demand for groundwater in response to climate change, as discussed earlier in this paper. It is well established that, where groundwater and surface water are in hydraulic connection, groundwater extraction can intercept water that would otherwise discharge as baseflow to the surface (Winter et al., 1998; Morgan and Jones, 1999). Baseflow capture is already a significant water resources management concern in many areas of Washington State, even without considering the future effects of climate change (e.g., Ely et al., 2011; Johnson and Savoca, 2011; Vaccaro et al., 2015; Johnson et al., 2011; Tetra Tech Inc., 2004).

In extreme cases, groundwater pumping can even induce streamflow loss by reversing the hydraulic gradient between the pumping well and the river, effectively capturing and rerouting surface water to the subsurface. An increase in groundwater pumping in aquifers that are in hydraulic connection to overlying surface water (particularly during the summer season of highest water demand and lowest streamflow), could significantly reduce baseflow inputs and streamflows in many basins.

As described earlier, Vaccaro et al. (2015) evaluated how changes in water demand could potentially lead to profound changes in groundwater storage conditions in the Columbia Plateau aquifer system. These pumping-related changes in storage would also have a profound impact on groundwater discharge rates within the basin. Water budget results indicate that, by 2050, the 13% increase in irrigation pumping (the projection used by the authors to account for increased crop water demand) would lead to a greater than 700 ft^3/sec reduction in groundwater discharge to streams in the study area, affecting an area greater than 20,000 mi^2 in size.

The USBR (2014) likewise examined potential climate change impacts on groundwater and surface-water exchange in the Hood River Basin of northern Oregon. Using a simplified numerical flow model, the authors demonstrated that the direct impact of climate change on aquifer discharge is likely to be relatively modest out to the year 2060. However, when the authors increased the groundwater pumping rate in the model domain to account for indirect impacts (a predicted reduction in the availability of surface water for irrigation and a predicted increase in summertime PET/crop water demand), they observed a significant reduction in the baseflow rate to the study area streams (up to a 60% decline in summer baseflow, despite a predicted increase in wintertime recharge and groundwater storage).

If the baseflow timing changes discussed above coincide with substantial increases in demand for groundwater, the impact on groundwater/surface-water exchange could be significantly compounded, posing even more stress on stream ecosystems and water supply. Such changes can set up negative feedback loops that aggravate problems with baseflow reduction. For example, by limiting water availability in the season of highest water demand, direct reductions in summer baseflows due to climate-driven changes in the timing of the snowmelt and recharge could prompt even more groundwater pumping to meet demand, further reducing baseflows and potentially groundwater storage.

It is also possible that indirect climate-related changes in irrigation practices could affect groundwater/surface-water interactions. While future improvements in irrigation efficiency may help to stabilize overall water use, many authors predict an increase in summer irrigation rates in response to climate warming (due to higher summertime temperatures, ET rates, and crop water demand, or because more irrigation water is applied due to a longer growing season). If irrigation rates do rise, rates of return flow are also likely to increase, leading to a corresponding increase in baseflow to downgradient streams and drainage canals (e.g., Toews and Allen, 2009b).

The influence of hydrogeologic setting on the sensitivity of streamflow to climate change

In the past several years, a number of papers have been published that describe the important role that the hydrogeologic character of a basin can play in determining the vulnerability of stream discharge to climate change, particularly in settings that receive a larger percentage of winter precipitation as snowfall (Safeeq et al., 2013; Safeeq et al., 2014a; Safeeq et al., 2014b; Tague and Grant, 2009; Tague et al., 2008; Mayer and Naman, 2011; Allen et al., 2010b).

Declines in summertime streamflows have been observed in a number of western U.S. watersheds over the past several decades (Luce and Holden, 2009). Earlier research concluded that these reductions were largely a function of climate-driven declines in snowpack volume and earlier snowmelt (e.g., Hidalgo et al., 2009). More recent papers, however, have shown that climatic (and topographic) controls *combine with* the hydrogeologic character of a basin to ultimately dictate streamflow sensitivity to warming or drought. Together, these factors can be used to forecast spatial differences in spring and summertime streamflow response to future changes in the timing and magnitude of mid- to high-elevation snowmelt caused by climate change.

Researchers have determined that streamflows can respond differently to changes in snowpack depending on a watershed's drainage efficiency, which is a function of the hydrogeologic setting and recharge zone permeability. In *runoff-dominated* basins with lower permeability geology, snowmelt is quickly drained downslope as overland flow, with only limited groundwater recharge or deeper baseflow contribution to streamflow. In such basins, surface discharge rapidly recedes after late-spring to early-summer peak melt, and mid-summer to late-summer streamflows are typically quite limited.

In *groundwater-dominated* basins with higher permeability geology, by contrast, transfer of the water contained in winter snowfall down to the base of the watershed occurs more slowly. In such settings a larger percentage of the snowpack melt enters the groundwater system as recharge as temperatures warm. The water that enters the groundwater system subsequently drains more gradually back to surface streams as baseflow rather than surface runoff. These baseflow contributions tend to smooth and delay the recession hydrograph, allowing volumetrically higher summertime streamflow rates.

The papers cited above have shown through analytical modeling, analysis of historic streamflow data, and spatial mapping of the baseflow recession constant across the PNW, that summertime streamflows can be *more* sensitive to climate-related snowpack and snowmelt changes in *groundwater-dominated* drainages than in runoff-dominated drainages. This finding is somewhat counterintuitive. It might be expected that basins that have a greater degree of groundwater baseflow contribution to streamflow would be buffered from climate change impacts in comparison to runoff-dominated watersheds (e.g., Surfleet and Tullos, 2013; Chang and Jung, 2010). However, many authors suggest that, depending on geologic setting, the climate-related shifts in the timing and magnitude of snowmelt-driven recharge can drive corresponding shifts in groundwater discharge timing and magnitude.

In groundwater-dominated basins where streams depend more heavily on baseflow contributions, these shifts are predicted to lead to larger *absolute* reductions in dry season flows, from a volumetric standpoint, than will occur in runoff-dominated watersheds (where later summer flows are already limited).[12] Mayer and Naman (2011), for example, found that summertime streamflow losses in groundwater-dominated basins could be as much as an order of magnitude greater than in runoff-dominated drainages. Although percent changes in future summer streamflows may be greater in runoff-dominated systems (in comparison to historical conditions), the large volumetric reductions in summer flows predicted for groundwater-dominated settings would have important consequences for state water supply, stream temperatures, and aquatic habitat viability.

Safeeq et al. (2014a) presented a set of maps for the PNW that show the results of their analysis in terms of the intrinsic sensitivity of summertime surface drainage to a unit change in the timing

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[12] As discussed earlier, recharge processes in basins that are already rain-dominated are not predicted to change as much in response to climate change as basins that currently receive snowfall during the winter. As a result, summer streamflows in such watersheds are predicted to show a smaller degree of sensitivity to a warmer climate.

or magnitude of recharge (Figure 2).[13] The maps show that streamflow sensitivity to changes in recharge conditions is predicted to diminish over the course of the summer. The largest streamflow reductions to a unit change in recharge are most likely to occur during the month of July. As expected, streamflows in areas that have historically been snow-dependent are predicted to be the most sensitive to climate-driven hydrologic changes in snowmelt and melt-derived recharge. In Washington State, this would include the northern and eastern slopes of the Olympic Mountains, the high elevation portions of the Cascade Mountains, and a large portion of northern Washington lying east of the Cascade divide. The central Columbia Basin (a colder setting less vulnerable to climate warming) and much of western Washington (where recharge processes are already largely dominated by rainfall) show significantly less sensitivity.

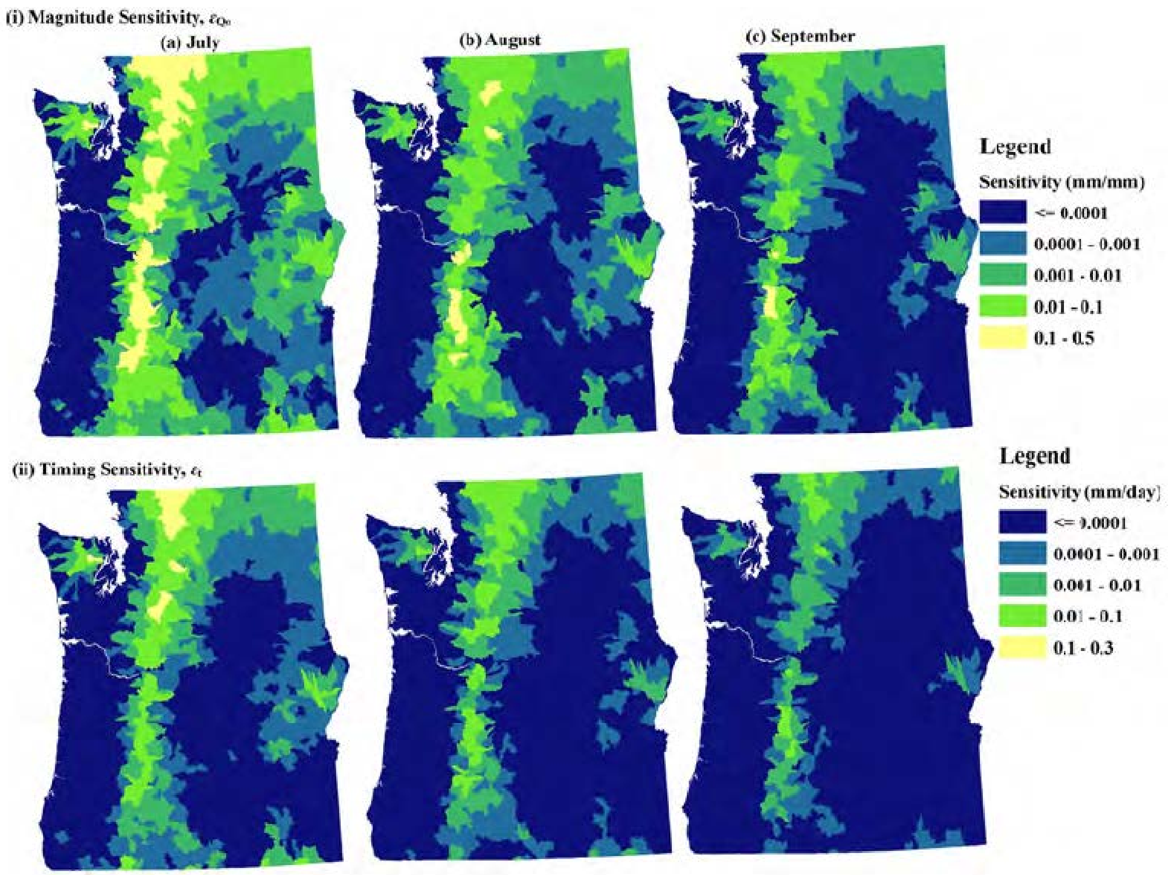

Figure 2. Spatial distribution of July, August, and September streamflow sensitivity to a change in the magnitude (i) and timing (ii) of recharge, Pacific Northwest (from Safeeq et al., 2014a)

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[13] These maps do not show the absolute changes in streamflow that will occur in the future in response to climate change; on-the-ground streamflow responses to changes in conditions will be the product of both the basin's hydrogeologic sensitivity to recharge modifications (Figure 2) and the specific changes in recharge timing and magnitude brought about by the given climate condition at the time.

Safeeq and coauthors further integrated the data from the sensitivity maps shown on Figure 2 with the modeled average changes in snowmelt magnitude and timing between a warm, dry year (2003 El Niño) and a cool, wet year (2011 La Niña). The results of combining the inherent sensitivity of the landscape with a specific climate change scenario showed that streamflows in the high Cascades can vary by >50% in the early part of the summer.

It should be noted that the dominant driver of the intrinsic streamflow sensitivity shown on Figure 2 can vary between watersheds, depending on local conditions. For example, the high summer streamflow sensitivities predicted in northern Washington are less a function of geologic setting and groundwater-driven recession, and more a function of the large role that snowmelt plays in summer flows in this area. The volumetric magnitude of snowmelt contribution to summer flows is comparatively higher in this area, and the timing of that snowmelt is typically later than in other areas, therefore streams in this portion of the state have a greater relative sensitivity to climate-driven changes in snowmelt.

4. Climate Change Impacts on Groundwater Quality

Key Findings

- Research on climate change impacts on groundwater quality is limited, and predictions have a high degree of uncertainty.
- The *indirect* impacts of climate change are more likely to drive groundwater quality problems than direct impacts.
- The published studies on this topic suggest that climate change is likely to result in increased rates of leaching of soluble contaminants such as nitrate.

Research on the potential impacts of climate change on ambient groundwater chemical quality is scarce in the current literature, and few studies specific to Washington State aquifers were found during this evaluation. Current predictions of the likely groundwater quality response to climate change have a high degree of uncertainty.

A review of the current literature suggests:

- The primary mechanism for the downward transport of surface contaminants to the water table in Washington State is groundwater recharge, therefore the magnitude of the changes in recharge rates, due either to direct or indirect climate impacts, is a significant determining factor in the degree of groundwater quality responses to climate change.
- The *direct*, climate-driven changes in groundwater recharge rates are not likely to be great enough in Washington to cause significant changes in large-scale leaching losses of contaminants to the subsurface (see Section 2). As discussed earlier, many of the direct rate-changes predicted in recharge are likely to be focused largely in higher elevation areas of watersheds in association with changes in precipitation form and snowpack melt dynamics. This suggests that a significant proportion of any direct climate-driven changes in recharge that do occur will not take place in areas where chemical leaching to the subsurface is of high concern (due to the nature of the land use, lack of chemical sources, and low demand for groundwater supply in these areas).
- Increases in rainstorm intensity related to climate change, particularly in lowland areas where rates of land-surface loading of contaminants are higher, may increase downward mobilization of soluble chemicals resident in the vadose zone (e.g., nitrate, chloride) (Taylor et al., 2013). Alternatively, intense storms could produce precipitation rates that quickly exceed soil infiltration capacities. The related reductions in recharge could, in turn, reduce leaching.
- In arid and semi-arid areas of Washington State where larger reservoirs of soluble nitrate have accumulated over time in the vadose zone due to intensive long-term agricultural production and fertilization practices (e.g., the central Columbia Basin and the Yakima basin), increased storm intensity related to climate change may flush additional nitrate mass to the water table (Klove et al. (2014), Dragoni and Sukhija (2008), Gurdak et al. (2007), and Earman and Dettinger (2011). Increases in recharge rates related to reductions in frozen ground area could also increase leaching.

- Most of the authors evaluating this topic conclude that the *indirect* anthropogenic responses to climate change may pose the most significant concern for groundwater quality (e.g., Stuart et al., 2011; Baron et al., 2013; Li and Merchant, 2013; UNESCO, 2008; Green et al., 2011; Bloomfield et al., 2013; Zhou et al., 2010; Treidel et al., 2012). As temperatures, ET rates, and atmospheric CO_2 concentrations rise with climate change, plant growth and crop water-demand are both expected to increase. Under these circumstances the profitable growing season may lengthen; in some settings, farmers may even decide to increase the total number of planting/harvest cycles per year. These changes are likely to lead to increases in the amount of irrigation water, fertilizer, and pesticides applied to crops, increasing the potential for the chemical leaching to groundwater. Since different crops have different fertilization requirements and leaching potentials, changes in crop types in response to climate change (e.g., cultivating corn or soybeans instead of wheat or alfalfa) could lead to an increase in groundwater quality impacts. Reductions in the depth of the water table and shortening of residence times of solutes in the soil column and vadose zone due to an increase in irrigation rate could also increase the vulnerability of shallow aquifers to contamination. Such changes could be limited in scope if water supply availability becomes a limiting factor to irrigated farming, or if the farming community makes significant technical advances in irrigation efficiency.
- Changes in the timing of recharge may also effect nitrate leaching losses. For example, Allen (2012) demonstrated the important role that spring recharge can play in the leaching of nitrate to groundwater in the Abbotsford-Sumas aquifer in northwestern Washington and southwestern British Columbia. Although there is a relatively high amount of uncertainty in the predictions, Allen's modeling analyses suggest there may be an increase in the springtime recharge rate to the aquifer in the future due to climate change. If this increase occurs coincident with an increase in spring crop irrigation and spring fertilizer application, nitrate leaching losses to groundwater could rise.
- The increases in storm intensity and surface flooding expected to accompany climate change may drive the expansion of storm water control infrastructure that routes a larger volume of storm runoff to the subsurface (particularly in urban and suburban areas with a high density of impervious surface). This indirect climate impact could potentially result in an increase in the amount of dissolved toxic chemicals and nutrients in storm runoff that is redirected to the subsurface in developed areas, increasing the vulnerability of shallow aquifers to contamination (UNESCO, 2008; Green et al., 2011; Kundzewicz and Döll, 2009; Clifton et al., 2010).
- Some authors have suggested that since temperature can be a key factor in reaction kinetics and dissolved oxygen concentrations, even small increases in groundwater temperatures due to climate change (see Section 5 below) could have a significant impact on groundwater chemical quality (Gunawardhana and Kazama, 2012; Kurylyk et al., 2014b). Increased groundwater temperatures may alter the geochemical processes (particularly redox reactions) that can exert control on the dissolved concentration and mobility of a wide variety of chemical contaminants (e.g., nutrients, trace metals, iron, and manganese). This may be of particular concern for supply wells that derive their water from river bank infiltration. As stream temperatures rise and dissolved oxygen concentrations decrease, the reducing conditions created in near-stream groundwater could in turn mobilize solid phase iron and manganese. These dissolved constituents could later re-precipitate, fouling the infrastructure

of water systems drawing water from aquifers fed by river-bank infiltration (Figura et al., 2011; Klove et al., 2014).

- Other authors have suggested that rising temperatures could potentially increase soil mineralization rates of organic N to nitrate, leading to an increase in the potential for nitrate leaching to the water table in agricultural areas that receive large surface loads of N-bearing fertilizer (Stuart et al., 2011; UNESCO, 2008).[14]
- Anticipated changes in groundwater baseflow to streams (earlier peak discharge, reduced baseflow during the summertime) are not likely to play a major role in altering groundwater quality, but could lead to significant impacts on surface-water quality. Uncontaminated groundwater baseflow can help to dilute contaminant concentrations in streams, particularly during biologically critical time periods when baseflow supports a large percentage of stream discharge. If baseflow rates decline due to changes in climate, the beneficial effects of contaminant dilution in rivers and streams may be reduced.
- Ficklin et al. (2010) suggest that climate-related reductions in groundwater recharge rates (due to increased temperature, plant growth, and PET) in semi-arid irrigated settings like the San Joaquin Valley in central California could lead to a reduction in the leaching of agricultural chemicals to the underlying groundwater system.
- Destouni and Darracq (2009) suggest that the large reservoir of nitrate that has historically been loaded to a groundwater system in Sweden will serve as a long-term source of nutrient loading to downgradient coastal waters, regardless of climate change impacts.
- An increase in water demand associated with climate warming, compounded by existing long-term declines in aquifer water levels (particularly in arid and semi-arid settings), may prompt irrigators or municipalities to (1) deepen existing wells or (2) drill new supply wells deeper into the underlying aquifer system. This indirect response to climate change may lead not only to increased pumping costs but also to important changes in the water quality of the groundwater used for supply. Deeper groundwater has typically experienced a longer residence time in the subsurface. The longer groundwater has been in contact with the geologic matrix of an aquifer, the more mineral dissolution can occur. As a result, older, deeper groundwater typically has a higher dissolved mineral content (Freeze and Cherry, 1979). Deep groundwater may also have a lower dissolved oxygen concentration than shallow groundwater, potentially leading to reducing conditions that can dissolve and mobilize metals such as iron or manganese. These factors can degrade the aesthetic quality of water for consumption, reduce irrigated crop yield, and have costly consequences for water treatment and water conveyance systems.

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[14] Note that recent research by Chantigny et al. (2015) suggests that warmer winters will not necessarily have a significant impact on nitrification rates, since cold season nitrification is already occurring even in frozen soil settings.

5. Climate Change Impacts on Groundwater Temperature

Key Findings

- Contrary to commonly held assumptions, recent research suggests that groundwater temperatures may be more sensitive to climate warming than previously thought.
- Warmer groundwater temperatures could have significant, negative consequences on groundwater-dependent aquatic habitats. Groundwater discharge may not buffer stream temperatures as much as assumed in the past.
- Modeling studies of stream-temperature sensitivity to climate warming should account for the potential for a substantial increase in groundwater-discharge temperatures in the future.

Although no predictive studies of climate change impacts on groundwater temperature specific to Washington State were identified in the literature, the reviewed information suggests that rising groundwater temperatures could be an important concern for the PNW region.

There has been a commonly-held assumption that groundwater is largely buffered or insulated from changes in temperatures at the surface, or that thermal impacts to groundwater will only occur over very long time-scales to shallow depths. New studies, however, suggest that groundwater temperatures to depths up to 100 meters (>300 ft) below ground surface are potentially sensitive to (and at shallow depths can respond rapidly to) the direct atmospheric warming associated with climate change. Groundwater temperatures can also show significant sensitivity to changes in overlying land use or vegetation cover that may occur in response to climate-driven increases in air temperature, atmospheric CO_2 concentration, ET rates, or wildfires (Gunawardhana and Kazama, 2012; Kurylyk et al., 2014a, 2014b, 2014c; Figura et al., 2011; Bovolo et al., 2009; Menburg et al., 2014; Taylor and Stephan, 2009).

While increases in groundwater temperatures may have some direct consequences for groundwater chemical quality (see Section 4), the far larger concern is the potential impact of warmer groundwater temperatures on downgradient aquatic habitats that depend on groundwater discharge (Klove et al., 2014). Baseflow discharge of comparatively cool groundwater to streams (or springs) is a critical supporting factor in fish population viability, providing cold-water refugia in aquatic ecosystems across the Pacific Northwest, particularly during the low-flow, high-temperature summer season (e.g., Brown et al., 2007; Torgersen et al., 2012; Kurylyk et al., 2014b; Pitz and Sinclair, 1999; Earman and Dettinger, 2011; UNESCO, 2008; Mantua et al., 2010; Pike et al., 2010; Mayer, 2012; Yeakley et al., 2014). In addition to the potential for additional heat contributions to surface streams, reductions in groundwater baseflow volume can also decrease the thermal buffering capacity of a surface-water system, potentially accelerating increases in surface-water temperatures as climate warming unfolds (see Section 3).

Several of the papers reviewed during this project (e.g., Kurylyk et al., 2014a) caution that previous studies designed to predict the thermal sensitivity of rivers and streams to climate warming have not adequately accounted for the possibility of concurrent warming of shallow groundwater, and the resulting increase in heat contributions to surface water from baseflow discharge.

Some authors (e.g., Klove et al., 2014; Chu et al., 2008) have suggested that groundwater-dominated streams will be buffered from the temperature impact of climate change in comparison to runoff-dominated systems due to the influx of low temperature groundwater. These conclusions are based, in part, on the results of previous field observations that have shown groundwater temperatures to be comparatively immune to surface temperature changes over multi-year periods. These short-term records of groundwater response, however, are not necessarily adequate to judge the true thermal sensitivity of aquifers (and ultimately, baseflow discharge) to longer term (multi-decadal) changes in climate (or land cover). Failing to account for the potential heat flux delivered to surface water in the coming years by warmer groundwater discharge has likely led to under-predictions of stream sensitivity to climate change.

Although the impacts of a climate-driven increase in surface air temperature are damped and delayed in the subsurface, the studies reviewed during this evaluation have reported model-predicted increases in summertime groundwater-discharge temperatures in response to climate warming up to 4.5°C (~7°-8°F), depending on the climate scenario employed for modeling and the hydrogeologic conditions of the system modeled. Subsequent transport of this heat back to the surface via baseflow discharge could have significant biological consequences, by raising surface-water temperatures and reducing the spatial extent of cold-water refugia. Increased groundwater temperatures could also cause decreased dissolved oxygen concentrations, which could have consequences for downgradient surface-water ecosystems that receive discharge from shallow aquifers (Bloomfield et al., 2013).

The lag time between a surface air temperature increase and a corresponding increase in groundwater-discharge temperature is a function of the rate of thermal transport through the vadose zone and aquifer matrix (Kurylyk et al., 2014a). This rate is, in turn, a function of recharge rates, aquifer dimensions, groundwater velocities, the thermal properties of the subsurface matrix, groundwater depth, and the rate of thermal warming on the surface. Research has shown that for some shallow groundwater systems, lag times as short as 5 years or less are possible, a response timeframe significantly shorter than previously thought.

The most vulnerable aquifers to climate-driven temperature increases are likely to be those that are overlain by a thermally conductive vadose zone matrix, have comparatively shallow depths to groundwater, and have higher annual recharge rates. Deeper aquifers overlain by less thermally diffusive soils would be less vulnerable to change. Gaining streams and rivers supported by baseflow from deeper aquifer systems with longer subsurface transport pathways will likely experience less warming. This suggests that streams in higher elevation portions of watersheds that are fed by shallower groundwater that has traveled shorter distances in the subsurface are the most likely to be vulnerable to climate-driven changes in groundwater temperatures. Contrary to earlier research, Kurylyk et al., 2014a suggest that groundwater-dominated streams may not necessarily be less sensitive to future climate temperature increases.

The findings of this evaluation indicate that it will be critical to account for the potential warming of baseflow discharge in future efforts to model climate temperature impacts on fish and aquatic habitat. The potential reduction of the spatial extent of groundwater-supported thermal refugia in surface streams could have significant environmental consequences, particularly in light of the likelihood of an increasing reliance on such refuge locations in a warming climate.

6. Impacts of Sea-level Rise on Groundwater

Key Findings

- Although climate-driven changes in sea-level position would increase the potential for sea-water intrusion into coastal aquifers, poorly managed near-shore groundwater pumping is likely to continue to be the dominant factor driving intrusion in most coastal communities. Increases in near-shore pumping rates in response to climate change could further impact coastline areas that have a demonstrated sensitivity to saltwater intrusion.
- The direct impacts of sea-level rise (saltwater intrusion and saltwater inundation) on groundwater are likely to be largest in settings with very low topographic relief and very low hydraulic gradients between freshwater and marine water (<0.001). In Washington State, coastal aquifers south of Point Grenville are the most likely to experience future problems from sea-level rise.

In total, Washington State has more than 5000 kilometers (>3000 mi) of marine coastline, suggesting that predicted sea-level rise is likely to have a significant impact on near-shore communities and coastal ecosystems. Local and regional physiographic factors will ultimately influence how future climate-driven changes in sea-level elevation manifest at any given point along the Washington coast. Uplift and subsidence activity of tectonic plates beneath western Washington will also exert an important control on the relative amount of response that occurs along Washington’s coast, respectively lessening or amplifying local sea-level change in the context of global-scale sea-level trends (Dalton et al., 2013).

While few technical papers were identified during this evaluation that specifically address the impact of climate change on saltwater intrusion for Washington State, a number of studies have recently been conducted either for other locations in the U.S., or by evaluating the problem from a theoretical standpoint. Both analytical and numerical models have been used by various authors to evaluate the sensitivity of saltwater intrusion to different physical characteristics of coastal groundwater systems, including recharge rate, aquifer thickness, hydraulic gradient, flow path length, pumping rate and location, and geologic setting (Werner and Simmons, 2009; Werner et al., 2012; Webb and Howard, 2011; Rozell and Wong, 2010; Loaiciga et al., 2012; Payne, 2010; Ferguson and Gleeson, 2012; Frans et al., 2011). A number of these studies have specifically examined the relative significance of sea-level rise versus pumping in driving the freshwater-saltwater interface inland.

In coastal settings where fresh upland groundwater and saline marine water meet, groundwater in the near vicinity of the shoreline tends to float on top of saltwater, largely due to a difference in water density. Under dynamic equilibrium conditions, the approximate position of the subsurface interface that separates saltwater from fresh water (in actuality, due to tidal mixing and diffusion/dispersion effects, a transition *zone*) is commonly estimated for unconfined aquifers using the Ghyben-Herzberg relation (Todd, 1980). According to the Ghyben-Herzberg principle, in unconfined coastal aquifers, the depth of freshwater that extends below sea level is approximately 40 times the height of the water table above sea level. This density/hydrostatic head relationship ideally results in freshwater and saline water being separated by an inclined plane (or zone) reaching inland beneath the shoreline area (Figure 3).

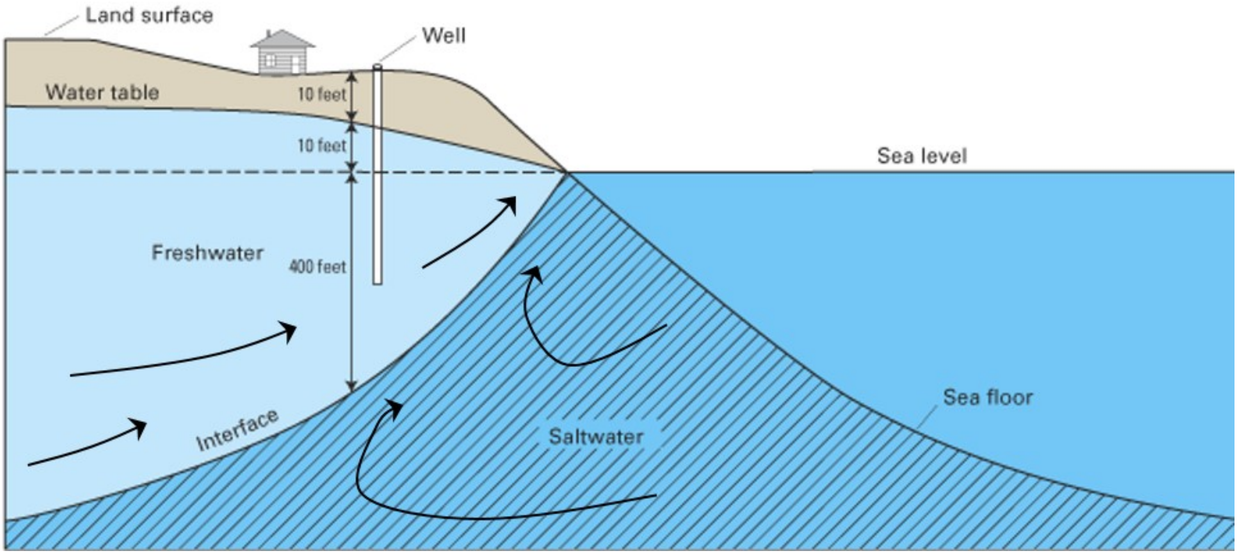

Figure 3. Idealized conceptual model of the freshwater-saltwater interface for an unconfined coastal aquifer, with example water table relationship to interface depth (modified from Barlow, 2003; not to scale).

Any process that alters the hydrostatic equilibrium between groundwater and sea water can result in a change of the position of the interface, both laterally and vertically. There are three primary mechanisms that can induce saltwater intrusion: (1) a reduction in the long-term upland recharge rate (e.g., Luoma and Okkonen, 2014), (2) a rise in sea-level position, or (3) an increase in groundwater extraction upgradient of the shoreline. Each of these processes can modify the vertical position of the water table and the slope and direction of the hydraulic pressure gradient, which would, in turn, alter the position of the interface. The specific degree of intrusion that will occur, and the time it will take to fully unfold, are a function of a complex set of factors (e.g., aquifer permeability and effective porosity, hydraulic gradient, aquifer dimensions, recharge rate, pumping rate, pumping location, presence or absence of confining units). As the interface position intrudes inland (and upwards), the fresh water lens can decrease in volume, and salinity concentrations can increase in the near-shore aquifer. Such changes can result in a significant water quality impact in coastal-area aquifers used for supply purposes.[15]

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[15] A primary component of seawater salinity is dissolved chloride. The USEPA and the State of Washington have both established a secondary Maximum Contaminant Level (MCL) for chloride in drinking water of 250 mg/L. Fresh groundwater in Washington State coastal aquifers that is uncontaminated by seawater typically has a chloride concentration of <10 mg/L. Elevated chloride concentrations in water may cause high blood pressure if consumed, may adversely affect the aesthetic quality of the water (taste, odor), and may corrode or stain pipes, fixtures, and appliances (USGS, 2000).

As discussed in Section 2, the current, available research does not indicate that climate change will necessarily cause large reductions in long-term annual groundwater recharge rates in the future in low-elevation areas of western Washington[16]. This suggests that either a rise in sea level or an increase in near-shore pumping (or a combination of both) may be the main factors of climate concern for Washington State groundwater resources in coastal areas.

Per the Ghyben-Herzberg relation, in an unconfined aquifer the depth of the freshwater-saltwater interface is defined as a function of the height of the water table above sea level. If the water table in a near-shore aquifer can rise unimpeded in response to a rise in sea level, the pressure relationship between freshwater and marine water would largely be maintained, and there would be limited change in the equilibrium position of the interface. Although some deeper near-shore wells may have to be replaced by shallower wells under this scenario, the overall freshwater volume of the aquifer is largely unchanged. If, however, the amount of water table rise is, for any reason, restricted to less than the amount of sea-level rise (due, for example, to groundwater pumping, or the water table intersecting the ground surface), significant saltwater intrusion can occur, and the freshwater volume reduced. For example if the height of the water table above sea level at a given point is currently 4 feet, but this height reduces to 2 feet after sea-level rise, the Ghyben-Herzberg relation predicts the interface position will rise vertically ~80 feet in the aquifer at that point.

Werner and Simmons (2009), Titus et al. (2009), Heimlich et al. (2009), Webb and Howard (2011), and Werner et al. (2012) have demonstrated through analytical modeling techniques that the distances of lateral saltwater intrusion under *head-controlled* conditions (i.e., when the water table is maintained in a fixed position as sea level rises) are significantly greater than under *flux-controlled* conditions (i.e., when the water table is free to rise in response to a sea-level rise). These findings suggest that settings where the inland water table position is already very close to ground surface, or where groundwater pumping prevents a rise in the water table position, will be the most vulnerable to sea-level rise.[17]

Sea-level rise cannot only cause saltwater *intrusion* by moving the position of the interface inland and upwards (by changing the pressure head relationship between sea water and freshwater), but it can also *inundate* low elevation portions of a coastline with seawater (Mauger et al., 2015). This surface flooding (saltwater inundation), which may be exacerbated in the future by an increase in coastal storm surges related to climate change, can subsequently infiltrate downward, salinizing the underlying groundwater system (Figure 4a). The large majority of the populated Washington coastline, however, has relatively steep relief beyond the

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[16] It is possible that climate-driven increases in the length and intensity of cyclical drought could produce periods of lower than average recharge. The episodic reduction in recharge could lead to periods of increased sensitivity to saltwater intrusion in areas already susceptible to such problems.

[17] Webb and Howard (2011) demonstrated through transient numerical modeling exercises that the length of time required to re-equilibrate the position of the interface in response to a change in sea level position can be as great as several hundred years, depending on the hydraulic properties of the aquifer and the permeability/recharge rate ratio.

immediate area adjacent to the shoreline, limiting aquifer susceptibility to inundation in many of these areas (e.g., the Olympic peninsula, the San Juan Islands, Whidbey Island, the mainland Puget Sound coast). Due to low elevation and comparatively flat topographic relief, the Washington coastline south of Point Grenville is the most likely area to experience future problems with saltwater inundation. This portion of the Washington coast is not heavily populated at this time.

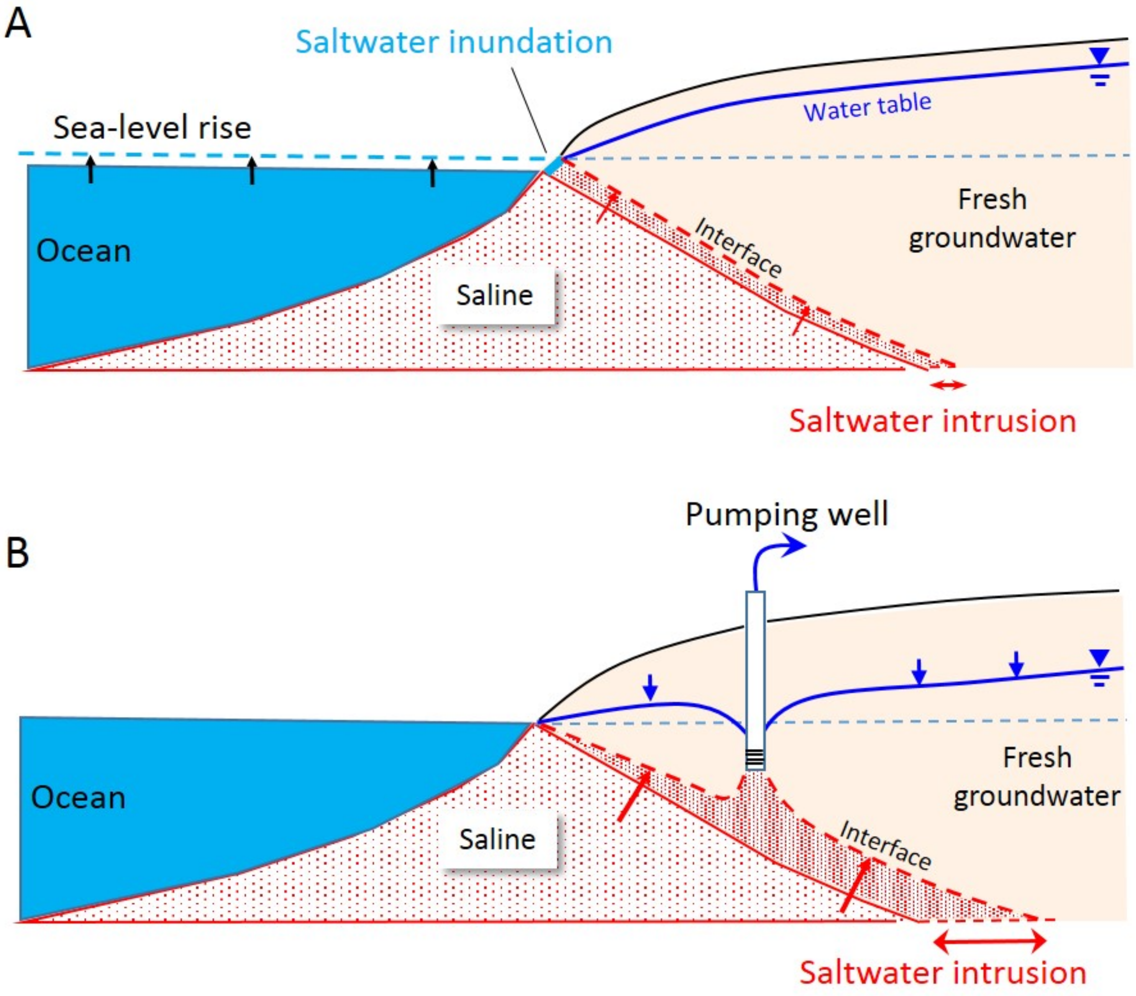

Figure 4. Idealized conceptual model of the freshwater-saltwater interface in an unconfined coastal aquifer (after Ferguson and Gleeson, 2012; not to scale).

The red dashed line indicates a change in the position of the interface that can result from either (a) sea level rise or (b) groundwater pumping.

Pumping-induced saltwater intrusion into freshwater aquifers was recognized as a problem in many coastal and island communities in Washington well before concerns about global sea-level rise came to light (Dion and Sumioka, 1984; USGS, 2000; Kelly, 2005; Sinclair and Garrigues, 1994). Per the Ghyben-Herzberg relation, in settings where a well overlies the interface, every foot of water table drawdown induced by pumping would result in an approximately 40 foot vertical rise in the interface position. In some cases this can result in substantial upconing of saline water in the vicinity of a pumping well (Figure 4b). If multiple pumping wells cause a distributed decline in the water table, the position of the freshwater-saltwater interface would shift inland and upwards, potentially resulting in significant saltwater intrusion to an aquifer.

A variety of studies have demonstrated that on-shore groundwater pumping can result in the landward movement of the freshwater-saltwater interface by hundreds or even thousands of meters. This indicates that if climate change indirectly drives an increase in groundwater pumping rates in coastal communities (for instance by increasing water demand during the summer), or if pumping rates increase due to coastal population growth or land use change, existing problems in coastline areas that already have a demonstrated sensitivity to saltwater intrusion would be intensified (and previously un-impacted areas may begin to experience intrusion problems). In Washington State, island-based aquifer systems located in the rainshadow of the Olympic Peninsula (e.g., San Juan Islands, Marrowstone Island, Guemes Island) are likely to continue to experience the greatest sensitivity to pumping-induced intrusion. This is due to the combination of comparatively lower rates of recharge, reliance on lower yield bedrock aquifers for supply, and the concentration of development in the near vicinity of the shoreline where groundwater is most vulnerable to intrusion.

The general consensus of most of the peer-reviewed technical papers reviewed during this project is that groundwater extraction upgradient of the marine coastline will continue to be the dominant factor in determining aquifer vulnerability to saltwater intrusion along most coastlines in the future (e.g., Ferguson and Gleeson, 2012; Loaiciga et al., 2012; Payne, 2010; Treidel et al., 2012). Sea-level rise or reductions in near-shore recharge rates (if they do occur), by contrast, are predicted to have only a modest impact (<50 m) on the lateral position of the interface in the majority of coastal aquifers, both unconfined and confined. These conclusions are consistent with the findings presented by Frans et al. (2011) of a detailed modeling analysis conducted for the Bainbridge Island groundwater system here in Washington State. As Kelly (2005) showed for the coastal aquifers of Island County, Washington, the specific impact of pumping on saltwater intrusion is a function of, among other factors, the hydrogeologic setting, the proximity of the pumping well to the coastline, and the water table elevation condition between the shoreline and the well.

Ferguson and Gleeson (2012) showed through analytical modeling that coastlines with only very low hydraulic gradients between freshwater and saltwater (<0.001) are likely to show significant vulnerability to a change in sea level, and they predict that such areas are likely to be impacted by saltwater inundation before saltwater intrusion. This suggests that the coastal aquifers found along the southwestern Washington shore (e.g., the Long Beach Peninsula and the Grays Harbor/ Ocean Shores area) will be the primary groundwater systems of concern from a sea-level rise standpoint. These areas, already known to be at risk from pumping-induced intrusion, could face a “double-jeopardy” in the future. Assuming current sea-level rise predictions are accurate, over-pumping would have far greater impact on groundwater conditions for the remainder of the state coastline.

Recommendations

Climate change has the potential to introduce significant new stresses on groundwater in Washington State, compounding existing large-scale problems with overdraft and groundwater quality. Although the predictions presented in this report attempt to bring an improved picture of how the future may unfold as our climate changes, there remains a large amount of uncertainty in the forecasts. Water resource managers responsible for overseeing the sustainability of state aquifers will need to account for a range of possible hydrologic responses to climate change in their decision-making and water-allocation planning.

The changes and stresses facing state aquifers in the future, and the uncertainty in predicting the absolute responses to those pressures, highlight the need for a rigorous, long-term, reliably-funded, and strategic groundwater monitoring program for Washington.

Role of Groundwater Monitoring in Adapting to Climate Change

Although the response to the water resource challenges that lie ahead will require a complex combination of political debate, technical analysis, policy and regulatory decisions, and infrastructure investment, the collection and assessment of good quality groundwater monitoring data should play a central role in guiding and informing all of these factors. Monitoring is a common-denominator need for cost-effective groundwater management. Improvements in groundwater data collection and assessment will provide the on-the-ground information necessary to help quantify the actual impacts of climate change (due to both direct and indirect factors) on state aquifers as those impacts unfold. Reliable monitoring data also will help verify and improve numerical model forecasts of hydrologic response to climate change, in turn reducing predictive uncertainty (Taylor and Alley, 2001; Earman and Dettinger, 2011; Green et al., 2011; Georgakakos et al., 2014; Alley et al., 1999).

Preventing further groundwater storage losses, and the hydrologic, biologic, and surface water quality consequences associated with such losses, is a critical priority for state water managers in the coming decades. As described throughout this report, the potential for an increase in net groundwater withdrawals from state aquifers in response to regional warming is the highest climate concern related to groundwater. While this is particularly true in arid and semi-arid areas of eastern Washington, any location where pumping exceeds local recharge, intercepts groundwater flow to streams, or induces saltwater intrusion, is of potential concern. Increased demand for groundwater could not only restrict the availability of water supply for consumption and irrigation, but could also have undesirable (and potentially costly) consequences for summer streamflows/spring flows, surface-water and groundwater quality, and biologic habitats of high environmental value to the state.

In light of the findings of this evaluation, *the highest priority information-need for groundwater in the coming decades is accurate data about state groundwater storage status and trends, with a particular focus on how groundwater pumping is affecting state aquifers.* Improved monitoring of statewide groundwater storage changes will not only provide the information required to make defensible and informed choices about water supply, but will also help scientists track and forecast closely-related changes in recharge and baseflow discharge (hydrologic processes that are intimately connected to storage).

An ongoing program to monitor and assess groundwater levels in state aquifers is the primary tool for tracking groundwater storage conditions. As Taylor and Alley (2001) report:

> *"Ground-water systems are dynamic and adjust continually to short-term and long-term changes in climate, ground-water withdrawal, and land use. Water-level measurements from observation wells are the principal source of information about the hydrologic stresses acting on aquifers and how these stresses affect ground-water recharge, storage, and discharge. Long-term, systematic measurements of water levels provide essential data needed to evaluate changes in the resource over time, to develop ground-water models and forecast trends, and to design, implement, and monitor the effectiveness of ground-water management and protection programs."*

The increased awareness of the important modifications long-term climate change are likely to impose on state aquifers (above and beyond existing stresses) makes Taylor and Alley's observations even more relevant today.

Technical Recommendations

In light of the above information, the following recommendations are offered.

Data consolidation

- Continue consolidating and standardizing Ecology-related groundwater monitoring information:
  - Use the groundwater module of Ecology's Environmental Information Management data system (EIM-Groundwater) to centrally manage all groundwater data collected by all Ecology programs conducting or overseeing field monitoring.[18]
  - Adopt agency-wide minimum data quality standards for all groundwater monitoring measurements and samples collected by Ecology employees.
  - Require all external organizations collecting groundwater monitoring data using state funding to meet Ecology data quality standards and to import the monitoring information to the EIM-Groundwater system.

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[18] This recommendation does not apply to groundwater monitoring information collected in association with the Hanford site. Groundwater data from the Hanford facility is stored and managed in a federal-level, Department of Energy data system.

State groundwater monitoring council

- Establish and fund a state groundwater monitoring council to improve data sharing, standardize data quality, and leverage existing monitoring efforts to the maximum extent possible. Include representatives from Ecology, the U.S. Geological Survey, the Washington Dept. of Agriculture, the Washington Dept. of Natural Resources, the Washington Dept. of Health, and local agencies or organizations conducting ongoing groundwater monitoring at the basin or sub-basin scale:
    - Use the groundwater monitoring council to identify and prioritize monitoring gaps.
    - Develop cooperative agreements for use of external-agency (non-Ecology) groundwater data for statewide assessment purposes.
    - Expand the function of the EIM-Groundwater system to allow import of groundwater monitoring data collected by Washington State government agencies other than Ecology. Encourage the use of the EIM-Groundwater system as the central groundwater data management tool for all state agencies.

Groundwater monitoring and assessment

- Establish a permanent, formal state monitoring and assessment program to track groundwater storage changes and trends. Dedicate long-term funding and staff to the program activities.
    - In cooperation with external partners participating on the monitoring council, collect, synthesize, and assess groundwater water-level data across Washington to support ongoing evaluation of state aquifer storage conditions. Focus monitoring primarily in areas that have shown long-term water level declines or are experiencing an increase in net groundwater pumping.
    - Assemble, collect, and assess groundwater-usage data to support interpretation of groundwater storage changes.
    - As appropriate, incorporate long-term ambient monitoring data for key groundwater quality parameters of concern (nitrate, chloride, and temperature) to track trends in large-scale water quality conditions over time.
    - On an annual basis, report the findings of the storage and water quality status-and-trends assessment to the public and the state legislature.

- Support the development and ongoing operation of the USGS Washington Climate Response Network to track baseline conditions for groundwater storage changes in areas away from pumping effects.

- As a follow-up to Pitz and Sinclair's 1999 analysis, assess and continue to track long-term trends in baseflow discharge across Washington using existing streamflow data records. Use the findings from the groundwater storage assessment to inform the baseflow analysis and help forecast baseflow conditions in future years.

Modeling and remote sensing

- Continue to support efforts to apply and improve numerical models to forecast climate change impacts on groundwater in Washington. Due to the potentially very long timeframes required for a change in climate condition to be fully manifested in larger scale, multi-layer aquifer systems, models will be an important supplemental tool to empirical field measurements.
    - Use, or where necessary update, existing numerical models (e.g., USGS Yakima Basin groundwater model; Ely et al., 2011) of state aquifer flow systems to test climate change impacts on groundwater storage and baseflow discharge. Models that are designed to closely couple groundwater and surface-water processes are the most likely to provide accurate predictions of groundwater stress response to climate change [e.g., the GSFLOW model developed for the Chamokane Creek Basin (Ely and Kahle, 2012)].
    - In cooperation with water managers, hydrologists, agricultural economists, and policy makers, develop or refine forecasts for future state pumping and irrigation scenarios. Incorporate representation of these forecasts into all modeling analyses conducted to assess future climate change impacts on groundwater.

- Explore the use of emerging remote-sensing tools to improve tracking of large-scale changes in state groundwater storage conditions. New tools such as GRACE satellite imagery have proven to be a useful complement to field scale monitoring and modeling efforts in California to track broad changes in aquifer storage in response to drought and overdraft (Famiglietti et al., 2011; Famiglietti and Rodell, 2013). Although Alley and Konikow (2015) have emphasized key limitations in the information produced by current-generation GRACE tools, future improvements in the spatial resolution of the GRACE data, combined with improved field confirmation of groundwater levels and groundwater use, could support application of this approach in Washington State in the future.

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Appendices

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Appendix A. Annotated Bibliography for Select References

ALLEN, 2010 - HISTORICAL TRENDS AND FUTURE PROJECTIONS OF GROUNDWATER LEVELS AND RECHARGE IN COASTAL BRITISH COLUMBIA, CANADA

This paper describes an analysis conducted to explore how climate change may influence groundwater conditions in the Gulf Island area of southern coastal British Columbia. The author examines historic groundwater level, chloride sample, and precipitation records to identify longer term trends in groundwater recharge, storage, and water quality, as related to climatic conditions. Recharge modeling simulations (using the HELP model) were also conducted, first to estimate historic recharge conditions, and then to evaluate projected recharge under future climate values predicted by downscaling the data from a GCM (CGCM1). Interest in learning more about how a warming climate will impact groundwater conditions in this setting is driven by recognition of the potential sensitivity of coastal aquifers to such change (due to sea-level rise, pumping pressures related to coastal development, and potential reductions in natural recharge).

The author found that many of the wells examined have exhibited negative trends in groundwater levels during the period of interest (1976 – 1999). Analysis of the weather data for this period indicate opposing seasonal trends, with an increasing trend in precipitation during the winter recharge season, and a decreasing trend during the summer months. The cause of the declining water levels is assumed to be the result of a combination of an overall decrease in recharge and over-pumping for supply. Chloride concentrations in wells were inversely correlated to groundwater levels, suggesting that future shifts in recharge due to climate change could cause changes in groundwater quality.

Allen notes that modeling simulations indicate that future mean annual recharge for the study area is predicted to increase in comparison to historic conditions, based on downscaled climate data from the CGCM1 model. Recharge increases over historic conditions as great as 111% are predicted through the year 2069, and the proportion of annual precipitation that becomes recharge is predicted to rise by 8% in that same timeframe. It's important to note, however, that the author found that significantly different changes in recharge are predicted using different GCMs, including in some cases reductions from historic recharge rates as great as -11%. The uncertainty introduced into recharge predictions by the choice of GCM for downscaled climate data should be accounted for in water management planning.

ALLEN ET AL., 2010A - VARIABILITY IN SIMULATED RECHARGE USING DIFFERENT GCMS

Allen and coauthors describe a modeling effort to evaluate how simulated recharge to a transnational aquifer in northern Washington State and southern British Columbia (the Abbotsford-Sumas aquifer) varies as a function of the GCM chosen to represent forecasted climate conditions.

The climate model predictions from a suite of four major GCMs (CGCM3.1, ECHAM5, PCM1, and CM2.1; all using the A2 emission scenario) were all processed using the same statistical downscaling method (the TreeGen model). The resulting climate data series were then used as input variables to the HELP hydrologic model to develop estimates of spatially distributed recharge for the study area. The study was motivated by the recognition of the uncertainty associated with the climate downscaling predictions used for a previous study.

The recharge predictions derived from the downscaling of the various GCM models were compared to recharge values that were considered to represent a base case historical condition. Out to the year 2099 a range of both negative and positive responses were observed, with most of the models predicting modest long-term increases in recharge to the aquifer in comparison to the base case condition (-1.5% to +23.2%; mean = +4.6%). The authors note that trends in baseflow to streams in the study area would be predicted to vary as a function of the changes predicted in recharge – i.e., model scenarios predicting an increase in recharge would be expected to experience a similar increase in baseflow, due to a rise in the regional water table position. [*Note: this point is later debated by Huntington and Niswonger, 2012*]

The authors emphasize that their analysis indicates that there are a variety of potential sources of uncertainty when using climate predictions to forecast changes in groundwater and baseflow response to climate change, including the choice of GCM for modeling, the method of downscaling the GCM data to the landscape scale (*this point is also reported by Stoll et al. 2011*), the method of modeling recharge rates using the downscaled data (most importantly the ability to properly represent seasonally-based processes that effect recharge), and finally, the uncertainties inherent in groundwater flow models that use these recharge predictions. In this study, only one of those variables was modified, and the range of possible outcomes was nonetheless significant. The authors highlight the need for water managers to recognize the potential variety of outcomes in groundwater recharge, storage, and baseflow response to climate change, and adapt to this uncertainty accordingly.

BARON ET AL., 2013 - THE INTERACTIVE EFFECTS OF EXCESS REACTIVE NITROGEN AND CLIMATE CHANGE ON AQUATIC ECOSYSTEMS AND WATER RESOURCES OF THE UNITED STATES

This paper presents a broad examination of the how climate change may alter the interrelation between excess nitrogen present across the US landscape and freshwater resources. The authors conclude that several of the predicted responses directly or indirectly associated with climate change (more intense storm events, increased winter and spring precipitation, increased irrigation) are likely to reduce residence times of water in the soil column and vadose zone and increase leaching of nitrogen to the subsurface. These conditions are likely to diminish the potential for assimilation/denitrification below farm fields and accelerate the transport of nitrogen to groundwater. The authors note that a predicted increase on groundwater as a source of drinking water for US citizens under a changing, warmer climate is likely to lead to increased costs related to the treatment of nitrate in groundwater pumped for this purpose. They call for the capture and treatment of a larger portion of both human and livestock related wastes, including the expansion of municipal sewage treatment and increased regulation of confined animal feeding operations. The long transport timeframes associated with groundwater suggest that decades may be required for improved nitrogen management practices to be realized under future climate conditions.

BARRON ET AL., 2010 - THE IMPACT OF CLIMATE CHANGE ON GROUNDWATER RESOURCES: THE CLIMATE SENSITIVITY OF GROUNDWATER RECHARGE IN AUSTRALIA.

Concern about the potential impacts of climate change on the groundwater resources of Australia prompted the analysis described in this report. The project included an evaluation of how diffuse recharge processes differ between climatic regions, and an assessment of the differences in projected future recharge estimates using different GCMs, downscaling methods, and hydrologic models.

Among the findings presented in the report:

- While the amount of annual rainfall is an important factor influencing recharge in Australia, recharge rates were more closely correlated to metrics that reflect rainfall intensity and duration.
- Climate change is likely to cause changes in vegetation cover in some regions of Australia, resulting in a transition of those region's climatic type in the future. Since vegetation cover can play a significant role in rates of recharge to the underlying groundwater system, transitions in regional climate type and vegetation structure (for example semi-temperate areas transitioning in the future to arid areas) need to be considered when modeling future recharge.

There was significant variability in the predictions produced by the different GCMs, data downscaling methods, and hydrologic models evaluated by the authors. When different combinations of these data processing steps were assembled, a wide range of future groundwater recharge rates were predicted. The authors concluded that this high degree of uncertainty emphasizes the need to use a suite of predictive tools when attempting to estimate ranges of likely recharge conditions in the 21st century.

CROSBIE ET AL., 2011 - DIFFERENCES IN FUTURE RECHARGE ESTIMATES DUE TO GCMS, DOWNSCALING METHODS AND HYDROLOGICAL MODELS.

Predictions of changes in groundwater recharge rates are often developed by downscaling climatic condition predictions from GCMs, and using the downscaled values as input into hydrologic models. This paper examines the relative degree of uncertainty introduced into the recharge predictions by each of the three principal components of this type of modeling work – the choice of the GCM, the choice of the data downscaling method, and the choice of the hydrologic model. The authors found that the choice of the GCM used for predicting future temperature and precipitation conditions was the largest source of uncertainty, followed by the method chosen to downscale the GCM data (from a global to a regional or local scale for input to the hydrologic model). They conclude that future studies of groundwater recharge changes due to climate change use multiple GCMs to provide a bracketed range of possible climate outcomes.

DESTOUNI AND DARRACQ, 2009 - NUTRIENT CYCLING AND N_2O EMISSIONS IN A CHANGING CLIMATE: THE SUBSURFACE WATER SYSTEM ROLE

Groundwater flow is known to serve as a significant transport mechanism for anthropogenic nutrient loads to surface waters, contributing to eutrophication problems in many water bodies across the world. In this paper, the authors evaluated how climate change may influence future loading rates of nitrogen and phosphorus to the coastal waters of Sweden via groundwater discharge.

Climate change data from two future climate model scenarios were used as input to a hydrologic model of a study area in Sweden (using the POLFLOW water flow and nutrient attenuation model) to allow predictions of future nutrient fluxes, assuming land use inputs of nutrients to the subsurface remain consistent with current conditions. The modeling results indicate that due to changes in precipitation rates, water flow through the groundwater system and out to the sea would increase by approximately 26% out to the year 2100. The results also predict a significant increase in both nitrogen and phosphorus annual loads to the coast by that date. The authors emphasize that the nutrient loading increase would not, however, be a result of the climate-driven changes in flow, but would instead be due to the arrival of delayed nutrient inputs to the aquifer system that occurred earlier in time. This *long memory*, a function of the comparatively long transport times from nutrient point of release to point of discharge, is the significant controlling factor in the predicted increase in nutrient flux, irrespective of climate scenario. The authors acknowledge that these predictions do not account for any climate-related changes in nutrient attenuation or transformation rates.

DUCHARNE ET AL., 2010 - CLIMATE CHANGE IMPACTS ON WATER RESOURCES AND HYDROLOGICAL EXTREMES IN NORTHERN FRANCE.

Downscaled climate data from an ensemble of 12 different GCM model scenarios (A2 emissions scenario) were used by these authors to predict water resource responses to climate change in two basins in northern France. The temperature and precipitation results from these scenarios were used as input variables for 5 different hydrologic models (MODCOU, SIM, CLSM, EROS/GARDENIA, and GR4J). The modeling predictions indicate that groundwater levels (and river discharge) will decline significantly in the study areas over the course of the 21st century. The predicted changes are much larger than the uncertainty estimated for the model results. Most of the model estimate uncertainty is assigned to the choice of GCM, followed closely by the choice of data downscaling method and choice of hydrologic model.

The authors of the paper note that in response to declining surface discharge and a warmer climate, irrigation demand, mostly met by groundwater extraction, is predicted by the STICS crop model to increase significantly in the study basins (up to +60%). Modeling showed that aquifer water levels are predicted to decline by as much as 3 m (~9.8 ft) locally as a result of the extra pumping. However, water level declines related to the climate-change-driven reduction in aquifer recharge significantly outweigh the effect of pumping, resulting in a lowering of the water table by as much as -15 m. The predicted water level changes will also result in reduced baseflow to basin streams; the combined impacts of climate change will threaten the sustainability of water supply in the study areas.

FERGUSON AND GLEESON, 2012. VULNERABILITY OF COASTAL AQUIFERS TO GROUNDWATER USE AND CLIMATE CHANGE

This paper provides a large-scale vulnerability analysis of coastal United States aquifers to both population-driven increases in groundwater pumping and climate-change-driven, sea level rise. For the purposes of this work, the authors classified two distinct concerns: (1) sea water *intrusion*, defined by the landward movement of the toe of the freshwater/saltwater interface, and (2) sea water *inundation*, defined by the landward movement of the coastline.

To quantitatively assess aquifer vulnerability, the authors mapped a variety of characteristics in a Geographic Information System (GIS) environment, including the spatial distribution of the horizontal hydraulic gradient, topographic gradient, and population density of US coastal watersheds. This information was synthesized with the results from a steady-state, two-dimensional analytical groundwater flow model that was used to estimate the sensitivity of the position of the saltwater interface to different control variables (e.g., extraction rate, hydraulic gradient, aquifer thickness, hydraulic conductivity). The base case model parameter assumptions used during the analysis include a 0.59 m (~2 ft) rise in the steady-state sea level by years 2090-2099, an extraction well located 1 km (~0.6 mi) inland of the shoreline, and a 30 m (~98 ft) thick aquifer with a median hydraulic conductivity for coastal aquifer materials of 1.6E-3 cm/sec (~4.5 ft/day). The mean US domestic usage of 550 L/day (~145 gal/day) was assumed as the per capita groundwater extraction rate for each model analysis.

The analysis demonstrates that the impact of groundwater extraction on coastal aquifers is likely to be a significantly larger factor in determining aquifer vulnerability than sea-level rise or change in recharge rate. The modeling predicts that sea-level rise will only have a significant impact on sea water intrusion in areas where the horizontal hydraulic gradient of the near-shore aquifer is very low (<0.001); the authors note that most low gradient coastal aquifers in the US are sparsely populated [*Note: the large majority of the Washington State coastline aquifers were estimated by the authors to have a hydraulic gradient >0.001*]. Variability in recharge rate, aquifer thickness, flow path length, and aquifer hydraulic conductivity exerted a more limited control on intrusion. The modeling also shows that sea water inundation will be of concern in only a small number of coastal aquifers across the US – in particular those with topographic gradients <0.001.

The study findings indicate that for the majority of coastal US aquifers, groundwater extraction management practices are likely to have a significantly greater influence on impacts to the freshwater/saltwater interface position than sea-level rise.

FERGUSON AND MAXWELL, 2012 – HUMAN IMPACTS ON TERRESTRIAL HYDROLOGY: CLIMATE CHANGE VERSUS PUMPING AND IRRIGATION (SEE ALSO FERGUSON AND MAXWELL, 2010; KOLLET AND MAXWELL, 2008)

The authors of this paper used a fully integrated groundwater/surface-water/land-vegetation model (ParFlow) to compare the relative effect of climate change and water management practices on energy fluxes, land-atmosphere interactions, and hydrologic processes for an agricultural watershed in the southern Great Plains of the United States.

The authors developed a series of modeling scenarios to independently examine the effects of both climate change and water management practices. A set of three potential climate scenarios (hot, hot-wet, hot-dry) were developed for the study area based on climate projections generated by a suite of 20 GCMs, out to the year 2050. The associated temperature and precipitation estimates generated for each climate scenario were used as input boundary conditions in the ParFlow model. For an additional set of model runs, the authors left observed meteorological inputs unperturbed, but modified the model inputs to reflect differing water management scenarios for the study area (irrigation, groundwater pumping, irrigation+pumping). Each climate and water management model scenario was run independently until a quasi-steady state condition was achieved in the water and energy balances. The resulting changes in model hydrologic response were compared to a calibrated control scenario that was based on observed meteorological conditions, and run without pumping or irrigation effects.

A comparison of the modeling predictions between the different scenarios indicated that the local-scale spatial distribution of climate and water management effects were significantly different. The averaged, basin-scale impacts of pumping and irrigation practices on surface and subsurface water budget components (particularly stream discharge and groundwater storage), however, were nearly equivalent in absolute magnitude to the impacts caused by anticipated changes in the climate of the study area (e.g., a 2.5°C temperature increase). Both the climate and water management scenarios resulted in significant declines in groundwater storage ($\geq$1 m; ~3.3 ft) within the study area, although the spatial distribution of the impact showed distinct differences.

These findings emphasize the importance of accounting for water management practices whenever attempting to model hydrologic and land-energy responses to climate change, particularly in semi-arid and arid settings. The authors note that an increasing reliance on groundwater pumping in response to climate change is likely to exacerbate the hydrologic impacts of a warmer climate, and lessen the resilience of local communities in the face of a changing environment.

FICKLIN ET AL., 2010 – SENSITIVITY OF GROUNDWATER RECHARGE UNDER IRRIGATED AGRICULTURE TO CHANGES IN CLIMATE, CO_2 CONCENTRATIONS AND CANOPY STRUCTURE

In this paper, the HYDRUS 1D model was used to assess changes in vadose zone hydrology and groundwater recharge predicted to occur in response to assumed changes in both atmospheric CO_2 and average daily temperature. The modeling was conducted for three typical agricultural crop types (alfalfa, tomatoes, and almonds) in the irrigated, semi-arid Central Valley of California.

The modeling analysis accounted for changes in crop growth and transpiration rates that would likely occur in response to increases in atmospheric CO_2 concentration in comparison to current conditions. Both factors can affect ET, a key control on recharge rate. As the Central Valley climate warms due to climate change, reliance on groundwater is expected to increase significantly, so an accurate understanding of climate-driven responses in recharge are critical for sustainable management of the resource.

The HYDRUS 1D model provides a one-dimensional simulation of water flow, root water uptake, root growth, and evaporation from the soil surface in variably saturated media (using the Penman-Monteith equation to account for the effects of elevated CO_2). Crop specific values for water uptake, and soil hydraulic properties can be accommodated in the model. For modeling purposes, the authors assumed an increase in atmospheric CO_2 to a concentration between 550 and 970 ppm, and an increase in average daily temperature between 1.1 and 6.4°C (~2 to 11.5°F) in comparison to current conditions (both assumptions based on IPCC emission scenarios out to the end of the 21st century). Precipitation rates in the Central Valley were assumed to remain the same as current conditions. Irrigation rates for use in the HYDRUS 1D model were estimated using an independent crop water demand and soil moisture deficit program (Basic Irrigation Scheduling-BIS) that accounts for local soil, plant and climate conditions.

The modeling results suggest that groundwater recharge rates may be highly sensitive to potential changes in climate in the future. The combined effects of increased daily temperatures and increased atmospheric CO_2 concentrations led to a decrease in groundwater recharge for all of the crop scenarios examined (between 8.4 and 95.3% reduction). These predicted decreases were related to a climate-driven reduction in growing season ET, which in turn led to a reduced demand for irrigation water (which is a primary source of recharge to the groundwater system). Changes in crop growth and water demand both have implications for future water agricultural management and groundwater quality.

FRANS ET AL., 2011 (AND PERSONAL COMMUNICATION) - CONCEPTUAL MODEL AND NUMERICAL SIMULATION OF THE GROUNDWATER-FLOW SYSTEM OF BAINBRIDGE ISLAND, WASHINGTON

This report documents the development of a three-dimensional numerical groundwater flow model for Bainbridge Island, in the central Puget Sound area of western Washington. Groundwater serves as the sole source of drinking water for this rapidly growing area. Concerns about supply and seawater intrusion prompt the need for a better understanding of the likely response of the island's aquifer system to further groundwater development.

A SEAWAT-MODFLOW model of the study area groundwater system was constructed and calibrated to current conditions. Recharge values for model input were estimated for the island using the Deep Percolation Model (DPM) and historical average climate conditions derived from Oregon State University PRISM climate data. The DPM model was applied to a small sub-basin within the study area and then recharge values for the remainder of the island were extrapolated on the basis of precipitation, land use, and soil type, using a regression analysis. A current-condition average annual precipitation-derived recharge value of approximately 16 inches was estimated for the study area. The authors note that under the current recharge/pumping/sea-level regime, water levels within the key water-bearing zones of the aquifer system have declined locally by more than 35 feet from predevelopment conditions (largely due to pumping for public supply purposes), but no evidence of induced saltwater intrusion was apparent.

Once the study area model was adequately calibrated to current conditions, the authors ran a series of additional predictive model scenarios to examine the potential of the combined effects of increased pumping, land use change, and changing climate. Three major scenarios were run to reflect *minimal*, *expected,* and *maximum* impact conditions. Potential change in climate was represented in the model by downscaling temperature and precipitation data from a suite of 21 GCM forecasts, and modifying the PRISM data inputs to the DPM recharge model out to the year 2035.

The authors report that under the maximum impact scenario (the most extreme stress the aquifer might be expected to experience), the average recharge rate to the aquifer system will decline slightly from current conditions. A significant proportion of this decrease was due to the predicted expansion of impervious surface within the model domain. Water level declines as great as 40 ft from current conditions are predicted in the different aquifers underlying the island under this worst-case scenario; the majority of these changes are interpreted to be due to the modeled increases in pumping (climate change-driven changes to recharge have a significantly smaller effect on water level decline). The authors of the report note that while groundwater flow directions may actually reverse under these conditions, the saltwater/freshwater interface remains offshore of the island. It should be noted, however, that the modeled scenarios of future conditions did not account for any climate-related sea-level rise.

GODERNIAUX ET AL., 2010 - HOW CAN LARGE-SCALE INTEGRATED SURFACE-SUBSURFACE HYDROLOGICAL MODELS BE USED TO EVALUATE LONG-TERM CLIMATE CHANGE IMPACT ON GROUNDWATER RESERVES?

The authors of this paper describe the use of an integrated, calibrated, finite element surface-subsurface hydrologic model (HydroGeoSphere) to examine long-term impacts of climate change on groundwater in a study basin in Belgium. In addition to simultaneously solving equations for both surface and sub-surface flow processes, estimates of future AET were developed by downscaling data from an ensemble of six regional-scale GCM model scenarios (A2 emissions scenario) out to the year 2100 in order to provide improved estimates of recharge rates to the model domain. The authors note that the use of an integrated model that accurately accounts for the closely connected fluid exchange processes between surface and sub-surface domains is superior to modeling efforts that don't numerically connect these two domains.

Under the conditions of a warmer, drier climate predicted for the study site, the model predicts a significant decline in groundwater levels of between 2 to 8 m (~6.5 to 26 ft) from historic conditions by the end of the 21st century (assuming groundwater pumping rates are held constant for the entire model period). In addition, surface flows at the base of the study basin are predicted to decrease between 9% and 33%, with the bulk of that decline occurring during the summer. The authors note that the modeling predictions are focused on the direct impacts of climate change; indirect impacts (such as those related to future adjustments to pumping) are not addressed.

GRAHAM ET AL., 2014 - CLIMATE CONTROLS ON NITRATE CONCENTRATION VARIABILITY IN THE ABBOTTSFORD-SUMAS AQUIFER, BRITISH COLUMBIA, CANADA

This paper describes an analysis that was conducted to evaluate the relationship between temporal changes in climatic condition and groundwater nitrate concentration measured in a regional-scale trans-boundary aquifer system in the Pacific Northwest. Elevated groundwater nitrate concentrations are a widespread concern in the Abbottsford-Sumas aquifer (northwest

Washington State and southwestern British Columbia). Establishing a systematic relationship between climate patterns and subsurface nitrate concentrations can allow the influence of climate variability to be accounted for when evaluating long-term nitrate concentration trends. Doing so would help stakeholders specifically determine how land-use changes and management practices are affecting groundwater quality.

Climatic cycles and temporal precipitation patterns have a substantial control on recharge, and on water table position. These factors can in turn affect contaminant transport (e.g., nitrate leaching). Without accounting for these effects, temporal trends in groundwater quality could be misinterpreted (e.g., large precipitation events may mobilize nitrate reservoirs in the vadose zone in arid and semiarid regions, but the spike in concentration may be incorrectly interpreted to be a function of a change in land use).

The authors note that nitrate concentrations are influenced by seasonal cycles in precipitation, and that leaching of nitrate that occurs during wetter periods is greater than the nitrate dilution effects that may result from increased recharge.

The authors determined that cyclical variations in groundwater nitrate concentrations correspond with variations in precipitation at both seasonal (1 yr) and longer-period (5-yr) scales. These precipitation cycles are estimated to affect nitrate concentrations by +/-30% of the drinking water Maximum Contaminant Level (10 mg/L as nitrogen) in the study area, although not all wells exhibit a direct correlation, due to local factors in the vicinity of the well that also have bearing on the nitrate concentration.

Interpretation of short-term trends in nitrate concentrations, without consideration of the role of climate oscillations, may lead to incorrect conclusions about the success or failure of management activities intended to reduce loading to the aquifer. It is very important to note that the period of record for data collection has to be long enough to capture the climatic oscillations, a point that reinforces the need for long-term groundwater monitoring.

GUNAWARDHANA AND KAZAMA, 2012. STATISTICAL AND NUMERICAL ANALYSIS OF THE INFLUENCE OF CLIMATE VARIABILITY ON AQUIFER WATER LEVELS AND GROUNDWATER TEMPERATURES: THE IMPACTS OF CLIMATE CHANGE ON AQUIFER THERMAL REGIMES

This paper describes a modeling analysis that was completed for a study site in northern Japan. The focus of the analysis was to examine how groundwater temperatures in a fine-grained alluvial aquifer are likely to respond to changes in climatic conditions occurring throughout the 21st century, as bracketed by an ensemble of 15 GCM/emission scenarios. The GCM data was downscaled and then applied to a two-dimensional VS2DH numerical model of the groundwater system to examine thermal responses to changes in air temperature and precipitation. The modeling results indicate that groundwater at a representative depth of 8 m (~26 ft) below ground surface may warm by between 1.0 and 4.3°C (1.8 to 7.7°F) by 2099 in comparison to conditions in 2007. The authors highlight the important implications these changes may have on surface aquatic ecosystems that are dependent on a regular supply of cold groundwater discharge. They also note that even small changes in groundwater temperature can alter the dissolved geochemical condition in the subsurface and lead to negative water quality effects (for example shifting redox potentials and leading to changes in metals solubility and sorption).

HANSON ET AL., 2012 – A METHOD FOR PHYSICALLY BASED MODEL ANALYSIS OF CONJUNCTIVE USE IN RESPONSE TO POTENTIAL CLIMATE CHANGES

This paper describes an effort to use a linked modeling approach to evaluate the potential effects of climate change on the conjunctive use of groundwater and surface-water resources in the Central Valley of California through the end of the 21st century. The analysis was conducted by initially linking downscaled temperature and precipitation data from a GCM model (GFDL; A2 emission scenario) to a precipitation-evapotranspiration-runoff hydrologic model (MHWM-BCM) for the mountainous landscape draining to the Central Valley. Runoff and recharge outputs from the MHWM-BCM model were used as input boundary conditions for a linked, fully integrated hydrologic model of the valley's surface-water/groundwater system (CVHM), accounting for predicted future agricultural, municipal, and native vegetation water demand, and irrigation inputs and return flows (using the MODFLOW-FMP, Farm Process model). Future changes in crop water demand due to increased atmospheric CO_2, or changes in land use and cropping patterns were ignored, but sea-level elevation at the lower basin boundary was adjusted to reflect predicted sea-level rise.

The linked model predicts that as the Central Valley warms and dries through the 21st century due to climate change, annual ET will rapidly increase, and a sustained drought condition will prevail across the model domain in the second half of the century. These changes will lead to as much as a 65% reduction in upland runoff, limiting surface water available to meet a simultaneously rising crop water demand (~50% increase over historic conditions). In the CVHM model, this reduction in available supply from surface streams led to a shift of the agricultural system in the valley to a significantly heavier reliance on groundwater pumping (3.5X increase from current conditions). The increase in pumping is compounded by reductions in groundwater recharge that occur in association with reductions in streamflow infiltration to the aquifer system. These changes are predicted to cause significant declines in overall groundwater storage (with 10's of meters of water level decline in valley aquifer locally), as well as reductions in baseflow to study area streams.

The authors conclude that the use of an ensemble approach to modeling can allow useful predictions of how a regional scale hydrologic system will respond to climate change (and climate variability) via a complex set of feedback processes. These tools can help water supply managers evaluate conjunctive-use supply and demand responses to a warming climate. The uncertainty inherent in GCMs precludes accurate predictions of the actual future outcomes of climate change, but the modeling approach helps to reveal likely vulnerabilities, trends, and component changes in study area water budgets.

HUNTINGTON AND NISWONGER, 2012 - ROLE OF SURFACE-WATER AND GROUNDWATER INTERACTIONS ON PROJECTED SUMMERTIME STREAMFLOW IN SNOW DOMINATED REGIONS: AN INTEGRATED MODELING APPROACH

Monitoring data records are showing a broad decreasing trend in summertime streamflow rates across the western United States under changing temperature and precipitation conditions. This paper describes a modeling study the authors conducted for a high elevation watershed complex in the Sierra Nevada. The purpose of the modeling was to attempt to identify the physical mechanisms and hydrologic processes that are leading to these streamflow declines, with a particular emphasis on how changes in climate drive changes in groundwater/surface-water interactions.

The authors used predictive results from a suite of 12 GCMs to generate climate input data for an integrated groundwater/surface-water numerical model of the study area (USGS GSFLOW). GSFLOW couples the Precipitation Runoff Modeling System (PRMS) with MODFLOW to simultaneously simulate flow throughout the entire hydrologic cycle. The authors noted that many previous efforts to evaluate climate impacts on groundwater recharge and groundwater/surface-water interactions did not rely on the use of hydrologic models that closely couple surface and subsurface processes. Doing so can lead to inaccurate predictions of hydrologic response due to a failure to realistically simulate feedback mechanisms between differing hydrologic processes. The use of the GSFLOW model was intended to address this shortcoming.

The authors found that, in the dry montane setting of the Sierra Nevada, the timing of peak groundwater discharge to a stream is inversely correlated to snowmelt runoff, due in large part to bank storage effects and reversal of the hydraulic gradient between the surface and the subsurface across seasons (i.e., high snowmelt-driven runoff in the spring temporarily directs the hydraulic gradient towards the aquifer; the gradient reverses and baseflow from the aquifer initiates after recession of peak flow begins). Most notably, the authors highlight that the modeling indicates that groundwater discharge to streams will decrease in the study area in the summertime by more than 30% under a projected warming climate, even if projected annual precipitation and groundwater recharge increase.

This seeming paradox is largely the result of a shift in the timing of the peak snowmelt to earlier in the year, which in turn leads to a corresponding shift in the timing of peak groundwater discharge to the stream (i.e., shallow aquifers adjacent to streams will drain earlier in the year). This finding contradicts conclusions drawn by earlier researchers (e.g., Allen et al., 2010) that since climate change-related increases in precipitation are likely to increase annual groundwater recharge, summertime flows are likely to increase as well.

JIN AND SRIDHAR, 2012 - IMPACTS OF CLIMATE CHANGE ON HYDROLOGY AND WATER RESOURCES IN THE BOISE AND SPOKANE RIVER BASINS

This paper includes an analysis of the potential future effects of climate change on the hydrology of the Spokane River Basin. Decadal scale climate projections from a suite of five GCMs (CCSM3, HADCM3, IPSL CM4, MIROC 3.2, and PCM) were downscaled for use in the SWAT (Soil and Water Assessment Tool) model in order to develop predictions of future hydrologic response (magnitude and timing of flow) and water budget estimates for the watershed under a warming climate.

Groundwater interactions with the Spokane River watershed play a significant role in system hydrologic behavior. The river is in close connection with the Spokane Valley-Rathdrum Prairie Aquifer (SVRPA) system, and pumping effects from the aquifer have the potential to significantly impact summer baseflow to both the Spokane River and the Little Spokane River. The SWAT model, which can simulate both surface and subsurface hydrologic processes, was modified for use in a snowmelt-dominated basin, and calibrated using automated model optimization procedures.

The ensemble climate model for the Spokane River watershed predicts a range of temperature change between 0.31 to 0.42°C per decade out to the year 2060, and a range of annual precipitation change of between -7% and +18% (average: ~+5%, depending on climate model). Among the various components of the mid-21st century basin water budget estimated using these forecasted climate conditions, the SWAT modeling results predict a future groundwater recharge rate to the SVRPA ranging between 50-100 mm/yr (~2-4 in/yr). This estimate suggests that there may be a potential reduction in annual recharge in comparison to estimated current conditions (25-500 mm/yr; ~1-20 in/yr). The authors acknowledge that a significant degree of uncertainty in the recharge estimates presented is introduced by uncertainties in the both the downscaled GCM results and the hydrologic modeling process.

JOHNSON AND SAVOCA, 2011 - NUMERICAL SIMULATION OF THE GROUNDWATER-FLOW SYSTEM IN TRIBUTARY SUBBASINS AND VICINITY, LOWER SKAGIT RIVER BASIN, SKAGIT AND SNOHOMISH COUNTIES, WASHINGTON.

The authors of this report developed a calibrated numerical groundwater flow model (MODFLOW-2000) of the aquifer system underlying a sub-basin located in northwestern Washington State. Once the model was calibrated to current conditions, a variety of future model scenarios were run to predict the response of the groundwater system to potential future changes in hydrologic condition. One of the scenarios examined by the authors (Simulation 5) tested how steady state groundwater levels would respond to a 20% reduction in annual recharge, an adjustment intended to represent a possibly drier future climate. The model results indicate that under these conditions, water levels in the principal aquifer used for water supply purposes would decline from 1 to 40 ft, with maximum declines as great as 116 ft. From a flow perspective, the reduction in recharge would be almost entirely manifested as an equivalent reduction in discharge to model domain surface streams.

JOHNSON ET AL., 2011 - NUMERICAL SIMULATION OF THE GROUNDWATER-FLOW SYSTEM IN THE CHAMBERS-CLOVER CREEK WATERSHED AND VICINITY, PIERCE COUNTY, WASHINGTON

This report describes the construction and calibration of a numerical groundwater flow model (MODFLOW-2000) for a regional-scale study area in central western Washington, bordering Puget Sound. The model was used to evaluate how potential future changes in hydrologic or pumping conditions would impact the groundwater system. One of the scenarios presented by the authors (Scenario 1) involved the modification of the annual steady state groundwater recharge rate to represent a possibly drier climate in the future (an assumed 20% reduction in recharge). The model results indicated that, in comparison to the current condition *base case*, the net exchange of water between the aquifer system and surface water would actually reverse under the reduced recharge condition. Reduced recharge rates (~34,000 acre-ft/yr) would result in the reversal of hydraulic gradients and allow additional downward infiltration from study area streams and lakes into the aquifer system (~40,000 acre-ft/yr increase in stream and lake loss to groundwater). In addition, there would be a reduction in the amount of spring discharge, and discharge of groundwater to Puget Sound shorelines. Water levels in the primary water supply aquifer would decline from 1 to 30 ft on average, with a maximum decline of 64 ft (no adjustment to sea-level conditions were made during the modeling).

KIDMOSE ET AL., 2013 - CLIMATE CHANGE IMPACT ON GROUNDWATER LEVELS: ENSEMBLE MODELING OF EXTREME VALUES

The purpose of the study described in this paper was to apply extreme value statistical analysis to predictions of groundwater level response to future climate events in order to determine the likely frequency of extreme high groundwater levels. This central Denmark study area is vulnerable to groundwater flooding; predictions of climate-driven changes in groundwater levels could support future surface infrastructure planning efforts.

Climate change condition predictions from an ensemble of a total of 18 GCM scenarios were downscaled using two different methods, and applied as input parameters (temperature, precipitation and PET) to an integrated surface water/groundwater numerical model (MIKE-SHE) to estimate climate change impacts on the study site hydrology. Hydraulic head changes in the modeled aquifer system were predicted out to the year 2100. The analysis included an assessment of the degree and sources of uncertainty in the predictions due to uncertainties in the climate-related model input values.

The modeling analysis predicts only modest changes in groundwater levels in the study area, even under extreme storm events (assuming that land use, surface drainage infrastructure, and groundwater pumping rates remain consistent with current conditions). The authors note that while some of the uncertainty in the groundwater level response predictions is related to the choice GCM scenario, most of the uncertainty is related to the predictions of extreme storm events.

KURYLYK ET AL., 2014A. SHALLOW GROUNDWATER THERMAL SENSITIVITY TO CLIMATE CHANGE AND LAND COVER DISTURBANCES: DERIVATION OF ANALYTICAL EXPRESSIONS AND IMPLICATIONS FOR STREAM TEMPERATURE PROJECTIONS

The authors of this paper suggest that previous studies that have attempted to predict the thermal sensitivity of rivers and streams to climate warming have failed to adequately account for concurrent changes that are likely to occur in groundwater temperatures and heat flux contributions to surface water. Previous research has assumed that groundwater thermal responses to a warming climate will have very long lag times (decades or centuries), or failed to account for changes in groundwater temperatures that will arise in response to climate-driven changes in land cover. These omissions have led to the conclusion that groundwater dominated streams will generally warm less than runoff dominated streams under the same climate warming condition. There is increasing evidence that groundwater temperatures in shallow aquifers can show significant sensitivity to climate change and changes in land cover due to deforestation or wildfires, in some cases.

The authors of this paper develop a series of one-dimensional analytical solutions of subsurface heat transfer in order to investigate the factors that drive the thermal sensitivity of groundwater to different surface temperature changes occurring due to climate change or land cover disturbances. On the basis of their analysis, they draw the following conclusions:

- Shallow groundwater temperatures are susceptible to warming due to atmospheric climate change (or the potential changes in land cover related to climate change), to depths at least 20 m (~66 ft) below land surface.
- The degree of groundwater thermal sensitivity is a function of the rate of warming, subsurface thermal properties, aquifer depth, vertical groundwater velocity, and recharge rate. Aquifers with shallower depths to water, higher recharge rates, and higher thermal diffusion constants result in more groundwater warming.
- In areas of shallow groundwater with a thermally conductive vadose zone matrix, significant long-term climate-related warming of groundwater can occur.
- Groundwater is less sensitive to short term seasonal or inter-annual changes in temperature than to long-term (multi-decadal scale) changes, so short term records of groundwater temperature response are not adequate to judge the spatial thermal sensitivity of aquifers to climate or land cover changes.
- Streams sourced from deep aquifers overlain by less thermally diffusive vadose zone soils will not experience as much increase in streambed advective heat flux as streams fed by shallow groundwater overlain by more thermally diffusive soils.
- The additional heat flux from groundwater is often not accounted for in models of stream temperature response to climate change-related warming. This additional source of heat could have significant temperature implications for groundwater-dominated streams and cold water refugia, (particularly smaller scale streams), and should be incorporated into future stream temperature predictive models addressing climate change effects.

KURYLYK ET AL., 2014B. CLIMATE CHANGE IMPACTS ON THE TEMPERATURE AND MAGNITUDE OF GROUNDWATER DISCHARGE FROM SHALLOW, UNCONFINED AQUIFERS

Previous research has shown that the inflow of groundwater to surface streams is a key factor in supporting critical summertime thermal refugia for salmonids and other aquatic species. The authors of this report where interested in examining how climate change is likely to affect shallow (<10 m; ~33 ft)) groundwater temperature and discharge patterns (timing and magnitude) to an adjacent stream.

Downscaled climatic data from a suite of seven GCMs were used as input to a HELP3 model in order to generate daily groundwater recharge values for a study area in New Brunswick, Canada, out to the year 2065. These recharge values, along with modeled ground surface temperatures, were in turn used as input boundary conditions for a two-dimensional, variably-saturated groundwater flow and heat transport model (SUTRA) of a conceptual shallow unconfined aquifer providing discharge to an adjacent stream. The SUTRA modeling was focused on identifying changes that occur in groundwater-discharge temperature and rate under several differing aquifer/stream physical configurations, in the context of the likely range of future climate conditions.

The authors determined that all but one of the GCM-based model scenarios predicted significant increases in groundwater-discharge temperatures to the model stream, both during the summer, and on an annual basis. Summer groundwater-discharge temperatures in the study area were predicted to increase as much as 3.6°C (~6.5°F), driven largely by predicted increases in air and precipitation (recharge) temperature. The predicted thermal response of groundwater discharge to climate change was shown to be dependent on aquifer geometry, indicating that differing aquifer/stream systems will have differing sensitivities to long-term (decadal scale) climate change. For shallow groundwater systems, the lag time between changes in climatic condition and corresponding changes in groundwater temperature can be quite rapid (<5 yrs). This suggests that shallow groundwater (<10-20 m; ~33-66 ft), and groundwater-discharge temperatures can be highly sensitive to decadal scale changes in air temperature. These temperature increases could in turn place in-stream cold water refugia that are groundwater dependent at risk.

The modeling also showed that climate change-driven shifts in recharge timing can also result in reductions to the rate of groundwater discharge during the later summer, potentially reducing the spatial extent of the thermal refugia in baseflow-dominated streams (which may already be overpopulated by aquatic species during high temperature events).

These findings suggest that groundwater discharge to streams should not necessarily be counted on to buffer temperature stresses in streams caused by future climate change, and that temperature increases in groundwater discharge associated with a warming climate may be expressed in shorter timeframes than previously thought. Where surface-water regimes and thermal refugia are strongly influenced by groundwater discharge, assessments of future surface-water temperature responses to climate change need to account for associated changes in groundwater-discharge temperature.

KUSS AND GURDAK, 2014. GROUNDWATER LEVEL RESPONSE IN U.S. PRINCIPLE AQUIFERS TO ENSO, NAO, PDO, AND AMO

The authors of this paper conducted a series of statistical tests to determine how changes in groundwater levels in principal aquifers across the United States correlate to natural periodic, lower-frequency (inter-annual to multi-decadal) ocean-atmosphere climate cycles such as the El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). The authors found that longer term groundwater level changes in large aquifer systems across the country show a significant correlation (with lag) to these cycles, likely independent of temporal trends in groundwater pumping. The authors suggest that the findings presented in this paper offer an additional tool for water managers to guide future conjunctive use strategies. Knowledge of the relationship between low-frequency climate variability and groundwater storage changes can highlight how such cycles will magnify or lesson the impacts of anthropogenic-driven changes in climate, helping to inform sustainable use of groundwater in a non-stationary environment.

LI AND MERCHANT, 2013 - MODELING VULNERABILITY OF GROUNDWATER TO POLLUTION UNDER FUTURE SCENARIOS OF CLIMATE CHANGE AND BIOFUELS-RELATED LAND USE CHANGE: A CASE STUDY IN NORTH DAKOTA, USA

The purpose of this paper was to examine how future changes in both climate and land use are likely to affect groundwater quality and aquifer vulnerability to contamination. Previous efforts to model groundwater vulnerability to chemical contamination have assumed static hydrogeologic and land use conditions. However, many of the factors key to assessing vulnerability (depth to water, recharge rates, land use, agricultural chemical application rates) are expected to be altered by changes in climate and associated shifts in land use activities expected in the coming decades (such as crop choice or expansion of land under cultivation). In North Dakota, a significant increase in biofuel cultivation is anticipated in response to both changes in climate, and changes in national fuel policy.

The authors of this paper use a GIS-based modeling approach to integrate these variables in order to predict impacts on groundwater vulnerability to nitrate loading, out to the year 2050. A suite of 16 GCM climate models were used to generate downscaled projections of changes in monthly temperature and precipitation for the study area. The climate projection data was used both to support predictions of future changes in the acreage dedicated to the production of biofuel-related crops, and to calculate estimated changes in groundwater recharge rate for the four major soil hydrologic groups found across the state. Changes in the recharge rate were, in turn, used to predict longer-term changes in the depth to groundwater across the state in comparison to current conditions, using the water table fluctuation method [suggesting up to 20 cm (~8 in) increase in state groundwater levels by 2050].

The authors combined and spatially ranked all of the factors that influence groundwater vulnerability, both those likely to undergo change in the 21st century described above, and those that are likely to remain static (e.g., slope data, the nitrate attenuation capacity of soil, vadose zone attenuation capacity) Once compiled, the information was used to develop a vulnerability ranking using in a revised version of the DRASTIC groundwater vulnerability model (DRSTIL).

The modeling results indicated a significant increase in the amount of land area in the state that will be categorized as highly vulnerable to groundwater quality impacts from nitrate leaching. This change is due largely to changes in land use, in particular the predicted expansion of the cultivation of corn and soybean for biofuel production. Both crops are associated with higher fertilizer inputs and higher nitrate leaching potentials (as opposed to dominant current condition crops of wheat and alfalfa).

The analysis suggests that socio-economic responses to climate change, in this case manifested as large-scale shifts in land use and cropping patterns, will have a significantly greater impact on groundwater vulnerability than the direct hydrologic effects of climate change such as recharge rate or depth to water.

LIU ET AL., 2013 - SPATIAL-TEMPORAL VARIATIONS OF EVAPOTRANSPIRATION AND RUNOFF/PRECIPITATION RATIOS RESPONDING TO THE CHANGING CLIMATE IN THE PACIFIC NORTHWEST DURING 1921-2006

This paper describes a recent application of the Variable Infiltration Capacity (VIC) model to evaluate how ET and other hydrologic processes vary spatially and temporally across the Pacific Northwest in response to changes in temperature and precipitation brought about by a changing climate.

After testing the ability of the VIC model to reasonably reproduce the historical record for surface runoff across the study region, the authors identify long-term historical trends in both temperature and precipitation. They note that between 1921 and 2006, average temperatures in the region have risen by 0.8°C, and precipitation has increased an average of 10% over the same time period (with more precipitation falling as rain, and less as snow). The authors then used the VIC model to evaluate how the observed changes in temperature and precipitation have influenced trends in hydrologic processes across the PNW.

The modeling analysis indicates that there has been an approximately 9% total increase in ET across the PNW in the past century, with the highest relative increases in water-limited areas such as the Central Columbia River Basin of eastern Washington and Oregon. The authors found that observed annual and warm-season trends in ET are strongly controlled by trends in precipitation; increasing precipitation has resulted in increasing ET, particularly in semi-arid areas. ET trends are also a function of temperature, with rising winter temperatures result in rising winter ET rates.

The authors grouped ET spatial responses to changes in climate as a function of whether (and when) a region is water-limited (generally warmer and drier climate – includes the large majority of the area of Washington east of the Cascade Mountain crest) vs. energy-limited (generally wetter and colder climate – includes most of the areas west of the Cascade crest). Overall, the largest increases in ET have occurred in water-limited areas of the PNW.

These findings suggest that as the climate continues to warm, there will be continuing increases in ET across the PNW, driven by spatial variations in water and energy balances. Any increased warm-season precipitation will largely be offset by coincident increases in ET. The authors did not directly address the potential consequences of these changes on annual or seasonal groundwater recharge rates.

The authors do note that the VIC model is not calibrated directly to ET observations, and has trouble simulating ET responses in certain settings, potentially due to model scaling effects or the failure to properly represent groundwater storage and redistribution processes in the model domain [*Note: this point has also been noted by other authors; see Safeeq et al., 2014b*]. While these factors continue to be a sources of uncertainty in the model simulations, it is apparent that areas currently experiencing water scarcity in the PNW will see increasing stress on freshwater availability.

LOAICIGA ET AL., 2012. SEA WATER INTRUSION BY SEA-LEVEL RISE: SCENARIOS FOR THE 21ST CENTURY

This paper describes the use of the FEFLOW numerical groundwater flow and solute model to examine the relative impacts of climate-driven, sea-level rise and groundwater extraction on sea water intrusion to a coastal aquifer system in California.

For the purposes of the analysis, sea water intrusion was defined by the landward advance of the 10,000 mg/L iso-salinity line. Multiple model scenarios were used to independently test the relative contribution of sea-level rise and groundwater extraction on intrusion. A linear 0.5 to 1 m (~1.6 to 3.3 ft) rise in baseline sea level out to the year 2106, and a 5610 m^3/day (~1.5 M gal/day) increase in groundwater extraction rate over the estimated sustainable study area yield of 9730 m^3/day (~2.6 M gal/day) were assumed for the model basin for the analyses (fixed coastline).

The modeling analysis showed that in this setting (relatively high topographic relief, steep horizontal groundwater gradient, and unconfined flow with simple stratigraphy), an increase in groundwater extraction rate within the study basin would have a significantly larger impact on saltwater intrusion than the rise in sea level predicted to occur in this area by the end of the 21st century. Without sea-level rise, the modeled groundwater extraction alone would induce a 745 m (~2444 ft) inland movement of the benchmark iso-salinity line. Adding the change in sea level to the model scenario only moved the same line inward by an additional 12 to 18 m (~39-59 ft) over the 100 year period of analysis. The authors suggest that the modeling approach described in the paper could be modified to alternatively determine what changes in groundwater pumping (or sea-level rise) would result in a specified groundwater salinity concentration at a specific monitoring location.

LUOMA AND OKKONEN, 2014 - IMPACTS OF FUTURE CLIMATE CHANGE AND BALTIC SEA LEVEL RISE ON GROUNDWATER RECHARGE, GROUNDWATER LEVELS, AND SURFACE LEAKAGE IN THE HANKO AQUIFER IN SOUTHERN FINLAND

This paper examines the predicted impact of climate change and sea-level rise on groundwater conditions and groundwater/surface-water interactions in an unconfined aquifer in coastal southern Finland. The authors used climate data and sea-level change predictions from eight different GCM emission scenarios out to 2100 as input for a coupled unsaturated zone-groundwater flow model that was calibrated to current conditions (USGS UZF1 model package coupled to MODFLOW).

The model results varied as a function of climate scenario, but in general indicated that seasonal groundwater recharge peaks will shift earlier in the year by approximately one month by the end of the 21st century, with a predicted increase in annual recharge rate (up to 33% additional recharge), but a significant decline in summer recharge. The additional recharge is predicted to raise groundwater levels within the modeled aquifer under most climate scenarios, potentially resulting in additional winter and early spring flooding in low lying areas. Sea-level change varied between climate scenarios, with a maximum increase of 0.5 m (~1.6 ft). Depending on scenario, the relative change between sea level and the groundwater level in the modeled aquifer ranged from -17% (more groundwater flow to the sea) to +27% (more sea water inflow to the aquifer). Increases in saline inflow would have a significant impact on groundwater quality in near-shore areas of the aquifer, and reduce the potable aquifer size.

MARKSTROM ET AL., 2012 - AN INTEGRATED WATERSHED SCALE RESPONSE TO CLIMATE CHANGE FOR SELECTED BASINS ACROSS THE UNITED STATES (SEE ALSO MASTIN, 2008)

This report describes the results of hydrologic modeling analyses that were conducted for a number of basins throughout the United States, including the Naches basin on the eastern slopes of the Cascade Mountains in central Washington. The focus of these modeling efforts was to examine how climate change is expected to affect surface runoff in different settings in the US.

The modeling was conducted using the Precipitation Runoff Modeling System (PRMS), a deterministic, distributed-parameter, process-based watershed model. Although the purpose of the modeling work was primarily directed towards examining surface-water responses, PRMS includes estimation of ET, groundwater recharge, and groundwater flow to streams as components of the overall hydrologic budget for each study area.

Downscaled precipitation and temperature data from a suite of five GCMs (BCCR-BCM2.0, CSIRO-Mk3.0, CSIRO-Mk3.5, INM-CM3.0, MIROC3.2) and four carbon emission scenarios (20C3M, A1B, B1, A2) were used as inputs to the PRMS model. Consistent with other investigations, temperatures are expected to rise through the 21st century in the Naches Basin, and significant changes are expected in the timing and form of precipitation (a shift from less snow to more rain, with earlier seasonal snowmelt).

In response to the predicted changes in climatic conditions, annual ET and precipitation rates are both expected to rise modestly over the course of the next century within the Naches basin. Significant shifts in the seasonal variability of precipitation are predicted, with the largest increases in precipitation rates occurring in the winter, and the largest decreases occurring in mid-summer. Annual groundwater recharge rates show little change out to the year 2090, although the timing of recharge is predicted to shift, with rates increasing from November to February, and decreasing in the spring and early summer (driven in part by similar seasonal shifts in ET rates). A slight increase in annual groundwater flow to basin surface drainages is also predicted (up to ~2.5 m^3/sec increase by 2090), with seasonal increases in baseflow between December and March, and seasonal reductions in baseflow from May through August. Consistent with other predictive modeling efforts, although overall trends are often consistent, there is a significant degree of uncertainty in the parameter estimates, depending on the GCM/emission scenario chosen.

MASTIN AND JOSBERGER, 2014 - MONITORING RECHARGE IN AREAS OF SEASONALLY FROZEN GROUND IN THE COLUMBIA PLATEAU AND SNAKE RIVER PLAIN, IDAHO, OREGON, AND WASHINGTON

This study describes the use of remote-sensing data to track spatial and temporal trends in the extent of frozen ground in two major basins of the Pacific Northwest (upper Crab Creek Basin in the Columbia Plateau of Washington State and Reynolds Creek Basin in the Snake River Plain of Idaho). In semi-arid areas such as the study basins described, the large majority of groundwater recharge occurs during the cold season between October and March. The extent and duration of frozen ground during this key period can exert a significant effect on the total amount of recharge that infiltrates through the soil profile (because frozen ground normally rejects potential recharge). Refining techniques to help monitor on-the-ground changes in distribution and timing of frozen ground at the regional scale can in turn provide an improved understanding of how climate change may alter infiltration processes in the future.

The authors applied a set of data processing algorithms to a 21-year record of passive microwave satellite observations to determine the daily thermal state of the ground surface across the study areas (bare ground, frozen ground, or snow covered ground). The predicted thermal state results were then compared to in-situ soil temperature observations to assess the capability of a remote-sensing approach to properly track frozen ground conditions. This proof-of-concept approach illustrated that this type of information could be useful for monitoring regional scale changes in frozen ground extent that may occur as the PNW climate warms in the coming century.

To evaluate how changes in frozen ground impact potential recharge rates to groundwater, the authors also used a watershed hydrologic model (PRMS) that was modified to simulate runoff and recharge response to frozen ground. The PRMS model included an algorithm used to estimate when frozen soil conditions exist within a model cell (the Continuous Frozen Ground Index - CFGI). Each time the CFGI indicated frozen ground, the model routs all potential infiltration to surface runoff, eliminating recharge for that component of the simulation.

The modified PRMS model for the upper Crab Creek basin, built and calibrated for current climate conditions during an earlier study, was used to run simulations of future hydrologic response under a suite of different GCM/emission scenarios (the same as those used by Markstrom et al., 2012), out to the year 2099. Temperature and precipitation data were downscaled from the GCMs for input into the PRMS model; the data were subsequently indexed with a CFGI value. The PRMS modeling results for these different climate change scenarios illustrate the range of possible responses of basin recharge to changes in frozen ground conditions.

Consistent with the findings of other climate change studies for the Pacific Northwest, the PRMS modeling results indicate that temperatures are likely to gradually increase in the upper Crab Creek basin through the remainder of the 21st century. With a rise in temperature, the extent and duration of frozen ground will decline, and the region will experience increasing ET rates over time. The modeling results also indicate that there is likely to be an increase in total annual precipitation within the basin over the same timeframe (mostly during the winter months). Evaluation of the PRMS hydrologic budget predictions indicates that the loss of soil moisture driven by increased ET will be counteracted by the predicted increase in precipitation. Changes in these two processes will essentially cancel one another out – resulting in no significant long term change in annual groundwater recharge rates. Consistent with earlier studies, there are predicted shifts in the seasonality of recharge within the basin, with an increase in recharge during the December and January timeframe, and a decrease in recharge in March.

MCCALLUM ET AL., 2010 - IMPACTS OF CLIMATE CHANGE ON GROUNDWATER IN AUSTRALIA: A SENSITIVITY ANALYSIS OF RECHARGE

This paper describes an analysis of the sensitivity of modeled diffuse groundwater recharge estimates to changes in various climate variables (rainfall rate, CO_2 concentration, temperature, vapor-pressure deficit, solar radiation, and rainfall intensity). The authors used an unsaturated zone soil-vegetation-atmosphere-transfer model called WAVES to develop recharge estimates for three locations in Australia, systematically varying the climate input parameters to evaluate the relative recharge prediction responses to each parameter individually. The authors concluded that the recharge estimates for the study locations were most sensitive to increases or decreases in rainfall rate; in the water limited settings evaluated for this paper, recharge responses to rainfall exhibited a 2:1 change ratio (i.e., a 1% change in rainfall rate resulted in an approximately 2% change in recharge). Changes in temperature and rainfall intensity were also shown to lead to significant change in predicted recharge. When all climate variables (including solar radiation, carbon dioxide concentrations, and vapor pressure deficit) were adjusted simultaneously, the amount of recharge estimated was consistently greater than predicted if only a change in rainfall rate alone had been considered. These results indicate that diffuse recharge in Australia is effected by feedback mechanisms between multiple climate factors. This suggests that attempting to predict changes in recharge by using climate model predictions of precipitation change alone could lead to inaccuracies. Accurate estimates of recharge changes due to climate change require consideration of a suite of complex interactions between soil, vegetation, and climate.

MENBURG ET AL., 2014 – OBSERVED GROUNDWATER TEMPERATURE RESPONSE TO RECENT CLIMATE CHANGE

Groundwater temperature increases driven by a warming climate may have important consequences for groundwater quality and the thermal regime of aquatic ecosystems dependent on groundwater discharge. In this paper, the authors investigated the physical processes and relationships between global scale increases in atmospheric temperatures and local scale temperature responses in shallow groundwater.

The authors assembled time series temperature data from observation wells for two shallow unconfined aquifers in Germany to evaluate the influence of regional temperature conditions on groundwater thermal responses. Stochastic statistical analysis of the data records against meteorological observations indicate that, accounting for a time lag in the subsurface response, increases in shallow groundwater temperatures were coupled closely to preceding increases in local-scale air surface temperatures, which in turn could be traced back to global scale increases in atmospheric temperature. Through the use of a one-dimensional analytical solution for representing conduction-advection heat transfer in the subsurface, the authors demonstrate that the time lag (and dampening) in groundwater temperature response is largely a function of the thermal properties and thickness of the soils overlying the aquifers evaluated (recharge rates and groundwater extraction can also exert an effect on thermal response).

Despite the fact that groundwater thermal responses to atmospheric shifts in global temperature are attenuated (more gradual and lower in magnitude), the authors reported that groundwater temperatures in the study area have already exhibited significant increases (>1°C; >1.8°F) in response to rising regional temperatures. They also note that the lag time for such increases can be comparatively short (<5 yrs). These observations have important implications for thermal impacts of groundwater baseflow to receiving surface-water ecosystems (particularly during the dry, warm baseflow season).

NG, G.-H.C., 2010. PROBABILISTIC ANALYSIS OF THE EFFECTS OF CLIMATE CHANGE ON GROUNDWATER RECHARGE

Predictions of climate change impacts on groundwater resources must address two significant sources of uncertainty: (1) how climate change will influence changes in precipitation and temperature at the local and regional scale, and (2) how recharge rates will respond to a specific change in climate.

Many authors in the past have addressed precipitation and temperature forecast uncertainty by considering multiple GCMs and global emission scenarios, while others use stochastic weather generation models to account for natural fluctuations. Using downscaled predictions of temperature and precipitation, hydrologic models (sometimes coupled surface-subsurface models) are often then used to evaluate the aggregate effects of the many factors that influence recharge responses to climate change (which include topography, vegetation, soil properties, etc.). Model predictions, however, are very sensitive to the model assumptions and error in the input parameter values.

This paper presents an alternative, probabilistic approach to modeling diffuse recharge response to climate change for a study area in the semi-arid southern High Plains of Texas and New Mexico (Ogallala Aquifer). The authors explicitly account for uncertainties in the many variables used to model recharge response to climate variability, including soil and vegetation properties, meteorological variables, and differing climate model forecasts. A Monte Carlo procedure known as ensemble forecasting was used to identify a set of many equally likely outcomes. This approach places an emphasis on evaluating the sensitivity of recharge rates to climate change using a probabilistic framework, rather than generating absolute predictions of outcomes. This approach can be particularly useful for settings where recharge can be highly episodic.

Recharge rates for the study area were estimated using a one-dimensional, unsaturated zone model that uses Richard’s equation to simulate soil moisture flux (SWAP 3.0.3). Data input for the recharge model were derived by applying *change factors* derived from a suite of 5 GCMs (IPSL-CM4, MIROC3.2, ECHO-G, BCCR-BCM2.0, and CGCM3.1; all A1B emissions scenario) to historical meteorological observations using a stochastic weather generator (LARS-WG 4.0), out to the year 2099.

The modeling results suggest that climate-driven precipitation changes in the future will have a greater effect on recharge rates than temperature changes. Notably, the predicted study area changes in average recharge (-75% to +35+) are larger than the changes predicted for average precipitation (-25% to +20%). This finding indicates that the impact of climate change may be amplified in the study area groundwater system, due in large part to potential future variability in the frequency, timing, and magnitude of episodic recharge events. These results reflect the significant degree of uncertainty that exists in how climate change will alter the amount and timing of short-term, episodic rainfall events (and terrestrial responses to those events) at the local and regional scale.

PANGLE, L.A. ET AL., 2014. RAINFALL SEASONALITY AND AN ECOHYDROLOGICAL FEEDBACK OFFSET THE POTENTIAL IMPACT OF CLIMATE WARMING ON EVAPOTRANSPIRATION (ET) AND GROUNDWATER RECHARGE

A complex set of interactions and feedbacks between local climate, vegetation, and soils will affect how a warming climate in the coming century will alter water storage and flux within the terrestrial landscape. To help improve understanding of how these processes are likely to respond to projected changes in climate, the authors of this paper conducted a mesocosm experiment at a grassland-setting test facility in Oregon State. Physically-based measurements of the response of the different components of the soil water budget to climate variability under controlled conditions provides additional insights into the theoretical estimates of how ET, soil moisture, recharge, and runoff will be modified in response to warmer temperatures.

The experimental approach relied on a set of sun-lit, 2 m^2, climate-controlled, closed, above-ground test chambers planted with native grassland vegetation (referred to as terracosms). The chambers were underlain by a large polypropylene tank that acted as a non-weighing soil moisture lysimeter (~1 m deep)(see: http://www.teraglobalchange.org/research/mesocosm-design). The lysimeter was thermally insulated to allow air temperature manipulations in the test chamber to be propagated below ground. The loam and silt loam soil profile within the lysimeter was instrumented vertically to assess temperature, soil moisture and other parameters. A wide variety of additional measurements, samples, and condition controls were employed within the terracosms (e.g., precipitation, ET, humidity, temperature, CO_2, deep leachate) to provide a complete, controlled accounting of the terracosm water budget. Throughout the experiment, temperatures within the chambers were maintained according to one of three major temperature regimes (including an ambient control regime). One of the regimes provided a constant 3.5°C (6.3°F) above the ambient outside temperature (the *symmetrical warming* scenario), established on the basis of GCM temperature projections for the Pacific Northwest by the year 2080. This study design allowed the authors to quantify how increased temperatures effects ET, and how warming-induced changes in ET modify recharge to the subsurface.

The authors found that, contrary to their original hypothesis, a controlled temperature increase did not significantly reduce total recharge on a water-year basis. The timing and magnitude of ET and recharge were affected at seasonal time scales in both positive and negative directions, but the net result of these changes was no net change in annual or growing season ET or recharge flux in comparison to the ambient control. ET rates were observed to rise in the springtime under the warmer conditions, but ET was greatly reduced during the summer due to the limited soil moisture available after the spring. The authors observed that, in this setting, the impact of warmer air temperatures on recharge rates depended on the frequency and intensity of springtime rainfall events – due to increased deficits in soil moisture, intense rainfall occurring in the late spring may generate less recharge in a warmer climate than rainfall events occurring in early spring.

Although these findings may be unique to the test setting (Mediterranean climate and rainfall regime, grassland soils and vegetation), and do not account for potential changes in atmospheric CO_2, they highlight how a highly complex suite of temporal interactions and feedbacks between climate, vegetation, and soil moisture ultimately dictate ecosystem water balance response to climate warming at the local level.

PAYNE, 2010. EFFECTS OF SEA-LEVEL RISE AND PUMPAGE ELIMINATION ON SALTWATER INTRUSION IN THE HILTON HEAD ISLAND AREA, SOUTH CAROLINA, 2004-2104

The Hilton Head Island area off the southeastern coast of the United States has experienced problems with saltwater intrusion since the 1970s. This report describes the use of a variable-density groundwater flow and transport model to simulate the potential effects of long-term sea-level rise on groundwater salinity beneath the island, and evaluate the relative influences of pumpage and sea-level rise on saltwater intrusion.

To examine these questions, Payne refined a three-dimensional finite-element model of the study area based on the USGS SUTRA program. After model calibration to 2004 conditions, a variety of model scenarios were then run to examine the effects of different future pumping and sea-level rise conditions and combinations on the island aquifer. This included a model of predevelopment conditions (pre-pumping), and four additional scenarios run out to the year 2104 (continuation of the 20th century rate of sea-level rise of approximately 1 foot/century, a doubling of the rate of historic sea-level rise to 2 feet/century, a complete cessation of sea-level rise, and continuation of the historic rate of sea-level rise plus the elimination of all pumpage).

Although there is some uncertainty in the absolute model predictions, Payne found that pumping is (and will be in the coming century) by far the strongest driving force for controlling the extent of saltwater intrusion beneath the island; if 2004 pumping conditions are maintained into the future, saltwater intrusion will increase in the island aquifer system whether or not sea level continues to rise. Even if sea-level continues to rise, if all pumpage is eliminated, the extent of saltwater intrusion on the island is predicted to decrease. The only significant impact of sea-level rise on groundwater conditions is predicted to occur in the very low altitude areas of the model domain, primarily in response to inundation of marine water over those portions of the island. The rate of sea-level rise had little overall effect on the development of the island chloride plume except for the most low-lying areas.

ROZELL AND WONG, 2010. EFFECTS OF CLIMATE CHANGE ON GROUNDWATER RESOURCES AT SHELTER ISLAND, NEW YORK STATE, USA

The authors of this paper used a two-dimensional, variable-density transient groundwater flow model (SEAWAT) to evaluate the predicted impact of climate change on freshwater resources of a small, sandy island in coastal New York State.

In addition to a baseline current-condition calibration of the model (Scenario 1), two additional model scenarios were used to represent the potential range of changes expected in long-term island recharge and adjacent sea-level elevation by the end of the 21st century. Scenario 2 represented likely minimal effects of climate change (a 15% increase in precipitation, and a sea-level rise of 0.18 m (~0.6 ft) from current condition). Scenario 3 represented a more severe climate impact case – precipitation was decreased by 2%, and long-term, sea-level elevation was increased by 0.61 m (~2 ft). In both cases, recharge was assumed to be 50% of the precipitation rate.

Under Scenario 2, the model predicted that there would be a small increase (3%) in the total volume of the fresh water lens underlying the island. The volume increase was largely a function of the increase in precipitation, which resulted in an increase in recharge rate, a rise in the island water table, and the seaward movement of the fresh water/salt water interface by 23 m (~75 ft). By contrast, the Scenario 3 model predicted a 16 m (~52 ft) movement of the salt water interface towards the interior of the island, accompanied by a modest increase (1%) in the freshwater volume due to a rise in the water table.

The authors noted that a low permeability clay unit that underlies the island serves to deform the geometry of the fresh water/salt water interface, reducing the overall thickness of the freshwater lens underlying the island that would otherwise be predicted by the Ghyben-Herzberg approximation. This feature played a significant role in the island's response to the climate-driven hydrologic changes, restricting the movement of the bottom of the interface, and allowing an increase in the freshwater volume despite the decrease in recharge. This suggests that Shelter Island fresh water supplies may be less vulnerable to sea-level rise than other islands, but will also not benefit significantly from additional recharge.

SAFEEQ ET AL., 2013 - COUPLING SNOWPACK AND GROUNDWATER DYNAMICS TO INTERPRET HISTORICAL STREAMFLOW TRENDS IN THE WESTERN U.S.

Safeeq and coauthors note that streamflow records in the western United States over the past 60 years indicate that the fraction of annual streamflow occurring during the winter has shown modest increases, while summer flow rates have been declining significantly. Previous research has suggested that this observed shift is largely a function of changes in snowpack dynamics due to climate warming. These authors, however, suggest that the changes in summer streamflow are equally the result of the geologic characteristics of the watersheds in which they occur – in particular an intrinsic physical factor they refer to as *drainage efficiency*. The authors show that this additional factor can be used to explain spatial differences in the historic record across the western US of how streamflow is responding to a changing climate.

The work described in this paper builds on an earlier conceptual model (described by Tague and Grant, 2009) of how geologic setting controls hydrologic responses to climate change. This model assumes that summer streamflow in many western watersheds is related to two primary and equally important classification factors: (1) the primary form of precipitation within the watershed and related snowpack dynamics (controlled by climate and elevation), and (2) how efficiently recharge to the subsurface is transformed into discharge back to surface (a function of the underlying geology of the watershed). These factors interact to dictate the timing and rate of surface runoff in a watershed, particularly in the spring and summer.

The authors examine how the interaction between watershed drainage efficiency (represented by a calculated recession constant for a watershed) and the fraction of watershed precipitation falling as snow can be used to explain the historic trends and shifts in streamflow that have been observed. They found that spatial differences in historic streamflow trends are consistent with the Tague and Grant conceptual model – i.e., that watershed geology plays a significant mediating role in how streamflows respond to climate warming. This conceptual model can be used to help anticipate streamflow changes in ungauged watersheds into the future.

The analysis presented in this paper suggests that summer streamflows in watersheds that drain more slowly (i.e., are groundwater-dominated) and receive precipitation primarily as snow (or a mix of snow and rain) are the watersheds most sensitive in the Western US to climate warming.

This result is somewhat counterintuitive, as one might expect that streamflow in watersheds that are groundwater dominated would be buffered against climate change. However, in groundwater-dominated watersheds in which a significant proportion of winter precipitation becomes recharge and is drained more slowly from the subsurface, baseflow rates to streams are typically higher and more long-lasting throughout the summer than in snowmelt-dominated systems that drain winter precipitation more quickly. Climate-driven reductions in snowpack in groundwater-dominated basins therefore result in greater *absolute* reductions in streamflow in the late summer than in snowmelt dominated systems. By contrast, summer flows are already typically very low in snowmelt-dominated systems with fast recession, so these systems are less sensitive to changes in climate at this period of the year.

SAFEEQ, M. ET AL., 2014A – A HYDROGEOLOGIC FRAMEWORK FOR CHARACTERIZING SUMMER STREAMFLOW SENSITIVITY TO CLIMATE WARMING IN THE PACIFIC NORTHWEST, USA

Many regional scale analyses of predicted climate impacts on watershed hydrology and summer streamflow rely on the downscaling of GCM precipitation and temperature data for input into hydrologic models. There are significant uncertainties introduced by this *top-down* approach, and many hydrologic models such as the VIC model fail to accurately predict flows in settings where there is a proportionally high groundwater contribution to streamflow.

The authors of this paper present an alternative approach, applying an analytical hydrogeologic framework to basins across the Pacific Northwest to support improved spatial analysis of streamflow response to changes in the timing and magnitude of recharge (driven by changes in precipitation and snowmelt dynamics, future ET changes ignored). They suggest that this approach, founded on work by Tague and Grant (2009), better captures the combination of both climatic and geologic controls that ultimately dictate the sensitivity of streamflow to climate change. The advantage of this approach is that it allows streamflow sensitivity to changes in climate (and consequently recharge) regime to be mapped as an intrinsic property of the landscape, independent of future climate outcome.

The authors calculated recession constant values (k) from long-term streamflow records for 227 unregulated watersheds across the states of Oregon and Washington. A multiple linear regression model accounting for relief, slope, soil permeability, and aquifer permeability was then used to extend the calculated k values to the entire study area landscape (at the fifth-field HUC code scale). Lower k values on the resulting maps represent deep-groundwater-dominated systems with slower recession character (for example the high Cascades and Okanogan highlands areas); higher k values represent surface-flow-dominated systems with more rapid recession character (for example portions of the central Columbia Basin). Streamflow sensitivity was calculated as a function of the first derivatives of the relationship between a) discharge and recharge magnitude, or b) discharge and recharge timing.

The calculated relationships between observed climate and observed streamflow response characteristics were used to extend the estimates of streamflow sensitivity into ungauged areas of the study region. The authors ultimately present a series of sensitivity maps (as degree of change to existing summer streamflows per unit change in recharge timing and magnitude) across the entire study area, for the three key months of the summer season (July, August, September). These maps were validated against historic streamflow response to climate extremes in the past.

The analysis results indicate that summer streamflows in the PNW are most sensitive to changes in timing and magnitude of peak recharge in the higher elevation areas of the Cascade Mountains, northern Washington State, and the east and north slopes of the Olympic Mountains. In Washington State, this reflects the strong reliance of summer streamflow on snowmelt in these areas. Relative sensitivity declines from July to September, and streamflows become increasingly influenced by the recession characteristics of the watershed as the summer season progresses.

The authors emphasize that the maps produced by this analysis only represent spatial streamflow sensitivity in a relative sense; the analysis was not intended to provide absolute estimates of discharge, which are ultimately a function of both the geologic-driven recession characteristics of the basin and the specific climate variation. The approach presented is intended to complement traditional *top-down* modeling efforts that rely on the coupling of climate and hydrologic models to generate absolute predictions of stream discharge.

The authors also demonstrate how climate-driven seasonal changes in spring-flow discharge throughout the basin are predicted to be closely related to the scale of the groundwater flow paths supporting those springs (note: responses of groundwater systems to longer-term climate cycles, i.e., decadal or multi-decadal, are proportionally similar across spatial scales). Springs located in the higher elevation portions of the watershed that are supported by local scale groundwater catchment areas will show significantly larger variability in discharge than springs in low elevation areas of the basin interior under future climate warming. Discharge pulses to smaller, higher elevation springs and spring complexes are likely to occur 1 to 2 months earlier in the year than in the past.

In contrast, volumetrically larger, lower elevation spring systems are not likely to exhibit significant change in discharge pattern, despite climate-related changes in recharge rates, because seasonal recharge pulses are largely filtered out or smoothed along longer flow paths. These findings of scale dependency could have significant implications for water management and for the vulnerability of groundwater dependent ecosystems at the terminus of shorter flow-path catchment areas.

SAFEEQ ET AL., 2014B - COMPARING LARGE-SCALE HYDROLOGICAL MODEL PREDICTIONS WITH OBSERVED STREAMFLOW IN THE PNW: EFFECTS OF CLIMATE AND GROUNDWATER.

This paper presents a rigorous statistical examination of how well the VIC model (a large-scale land-surface hydrologic model) does in matching observed streamflows in small-scale watersheds across the Pacific Northwest.

Although the VIC model has been used extensively in the PNW to predict streamflow responses to climate change and reduced snowpack, there is some concern that the model predictions may fail to accurately account for the effect of groundwater on streamflow response in groundwater-dominated watersheds (a finding that was confirmed by work by Wenger et al., 2010). This is because the VIC model does not explicitly incorporate groundwater flow into the model structure, but instead approximates groundwater baseflow inputs to streams through the use of a multi-layer soil-profile model compartment. In VIC, baseflow to streams is derived from the lowest soil sub-layer as a function of the soil moisture content. This approach has been shown to under-predict summer streamflows and extreme low flows in groundwater-dominated watersheds. A systematic analysis of the performance of the VIC models can help to identify the settings most appropriate for using the VIC model predictions, and suggest ways to improve the model for settings where the model does not perform well.

In order to conduct their analysis, the authors grouped over 200 watersheds from across the PNW as a function of their streamflow recession behavior (as represented by a hydrograph recession constant calculated for each watershed). The recession constant serves as a surrogate for geologic setting and the relative contribution of groundwater to streamflow. In watersheds with lower recession constants, surface runoff is the dominant watershed drainage mechanism; in watersheds with higher recession constants, groundwater movement to streams is the dominant drainage process.

The results of the analysis show that the VIC model consistently under predicts summer streamflows and extreme low flows in watersheds with higher relative groundwater contribution to drainage (percent bias = -13%). In turn, the model consistently over predicts summer runoff in surface-runoff dominated basins (percent bias = 48%). Low flows (5th percentile) were under predicted in groundwater dominated basins (percent bias = -51%), and over predicted in runoff dominated basins (percent bias = 19%). These findings indicate that the hydrogeologic setting of a watershed has a significant influence on the ability of the VIC model to accurately predict climate effects on streamflow, particularly during the key summer portion of the year (although other factors, such as inaccuracies in meteorological forcing, may also play a role in the systematic biases observed in the model predictions).

SCIBEK ET AL., 2008 - QUANTIFYING THE IMPACTS OF CLIMATE CHANGE ON GROUNDWATER IN AN UNCONFINED AQUIFER THAT IS STRONGLY INFLUENCED BY SURFACE WATER

In this study, the authors describe the use of a calibrated, transient groundwater flow model (MODFLOW) to evaluate how changes in climate are predicted to impact groundwater conditions in an unconfined, valley-bottom aquifer that is closely interconnected to overlying streams.

The Grand Forks aquifer is located in a semi-arid part of southern British Columbia, bordering the Okanogan region of Washington State. The aquifer matrix is comprised of unconsolidated valley fill deposits bordered by bedrock foothills. Groundwater baseflow to the mainstem streams of the valley (the Kettle and Granby Rivers) is limited during portions of the year; during the wet season, the streams lie above the regional water table and act as a recharge source to the aquifer, with the recharge rate a function of stream stage. In the dry season, this process is reversed, and groundwater discharges back to surface as baseflow.

The authors note that changes in temperature and precipitation modify groundwater recharge rates, which in turn can cause changes in subsurface storage volumes and exchange rates with surface streams. Therefore any analysis of how climate change will impact groundwater conditions hinges on an accurate evaluation of how recharge rates will be affected over time by the climatic conditions expected later in the 21st century. In turn, climate-change-driven modifications to surface flows in streams that are closely coupled to an underlying groundwater system may also result in significant changes in volume flux between the surface and subsurface.

For this study, spatially and temporally distributed recharge estimates were developed by downscaling climatic data from GCM predictions (using the CGCM1 model; GHG+A1 emissions scenario), and entering the downscaled values into the USEPA's HELP hydrologic model. Recharge values were derived using the HELP model for a current condition scenario, as well as two future scenarios (2010-2039, 2040-2069). The authors note that while it is recognized that downscaled GCM climate data does not accurately re-create climate conditions at the local scale (suggesting a level of uncertainty in the absolute values), the relative changes in climate predicted by the GCM still support the use of the modeling for testing the sensitivity of the groundwater system to future climate variation.

The HELP model predictions indicate that recharge as a percentage of precipitation will generally increase in the future in the study area (for the 2040-2069 scenario, an 11% to 25% increase in mean annual recharge over the current rate), with the highest increases in the late spring and summer seasons (up to a factor of 3X higher than current spring recharge rates). By contrast, recharge rates are predicted to decline during the late winter, largely in response to declines in precipitation.

The GCM-based predictions of future recharge and surface runoff conditions were used as input values to a transient MODFLOW model developed for the study area. Despite the predicted increase in annual recharge, the MODFLOW model indicated that there is relatively little overall change expected for groundwater levels within most of the underlying aquifer system out to the year 2069 (<20 cm; <8 in). The most significant climate impacts on groundwater occur in relation to changes in the timing of peak surface runoff, in response to changes in the timing of spring snowmelt. In areas of the aquifer where groundwater and surface water are most closely connected (i.e., in the near vicinity of mainstem streams), groundwater levels are predicted to rise seasonally up to 50 cm (~20 in) higher than current conditions, due to infiltration of surface water during peak flow periods. This local increase in groundwater storage is quickly lost; as surface discharge recedes, hydraulic gradients in the aquifer reverse and the extra water drains back to the stream within several months' time.

SMERDON ET AL., 2010 - EVALUATING THE USE OF A GRIDDED CLIMATE SURFACE FOR MODELING GROUNDWATER RECHARGE IN A SEMI-ARID REGION (OKANAGAN BASIN, CANADA)

This study compares different methods of processing climate data for estimating spatially distributed recharge for an inter-mountain valley-fill aquifer in a semi-arid area of south central British Columbia. Recharge estimates are a critical input component for modeling groundwater storage responses to climate change, so it is important to better understand the sensitivity of recharge values to the method used for estimation. Recharge estimates in semi-arid areas are themselves particularly sensitive to accurate estimates of potential evapotranspiration (PET) and actual evapotranspiration (AET).

Two main approaches were used to develop model estimates of recharge for the study area. The first method, a simpler approach, applied climate data from a single meteorological station across the entire model domain, and used both the Thornthwaite and Penman-Monteith equations to estimate PET. The second method, a more complex effort, relied on the generation of a spatially-gridded climate surface (500 x 500 m resolution) for the region encompassing the model area, and used the Penman-Monteith equation for PET estimation. The different climate data treatments were used as input to a MIKE-SHE model developed for the study area to generate spatially distributed predictions of recharge. Model timeframes, soil properties, and land cover characteristics were the same for all model runs.

The authors found subtle but important differences in the recharge values that were estimated by the different data processing approaches. Recharge rates that relied on PET estimates developed using the Thornthwaite method were typically higher on an annual basis than those estimated using the Penman-Monteith method, a result of an underestimation of AET during the winter months. The authors also noted differences in PET estimation between the two different treatments of the climate data (single-station vs. gridded surface); the use of gridded climate data better reflected spatial variations in study area temperature that are key to accurately estimating PET. The consequences of these differences are likely to be amplified when assessing future climate/recharge scenarios in semi-arid settings.

In this setting, the highest seasonal rate of recharge occurs in the spring, in close relationship with snowmelt. This suggests that the use of PET and recharge estimation methods that best capture snowmelt processes is important when modeling recharge in a semi-arid setting with colder temperatures. Summertime and fall recharge rates derived from the various climate data treatments were consistently near or below zero, indicating that the climate processing approach is not as important for these portions of the year.

In addition to comparing the different climate data processing steps and PET estimation methods, the authors compared the effect of soil texture, and depth to groundwater on recharge rate. Both factors play an important role in determining recharge rate on a seasonal time scale. This indicates that future attempts to model the spatial and temporal changes in recharge likely to occur as a result of climate change in this type of setting should account for each of these factors.

Recharge rates in semi-arid areas similar to the Okanagan basin will likely be particularly sensitive to a warming climate, due to the strong dependence on ET rates, and snowmelt controls on spring recharge.

STOLL, S. ET AL., 2011A. ANALYSIS OF THE IMPACT OF CLIMATE CHANGE ON GROUNDWATER RELATED HYDROLOGICAL FLUXES: A MULTI-MODEL APPROACH INCLUDING DIFFERENT DOWNSCALING METHODS

Stoll and coauthors investigate the importance of the method used to downscale climatic data from GCMs for use in modeling analyses of local scale hydrological response to climate change. In many cases precipitation and temperature data downscaled from GCMs do not support an adequate representation of the temporal or spatial patterns in local scale precipitation or ET that are key to accurately predicting changes in groundwater recharge rates.

To conduct their analysis, the authors used a fully coupled, three-dimensional, surface/sub-surface hydrologic model (MIKE-SHE) for a study area in northern Switzerland. Climate data (precipitation and other variables that dictate potential ET using the Penman-Monteith method) from a suite of eight different RCM-GCM combinations were downscaled and bias-corrected to provide forcing boundary conditions for the hydrologic model. Three different downscaling procedures were used to refine the RCM-GCM data: (1) factor correction, (2) annual cumulative probability distribution function (CDF) correction, and (3) monthly CDF correction. Predictions of study area hydrologic response to these inputs out to the year 2100 were generated. Particular focus was placed on examining the sensitivity of the model water flux and water level predictions to the climate data downscaling procedure.

In general, the modelling predicts modest reductions in annual study area ET, and an overall small increase in groundwater levels (~0.8 m; ~2.6 ft) over the model timeframe. Recharge rates to the study area aquifer increase during the winter season, and decreased in the summer, but there is little predicted change in annual recharge. The authors note that the results of the analysis indicated that the model predictions were highly sensitive to the downscaling approach.

The observed uncertainty introduced by the different data refinement methods leads the authors to conclude that it is difficult to make reliable predictive statements about groundwater responses to changes in climatic conditions. As a result of these concerns, the authors recommend less dependence on the use of GCM-driven hydrologic models to predict the future, and more reliance on the evaluation of the historic record to determine how groundwater has responded to changes in the climate in the past (see Stoll et al., 2011b). They also note the importance of considering anthropogenic factors (land use, pumping) when evaluating historic data in this manner.

STOLL ET AL., 2011B. WHAT CAN WE LEARN FROM LONG-TERM GROUNDWATER DATA TO IMPROVE CLIMATE CHANGE IMPACT STUDIES?

The authors of this paper note that the majority of research studies focused on evaluating the potential impact of climate change on groundwater conditions follow a standard approach – large-scale temperature and precipitation data from a variety of GCMs and global emission scenarios are downscaled to provide a probable range of forcing boundary conditions for a hydrologic model(s). These hydrologic models are in turn used to predict future changes in groundwater fluxes and storage. They note that each step in this sequence can introduce a degree of uncertainty in the estimation process; the cumulative effect of all of these sources of uncertainty can make it difficult to develop reliable projections of groundwater response to climate change.

The authors argue that an improved understanding of the processes that drive groundwater responses to climate change is essential to making accurate predictions for the future. They suggest that careful evaluation of long-term, large-scale historic groundwater records can (a) help to reveal important insights into those processes, (b) clarify the relationship between groundwater dynamics and climate variability, and (c) guide the determination of how aquifers will respond to future changes in climate (the past as an analog to the future).

For this study, a one-dimensional MIKE-SHE hydrologic model was used to calculate recharge from observed meteorological data across northern Switzerland and southern Germany. These recharge estimates were evaluated against long-term groundwater level and spring-flow data to help clarify pattern relationships between recharge, storage, and discharge, in the context of climatic variability. The recharge modeling process ignored the influence of anthropogenic factors such as pumping and land use change so that trends or patterns in groundwater levels associated specifically with the climate signal could be identified.

Due to the lack of reliable long-term records for land use change and groundwater pumping, a qualitative approach was used by the authors to further distinguish when changes in groundwater conditions were the result of climate variability versus an anthropogenic effect. If groundwater levels, spring flows and model-estimated recharge all showed similar patterns, it was assumed that climate variability was the likely cause of that pattern. However, if patterns were observed in one variable, but not in the others, those changes could be assigned as appropriate to an anthropogenic effect (e.g., if a similar trend in both water levels and spring flow were observed, but not in recharge, land use was assumed to be the likely cause of the change; if a water level trend was not similarly recognizable in spring-flow records or recharge estimates, pumping was interpreted to be the likely cause of the change).

Using these techniques, the authors were able to recognize strong meteorological signals in the groundwater dynamics of the study area (a strong intra-annual scale relationship between winter precipitation and groundwater droughts; a distinct relationship between large scale atmospheric circulation patterns and groundwater response). They were also able to identify a relationship between pumping demand and climatic variability. The authors suggest that clarifying these relationships and feedback processes could help to guide the development of improved climate data downscaling and hydrologic modeling approaches, and provide more reliable predictions of groundwater response to climate variability in the future.

STUART ET AL., 2011 - A REVIEW OF THE IMPACT OF CLIMATE CHANGE ON FUTURE NITRATE CONCENTRATIONS IN GROUNDWATER OF THE UK.

This review paper evaluates the potential impact of a changing climate on nitrate concentrations across the United Kingdom (UK). The authors used a source-pathway-receptor conceptual model to provide a framework for predicting how changes in temperature, precipitation rates and patterns, and atmospheric carbon dioxide will affect nitrate fluxes to the subsurface. The authors note that changes in climatic condition will change agricultural source contributions due to related changes in soil processes (mineralization rates, infiltration characteristics) and agricultural productivity. Although the driving processes are highly complex, and not always well understood, the evaluation indicates that changes in soil mineralization of nitrogen (due largely to increased future temperatures), precipitation, recharge, and irrigation of crops are likely to result in an increased rate of nitrate leaching, ranging from modest increases to a upper-bound potential for a doubling of nitrate groundwater concentration averages in the UK by 2100. The authors acknowledge that significant uncertainty exists in these predictions, and suggest that addition site-specific studies and monitoring data are required. They also acknowledge that economic responses to climate change, and the potential for the reduction of nitrate loading due to more efficient agricultural practices, may also significantly affect future outcomes.

SURFLEET AND TULLOS, 2013 – UNCERTAINTY IN HYDROLOGIC MODELING FOR ESTIMATING HYDROLOGIC RESPONSE DUE TO CLIMATE CHANGE (SANTIAM RIVER, OREGON)

The authors of this paper describe the use of the GSFLOW coupled groundwater/surface-water numerical model to evaluate the hydrologic impacts of climate change for the Santiam River basin in western Oregon. After initial calibration to current meteorological conditions, the GSFLOW model (which integrates DPM model estimates of runoff and groundwater recharge with MODFLOW-based representation of subsurface flow and discharge) was run using daily time-step meteorological predictions downscaled from a suite of eight GCM models (based on two emission scenarios – A1B and B1). Hydrologic responses to the downscaled conditions were modeled out to the year 2099.

The model predictions indicate that 10-year, 7-day low flow values for the study area streams varied from subbasin to subbasin as a function of the degree of groundwater contribution. In subbasins that are dominated by surface runoff, and geologic conditions limit groundwater contributions to streamflow, low flow values tended to decline over the course of the century. By contrast, subbasins where groundwater significantly affects streamflow were predicted to experience a slight increase in low flows over current conditions. Although they acknowledge the high degree of uncertainty in the predictions, the authors suggest that changes in summer low flows in response to climate change will be mediated in basins that experience higher proportions of deep groundwater inflow to streams. Such basins experience longer residence times for water stored in the deep subsurface, resulting in a delayed, but more consistent discharge to overlying surface streams.

In the context of this basin-specific analysis, the authors present the results of an evaluation of the relative contribution of uncertainty to the hydrologic predictions by the different components of the modeling process. They report that an average of 66% of the uncertainty in the model estimates of future flow conditions is from uncertainty in the GCM results used as model input. The amount of uncertainty introduced into the predictions from the GSFLOW hydrologic model was significantly smaller (8%). Acknowledgement of the sources of uncertainty in these types of model predictions, and recognition of the range and likelihood of possible outcomes identified during the modeling are essential requirements when applying the findings to water resources planning activities.

TAYLOR AND STEPHAN, 2009. SHALLOW GROUNDWATER TEMPERATURE RESPONSE TO CLIMATE CHANGE AND URBANIZATION

This paper examines how climate change and urban development are likely to change the temperature of shallow groundwater in the Minneapolis/St. Paul area in the future. In the temperate climate at this latitude, groundwater temperatures up to at least 15 m (~49 ft) below land surface are known to respond to changes in ground surface temperature. Mean ground surface temperatures are sensitive to modifications of both climate, and land use.

Heat transfer from the land surface through the vadose zone to the groundwater system can occur by a combination of both diffusion- and advection-related processes. The authors developed and applied an unsteady, 1-D vertical heat transfer equation that accounts for these processes in order to evaluate the link between changes in climate and land use at the land surface, and the underlying shallow groundwater temperature response.

The model results indicate that, in this study area, a conversion in land use from agriculture (bare soil or sod) to urban development is expected to raise the mean annual shallow groundwater temperature beneath the Minneapolis/St. Paul area by 2.9°C (~5.2°F), independent of the effects of climate change. This temperature increase is primarily a function of ground surface temperature increases due to the presence of paved surfaces, and has been confirmed by empirical field measurements.

To examine how a warmer future atmosphere may itself potentially affect shallow groundwater temperatures, the authors assumed that atmospheric carbon dioxide (CO_2) will double in the future out to the year 2100. Air temperature changes predicted in response to this scenario were derived from a Canadian Climate Center GCM, and then fed into a heat balance model to obtain predicted future ground surface temperatures (which are a function of the complex interaction of air temperature, wind speed, surface type, etc.). Under these conditions, thermal transfer from the ground surface to the subsurface would result in climate-driven increases in average shallow groundwater temperatures by as much as 4°C (~7.2°F) across different land use types. Temperature increases in shallow groundwater due to the compounded effects of both climate change and urbanization could be as great as 5°C (~9°F) at this latitude by the year 2100.

TOEWS AND ALLEN, 2009A - EVALUATING DIFFERENT GCMS FOR PREDICTING SPATIAL RECHARGE IN AN IRRIGATED ARID REGION

The authors of this study note that groundwater systems in arid regions are likely to be particularly sensitive to climate change due to the strong dependence of ET rate on temperature and likely shifts in precipitation and snowmelt timing. Each of these factors plays a significant role in controlling recharge to aquifers. In addition, in arid areas, irrigation is often a major component of the water budget, and as temperatures rise (as predicted in the coming century), soil moisture demands increase, summer precipitation and surface discharge decreases, the growing season lengthens, and the need to irrigate to sustain crops through the growing season expands.

This study used climate data predictions from three different GCM/emission scenarios (CGCM1-A1, CGCM3.1-A2 and HadCM3-A2) to determine the sensitivity of recharge to climate change in an intermountain valley fill aquifer receiving significant irrigation inputs during the growing season (the arid Oliver region of the southern Okanagan Basin in British Columbia).

The GCM data were downscaled, and processed using a synthetic weather generator to derive daily values for weather and ET. The daily weather values were then used as input into the HELP hydrologic model to develop both temporal and spatial estimates of recharge for the study area. The HELP model in this study included estimates of spatially distributed soil characteristics. Deep infiltration of irrigation to the aquifer (*return flow*) was added to the daily precipitation estimates. Return flow was estimated as a function of expected crop demand under the forecasted precipitation and ET conditions, adjusted for irrigation efficiency.

The results of the modeling analysis indicate that modest increases in annual recharge are expected in the study area in the coming 70 years (up to a 2 inches increase over current conditions), although the magnitude of change varies between GCM models. In non-irrigated areas of the study basin, peak recharge occurs earlier in the year as a result of earlier snowmelt and ground thawing. In irrigated portions of the valley, predicted changes in recharge to groundwater are related to the GCM model used for the analysis, and the irrigation efficiency selected for recharge modeling (since irrigation is the dominant control on recharge in these settings). For the purposes of modeling, current irrigation practices were assumed to remain constant into the future, but the modeling results suggest that any changes that do occur to such practices in response to climate change will have a significant impact on recharge.

The authors acknowledge that while the absolute recharge values generated by the HELP model may not accurately reflect field conditions, the relative changes in recharge rate as a function of climate change are reasonably reliable. The study highlights the fact that predictions of recharge response to climate change are sensitive to the choice of the GCM, and choice of emission scenario used to derive estimates of future climate conditions. Future recharge modeling efforts reliant on GCMs should use a broad range of models (and emission scenarios) to help bracket hydrologic response.

TOEWS AND ALLEN, 2009B - SIMULATED RESPONSE OF GROUNDWATER TO PREDICTED RECHARGE IN A SEMI-ARID REGION USING A SCENARIO OF MODELED CLIMATE CHANGE

This paper describes a follow-on modeling analysis of the study area described in the paper above. In this case, a regional-scale, transient numerical groundwater flow model was used to integrate the variety of complex factors involved in evaluating groundwater response to climate change. The focus of the modeling effort was to closely track recharge to the study area aquifer system from a combination of precipitation, irrigation, and infiltration from small streams entering the valley aquifer from the surrounding uplands.

A three dimensional MODFLOW model (MODFLOW-2000) was constructed for the study area. Spatially and temporally variable recharge values were developed for input into the topmost layer of the model using the HELP hydrologic model. In addition to precipitation, the recharge modeling accounted for changes in irrigation *return flow* (i.e., infiltration of excess irrigation to the water table) that are expected to occur in response to changes in future growing-degree days, crop water demand, temperature, precipitation, and ET (all other assumptions about irrigation practices into the future were kept constant).

Once a current condition base case was established for the groundwater model, recharge and streamflow were varied as predicted for the 2050s and 2080s by downscaling data from a GCM (CGCM3.1 – A2 emissions scenario) and using these values as input to HELP. Streamflow values (input as stage changes for model river boundary cells) were also adjusted for a seasonal shift in surface discharge due to earlier and more rapid snowmelt, while keeping annual streamflow totals consistent with current conditions.

The model predicts that under the expected changes in climate (warmer temperatures, particularly in late summer; shifts in precipitation and snowmelt timing) and crop water demand (longer growing season and higher irrigation rates required due to higher temperatures and ET), recharge to the study area aquifer system will increase. This increase is primarily related to an increase in irrigation losses to the water table. The increase in recharge rate is predicted to raise the study area water table (median increase 0.7 m by the 2080s; ~2.3 ft); eventually the additional water in storage discharges back to the mainstem stream as baseflow. The authors note that the predicted increase in storage within the aquifer suggests that groundwater pumping would be a reasonable management response to rising demand for irrigation water in this study area.

The authors of this paper note that it was not possible to anticipate or predict how every variable of the model would change in response to climate change – in some cases these variables were simply kept constant during the model runs. The model can nevertheless indicate how the groundwater system will respond to the complex interaction of the many factors that drive spatial and temporal patterns in recharge as those factors change in response to a changing climate. The modeling effort also highlighted the critical role irrigation efficiency and irrigation infiltration can play in climate change impact studies.

TOEWS ET AL., 2009 - RECHARGE SENSITIVITY TO LOCAL AND REGIONAL PRECIPITATION IN SEMIARID MIDLATITUDE REGIONS

This study examined the relative role both local and regional precipitation events play in contributing to total recharge to a groundwater system in a semi-arid setting in south central British Columbia (the same study area described in the two papers above). Local precipitation is defined as higher intensity storms that are spatially and temporally limited (convective events), while regional precipitation is defined as lower intensity events that are more widely distributed and are longer in duration (strataform events).

The authors first classified daily precipitation data values by the percent contribution from either local or regional events. These daily values were used as input variables for modeling recharge using the HELP hydrologic model, for a selection of 86 type soil profiles found throughout the study area.

The results of the study indicate that local precipitation plays an insignificant role in total recharge in comparison to regional events. On this basis, the authors conclude that even though it is difficult to accurately represent local precipitation events when downscaling climate data from a GCM, such data can still provide reasonable estimates of groundwater recharge.

U.S. BUREAU OF RECLAMATION, 2014 - HOOD RIVER BASIN STUDY: GROUNDWATER MODELING AND ANALYSIS TECHNICAL MEMO (DRAFT)

This report describes a modeling analysis that was conducted to examine future water supply and demand scenarios for the Hood River basin in north central Oregon adjacent to the Columbia River, with particular consideration of the potential impacts of future climate change on basin groundwater hydrology.

A simplified, three dimensional, single-layer groundwater flow model (MODFLOW) was developed to examine the role that groundwater plays in the overall hydrologic budget of the basin. Special focus was given to evaluating how climate change will drive changes in groundwater recharge rates. The modeling work is described by the authors as *appraisal level*, suggesting that the model predictions should be interpreted on a qualitative rather than quantitative basis. The model results are best suited to facilitating relative comparisons of different water management and climate scenarios into the future.

Current-condition values for quarterly recharge rates for input into the flow model were developed using a regression equation previously formulated for the Columbia River Basin by the USGS. The equation, based on the relationship between observed precipitation and recharge estimates developed using the Deep Percolation Model (DPM), was applied to the study area against spatially distributed study area precipitation values derived from Oregon State University PRISM meteorological data.

The MODFLOW model of the study area aquifer system was run as both a steady state and transient solution. Once the model was calibrated to current conditions, additional model scenarios were run to represent basin groundwater response to climate change. Climate change impacts were represented in the modeling in two major ways: (1) adjusting recharge input rates to the model domain to reflect potential changes in future precipitation rates (designated *direct impacts*), and (2) modeling increased groundwater pumping anticipated to occur in response to increased crop water demand and decreased surface water availability (*indirect impacts*).

The authors estimated predicted changes in precipitation for the study area by reviewing results from a suite of 112 GCMs. From these collective predictions, three major potential climate change outcome groups were identified out to the year 2060 (A: higher warming/dryer climate, B: less warming, wetter climate, and C: median expected change). The changes predicted in precipitation under these three outcome possibilities were used to adjust the current-condition seasonal recharge values for use in the climate change model scenarios. Only the volume of precipitation was adjusted in the recharge estimation equation; changes in other factors such as the intensity, duration, and frequency of precipitation events were ignored. Although changes in temperature are also likely to have an impact on future recharge rates, they too were ignored for this analysis.

Estimates of future groundwater pumping increases within the model domain were developed by accounting for two distinct factors: (1) an expected increase in PET, and (2) an expected decrease in surface-water availability for irrigation. For the first case, increases in PET resulting from climate change were estimated using the Distributed Hydrology Soil Vegetation hydrologic model (DHSVM). Changes in pumping rate were then related 1:1 to predicted changes in PET (i.e., a 2% increase in PET was translated as a 2% increase in groundwater pumping within the basin). In the second case, decreases in surface-water runoff due to climate change were also estimated using the DHSVM model (for the spring and summer seasons). A pumping rate increase equal to 50% of the modeled runoff reduction was then applied to the model, distributed evenly among all of the pumping wells already incorporated into the model domain. This pumping increase was intended to represent how farmers might respond to restrictions in use of streams for irrigation supply.

The modeling results indicate that changes in groundwater storage due only to changes in recharge (direct impacts) were, for the most part, negligible across the study area (maximum response: <3 ft increase in water levels during the winter). The authors note that predicted declines in precipitation during the summer had very little effect on the groundwater system due to the fact that recharge rates during this period of the year are already near zero.

Significant water level declines up to 50 ft were, however, predicted when climate change-related pumping increases (indirect impacts) were accounted for in the model. The specific water level response in the aquifer depended on the proximity of pumping wells, the climate scenario used, and the season of the year (with the largest declines occurring during the April to June period). In addition to storage declines in the aquifer, large decreases in baseflow to surface streams were also observed when pumping increases were included in the model; depending on climate scenario, up to a 60% decline in baseflow. These findings highlight the critical importance of accounting for anthropogenic (indirect) reactions to climate change when attempting to model groundwater responses to a warming climate.

VACCARO ET. AL., 2015 – GROUNDWATER AVAILABILITY OF THE COLUMBIA PLATEAU REGIONAL AQUIFER SYSTEM, WASHINGTON, OREGON, AND IDAHO

This U.S. Geological Survey report describes the results of a multi-phase evaluation of groundwater conditions and availability in the regional-scale Columbia Plateau Aquifer system (encompassing approximately 44,000 mi^2 in total area, including all of southeastern Washington). The project included the development and calibration of a three-dimensional numerical groundwater flow model (MODFLOW-NWT) that covers approximately three quarters of the study area. Among other analyses, the authors of the report used the model to evaluate potential recharge, groundwater storage, and baseflow discharge responses within the study area to a future with a warmer climate.

The authors initially calibrated the flow model to historic conditions estimated for the 1920 to 2007 timeframe. A second model scenario was then run out to the year 2050 to characterize what the long-term response would be for the aquifer system if the recharge and groundwater pumping conditions estimated for 2007 were maintained into the future (termed the *equilibrium condition* scenario). Finally, a third model scenario was run using most of the same equilibrium conditions from 2007, but increasing the groundwater pumping rate across the model domain. The modification of the pumping rate for this scenario was used to account for a potential increase in groundwater extraction related to a projected increase in temperature across the study area due to climate change.

For the climate change model scenario, projected changes in temperature and precipitation were derived from a suite of six GCMs (unnamed), and downscaled to the central portion of the model domain (using the median of the GCM forecasts, based on the A1B IPCC greenhouse gas emission scenario). These predicted changes were used to adjust the historic daily climate data from five weather stations located within the study area. The adjusted climate data were in turn used as model input variables for estimating future recharge conditions under different crop types and land covers, using the Deep Percolation Model (DPM). The DPM was also used to predict changes in irrigation-related groundwater pumping in response to increased crop PET (an average 13% increase over current conditions). The report notes that GCM predictions of precipitation change in the study area show a significant range of uncertainty (both increases and decreases predicted, depending on the GCM). This uncertainty led the authors to simply maintain recharge at current condition rates for the climate change model scenario, while increasing the future pumping rate estimate.

The climate change model scenario predicted significant groundwater storage and discharge declines above and beyond those anticipated for the *equilibrium condition* model. Under the equilibrium condition scenario (i.e., if 2007 pumping and recharge rates remain constant through 2050), groundwater discharge to streams will decrease an additional 623 ft^3/sec beyond the historic reductions already observed, and broad areas of the Plateau would experience additional water level declines up to 50 ft in the primary basalt aquifer used for supply. If a 13% increase in irrigation pumping occurs in response to a warming climate and higher crop-water demand, the model predicts an *additional* 713 ft^3/sec decline in groundwater discharge to study area streams (affecting more than 20,000 mi^2 of the Columbia Plateau area). The authors suggest that the estimates of the effect of climate-related pumping increases are likely conservative (i.e., lower-bound); a variety of additional stresses on water resources that could drive even greater demand for groundwater are predicted, but were not explicitly accounted for in the climate change model scenario (e.g., population growth, higher summer demand for groundwater related to earlier snowpack melt dynamics, some high value crops potentially having a >20% increase in crop-water demand).

VAN ROOSMALEN ET AL., 2009 - IMPACT OF CLIMATE AND LAND USE CHANGE ON THE HYDROLOGY OF A LARGE-SCALE AGRICULTURAL CATCHMENT

This study describes a modeling analysis of the impact of predicted changes in climate, sea level, and land use for an agriculturally-based study area in west central Denmark, out to the year 2100. The authors used downscaled regional climate modeling predictions (from the HIRHAM RCM, downscaled from the HadAM3H GCM) for two GCM emission scenarios (A2 and B2) as the basis for downscaling temperature and precipitation values to the regional scale for input into a previously calibrated, integrated groundwater-vadose zone-surface water model (MIKE-SHE). In addition to the predicted changes in climate variables, scenario testing with the model included changes in irrigation demand (as a function of soil water content in the root zone), changes in vegetation cover type, and two scenarios of future sea-level rise (0.5 m and 1.0 m; ~1.6 to 3.3 ft).

In comparison to current conditions, the model results indicate that annual recharge rates will increase in the future across the study domain (+12% to +21%), with a shift to significantly more recharge during the winter, and less during the summer. Because most of the precipitation increase predicted by the model occurs in the winter, recharge increases occur despite a substantial increase in annual AET. The increased recharge causes an overall rise in modeled groundwater head (0.25 to 4 m, average 0.45 m; ~0.8 to 13 ft, avg. ~1.5 ft), limited somewhat by increased discharge to shallow surface drains present throughout the model area. Groundwater level rise due to sea-level change was also noted as far inland as 10 km (~6 mi), due in part to the low hydraulic gradient of the study area. Summer irrigation demand in the study area is predicted to increase from 50% to 89% due to temperature-driven reductions in soil moisture and summertime rise in AET. The additional pumping associated with this demand was shown to significantly impact summer baseflow to streams.

The authors conclude that the direct hydrologic changes caused by climate factors are likely to be greater than the indirect changes that will occur due to land use responses to a warmer climate (e.g., increased pumping demand). Although there are a variety of sources of uncertainty in the absolute model predictions (e.g., due to the GCM scenario, data downscaling methods, failure to account for future hydrologic extremes), the study area aquifer system is clearly highly sensitive to the combined effects of both future climate change and land use response. Improvements to the representation of how changing CO_2 concentrations will change vegetation cover, and how cropping patterns will be modified under a warmer climate would improve the accuracy of the model predictions.

WAIBEL, 2011 – MODEL ANALYSIS OF THE HYDROLOGIC RESPONSE TO CLIMATE CHANGE IN THE UPPER DESCHUTES BASIN, OREGON

For this study, mean predicted meteorological conditions downscaled from a suite of eight GCMs (for two major emission scenarios - A1B and B1) were used as input parameters in a daily mass and energy balance model (DPM) for the upper Deschutes Basin in Oregon. The DPM model was used to develop predictions of changes that may occur in the timing (and amount) of runoff and recharge, in response to future changes in climate and snowpack, out to the end of the 21st century. Output values from the DPM model were also used as input values to a pre-existing numerical groundwater flow model (MODFLOW) to help evaluate changes in groundwater discharge patterns in the future.

The model predictions indicate that although annual precipitation rates are not predicted to change significantly in the study area into the future, an increase in the mean annual basin-wide temperature will lead to important changes in basin hydrology, primarily as a result of a reduction in the amount of wintertime snowfall, and an acceleration in the rate of snowpack melt. These changes produce decreases in peak springtime runoff and late spring/early summer peak groundwater recharge, but also result in an opposing increase in wintertime runoff and recharge. These hydrologic shifts largely offset one another, resulting in minimal net annual volumetric change from current conditions. The authors also note important shifts in the spatial distribution of groundwater recharge and discharge will occur within the study area.

The shift in the timing of recharge from a spring dominated pattern to more winter recharge (with a more subdued spring recharge pulse related to melting of higher elevation snowpack that still persists in a warmer climate) is shown by modeling to result in significant changes in groundwater discharge to surface streams, despite only modest changes in annual precipitation. The largest seasonal variations that occur in discharge between current conditions and the end of the 21st century are focused in the small scale headwater streams in the higher elevation portions of the model domain. The authors attribute the spatial-dependency of discharge response to climate change in part to the length of the groundwater flow path between the point of recharge and the point of reemergence to a stream (changes in the timing and volume of recharge are propagated through the groundwater system more rapidly within short flow-path portions of the aquifer system, whereas these changes are attenuated or diffused along longer flow paths that ultimately discharge to higher-order streams; see Waibel et al. 2013 for detailed explanation).

WAIBEL ET AL., 2013 - SPATIAL VARIABILITY OF THE RESPONSE TO CLIMATE CHANGE IN REGIONAL GROUNDWATER SYSTEMS – EXAMPLES FROM SIMULATIONS IN THE DESCHUTES BASIN, OREGON

In the upper Deschutes River basin of east-central Oregon, the authors of this paper propose that the magnitude of seasonal fluctuations in the discharge rate of springs (and spring complexes) is a function of the supporting flow-path scale – the range of seasonal variations in spring discharge is inversely proportional to the discharge rate, which itself reflects the relative length of the flow path. This indicates that seasonal variability in recharge is essentially dampened in larger-scale (longer flow-path) systems in comparison to aquifers with shorter flow paths closer to the recharge source. This can have implications for the spatial distribution of groundwater discharge response to climate induced changes in recharge.

The authors used downscaled temperature and precipitation data from a suite of eight GCMs as input to a previously calibrated water balance model (DPM) for the study area, out to the year 2099. The DPM model was used to produce spatially and temporally distributed estimates of groundwater recharge to the study area aquifer system under a range of potential future climate conditions. The recharge values were averaged across all model cells for each GCM scenario and then used as input boundary conditions for a transient model of the subsurface groundwater flow system (MODFLOW). These tools were used to examine how changes in climate are likely to be manifested hydrologically at different spatial scales.

The model results predict that significant shifts in the timing of groundwater recharge will occur in the upper Deschutes basin over the course of the 21st century. As snowpack diminishes, and precipitation falls more frequently as rain, the spring recharge pulse that typically occurs in association with snowmelt diminishes. The remaining spring recharge is shifted back seasonally so that winter recharge rates increase. As a result the seasonal recharge curve smoothes and broadens between November and May, although annual recharge rates remain relatively consistent with longer term historic averages.

Spatially, changes in recharge rate in the coming century are predicted to be largely focused in the higher elevation portions of the model domain, with less change from current conditions in the lowlands. In the high Cascade Range, groundwater recharge rates are predicted to increase between 30% and 100% during the winter (December, January, and February). Modeled recharge rates throughout the region generally decline during the spring (March, April, and May); most of the recharge reductions during this period also take place in the higher elevation areas of the watershed (-10 to -35% from historic). Recharge does not change significantly in the basin during the summer months except in the very uppermost portions of the Cascades. The spatial distribution of seasonal changes in recharge reflects the shift in form and timing of precipitation during the winter in upper elevation areas, coupled with the lower ET rates that occur in the cold season.

WEBB AND HOWARD, 2011. MODELING THE TRANSIENT RESPONSE OF SALINE INTRUSION TO RISING SEA-LEVELS

The work described in this paper is a follow-on to the Werner and Simmons 2009 publication. Here the authors examine the same two-dimensional coastal aquifers tested previously, but in this case a series of transient numerical models (SEAWAT 4) were used to allow analysis of a more complex set of hydrogeologic assumptions, and to evaluate non-steady state processes for sea water intrusion. The modeling described allowed a systematic analysis of the relative contribution to saltwater intrusion (defined in this case as a salinity level in groundwater >250 mg/L) due to variations in recharge rates, discharge rates, aquifer properties, and aquifer dimensions (which in turn control hydraulic gradients).

For this paper, only *head-controlled* systems are evaluated, since the authors were most interested in understanding upper-bound predictions of saltwater intrusion response to changes in existing sea level [using an assumed 1.5 m (~4.9 ft) increase from baseline sea level in a linear manner out to 90 years, then remaining constant]. In order to better understand the timeframes required for the groundwater system to return to a state of dynamic equilibrium, model run duration was set to 750 years, but predicted conditions at the 90 year time step were of particular focus as a realistic timeframe for water management prediction. The position of the coastline was assumed to remain constant, which may lead to underestimates of the inland migration of the interface since it ignores the potential for saltwater inundation (surface flooding) in very low topographic relief settings.

Using a baseline set of hydrogeologic parameter values and assumptions (including isotropy and homogeneity of aquifer hydraulic properties), the model predictions indicate that a state of dynamic equilibrium in response to the assumed 1.5 m rise in sea level is not re-established until 390 years. At the 90 year model time step, the 250 mg/L salinity contour was predicted to have moved 170 m inland (~558 ft); the same contour moved an additional 138 m (~453 ft) inland by the time equilibrium was reached. For scenarios based on a smaller predicted rise in baseline sea-level, both the time to re-equilibrate, and the distance of inland migration of the interface, are significantly shorter.

The modeling also showed that the effective porosity of the aquifer sediments has a significant bearing on the transient responsiveness of the aquifer system to changes in sea level. As effective porosity decreases, the length of time necessary to return to a state of dynamic equilibrium also decreased; higher porosity settings were shown to require significantly longer timeframes to re-equilibrate (centuries). The ratio of aquifer hydraulic conductivity (K) to recharge (W) rate shows a similar response; aquifers with higher K/W ratios exhibit the longest timeframes for returning to an equilibrium condition and the furthest inland movement of the interface. This suggests to the authors that higher K aquifers that are traditionally most suitable for water supply development may be the most vulnerable, both in the short and the long term, to the impacts of sea-level rise.

WERNER AND SIMMONS, 2009. IMPACT OF SEA-LEVEL RISE ON SEA WATER INTRUSION IN COASTAL AQUIFERS

In this 2009 paper, the impact of sea-level rise on saltwater intrusion to coastal aquifers is evaluated using first-order, two-dimensional, steady state analytical methods. The conceptual framework used for the analysis assumes a series of idealized coastal aquifers, with horizontal flow, homogeneous and isotropic aquifer properties, constant recharge, and a sharp interface between freshwater and sea water. This framework provides the basis for developing insights into the major hydrogeologic processes and controls that drive the inland movement of the interface in response to a rise in sea-level elevation. The findings of this paper can be used to improve understanding of the likely sea-water intrusion behavior that can be expected across a range of hydrogeologic settings.

The authors describe the use of two end-member boundary condition scenarios for the modeled aquifer: (1) settings where inland groundwater heads are allowed to rise enough to maintain a constant flux of groundwater through the freshwater/saltwater interface (*flux-controlled* systems), and (2) settings where groundwater heads inland of the coast are maintained at a fixed position (*head-controlled* systems - due to the presence of surface controls on head rise such as drains, wetlands, and streams, or due to increases in pumping or ET rates).

The analysis showed that sea water intrusion impacts are likely to be relatively limited (lower-bound response) in flux-controlled systems. By contrast, head-controlled systems are predicted to show significantly greater inland movement of the toe of the freshwater/saltwater interface in response to a fixed increase in sea-level position. For flux-controlled settings, the upper limit for lateral sea-water intrusion for a sea-level rise of as great as 1.5 m vertical rise is ≤50 m (~4.9 ft: ≤165 ft) for typically-encountered ranges of recharge, hydraulic conductivity, and aquifer depth. Head-controlled settings, by contrast, may show values of inland migration of the interface position of >1 km (~0.6 mi) for the same sea-level rise. The authors conclude that the analysis highlights the importance of accounting for inland boundary conditions when developing predictions of seawater intrusion as sea level rises.

Appendix B. Acronyms Used in This Report

A1B, B1, A2, and 20C3M	IPCC greenhouse gas emissions scenarios. For full description of scenario assumptions, see https://www.ipcc.ch/pdf/special-reports/emissions_scenarios.pdf
AET	Actual evapotranspiration
ASR	Aquifer storage and recovery
BC	British Columbia
BCCR-BCM	Bergen Climate Model, from Bjerknes Centre for Climate Research, Norway
BIS	Basic Irrigation Scheduling model; from Univ. of California, Davis
CGCM	Coupled General Circulation Model; from the Canadian Centre for Climate Modeling and Analysis
CCSM	Community Climate System Model; from U.S. National Center for Atmospheric Research
CDF	Cumulative distribution function
CLSM	Catchment Land Surface Model; from NASA
CM2	Global coupled climate model set; developed by the NOAA Geophysical Fluid Dynamics Laboratory, USA
CRN	Climate Response Network; a national network of groundwater monitoring wells operated by the USGS to track groundwater storage responses to climate change
CSIRO-Mk	Global climate model from the Commonwealth Scientific and Industrial Research Organization, Australia
CVHM	Central Valley Hydrologic Model; hydrologic model of the Central Valley, California; from
DHSVM	Distributed Hydrology Soil Vegetation hydrologic model; from the University of Washington, USA
DPM	Deep Percolation Model; from USGS
DRSTIL	Depth-to-water table, Recharge, Soil media, Topography, Impact of the vadose zone, Land use; a groundwater vulnerability ranking model
ECHAM	A global climate model developed by the Max Planck Institute for Meteorology, Berlin
ECHO-G	A coupled global climate model; from the German Climate Computer Centre
ENSO	El Nino Southern Oscillation
EROS/GARDENIA	Ensemble de Rivieres Organise en sous bassins/Modele Global A Reservoirs pour la simulation de Debits et de Niveaux Aquifers; a hydrologic model suite from the Bureau de Recherches Geologiques et Minieres, France
ET	Evapotranspiration
FEFLOW	A finite element groundwater flow model; from DHI Group

GCM	General circulation model; a global-scale numerical model of climate
GFDL	Geophysical Fluid Dynamics Laboratory global climate model; NOAA/Princeton University
GIS	Geographic information system
GR4J	Gea’nie nie Rural a 4 parametres Journalier; hydrologic model from National Research Institute of Science and Technology for Environment and Agriculture, France
GRACE	Gravity Recovery and Climate Experiment; a NASA satellite mapping program
HADCM3	The Hadley Centre Coupled Climate Model; from the Hadley Centre, UK (also HadAM3H)
HELP	Hydrologic Evaluation of Landfill Performance model; from USEPA
HIRHAM	A regional climate model; from the Danish Climate Centre
HUC	Hydrologic unit code
HYDRUS 1D	A one-dimensional water flow, heat and solute transport model; from the U.S. Salinity Laboratory
INM-CM	A global climate model; from Institute for Numerical Mathematics, Russia
IPCC	Intergovernmental Panel on Climate Change
IPSL CM	Institute Pierre Simon Laplace Climate Model, France
LARS-WG	A stochastic weather generation model; from Rothamsted Research, UK
MCL	Maximum contaminant level
MIKE-SHE	An integrated hydrological model for both groundwater and surface-water flow; from the Danish Hydraulic Institute (currently: DHI Group)
MIROC	Model for Interdisciplinary Research on Climate; from the Center for Climate System Research, University of Tokyo
MODCOU	Modelisation Couplee; a hydrological model from the French National Centre for Meteorological Research
MODFLOW	A modular three-dimensional numerical groundwater flow model package from the U.S. Geological Survey (includes various versions and add-on packages such as MODFLOW-2000, SEAWAT, GSFLOW, NWT, UFZ1, FMP, etc.)
MHWM-BCM	Mountain hydrologic watershed model-basin characterization model
PARFLOW	Parallel watershed surface-subsurface flow model; from the Colorado School of Mines
PCM	Parallel Climate Model; a global climate model developed by the U.S. National Center for Atmospheric Research
PDO	Pacific Decadal Oscillation
PET	Potential evapotranspiration
PNW	Pacific Northwest
PRISM	Parameter-elevation Relationships on Independent Slopes Model; from PRISM Climate Group, Oregon State University

PRMS	Precipitation Runoff Modeling System; from the USGS
RCM	Regional circulation model; a regional-scale numerical model of climate
STICS	Simulateur mulTIdisciplinaire pour les Cultures Standard; a crop model from the French National Institute for Agricultural Research
SUTRA	2-dimensional finite element saturated-unsaturated groundwater flow and solute/heat transport model; from the USGS
SVRPA	Spokane Valley Rathdrum Prairie Aquifer
SWAP	Soil, Water, Atmosphere and Plant; water and solute transport model; from Wageningen University and Research Centre; Netherlands
SWAT	Soil and Water Assessment Tool; from the U.S. Department of Agriculture Agricultural Research Service
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity; a hydrologic model from the University of Washington
VS2DH	Variably saturated 2-dimensional water flow and energy transport model; from USGS

Units

°C	degrees Centigrade
°F	degrees Fahrenheit
acre-ft/yr	acre-feet per year
cm	centimeters
ft	feet
ft^3/sec	cubic feet per second
gal/day	gallons per day
in	inches
in/yr	inches per year
km	kilometers
L/day	liters per day
m	meters
M gal/day	million gallons per day
m^3/sec	cubic meters per second
mg/L	milligrams per liter
mi	miles
mi^2	square miles
mm/yr	millimeters/year
ppm	parts per million
yrs	years