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# Temporal and spatial variability of groundwater recharge on Jeju Island, Korea

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SUMMARY

Estimates of groundwater recharge spatial and temporal variability are essential inputs to groundwater flow models that are used to test groundwater availability under different management and climate conditions. In this study, a soil water balance analysis was conducted to estimate groundwater recharge on the island of Jeju, Korea, for baseline, drought, and climate-land use change scenarios. The Soil Water Balance (SWB) computer code was used to compute groundwater recharge and other water balance components at a daily time step using a 100 m grid cell size for an 18-year baseline scenario (1992–2009). A 10-year drought scenario was selected from historical precipitation trends (1961–2009), while the climate-land use change scenario was developed using late 21st century climate projections and a change in urban land use. Mean annual recharge under the baseline, drought, and climate-land use scenarios was estimated at 884, 591, and 788 mm, respectively. Under the baseline scenario, mean annual recharge was within the range of previous estimates (825–959 mm) and only slightly lower than the mean of 902 mm. As a fraction of mean annual rainfall, mean annual recharge was computed as only 42% and less than previous estimates of 44–48%. The maximum historical reported annual pumping rate of $241 \times 10^6$ m$^3$ equates to 15% of baseline recharge, which is within the range of 14–16% computed from earlier studies. The model does not include a mechanism to account for additional sources of groundwater recharge, such as fog drip, irrigation, and artificial recharge, and may also overestimate evapotranspiration losses. Consequently, the results presented in this study represent a conservative estimate of total recharge.

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## 1. Introduction

Freshwater on oceanic islands is derived exclusively from precipitation, and groundwater aquifers replenished by infiltrating rainfall are a primary source of freshwater. As examples, groundwater aquifers supply 80% of drinking water on the island of Guam (western Pacific Ocean), 92% of the freshwater on the island of Jeju (northwest Pacific Ocean), 98% of freshwater in the Azores archipelago (north Atlantic Ocean), 99% of drinking water in the Hawaiian Islands (central Pacific Ocean), and virtually all of the freshwater on the islands of Saipan (western Pacific Ocean) and Tutuila (south Pacific Ocean) (Gingerich and Oki, 2000; Cruz, 2003; Kim et al., 2003; Tribble, 2008). Given their isolation and limited storage capacity, groundwater resources on oceanic islands are particularly susceptible to overpumping (e.g., upconing), salt water intrusion (e.g., sea level changes, recharge decline), contamination from agricultural and urban development, and climate variability. An evaluation of the influence of these factors on groundwater availability is critical for sustainable water resource management. Inter-annual and multi-decadal climate variability has negatively impacted groundwater availability on several islands resulting in declining water levels and stream baseflow, and the thinning of basal freshwater lenses (Oki, 2004; Chu and Chen, 2005; Presley, 2005; Bailey et al., 2009). Groundwater recharge is a critical input for tools, such as groundwater flow models, that investigate freshwater availability and quality in critical island aquifers under different demand, climate, and land cover

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scenarios (Gingerich and Voss, 2005; Oki, 2005; Todd Engineers, 2005; Gingerich, 2008; Gingerich and Jenson, 2010). Hence, spatially distributed estimates of recharge are essential for assessing groundwater availability under changing land use, land cover, and climate.

Freshwater is a vital natural resource on the island of Jeju, Republic of Korea, with significant economic, agricultural, aesthetic, ecologic, and cultural importance. Jeju has experienced tremendous growth over the past 30 years and now supports a residential population of 583,000 and 8.7 million visitors annually (Jeju Special Self-Governing Province, 2013). As a consequence of the rapid growth and increased groundwater withdrawals, saltwater intrusion has become a persistent problem particularly in the eastern coastal portion of the island (Kim et al., 2003; Kim et al., 2006). In addition, increased fertilizer applications since the late 1970s and human waste have caused widespread nitrate groundwater contamination (Spalding et al., 2001; Koh et al., 2005; Koh et al.,2006a; Koh et al., 2009; Koh et al., 2012b). Finally, the frequency and intensity of extreme rainfall events across Korea, including Jeju, have increased significantly and show intensification of the annual monsoon (Choi et al., 2008; Jung et al., 2011; Park et al., 2011). These upward trends are projected to persist and continue well into the 21st century (Min et al., 2004; Boo et al., 2006; Im et al., 2011). Collectively, these changes in demand, land use, and climate have serious implications for freshwater availability on Jeju. Hence, robust estimates of groundwater recharge are critical for assessing the ability of the island's aquifers to meet current and future freshwater needs.

Groundwater recharge can be estimated using a variety of techniques including the soil–water balance, surface water, unsaturated zone, and saturated zone methods (Scanlon et al., 2002). Measurements needed to make these estimations are often difficult, and there are varying levels of uncertainty and different spatio-temporal scales associated with each method. The soil-water balance method is considered a reliable recharge estimation technique for broad, regional scale groundwater management purposes because it is not limited by any assumptions related to the mechanisms that control the individual components. Due to its flexibility, the soil–water balance method can be used to evaluate the effects of climate and/or land use change across a wide range of space and time scales. The method can also produce time series of spatio-temporal recharge and is thus very useful for assessing temporal trends. Hence, the method has been extensively used on Pacific islands to estimate groundwater recharge (Giambelluca, 1983; Izuka et al., 2005; Engott and Vana, 2007; Izuka et al., 2007; Engott, 2011; Johnson, 2012).

The water balance method follows a mass-balance procedure that accounts for water entering, leaving, and being stored within a soil–plant control volume (Thornthwaite and Mather, 1955; Thornthwaite and Mather, 1957; Scanlon et al., 2002). Water that infiltrates below the soil–plant control volume (i.e., root zone) is often called *potential recharge* to distinguish it from water that reaches the actual water table or *actual recharge* (Rushton and Ward, 1979). The distinction between potential and actual recharge becomes important when the unsaturated zone is thick because the time of travel to reach volcanic aquifers on oceanic islands can be on the order of years or decades (Voss and Wood, 1993; Koh et al., 2012a). Oki (2008) found that the accounting order of recharge and evapotranspiration (ET) in soil–water balance models can result in large uncertainty in recharge estimates if the soil moisture storage capacity is small and the water balance is computed using monthly time intervals, particularly in arid and semi-arid regions. Averaging water balance components over a longer time step, such as a month, tends to dampen out extreme precipitation events that may be most responsible for contributing recharge (Scanlon et al., 2002). Therefore, uncertainty in recharge estimates computed using a water balance method can be minimized using the shortest computation interval that the data allow.

Over the past 15 years, several studies have estimated groundwater recharge on Jeju using a water balance approach as part of efforts to assess freshwater availability (Hahn et al., 1997; Korea Water Resources Corporation (KOWACO), 2003b; Won, 2004; Koh et al., 2006b). These studies report that mean recharge as a fraction of rainfall varies from 44% to 48%. However, these water balance studies were computed using either monthly time steps or limited precipitation datasets. Hagedorn et al. (2011) used water table fluctuation and geochemical tracer methods to compute recharge rates of 9–39% on Jeju, which suggests that previous water balance studies may have overestimated recharge. However, their study may have biased low elevation-low rainfall areas, thereby excluding high-rainfall portions of the island with potentially much greater recharge rates. Thus, there is a need to test alternative methods to further improve and refine the island's total recharge estimate.

A variety of soil water balance codes have been developed to estimate potential groundwater recharge (Giambelluca, 1983; Schroeder et al., 1994; Finch, 2001; Batelaan and De Smedt, 2007; Dripps and Bradbury, 2007; Flint and Flint, 2007; USGS, 2008; Westenbroek et al., 2010; Johnson, 2012). Most of these codes use proprietary software, are implemented in a proprietary language, or are complicated to operate. The freely available Soil Water Balance (SWB) code was recently developed to estimate the spatial and temporal distribution of natural groundwater recharge in temperate-humid climates at a daily time step and at a user-specified grid resolution (Dripps and Bradbury, 2007; Westenbroek et al., 2010). A key advantage of SWB is the ability to calculate recharge using commonly available geographic information system (GIS) data layers in combination with tabular climate data. The SWB code has been successfully applied to temperate-humid climate areas in northern Wisconsin and around Lake Michigan (Dripps and Bradbury, 2007; 2010; Feinstein et al., 2010; Westenbroek et al., 2010) but it has yet to be applied to oceanic islands with similar climate.

In this study, the SWB code is applied to Jeju to estimate the spatial and temporal distribution of groundwater recharge and other water balance components including direct runoff, evapotranspiration, and precipitation. The information is critical for assessing the sustainability of the island's water resources under various climate and land-use conditions. The main specific objectives of the study are to (1) produce spatially and temporally distributed estimates of groundwater recharge under current (baseline) conditions, hypothetical drought, and climate-land use change scenarios, and (2) test the suitability of applying the SWB code to oceanic islands stressing model and data limitations. Unlike previous applications of SWB, the model domain in this study is comprised of mountainous terrain overlain with many highly permeable lava flows and thick unsaturated zones. Hence, the study described herein offers insights into SWB's use and limitations for applications in similar environments.

## 2. Study area

Jeju is located 85 km south of the Korean peninsula (33°N, 126°E) and encompasses an area of 1828 km$^2$ (Fig. 1) (KOWACO, 2003b). The island is comprised of a dormant shield volcano with one central mountain peak, Mt. Halla, rising to an elevation of 1950 m above sea level (masl). The climate varies from cool-temperate in winter to humid-monsoon in summer with mean air temperatures in the coastal areas ranging from 5 °C in January to 24 °C in August. Mean annual rainfall across the island is 2082 mm and varies from 1100 mm along the western coastline to over