Estimating recharge in fractured aquifers of a temperate humid to semiarid volcanic island (Jeju, Korea) from water table fluctuations, and Cl, CFC-12 and 3H chemistry

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1. Introduction

On Jeju Island (Korea), surface water resources are unreliable because aquifers with high hydraulic conductivity limit permanent surface runoff to only a few select locations near the coast (Hamm et al., 2005; Kim et al., 2003; Won et al., 2005, 2006). Given that groundwater provides ~92% of the potable water for the island’s ~600,000 residents (Kim et al., 2003), a detailed assessment of the temporal and spatial variations of recharge is important to evaluate and manage the island’s water resources sustainably.

Recharge on islands is generally estimated as the residual in a soil water budget (SWB) (Engott and Vana, 2007; Giambelluca, 1983; Giambelluca et al., 1996b; Izuka et al., 2007; Shade, 1995). The method is popular, considering that it is not hindered by limiting assumptions regarding the mechanisms that control the individual budget components (i.e., rainfall, evapotranspiration, direct runoff, baseflow/interflow in and outflow, vegetation interception and soil water storage) (Dripps and Bradbury, 2007; Scanlon et al., 2002; Tindall and Kunkel, 1999). In addition, the method does not require the drainage-basin boundary and groundwater divides to coincide; a condition that is hard to satisfy (Izuka et al., 2010). The major limitation of the approach is that the accuracy of the recharge estimate depends on the accuracy of the estimates of the other components in the SWB. This limitation is critical when the magnitude of the recharge rate is small relative to that of the other variables. As an illustration, on Jeju Island, direct runoff only occurs when a rainfall event exceeds a threshold value of 40–50 mm over several days (KOWACO, 2003). In this case,
averaging over longer time periods may dampen out extreme precipitation and runoff events, which mainly control recharge. The usefulness and reliability of the SWB has therefore been questioned in regions with low runoff (Gee and Hillel, 1988; Hendrickx and Walker, 1997; Lerner et al., 1990). Recharge estimates using SWB models can also differ substantially depending on whether irrigation is carried out (Giambelluca et al., 1996a), which adds another source of uncertainty if averaging values over time periods longer than days. Oki (2008) concluded that the accounting order of recharge and evapotranspiration may result in a large uncertainty of the estimate if soil moisture storage capacity is small and when water budgets are computed using monthly time intervals as compared to daily time steps. Furthermore, as the SWB yields recharge values only for below the root zone, it is not clear where and when exactly the infiltrating rainwater will cause the water table to rise if the unsaturated zone is thick and heterogeneous (Dripps and Bradbury, 2007; Westenbrook et al., 2010). It becomes clear that recharge estimates from the SWB method should be validated and refined by incorporating other independent estimates.

Many techniques exist for quantifying recharge rates. These include numerical modeling of groundwater flow, lysimeters installed in the soil zone, remote sensing, water table fluctuations, radioactive (e.g., $^3$H, $^{14}$C) or other (e.g., chlorofluorocarbons) tracers, and chemical mass balance (see, e.g., the reviews by Walker et al. (2002), Scanlon et al. (2002), Cartwright et al. (2007) and Brunner et al. (2007)). However, choosing appropriate techniques for a specific site is not straightforward, considering that a particular method can be more suitable for certain time and spatial scales. For example, water table fluctuations are more suitable for estimating local recharge over a few days to a few years, while $^3$H, chlorofluorocarbons (CFCs), $^{14}$C and Cl in groundwater provide average local recharge estimates over years to millennia (Herczeg and Edmunds, 2000; Scanlon et al., 2002; Walker et al., 2002). On Jeju Island, the residence time of groundwater is generally less than 50 years (Koh et al., 2007b, 2006a), there is low direct runoff (Won et al., 2006) and water table fluctuations show direct responses to episodic rainfall events (Koh et al., 2006c; Won et al., 2006). Considering these characteristics, recharge is estimated at multiple point locations from water table fluctuations (WTF), chloride mass balance (CMB), apparent CFC-12 ages and modeled $^3$H mean residence times. The main objectives of this study are to:

1. Assess the applicability of these recharge estimation techniques to Jeju and similar settings, and
2. Validate and refine previous recharge estimates based on the SWB method published by the Korean Water Resources Corporation (KOWACO, 2003). Special attention is given to Jeju’s volcanic island setting where water levels can be as low as 30 m below the land surface (Koh et al., 2006c), fractured high and low conductivity aquifers may alternate over several meters (Hahn et al., 1997), and rainfall minus potential evaporation is high, but direct runoff is low (KOWACO, 2003).

2. Jeju Island

2.1. Topography, climate and land use

Jeju Island is comprised of a dormant shield volcano with one central mountain peak, Mt. Halla, rising to an elevation of 1950 m (Fig. 1a). The island is elliptical in shape with a semi-major axis width of 74 km, a semi-minor axis width of 32 km, and a total area of 1830 km$^2$. The smooth flanks of Mt. Halla are disrupted by about 360 secondary cinder and tuff cones that are mainly located along the eastern and western coastal regions (Hahn et al., 1997). The 16 watersheds of the island are characterized by steep mountain slopes and narrow stream channels in the uplands and gently dipping plains towards the coast. Only a few perennial streams exist and drainage systems are most developed along the southern and northern flanks of Mt. Halla (Won et al., 2006).

The mountainous interior of Jeju provides a topographic barrier to prevailing southeasterly winds and divides the island into a humid southeastern region and a more arid northwestern region. Mean annual rainfall computed from concurrent daily rainfall data of 28 gages for the time period 1993–2002 (KOWACO, 2003) varies from a low of 1060 mm in the northwestern coastal region to a high of over 3590 mm at Songpanak just southeast of Mt. Halla (Fig. 2). 48% of the mean annual rainfall occurs in the summer monsoon between June and September with average monthly rainfall >200 mm. The winter climate is controlled by the dry and cold northwesterly winter monsoon with occasional snowfall in the highlands. Rainfall diminishes radially from the central maximum to the surrounding coastline and produces annual rainfall gradients ranging from 85 to 130 mm/km. The mean air temperature in the coastal zone is 14.6 °C and the mean monthly air temperature in Jeju City and Seogwipo ranges from 24 °C in August to 5 °C in January (KOWACO, 2003). Winter conditions are relatively mild and humid, compared with those of other regions at the same latitude (33°–33°35′ N), which is a result of the maritime influence of the warm Kuroshio Current (Chung, 2007). Estimates of mean annual potential evapotranspiration calculated for the coastal areas using the Penman–Monteith approach (Monteith, 1965; Penman, 1948) vary from a low of 963 mm at Seongsan to a high of 1070 mm at Gusan (KOWACO, 2003) and are expected to decrease with increasing elevation towards the interior. Average monthly potential evapotranspiration is less than the average monthly rainfall throughout the year allowing groundwater recharge to occur continuously if the soil moisture is low.

The main types of land cover on Jeju are natural forest (34.7%), cultivated land (i.e., meadows, paddocks, golf courses, tangerine, citrus and banana orchards) (61.0%); urban (4.0%); and rivers/reservoirs (0.3%) (KOWACO, 2003; Fig. 2). In the uplands, land use is mostly natural forests (Koh et al., 2009) with Mt. Halla National Park occupying the area above 600 m asl. The island has a residential population of 565,000 with most of the populace (72%) living in and around Jeju City (Jeju Special Self-Governing Province, 2010). In recent years, local governments of Jeju have tried to preserve groundwater resources by managing the expanding agricultural fields and recreational facilities in the uplands (Koh et al., 2009). There is also an increased effort to commercialize mineralized ground- and spring water for the bottled-water industry (Park, 2006). Assessing the island’s recharge is an important step towards implementing such efforts.

2.2. Geology and hydrogeology

Jeju Island was formed by continuous Pleistocene to Holocene volcanic eruptions within the Continental Shelf of southeastern Korea (Won et al., 2006). The volcanic rocks on Jeju have numerous interflow structures within a series of lava flows and unconsolidated scoriaceous formations. These rocks are characterized by high permeability and storage capacity (Koh et al., 2006a) and comprise the main aquifers of the island (Hahn et al., 1997; Kim et al., 2003; Won et al., 2005). A hydro-volcanic sedimentary formation (Seogwipo Formation) underlies the volcanic rocks. This Formation is composed of sand, tuffaceous material, basaltic rock fragments, and molluscan shells (Sohn et al., 2002). Aside from a few outcrops along the southern shoreline of Jeju, the Seogwipo Formation is continuously distributed below the surface with a thickness of 89–238 m (Hahn et al., 1997). The Seogwipo Formation is underlain by the U Formation that is mainly composed of unconsolidated sand and silt (Sohn, 1996; Won et al., 2006) and is continuously distributed below sea level with a thickness of
70–250 m (Koh et al., 2006a). The basement of the island consists of rhyolites, welded tuff, lapilli tuff and granite that formed in the late Cretaceous and early Palaeogene (Sohn, 1996; Yoon et al., 1995). Soils on Jeju are relatively thin (<1 m) (Davis et al., 1970; Kang et al., 2010) and are characterized by very high infiltration and very low runoff potential (KOWACO, 2003). Hence, surface runoff is generally very low and only a few perennial streams exist.

Hydraulic conductivity ($K$) values of the magmatic and sedimentary rocks on Jeju were estimated from pump test analysis of several hundreds of wells on the island (Hahn et al., 1997; Kim et al., 2009; Won et al., 2006). $K$ values can range from 0.1 m/d to 2400 m/d in the principal basaltic aquifer (average value: 234 m/d; Won et al., 2006), and from 1.4 m/d to 51.1 m/d in the Seogwipo Formation (average value: 10.1 m/d; Won et al., 2006). It is assumed that $K$ values of the U-Formation are similar to those of the Seogwipo Formation given their similar sedimentary textures (Koh et al., 2006b). The basement bedrock has a relatively impermeable conductivity of approximately 0.01 m/d (Kim et al., 2006c).

Fig. 1. (a) Location of Jeju Island, its 16 catchments and recharge monitoring bores, and (b) water level contours at wet and dry periods calculated based on cokriging analysis of hydraulic heads recorded from ~300 wells screened in high level, parabasal and basal groundwater (from Koh et al., 2006c).
Vertical K values for the basaltic aquifer have been estimated to range between 3 m/d and 28 m/d (Kim et al., 2003) indicating a vertical anisotropy in the range of 10–100. Though high and low conductivity basalt and andesite–trachyte aquifers may alternate on a meter scale (Hahn et al., 1997; Oh et al., 2000), the volcanic aquifers overlaying the Seogwipo Formation are regarded as unconfined (Hahn et al., 1997; Kim et al., 2003; Koh et al., 2007b, 2006a, 2006b; Won et al., 2005). This is because highly permeable structures, such as clinkers and vertical fractures have been commonly observed in all lava flows both in outcrops and rock cores (Oh et al., 2000). In addition, wells screened in volcanic aquifers are characterized by higher specific capacities (~1290 m²/day to ~2410 m²/day) and younger groundwater CFC-12 ages (~10 to ~30 years) than those screened in the sedimentary rocks (average specific capacity: 1010 m²/day; apparent CFC-12 age: ~20 to ~60 years) (Koh et al., 2006a; Won et al., 2005). This indicates that the travel time of groundwater from volcanic aquifers is distributed over a wide spatial range whereas groundwater movement within the confining Seogwipo Formation is greatly retarded.

2.3. Groundwater flow and hydrochemistry

Groundwater on Jeju has been classified into four general categories: high level, parabasal, basal and basement (Won et al., 2006 and references therein; Fig. 3). High level groundwater is assumed to be perched by relatively impermeable volcanic layers at high altitudes in the mountainous interior of the island without a direct hydraulic connection to the other types of groundwater. Basement groundwater occurs in fractures and joints of the granites and welded tuffs at depths of >300 m. Groundwater that is surrounded on all sides by seawater except for the atmospheric interface it is in contact with seawater and lies on the low permeability Seogwipo sediments. Won et al. (2006) additionally subdivided between upper and lower parabasal groundwater when the elevation of the top of the Seogwipo sediments is either above or below sea-level (Fig. 3). While the lower boundary of the high level groundwater is considered fixed and beyond the reach of sea water intrusion, both the lower and upper boundaries of basal and parabasal groundwater are in motion and every contraction of the freshwater lens is accompanied by lateral and vertical seawater movement (Won et al., 2006). Because the Seogwipo Formation (i.e., the barrier that separates parabasal groundwater from seawater) occurs at greatest depths in the eastern section of the island (KIGAM, 2011; Koh et al., 2006b), basal groundwater extends furthest inland along the eastern coast (Fig. 1).

Hydraulic heads vary significantly across the island (Koh et al., 2006c; Won et al., 2006). In the uplands, where high level groundwater prevails, the water table is at ~180 m asl, while towards the coast, in parabasal and basal groundwater areas, the water table is shallower, reaching elevations of ~2 m asl (Fig. 1b). Horizontal hydraulic gradients change from ~0.005 in the E–W direction to ~0.01 in the N–S direction (calculated from Koh et al., 2006c). Hydraulic heads are slightly lower in the dry spring months (March–May) than in the wet autumn months (August–October) as a result of lower rainfall and higher evaporation. Spatially, groundwater elevations roughly follow topography and increased rainfall with elevation (KOWACO, 2003) implies increasing recharge in topographically higher areas. Tidal groundwater level fluctuations of 0.7–0.8 m occur in coastal basal groundwater and are attenuated at distances of ~5 km away from the coast (Koh et al., 2006c).

Groundwater on Jeju is generally well oxygenated (DO > ~9 mg/L), displays circumneutral pH values (~6.5 to ~7.5), low Total Dissolved Solids (TDS) contents (<150 mg/L) (Koh et al., 2005, 2007a, 2006a) and δD and δ18O values that indicate only minor enrichment from springtime evaporation (Davis et al., 1970; Lee et al., 1999). Groundwater temperature varies between 4.5 °C and 16.5 °C (average value: 12.9 °C) (Koh et al., 2006b). High level and parabasal groundwater is dominated by a (Ca/Na)–HCO3 major ion composition (Koh et al., 2006b) reflecting the influence of plagioclase and/or secondary calcite weathering within the volcanic aquifers (cf. Tweed et al., 2005). Basal groundwater is influenced...
by seawater intrusion with more saline (TDS: ≥ 1500 mg/L) and Na–Cl dominated groundwater detected at horizontal distances of up to ~2.5 km inland (Kim et al., 2003). High concentrations of NO$_3$ (>2.5 mg/L) have been measured in groundwater throughout the island (Koh et al., 2009, 2005). By comparing groundwater CFC-12 residence times with the groundwater NO$_3$ concentrations, theory is illustrated (black dashed line). Parabasal groundwater is separated from seawater by the low-permeability Seogwipo Formation. The theoretical extend of the freshwater lens inferred from the G–H theory is illustrated (black dashed line).

Fig. 3. Schematic illustration of lithologic cross-section (E–W) and groundwater occurrence for Jeju Island (not to scale; modified from Koh et al., 2007b). Thin impermeable volcanic layers separate high level from parabasal groundwater. Basal groundwater overlies seawater according to the Ghyben–Herzberg (G–H) principle (Freeze and Cherry, 1979). The volcanic layers separate high level from parabasal groundwater. Basal groundwater overlies seawater according to the Ghyben–Herzberg (G–H) principle (Freeze and Cherry, 1979). Theoretical extend of the freshwater lens inferred from the G–H theory is illustrated (black dashed line).

2.4. Previous assessments of recharge and sustainable yield

The most recent recharge analyses on Jeju were carried out by KOWACO (2003) and Won (2004) using the SWB method. An estimated mean annual rainfall input of ~3.61 × 10$^9$ m$^3$/yr (~1980 mm/yr) was partitioned into estimates of evapotranspiration (33.5%), direct runoff (18.0%), and groundwater recharge (48.5%). Hydrologic data collected from 1993 to 2002 was used and recharge was computed for the entire island using multi-annual average estimates of rainfall, evaporation and direct runoff. Recharge was also partitioned into estimates for each catchment of the geographical districts (north, south, east, west) and for the different altitude zones (<200 m, 200–600 m, >600 m a dislike). It should be noted that the use of the large time step in the SWB analysis (i.e., annual average) can result in large errors in the recharge estimate if soil moisture storage capacities are low (cf. Oki, 2008). SWB studies should therefore best be carried out on daily time intervals. The SWB analyses for Jeju incorporated the spatial variability of rainfall, land cover/land use and soil type. Potential evapotranspiration (PET) was estimated at four coastal locations using the Penman and Penman–Monteith (PM) methods (Monteith, 1965; Penman, 1948). PET was scaled down to actual evapotranspiration (AET) at these four locations using a soil moisture stress function or coefficient termed ‘factor of evapotranspiration’ (KOWACO, 2003). It is not clear whether such a factor is a crop coefficient, a water stress coefficient that represents the scaling of PET, or a combination of both. It is also not clear if and how an adjustment was made to estimate AET in Jeju's interior. Annual direct runoff was modeled using the US Department of Agriculture (USDA) Natural Resources Conservation Service (formerly Soil Conservation Service: SCS) curve number approach (USDA-SCS, 1993). Rainfall was the only component that was directly measured. Irrigation return flows, vegetation interception losses and/or artificial recharge zones were not incorporated into the analyses. Recently, the Jeju government adopted an effective groundwater recharge area concept, which essentially excludes the region within 500 m from the coast in water budget calculations (Koh et al., 2006b). Thus, the effective recharge area was reduced and the water budget analyses recomputed as mean annual rainfall input of 3.43 × 10$^9$ m$^3$/yr (or ~1880 mm/yr) with 33.2% lost to evapotranspiration, 20.7% to direct runoff, and 46.1% to groundwater recharge.

The total pumping yield from 453 wells reported by Hahn et al. (1997) for the year 1993 was 557,000 m$^3$/d. The sustainable yield of Jeju's groundwater of 1.77 × 10$^9$ m$^3$/d (Koh et al., 2006b) was calculated based on groundwater recharge estimates from KOWACO (2003) and Won (2004), initial water levels from pre-pumping times, and assumed equilibrium water levels to be retained. Using the reported pumping rates from Hahn et al. (1997), groundwater withdrawal rates were equal to 37% of the sustainable yield. In light of growing water demands due to future population growth and agricultural expansion, assessing the uncertainty of previous recharge estimates using new independent estimation techniques is critical. Particularly for the eastern parts of Jeju, where seawater intrusion is a serious issue, groundwater recharge is a crucial component for sustainable water resource evaluations and must be quantified accurately.

3. Data

In this study, recharge (R in mm/yr) was calculated from available climate, physical hydrogeology and geochemistry data from the literature. Porosity and specific yield values were taken from Kwon et al. (1993) and Hahn et al. (1997), respectively. Hourly groundwater levels for the time period 01/01/2008 till 12/31/2009 used in the WTF method were provided by the Institute of Environmental Resource Research, Jeju Special Self-Governing Province (IERR-JSSGP, 2010). For the CMB approach, rainfall CI contents reported by Kang et al. (2003) and the Acid Deposition Monitoring Network in East Asia (EANET, 2010) together with
long-term rainfall isohyets reported by KOWACO (2003) and groundwater Cl data from Koh et al. (2005, 2006a, 2007b, 2009) were used. Recharge estimates from CFC-12 and \(^{3}H\) chemistry utilize groundwater CFC-12 and \(^{3}H\) data as well as information on rainfall \(^{3}H\) chemistry, bore altitudes, bore depths, bore screens and water levels reported by Koh et al. (2005, 2006a, 2007b). No groundwater samples from basal groundwater zones are considered for the CMB, \(^{3}H\) and CFC-12 techniques as mixing with seawater needed to be ruled out. Also, for the \(^{3}H\) and CFC-12 techniques, only groundwater sampled from basaltic aquifers was considered to ensure unconfined conditions. The hydrogeological and geochemical data used in this study are listed in Appendices A and B.

As an assessment of the applicability of the here presented recharge estimation methods to Jeju and similar volcanic island settings, median recharge values calculated for the different geographic districts are compared to those from the SWB carried out in 2003 (calculated from KOWACO, 2003). The dataset is subdivided into bores located below 200 m asl and between 200 m and 600 m asl representing altitude zones into which the SWB was subdivided. It should be noted that the different recharge methods apply to different spatial scales. The WTF method predicts recharge at the well, the CMB method estimates the mean recharge rate at the location where the water first entered the aquifer, and estimates based on CFC-12 and \(^{3}H\) dating are mean values for between where the sampled water first entered the aquifer and the well location. In this study it is assumed that all estimates are representative for recharge within the groundwater well altitude zone. As only 1 CMB data point and no WTF, CFC-12 and \(^{3}H\) data points from bores located at altitudes >600 m asl were available here, no discussion on the applicability of the here presented methods for recharge estimation in high altitude (>600 m asl) areas of Jeju was possible. Assessments of the accuracy of the above presented techniques assume that the published SWB recharge estimates are themselves an accurate measure of recharge.

4. Results and discussion

4.1. Bore water table fluctuations

Bore hydrographs recorded at regular intervals from multiple wells across the island show that recharge is episodic (Koh et al., 2006c; Won et al., 2006) and linked to seasonal rainfall cycles (Fig. 4). The variations in the water tables allow calculating recharge using the WTF method (Healy and Cook, 2002): 

\[
R = S_{b} \frac{dh}{dt} 
\]

(1) 

where \(dh\) = change in water level (mm), \(dt\) = change in time (years), and \(S_{b}\) = specific yield (dimensionless), defined as the volume of water released from an unconfined aquifer per unit surface area per unit decline in the water table (Freeze and Cherry, 1979). The method assumes that all recharging water immediately goes into storage, the inflow (i.e., tidal flow, pumping, interflow and baseflow) is balanced by the outflow, and that there is no evapotranspiration at the water table (Cartwright et al., 2007; Healy and Cook, 2002). These are simplifying assumptions; however, the magnitude of short-term (daily) water table fluctuations due to those other processes is generally much less than caused by interseasonal recharge (Healy and Cook, 2002).

While the bore hydrographs show a response to rainfall (Koh et al., 2006c), fluctuations in some deeper bores, where the well bottom is located much below the average water table, could also be caused by old, laterally flowing groundwater (cf. Cartwright et al., 2007). To calculate precipitation induced recharge only, we considered only the shallowest bores with total depths <25 m below the average 2008–2009 water table in this study. Furthermore, only bores located in downslope regions characterized by lower horizontal hydraulic gradients (<0.0001) were selected. Nevertheless, some attenuation of the recharge induced water table fluctuations most certainly occurs so the current calculations will provide minimum estimates of recharge.

Selecting appropriate \(S_{b}\) values is difficult for magmatic rocks that have undergone different degrees of chemical alteration. Hahn et al. (1997), based on pump test analyses of 455 wells across Jeju, estimated specific yields for the volcanic aquifers of \(10^{-6}\)–0.5 with most values lying within a range of about 0.05–0.1. The latter range is similar to that measured in mafic to intermediate volcanic aquifers elsewhere (Belcher et al., 2002; Nichols et al., 1996) and is used here to express uncertainty caused by low permeability zones. That this \(S_{b}\) range is lower than the probable porosities (i.e., 0.15–0.3) (Kwon et al., 1993) is due to the high specific retention of fine-grained rocks (Johnson, 1967; Johnson et al., 1963).

Values of \(dh\) and \(dt\) are estimated graphically from antecedent recession curves (cf. Healy and Cook, 2002) and the net recharge over two years is calculated by summing up individual recharge events. This allows calculating an average recharge rate that takes into account the variable yearly rainfall (cf. Cartwright et al., 2007) and time periods with no data. Some coastal bores screening basal groundwater (e.g., JW Gimneyong, JW Namwon, JW Pyeongdae and JW Goseong) show large episodic hourly variations of groundwater levels caused by tides (Fig. 4). For these bores, 24 point moving average trend lines that smooth out the hourly fluctuations in the data are used to show daily recharge patterns more clearly (Fig. 4c) and to estimate \(dh\) and \(dt\) values.

Recharge as a percentage of rainfall is calculated using the average rainfall for the time period 1993–2002 measured at 28 stations across the island (1980 mm) (Won et al., 2006). Recharge rates vary between 262 mm/yr and 1570 mm/yr with a median value of 687 mm/yr or 34.8% of rainfall. For the geographic districts, the median recharge values are 765 mm/yr (38.7% of rainfall) in the east, 728 mm/yr (36.5% of rainfall) in the south, 595 mm/yr (30.1% of rainfall) in the north and 392 mm/yr (19.9% of rainfall) in the west. The spatial trend relates to that of the SWB in the low altitude (<200 m) areas (Fig. 5a) supporting previous assumptions on highest recharge occurring in the more humid southern and eastern districts. However, WTF recharge estimates are generally lower than those of the SWB (~16.8% in the west, ~23.8% in the south, ~26.7% in the north and ~27.4% in the east). The fact that all bores used in the WTF analysis were located in the coastal plains (average bore altitude: 67.9 m asl), an area characterized by relatively low rainfall (Fig. 2), could explain these differences. Moreover, \(S_{b}\) underestimates and WTF attenuation within the aquifer could also explain these low values. More shallow monitoring bores with screens close to the average water table are needed for more accurate recharge estimates, especially for some higher altitude areas and the western district were hydrograph data of only one bore was available. Numerical flow models that highlight recharge areas with lowest horizontal hydraulic gradients are warranted to identify more bores suitable for the WTF method. Finally, a more accurate determination of the representative \(S_{b}\) value or range of the saturated aquifer in the vicinity of individual bores would reduce the range of uncertainty.

4.2. Chloride mass balance

Several authors have utilized Cl geochemistry to estimate groundwater recharge (Allison et al., 1990; Cartwright et al., 2007; Dassi, 2010; Subyani and Sen, 2006). For steady state, recharge is calculated as:

\[
R = \frac{P_{Cl}}{Cl_{g}} 
\]

(2)
Fig. 4. Bore hydrographs (hourly) from (a) northern, (b) southern, (c) eastern and (d) western districts of Jeju Island. Dashed lines in (d) are the antecedent recession curves used to calculate $dh$ and $dt$ (cf., Healy and Cook, 2002). (e) Daily rainfall between 2008 and 2009 for Gosan. Note the response of groundwater levels to rainfall events. Also note the episodic short-term variability of water levels of some coastal bores indicating the tidal influence on coastal groundwater levels (Koh et al., 2006c). A 24 point moving average trend line for JW Gimneyeong is shown.
where $P$ = mean annual precipitation (mm/yr), $C_{lp}$ = Cl concentration in precipitation (mg/L) and $C_{lg}$ = Cl concentration in groundwater (mg/L). The method assumes that Cl is inert in natural environments (Feth, 1981) and that all Cl is derived solely from evapotranspiration of precipitation.

The long-term (1993–2002) average precipitation at the individual groundwater sampling bore was estimated from isohyetal maps (KOWACO, 2003). It should be noted that using the precipitation rate at the well yields less reliable results in the high altitudes of Jeju, where the unsaturated zone is several hundreds of meters thick and where precipitated water can be channelized to areas far away from the well.

Selecting an appropriate $C_{lp}$ value is difficult as concentrations in precipitation events may vary as a function of (i) the origin and the trajectory of air masses, (ii) the storage of Cl in the atmosphere, (iii) the distance from the coast, (iv) the regional condensation altitude above which interception deposition is favored, and (v) the velocity of rain-out event (Seiler and Gat, 2007). As a result, most precipitation starts with high and continues with low Cl concentrations (Blackburn and McLeod, 1983; Garcia et al., 2007). Given this, it is important to use long-term weighted average $C_{lp}$ values calculated at multiple stations. Kang et al. (2003) and the Acid Deposition Monitoring Network in East Asia (EANET, 2010) reported volume-weighted mean Cl contents for rainfall sampled at Jeju City, Mt. Halla and Gosan (Fig. 1). These samples were collected at regular intervals during rain events from 1996 to 2002 (the Jeju City and Mt. Halla dataset) and 2001–2008 (the Gosan dataset). Reported $C_{lp}$ values are 1.02 mg/L at Mt. Halla, 2.32 mg/L at Jeju City and

![Recharge estimated from the SWB (data from KOWACO, 2003), and WTF, CMB, CFC-12 and $^3$H data for (a) low altitude (<200 m) and (b) high altitude (200–600 m) areas of the four geographic districts of Jeju. $n$ values represent available data points for the median recharge value calculation. For the SWB, each $n$ value reflects a recharge estimate from a catchment of a given district and altitude zone. For the WTF, CMB, CFC-12 and $^3$H methods, $n$ values represent groundwater samples that were subdivided based on groundwater bore location and altitude. Bars indicate median range of uncertainty calculated for $n$ samples.](image-url)
3.51 mg/L at Gosan. The range of 1.02–3.51 mg/L is used here as upper and lower limits of uncertainty in the recharge estimate.

Calculated recharge rates are between 50.0 and 2370 mm/yr (median value: 429 mm/yr). For the geographic districts, median recharge values are 759 mm/yr (38.3% of rainfall) in eastern catchments, 617 mm/yr (31.2% of rainfall) in southern catchments, 446 mm/yr (22.5% of rainfall) in northern catchments, and 245 mm/yr (12.4% of rainfall) in western catchments. These estimates, like those from the SWB and the WTF, follow the regional rainfall patterns (Fig. 2) with highest recharge in eastern and southern districts. In the case of the CMB and SWB methods, however, this trend is expected as rainfall rates are incorporated in the analyses. Estimates from the low altitude (<200 m) eastern districts and high altitude (200–600 m) western districts almost match those of the SWB, making the CMB a useful cursory estimate of recharge in those regions. That the CMB estimates are generally lower than those from the SWB in both low altitude (<200 m) and higher altitude (200 m–600 m) zones, however, is counterintuitive given that Eq. (2) should provide an upper limit for recharge in areas where direct runoff occurs (Herczeg and Edmunds, 2000; Scanlon et al., 2002; Walker et al., 2002) and on Jeju, direct runoff has been estimated to account for ~20% of the average annual rainfall (KOWACO, 2003).

One explanation for the discrepancy could be the atmospheric CI contribution from dry deposition cf. (Brunner et al., 2004) which has not been accounted for here. To the best of our knowledge, no data on atmospheric dry deposition rates of CI exist for Jeju. However, it has been shown that dry deposition contributes to significant amounts of the total atmospheric CI deposition, especially in coastal regions (Anatolaki and Tsitouridou, 2007). In a study carried out in two watersheds of southern Norway, Tørseth and Semb (1997) determined a contribution from dry deposition of about 10% relative to the total deposition of CI. More recently, Anatolaki and Tsitouridou (2007) estimated dry deposition to contribute to about 35% of the total atmospheric CI deposition in a city in coastal Greece. While the rates of dry deposition are subject to seasonal variations controlled by, e.g., rainfall amount and frequency, air mass origin, wind direction, wind speed and aerosol particle size (Park et al., 2002; Tanner et al., 2001), it becomes clear that a quantitative assessment of the average annual dry deposition flux of CI on Jeju is needed to better constrain the CMB recharge estimate. Another explanation for the relatively low CMB estimates could be non-atmospheric CI input from agricultural applications (i.e., KCl fertilizer), road salt and/or industrial and communal effluent. These sources have been shown to contribute to significant amounts of CI in streams and groundwater particularly in urban and agriculturally-developed areas (Grosbois et al., 2001; Katz et al., 2011; Lofgren, 2001; Roy et al., 1999; Williams et al., 2000). Information on where and how much anthropogenic CI is applied on Jeju would allow delineating "pristine" areas more suitable for the CMB method.

4.3. Apparent CFC-12 ages

Several studies have demonstrated the applicability of man-made chlorofluorocarbons (CFCs), specifically CFC-11 (CCLF3) and CFC-12 (CCL2F2), to determine the time since infiltrating rain water recharged groundwater and became isolated from the atmosphere assuming that the soil air is in equilibrium with the troposphere (Bauer et al., 2001; Busenberg and Plummer, 1992; Cook et al., 2003; Corcho Alvarado et al., 2005; Plummer and Busenberg, 2000; Plummer et al., 1993; Schlosser et al., 1989; Tweed et al., 2005). Apparent ages of 60 groundwater samples from mostly western and southern regions of Jeju were determined for CFC-11 and CFC-12 by Koh et al. (2006a) and Koh et al. (2007b) following the procedures outlined by Busenberg and Plummer (1992) and using North American air curves for CFC-12 as well as N2, Ar and Ne data to calculate recharge temperature and excess air. Apparent CFC-11 and CFC-12 ages of Jeju groundwater are generally identical within the limits of uncertainty (see Koh et al., 2006a, their Fig. 3; Koh et al., 2007b, their Fig. 5a). A bias of younger (<30 years) groundwater from the mountainous and more heavily vegetated interior of Jeju towards older apparent CFC-11 ages most likely reflects the larger susceptibility of CFC-11 to biodegradation in anaerobic environments (Cook et al., 1995; Katz et al., 1995). Only a few groundwater samples on Jeju displayed CFC-11 ages younger than the CFC-12 ages. These samples are considered contaminated with CFC-11, possibly during sampling (Dunkle et al., 1993). However, the overall positive correlation between apparent CFC-11 and CFC-12 ages indicates only minor effects of such factors as soil desorption and sorption, entrainment of excess air during recharge, mixing in the well casing, hydrodynamic dispersion, and contamination.

If the aquifers on Jeju were homogenous and matrix flow would dominate, a strong negative correlation between CFC-12 ages and depths to the water table would be expected as groundwater reaches the end of the flow path in the shallow coastal zone. However, there is a large scatter in apparent groundwater CFC-12 ages of Jeju at a given depth in the bedrock (Fig. 6). CFC-12 ages near the surface (i.e., depths to water <30 m) range from 14.3 years at bore FW 20 in the southwest to 59.8 years at bore M1 near Jeju City. That the range of CFC-12 ages decreases with depth indicates that in the uplands of Mt. Halla, where the unsaturated zones is thick (>150 m), groundwater is generally younger. Relatively high CFC-12 values (>30 years) in the upgradient areas (e.g., bore M16 in the western uplands) most likely reflect trapped groundwater from thick, poorly connected flow paths in the unsaturated zone. Low CFC-12 values in the coastal zone, in turn, are attributed to fast preferential flow in small fissures.

As documented by Vogel (1967) and Cook and Böhlke (2000), apparent groundwater CFC-12 ages can be used to calculate recharge as:

\[
R = (nb/t) \ln(b/(b-z))
\]

where \(b\) = thickness of the aquifer (mm), \(n\) = porosity, \(t\) = time travel (year), and \(z\) = depth below the water table (mm). For \(b\), we used the total depths of the wells which were drilled to the contact between the volcanics and the Seogwipo sediments (KIGAM, 2011). \(z\) was...
calculated as the distance between the water table and the midpoint of the screened zone of the well. Kwon et al. (1993) reported n values for volcanic rocks on Jeju of 0.02–0.36 with most values falling in a narrow range between 0.15 and 0.3. The latter range is consistent with that reported from other similar lithologies (Nichols et al., 1996) and is used here to express one source of uncertainty. Ideally, Eq. (3) holds for homogeneous, isotropic, and unconfined aquifers of constant thickness receiving uniform recharge of vertically flowing water. These are certainly simplifying assumptions for fractured aquifers, where flow through fissures can dominate over matrix flow. It is thus questionable if Eq. (3), which has been generally applied to sand aquifers (Hinkle et al., 2002; Kaown et al., 2009), is at all valid for complex fractured systems such as Jeju Island. However, Even though exact error estimates of recharge cannot be provided here, the use of a large data set (39 samples) is considered to provide a valuable cursory median estimate of recharge. The applicability of the CFC-dating approach to the Jeju Island setting will be assessed by comparing the recharge estimates to those from the other methods.

For the geographic districts, median recharge values calculated from the CFC-12 data are 248 mm/yr (12.7% of rainfall) in the northern district, 426 mm/yr (21.6% of rainfall) in the western district, 552 mm/yr (28.0% of rainfall) in southern district, and 510 mm/yr (25.8% of rainfall) in the eastern district. These values follow again regional rainfall patterns with highest recharge occurring in the southern and eastern districts. However, recharge values are much lower than those of the SWB (Fig. 5). This is explained by the overestimate of actual tracer flow time given by the apparent groundwater age in fractured media (Neretnieks, 1981). There is also a larger variability of recharge estimates from CFC-12 dating technique relative to those of the CMB, WTF and SWB methods. Some of this variability is mostly likely related to the use of an aquifer thickness that is based on the total well depth in all areas, where, in reality, groundwater in high level regions may be perched and the effective aquifer thickness may be less. This would, for instance, explain the very high mean recharge values (>1000 mm/yr) for some high level samples (i.e., FW 28 and 6; Appendix B). Thus, the results presented here most likely mix more reliable estimates for parabalasal groundwater zones (26 samples yielding a median value of 436 mm/yr) with less reliable estimates for high level groundwater zones (13 samples with a median value of 371 mm/yr). This highlights the need for a higher resolution dataset with more representative n, b and z values for more accurate recharge constrains. Moreover, more groundwater CFC-12 data from the northern, southern and eastern districts would greatly enhance the robustness of recharge estimates in these under-represented areas. It is also recommended to collect more CFC data from nested bore systems as this would allow calculating average age gradients below the water table equivalent to the vertical groundwater velocities (Cook et al., 1995, 1998). These, in turn, can be transformed into groundwater recharge rates if the effective porosity of the saturated aquifer is constrained (Cook et al., 1998; Scanlon et al., 2002).

4.4. 3H Mean residence times

Annual recharge into unconfined aquifers can be estimated from groundwater 3H mean residence times (3H t; in years) assuming that 3H in groundwater is derived from both annual input from precipitation and radioactive decay (Favreau et al., 2002; Le Gal La Salle et al., 2001). 3H t values can be modeled for different flow systems using lumped parameter models (Maloszewski, 1996; Ozyurt and Bayari, 2003, 2005; Zoellmann et al., 2002). In this study, BOXMODEL v3 (Zoellmann et al., 2002), a program that yields 3H t values as a function of a rainfall input chronicle and a chosen conceptual flow system model, is used. In the absence of continuous 3H measurements of precipitation on Jeju, the reconstructed 3H rainfall chronicle from Koh et al. (2005) is used as the rainfall input (Fig. 7a). The choice of the flow system model depends on the hydrogeological setting of the studied area. On Jeju, where fracture-hosted ground water flow is assumed to dominate, a piston flow model (PM) and a dispersion model (DM) are selected. In the PM it is assumed that the flow lines have the same transit time and the hydrodynamic dispersion and diffusion are negligible (Zuber and Maloszewski, 2001). The only parameter of this model is the mean residence time. The PM is the limiting case of the DM where the transit times of the flow lines are near equal for a low dispersion parameter ($\delta < 1$; Zoellmann et al., 2002). The dispersion effect relates to the extent of the well screen. If it is large (i.e., high $\delta$), the groundwater sample is a mixture of water from various depths including different flow paths and residence times. If the screen is short (i.e., low $\delta$), the sample is likely to reflect water from one location, with uniform flow paths and uniform residence times.

3H t values for different models and dispersion parameters are shown in Fig. 7b. Only the PM with a $\delta$ of 0.9 yields one unique 3H t value for a given groundwater 3H content. All other models yield several possible 3H t values for groundwater 3H contents > 2.43 TU (PM), > 2.82 TU (DM; $\delta = 0.001$), > 2.70 (DM; $\delta = 0.01$) and > 2.88 TU (DM; $\delta = 0.1$). To select the applicable 3H t value for individual samples, additional simultaneously measured tracers such as, e.g., CFCs or $^{85}$Kr are needed to provide a cross-check (Ekwurzel et al., 1994; Ozyurt and Bayari, 2005; Zoellmann et al., 2002). Here, the 3H t values that display the highest positive linear correlation with the simultaneously determined apparent
groundwater CFC-12 ages are selected (Fig. 8). A positive correlation ($r^2 \sim 0.65$) indicates that a PM, a DM with $\delta$ value of 0.01 and a DM with $\delta$ value of 0.1 describe the aquifers on Jeju well. Nevertheless, some samples deviate from the linear trend line. $^3$H $t$ values about 10–20 years higher than the respective apparent CFC-12 ages are calculated specifically for groundwater of the western district (Appendix B). These samples most likely reflect binary mixing of old groundwater ($^3$H: $<1$ TU; CFC-12: $<50$ pptv) and young, recently recharged groundwater ($^3$H: $\sim 3$ TU; CFC-12: $\sim 500$ pptv) in the downgradient zones (Koh et al., 2006a). Slow diffusion of CFCs in areas with thick unsaturated zones ($>5$ m) has been reported to result in older CFC ages than respective $^3$He/$^3$H ages and in non-zero groundwater CFC ages at the water table (Cook and Solomon, 1995; Cook et al., 1998). This would explain the occurrence of some groundwater samples to the right of the trend line in Fig. 8.

The $^3$H $t$ values shown in Fig. 8 together with the previously defined aquifer depths ($b$; in mm), porosities ($n$; dimensionless), and depths below the water tables ($z$; in mm) were used to calculate recharge from Eq. (3). The porosity range of 0.15–0.3 from Kwon et al. (1999) was again used to express one source of uncertainty. Median recharge rates are 186 mm/yr (9.37% of rainfall) and young, recently recharged groundwater ($^3$H: $\sim 3$ TU; CFC-12: $\sim 500$ pptv) in the downgradient zones. These recharge estimates in the western district (Appendix B) are relatively high (Fig. 1b), and (ii) urban and coastal areas such as in or around Jeju City and Seogwipo, where most pumping occurs. The median CMB estimates are lower than those of the SWB in all geographic districts and altitude zones (Fig. 5a and b). This is possibly due to unaccounted for atmospheric dry deposition and/or anthropogenic Cl inputs to groundwater. The method should hence be applied locally to rural and pristine areas where the annual atmospheric dry deposition rate of Cl is constrained. The CMB approach does not account for precipitation loss via direct runoff, the method should not be applied to the upper slopes of the northern and southern districts of Jeju where most direct runoff is assumed to occur (KOWACO, 2003).

Median recharge values estimated from CFC-12 and $^3$H data show a low correlation with those from the SWB in terms of spatial distribution as a result of the poor spatial sample coverage, and the many simplifying assumptions in the analytical Eq. (3) to complex volcanic aquifers. It is proposed to use these tracers only for local recharge estimates in the lower parabasal areas where very shallow water tables prevail. This would ensure close to unconfined and isotropic conditions. The advantage of the estimates from CFC-12 and $^3$H values, if sampled simultaneously in nested bore systems over large areas, is that they provide useful information on the conceptual groundwater flow system and mean groundwater residence times in aquifers. This information allows detecting areas where high recharge and preferential flow makes aquifers most vulnerable to contamination (Scanlon et al., 2002).

The most recent SWB analysis for Jeju did not account for the influences of, e.g., snowmelt and fog drip precipitation, irrigation, vegetation interception and soil water storage. These factors, however, have been shown to have a rather large effect on the net recharge magnitude in humid regions (Engott and Vana, 2007; Izuka et al., 2007; Westenbroek et al., 2010). The most recent SWB analysis for Jeju may, as such, not necessarily be the most accurate measure of recharge in all districts. Further research should thus focus on an updated SWB that operates on short (i.e., daily) time.

5. Conclusions and Implications

This study clearly demonstrates that the magnitude and spatial distribution of recharge may vary on Jeju depending on which estimation technique is chosen (Fig. 3). Relying solely on one method to quantify recharge can therefore be very misleading.

The main advantage of the WTF method in comparison to the CMB, CFC-12 and $^3$H techniques is that, alike the SWB, it can be used to detect both short-term interseasonal and long-term average recharge rates making it a useful calibration tool for local water resource evaluations (Cartwright et al., 2007; Dripps and Bradbury, 2007; Heppner et al., 2007). On Jeju, where time-series hydrograph data dating back to 2001 exist, the method is particularly useful for cross-checking the timing of daily recharge at the water table from SWB simulations as any SWB only yields recharge values for below the root zone (Westenbroek et al., 2010). The WTF method is also useful for determining the magnitude of changes in local recharge caused by, e.g., recent droughts and/or land use changes. Another advantage of the WTF method is that it can be related to time-series groundwater quality data making it a valuable constraint on how increased recharge controls the enrichment and/or dilution of contaminants (e.g., NO$_3^-$) in groundwater. The main limitation of the WTF method is that specific yield values of volcanic rocks can vary over several orders of magnitude (Hahn et al., 1997) making the method inherently inaccurate for extrapolations of local point estimates to the watershed scale. Another limitation is related to ensuring that fluctuations in water levels are due only to natural recharge. As such, the method should be applied with caution to: (i) the upper slopes of Mt. Halla, where hydraulic gradients are relatively high (Fig. 1b), and (ii) urban and coastal areas such as in or around Jeju City and Seogwipo, where most pumping occurs (Koh et al., 2006c).

Fig. 8. Correlation between apparent CFC-12 ages and modeled $^3$H residence times of Jeju groundwater. $^3$H residence times are selected according to best linear correlation with simultaneously estimated apparent groundwater CFC-12 ages.
steps and includes more recent climate and land use data. However, the median values of the four geographic districts for each of the here presented techniques are all lower than those of the most recent SWB (Fig. 5). Whether this implies that groundwater withdrawal is closely reaching the sustainable yield limit is difficult to discern given the inability of the here used methods to predict recharge in the more humid upslope areas from which, as yet, no groundwater data could be collected. Therefore, more WTF, Cl, CFC-12 and $^3$H data from these areas are needed to better calibrate the SWB estimates of recharge in the high precipitation areas. Furthermore, recharge prediction based on a numerical groundwater model calibration or inversion for the saturated zone based on information on hydraulic heads and hydraulic conductivity (Sanford, 2002) can provide another independent measure of the island-wide distribution of recharge. This model can also be useful to assess the potable water resource sustainability for different climate, land use and/or pumping scenarios cf. (Gingerich, 2002; Oki, 2006).

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Appendices A and B: Supplementary material

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References


