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Regional Assessment of Recharge Elevation of Tap Water Sources Using the Isoscape Approach

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The importance of mountains as "natural water towers" has been quantified by comparing water budgets in upstream (mountain) and downstream (lowland) areas, but their importance for tap water supplies has not been assessed. Here, we propose an isoscape approach to estimate the mean recharge elevation of tap water sources (rivers, reservoirs, springs, and wells) and apply it to a region in central Japan as a case study. Errors in the estimation of mean recharge elevation were estimated at 90–140 m. Results show that mean recharge elevations for about 90% of sources in the region are at 1000 m above sea level or higher. A little over half of the land area is above that elevation, while 98% of the population lives below it. These findings indicate that tap water disproportionally depends on recharge in mountains and is disproportionately supplied to lowland residents. Higher locations of spring water sources and longer (vertical) distances of groundwater flow for well water sources make the recharge-to-population disproportionality more remarkable. Furthermore, our results suggest that larger cities require higher natural water towers to meet greater water demand, complemented by intermunicipal water suppliers. Some low-elevation municipalities depend heavily on water recharged in mountains well outside their territories. The method proposed here helps clarify how people depend on water supplies from mountains, providing essential knowledge for integrated management of mountains and water resources.

Keywords: *Tap water; isotope; isoscape; mountain; recharge elevation; hydrology; Japan.*

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Introduction

Mountains are important recharge areas for freshwater resources, including those used by people living at lower elevations. Thus, they are often likened to water towers (Liniger et al 1998; Messerli et al 2004; Viviroli et al 2007). Mountains' role in the recharging and supply of water resources has been investigated by analyses of water budgets for mountains, downstream lowlands, and drainage basins. Meybeck et al (2001) stated that mountains account for 25% of Earth's total land area, 26% of the global population, and 32% of (surface) water runoff. Viviroli et al (2003) reported that the mountain contribution to river discharge averaged 63% for 20 selected catchments with a mean relative mountain area of 32%. The mountain contribution to river discharge is even greater, in some cases exceeding 95%, in arid and semiarid regions (Viviroli and Weingartner 2004). Viviroli et al (2007) suggested a new typology of mountain areas as natural water towers based on water budgets and human water needs, showing that >50% of the areas have an essential or supportive role in water supply to downstream areas.

The function of mountains as natural water towers depends mainly on 3 factors: greater precipitation, lower temperatures associated with less evapotranspiration, and greater water storage as snow or ice, maintaining river flow in dry periods (Zierl and Bugmann 2005). In addition, for tap water supply, the type of water source (river, reservoir, spring, or well) and its location affect the water supply function of mountains. Of the many aspects of this function, such as agricultural and industrial water supply, hydropower production, and provision of environmental services, tap water supply is the most vital, because it is directly linked to human health and daily life. Nevertheless, less is known about mountains as suppliers of tap water than about their supply of bulk (river) water.

Many scholars have argued that high-elevation environments are the most sensitive to global climate change (Thompson 2000; Diaz et al 2003). Recent studies have uncovered evidence of elevation-dependent warming (Mountain Research Initiative EDW Working Group 2015) and shifts toward earlier snowmelt runoff

(Yamanaka et al 2012, 2013). These elevation-dependent changes in mountains potentially affect tap water sources in terms of both quantity and quality. To ensure sustainable tap water supply with sufficient quantity and quality, we need scientific information, including information on the recharge elevation of water sources and linkages between recharge areas and beneficiaries.

This study used an isoscape approach to estimate the mean recharge elevation (MRE) of various tap water sources. Isoscapes are isotope landscapes, which can be visualized using isotope maps based on statistical, geostatistical, or combined models (West et al 2010; Bowen 2010a). Many precipitation isoscape models have been proposed for diverse regions, such as Canada (Delavau et al 2011), China (Liu et al 2008), Ireland (Fischer and Baldini 2011), Japan (Yamanaka et al 2015; Ichiyanagi and Tanoue 2016), Mongolia (Yamanaka et al 2007), New Zealand (Baisden et al 2016), the United States (Dutton et al 2005), the European Alps (Liebminger 2006a, 2006b; Kern et al 2014), Central America (Sánchez-Murillo and Birkel 2016), and the Mediterranean (Lykoudis and Argiriou 2007), and for the planet as a whole (Bowen and Wilkinson 2002; Bowen and Revenaugh 2003; Terzer et al 2013). Even for complex mountainous landscapes, spatially uniform isotopic lapse rates, which are divorced from inland effects, have given fairly good approximation as a multiannual (amount-weighted) mean on a regional (eg a few hundred kilometers) scale (Yamanaka et al 2015). This allows convenient and reliable estimation of MRE based on a precipitation isoscape over a mountainous region.

We measured stable hydrogen and oxygen isotopes in tap water from across central Japan and estimated MRE using precipitation isoscape models of the region. The main objectives were threefold: (1) to confirm the accuracy level of MRE estimates, (2) to reveal regional-level disproportionality in the elevational distributions of recharge and residential areas, and (3) to characterize municipalities based on recharge-to-population disproportionality (RPD).

Methods

Hydrogen and oxygen isotope ratios (^{2}H/^{1}H and ^{18}O/^{16}O) in water molecules are usually expressed as per mill deviations relative to Vienna standard mean ocean water by using δ notation (δ^2H and δ^{18}O). Meteoric precipitation δ values tend to show negative correlation with sampling site elevation. This correlation is known as the (isotopic) altitude effect (Ambach et al 1968; Siegenthaler and Oeschger 1980), where a global mean, isotopic lapse rate is –13.6‰ km^{-1} in δ^2H and –1.94‰ km^{-1} in δ^{18}O (Bowen 2010b). Although the δ value of precipitated water increases (ie the water is enriched with heavier isotopes) slowly on water surfaces or topsoil during evaporation, such an isotopic fractionation below the topsoil is negligible, because vaporization of water and accompanying vapor flux are small within deeper soils (Yamanaka et al 1998; Yamanaka and Yonetani 1999). However, the flux-weighted mean δ value of groundwater recharge can differ from that of precipitation because of the selection effect, which is caused by dissimilarity of temporal variation patterns between recharge and precipitation, as well as the fractionation effect (Gat 2010). The δ value of river water is basically invariant during downward flow for a few hours to days, with some exceptional cases of very shallow streams, of long-term stagnation in lakes and reservoirs, and in dry climates. Thus, assuming an annual or longer-term mean condition, isotopic composition of tap water samples taken from different water sources (rivers, reservoirs, springs, and wells) reflects approximately that of precipitation at their recharge areas. In cases in which horizontal distance between the water source site and its recharge area is not large (eg <100 km), the difference between tap water δ and precipitation δ enables MRE estimation based on a known isotopic lapse rate.

According to this principle, MRE can be estimated as

$$z_{mr} = 10^3(\delta_{tap} - \delta^*_{ppt} - \Delta)/\Gamma \quad (1)$$

where z_{mr} is MRE (in meters), δ_{tap} is the δ value (δ^2H or δ^{18}O) of tap water (in per mill), δ^*_{ppt} is the sea level δ value of precipitation (in per mill) as the amount-weighted long-term mean at given horizontal coordinates, Δ is the isotopic shift (in per mill) because of both fractionation and selection effects, and Γ is the isotopic lapse rate (in per mill per kilometer). The δ^*_{ppt} is estimated as

$$\delta^*_{ppt} = \delta_{ppt,ws} - \Gamma z_{ws} 10^{-3} \quad (2)$$

where z_{ws} is the elevation of the water source site (in meters) and $\delta_{ppt,ws}$ is the δ of precipitation at the site (in per mill), which can be obtained from precipitation isoscape models.

To test this approach, we selected the Nagano and Yamanashi Prefectures in central Japan as the study area (Figure 1). This region is characterized by mountainous topography with high relief (>3000 m) and a moderately sparse distribution of cities. In this region, we requested that all municipal and intermunicipal water suppliers to populations greater than 5000 provide raw (untreated) tap water samples for isotopic measurements. Although each water supplier typically has several water sources, we selected for every supplier 1 dominant source that supplied the largest amount. Raw tap water samples were collected from 66 water sources. Isotopic measurements of the samples were made by tunable-diode laser (cavity ring-down) spectroscopy using a liquid water isotope analyzer (L1102-I, Picarro, Santa Clara, CA, USA). At most sources, the tap water samples were collected twice (in May and October 2012). Because values measured from

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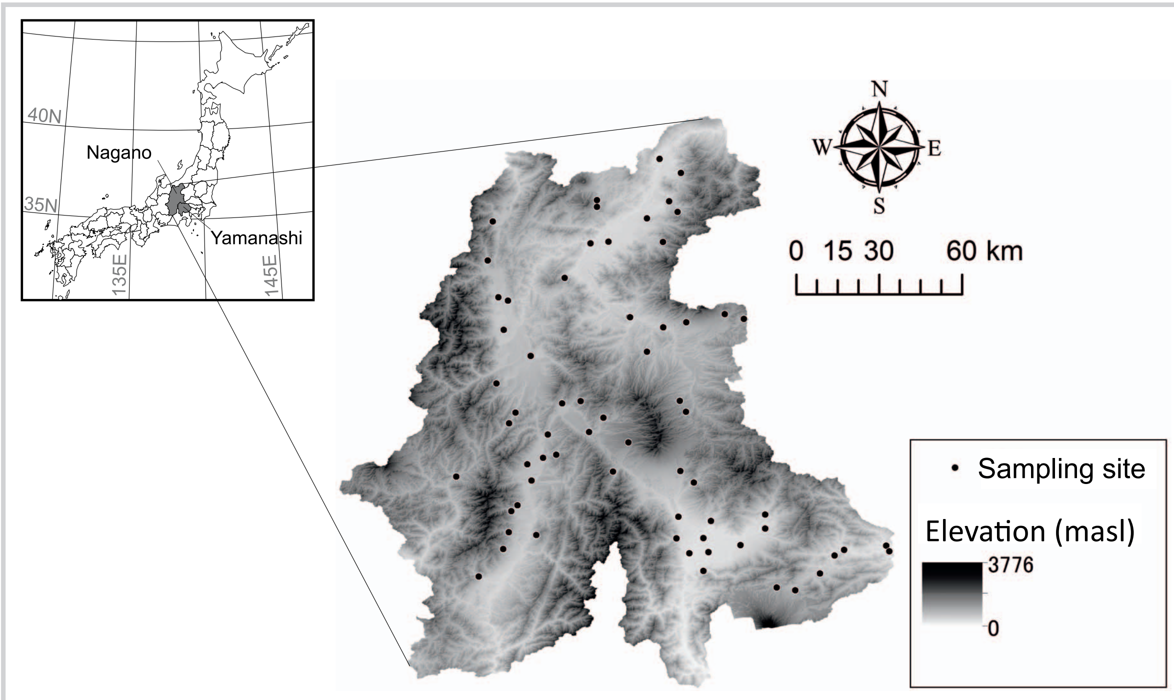
FIGURE 1 Map of the study area with locations of tap water sampling sites. (Map by ArcGIS 10.3.1 software [ESRI, Redlands, CA, USA] and Fundamental Geospatial Data [Geospatial Information Authority of Japan])



May and October samples did not differ, we used a mean value for each source to estimate MRE.

For the study region, Yamanaka et al (2015) proposed the following (multiannual amount-weighted) precipitation isoscape model (visualized maps are available at Yamanaka et al 2015):

$$\delta_{ppt} = \Gamma z 10^{-3} + ay^2 + by + cx + d \quad (3)$$

where z is elevation (in meters), y is latitude minus 36 (decimal degrees north), and x is longitude minus 138 (decimal degrees east); empirical constants a, b, c, and d are given with Γ in Table 1. The term of z represents the altitude effect (and temperature effect implicitly), and the terms of y and x represent the inland effect rather than the latitude effect. Combining Equations 2 and 3, we could estimate δ^*_{ppt} directly from the coordinate of the water source site (y_{ws}, x_{ws}) as follows:

$$\delta^*_{ppt} = ay^2_{ws} + by_{ws} + cx_{ws} + d \quad (4)$$

The Yamanaka et al (2015) model (hereafter model 1) can estimate δ_{ppt} with mean absolute errors of 4.8‰ for δ^2H and 0.63‰ for δ^{18}O. However, it has been pointed out that errors tend to increase in the northern part of the study region. Thus, we added northern site data from Yamanaka et al (2014) to calculate a new set of model constants (hereafter model 2). However, model 2 did not always yield improved results outside the northern area. Therefore, we used both models and examined their performance in estimating MRE (Table 1).

To validate the estimated MRE, we compared it for river (including reservoir) water sources with (annual) precipitation-weighted catchment mean elevation

TABLE 1 Parameter values in precipitation isoscape models.

Parameter (unit)	Γ (‰ km^{-1})	*a* (‰ DD^{-2})	*b* (‰ DD^{-1})	*c* (‰ DD^{-1})	*d* (‰)
δ^2H					
Model 1	−11.66	19.21	−10.98	−4.727	−65.87
Model 2	−14.40	15.99	−7.03	0.000	−62.26
δ^{18}O					
Model 1	−1.724	2.058	−1.244	−0.811	−9.281
Model 2	−1.979	1.037	−0.989	0.000	−8.840

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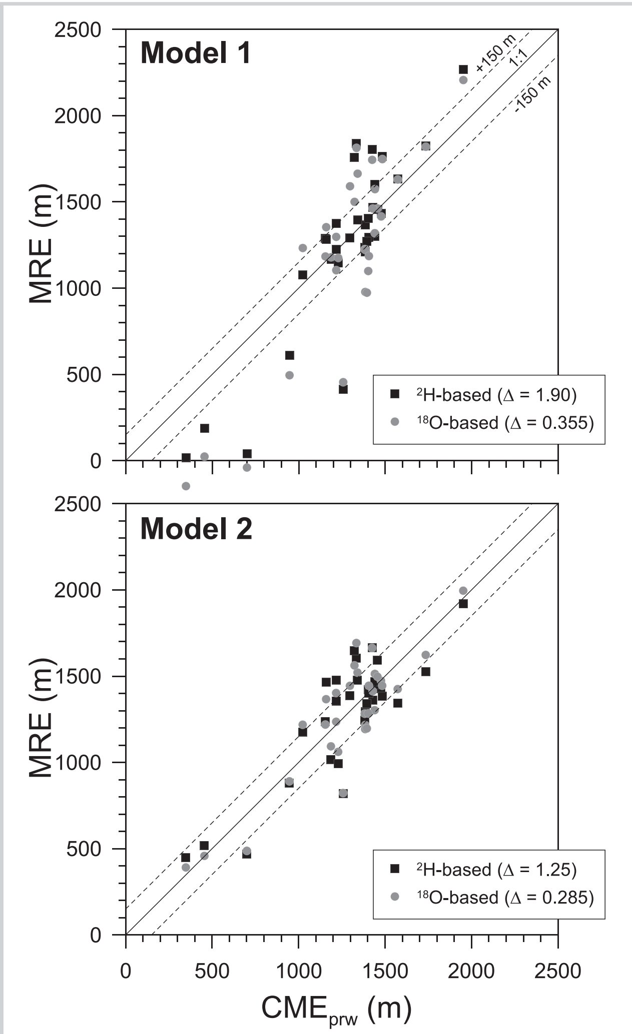
FIGURE 2 Comparison of CME_{prw} and estimated MRE using two models. Optimized values of total isotopic change because of fractionation and selection effects (Δ, in per mill) for δ^2H and δ^{18}O are shown in the legend.



(CME_{prw}), which can approximate the actual MRE. The CME_{prw} was computed using a geographic information system (GIS) with a 10-m mesh (resampled to a 100-m mesh) digital elevation model (DEM) and 1-km mesh climatic values for 1981–2010 (G02, National Land Numerical Information, Ministry of Land, Infrastructure, Transport, and Tourism of Japan; originally created by Japan Meteorological Agency). ArcGIS 10.3.1 software (ESRI, Redlands, CA, USA) and Fundamental Geospatial Data (Geospatial Information Authority of Japan) were used for this computation. Ideally, recharge flux (precipitation minus evapotranspiration) should be used for weighting. However, we used precipitation as a proxy for recharge flux, because there is no reliable way to estimate spatial distribution of evapotranspiration.

Although the Δ in Equation 1 can be considered to depend on the soil evaporation-to-precipitation ratio, the seasonality of the recharge-to-precipitation ratio, and other miscellaneous factors, it is difficult to determine it theoretically. In this study, the Δ value as a regional mean was obtained to minimize the mean absolute difference (MAD) between MRE and CME_{prw}. Because the MAD change with the Δ change was parabolic-like, this optimization could be simply done by iteration. As a result, Δ was estimated to be 1.90‰ for ^{2}H and 0.355‰ for ^{18}O in model 1 and 1.25‰ for ^{2}H and 0.285‰ for ^{18}O in model 2.

Maximum, minimum, and (arithmetic) mean elevations, as well as population-weighted mean elevation (ME_{pow}) for each municipality, were computed using GIS with administrative zones data (N03, National Land Numerical Information), 500-m mesh population data (Census 2010, Statistical GIS, Ministry of Internal Affairs and Communications of Japan), and the DEM mentioned earlier. Elevational distributions of land and population across the entire study region were computed with the same dataset. The MRE for each municipality was given as that of a single water source if there was only 1 water supplier. If there were 2 or more suppliers, including intermunicipal ones, an arithmetical mean MRE was used. We then applied our proposed recharge-to-population disproportionality index (RPDI) for each municipality, defined as RPDI $\equiv$ MRE $-$ ME_{pow}. This index has a dimension of elevation and can thus be compared with the elevation of the so-called natural water tower.

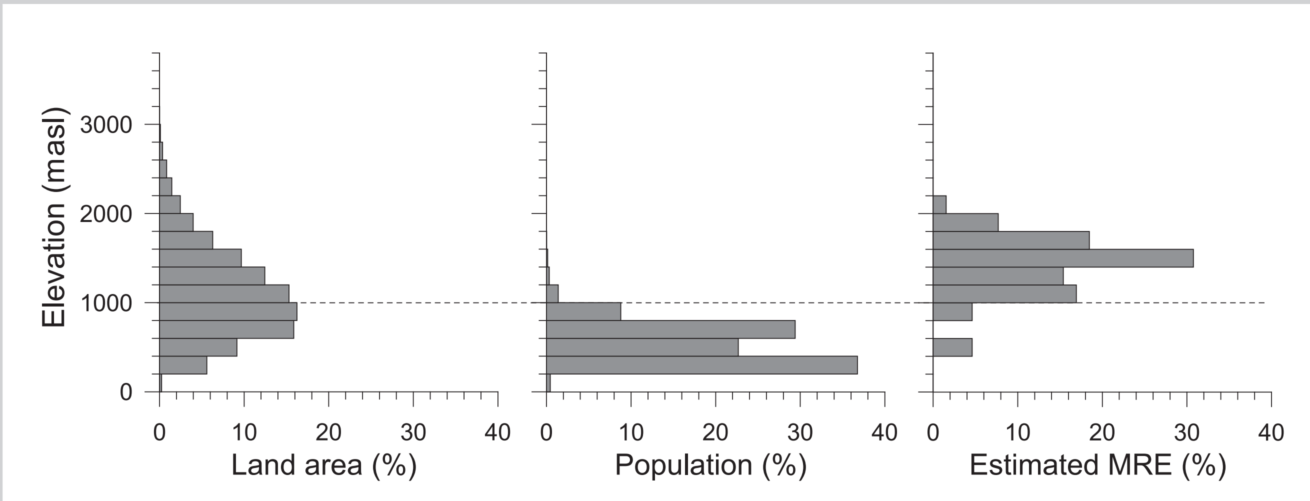
Results and discussion

Accuracy of MRE estimation

Measured isotopic values and estimated MRE are summarized in Table S1 (Supplemental Material, http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00066.S1). Figure 2 compares estimated MRE with CME_{prw} for river water sources ($n = 32$) for both model 1 and model 2. After optimizing Δ, in model 1, ^{2}H-based and ^{18}O-based MAD were reduced to 191 and 246 m, respectively; in model 2, the corresponding values were 143 and 134 m. Clearly, model 2 performance was superior to that of model 1, although the MAD values included not only errors in MRE estimation but also inconsistency between CME_{prw} and actual MRE. The errors in MRE estimation are mainly attributable to 2 factors: errors in modeled δ^*_{ppt} and Γ (factor A) and spatial variability of Δ (factor B). The inconsistencies between CME_{prw} and MRE are attributable to dissimilarity in spatial distribution between precipitation and actual recharge (factor C) and unclosed water balance within a catchment (ie subsurface inflow and outflow across the divide; factor D).

For model 1, the difference MRE $-$ CME_{prw} correlated with longitude ($r = -0.69$, $P < 0.001$) and CME_{prw} ($r = 0.49$, $P < 0.001$), suggesting the importance of error factor A given earlier. In contrast, for model 2, MRE $-$ CME_{prw} was significantly correlated with neither longitude ($r = -0.06$, P

FIGURE 3 Elevational distribution in the study area of land area, population, and estimated MREs in the study area.



> 0.1) nor CME_{prw} ($r = -0.08$, $P > 0.1$). However, MRE from model 2 was clearly underestimated at water source N03, because it was lower than the ground level of the water extraction site. This indicates that δ^*_{ppt} and/or Γ in model 2 is not always correct for all sites, although errors from factor A were substantially lower than those produced by model 1.

Results for reservoir water sources ($n = 4$) are also shown in Figure 2. Reservoir water is potentially more strongly affected by evaporation than river water. However, there were no significant differences in estimated MRE between reservoir and river sources. Although it is certain that Δ is not a constant, factor B is not simple and thus is difficult to calibrate.

The MAD between CME_{prw} and unweighted CME was only 13 m. Because the difference between CME_{prw} and recharge-weighted CME has the same or lower order of magnitude, factor C should be minor. Although we cannot estimate the magnitude of errors from factor D, it may be important only in some special cases.

For all water sources ($n = 66$), the MAD between ^{2}H-based and ^{18}O-based MREs was 155 m for model 1 and 90 m for model 2. These differences were caused by factors A and B (not factors C or D). Consequently, with some uncertainties, the accuracy of MRE estimation by model 2 is likely 90–140 m. In the following analysis, we used mean values of ^{2}H-based and ^{18}O-based MREs from model 2, excluding source N03.

Disproportionality in the distribution of MREs and population

Figure 3 shows elevational distributions within the study area of land area, population, and MRE for tap water sources. Just under half (47.1%) of the land area is below 1000 m above sea level (masl). Almost all residents (98.1%) live in that area, with the remaining 1.9% at higher elevations. In contrast, the MRE for 59 of 65 (90.8%; N03 was excluded) tap water sources is higher than 1000 masl. These facts indicate that tap water supply depends disproportionally on recharge in mountains but is supplied disproportionally to residents of lowlands. However, the threshold of 1000 masl is not an absolute limit for mountain areas. This disproportionality in MRE and population distributions (what we have called RPD) is greater than that reported by studies focused on river flows (Meybeck et al 2001; Viviroli et al 2003; Viviroli and Weingartner 2004).

Figure 4 shows the distribution of MRE, water-source site elevation (WSE), and differences between MRE and WSE for each water-source type (river, reservoir, spring, and well). There were no significant differences between river and reservoir sources for any of these values. MREs and WSEs for spring water sources were higher than those for the other sources. For well water sources, MRE was slightly higher than it was for river and reservoir sources and WSE was lower, resulting in MRE − WSE being the greatest for these sources. These results suggest that higher locations of spring water sources and longer (vertical) distances of groundwater flow for well water sources make the RPD greater for these sources than for river water sources.

Characterization of municipalities

The RPDI was no less than 500 m for 81.7% of municipalities. There seemed to be no systematic pattern in the geographic distribution of RPDI. However, that index had a weak positive correlation with population ($r = 0.22$, $P = 0.08$). Municipalities with large populations, some of which receive tap water from both municipal and intermunicipal suppliers, tended to have larger RPDIs. However, municipalities with small populations did not

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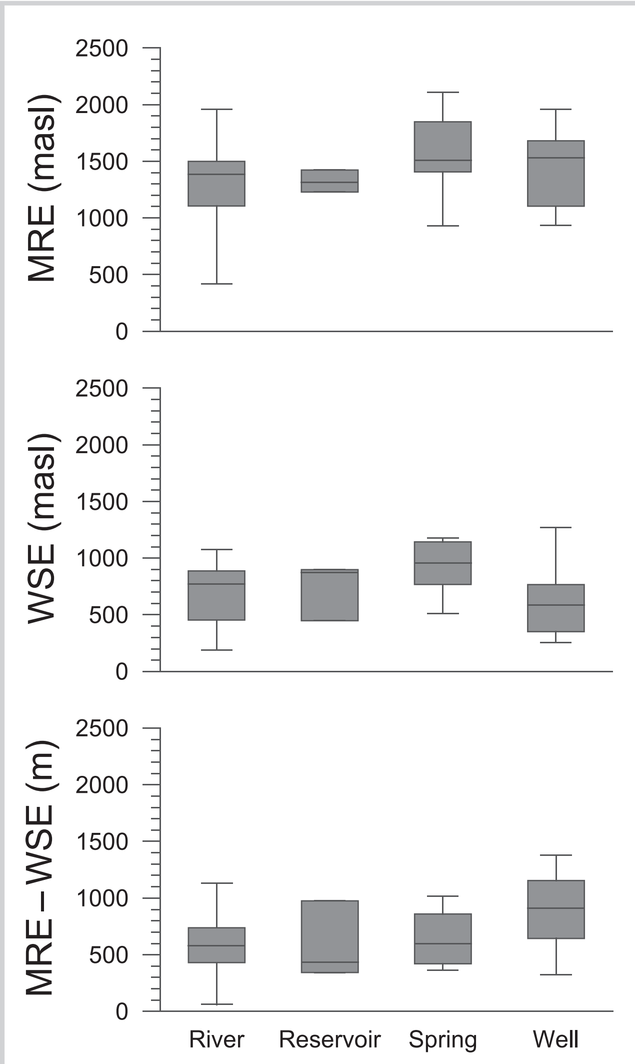
FIGURE 4 Differential distribution of water flow from recharge to intake (MRE, WSE, and their difference) for each type of water source.



always have smaller RPDIs. These findings indicate that large cities require higher natural water towers to meet a greater water demand and, in the case of shortages, must rely on intermunicipal suppliers.

Figure 5 compares the elevation of each municipality with MRE and ME_{pow}. For all municipalities, ME_{pow} was lower than the mean elevation and even near the minimum, suggesting a population disproportionality shifted toward lower elevations. The MRE was higher than the mean elevation of most municipalities, showing a recharge disproportionality shifted toward higher elevations. In some municipalities, the MRE clearly exceeded the maximum elevation of the municipality. These municipalities, whose mean elevation is often relatively low, depend heavily on water recharged outside their territory. Therefore, these lowland municipalities have to pay more attention to natural or hidden water supplies (ie supplies that do not come through water pipes) from adjacent mountainous municipalities.

Limitations and implications

In our approach to MRE estimation, some factors had the potential to introduce nonnegligible errors. Empirical determination of regional mean Δ is the most debatable. However, assuming $\Delta = 0$, the MAD between MRE and CME_{prw} became only 15–50 m greater than the corresponding optimized case. Therefore, even if we modified the determination of Δ, the accuracy of the MRE estimate (ie 90–140 m) would not be improved much. In a mountainous region with high relief, this accuracy is practically acceptable. However, the potential exists for large errors in some exceptional cases, as occurred with source N03.

Findings on RPD, which is derived from MRE estimation, could raise awareness among people living in lowland cities of how much they depend on mountains for their water supply. This important issue should be taken into account when allocating funding (eg via Payment for Ecosystem Services) for lowland and mountain communities.

In addition, MRE is useful information for protecting recharge areas. If we calibrate distributed runoff models or groundwater flow models taking MRE into account, recharge areas for each tap water source can be mapped with higher reliability. Synergy between MRE information and numerical modeling or GIS-based analysis must contribute more to management of headwater regions.

Conclusions

MRE for tap water sources in a study area in central Japan was estimated using newly proposed precipitation isoscape, of which the accuracy is higher in the northern part of the area than that of the previous model, with errors of about 90–140 m. Of the tap water sources, 90.8% were recharged above 1000 masl, while 98.1% of the population lived below that level; these lower elevations made up 47.1% of the total study area. Higher locations of spring water sources and longer (vertical) distances of groundwater flow for well water sources made the RPDI more pronounced than in the case of river flows. The RPDI tended to be larger in municipalities with a large population that receive tap water from both municipal and intermunicipal suppliers, suggesting that large cities require higher natural water towers to meet greater water demand and, in the case of shortages, must rely on intermunicipal suppliers. Some municipalities at lower elevations depended heavily on water recharged in mountains outside their territory.

The preceding findings contribute to a fuller understanding of the role of mountains in tap water

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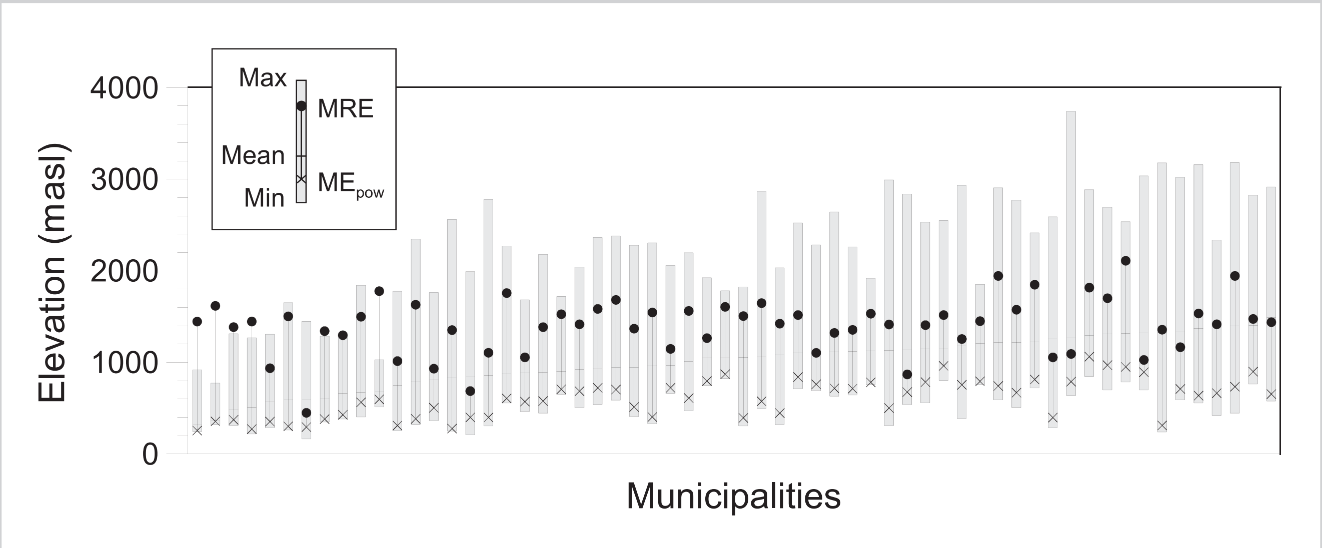
FIGURE 5 Maximum, minimum, and mean elevations of each municipality, with MRE and ME_{pow}. The length of the vertical line connecting MRE and ME_{pow} equals the RPDI. Municipalities are ordered by ascending mean elevation.



supply and can help inform the sustainable management headwater regions. Algorithms used in the regional assessment presented here appear to be applicable to other mountainous regions, although they should be further tested and modified before expanding the study to a continental scope. We may also have to consider continental or other effects in precipitation isoscapes and nonuniform isotopic lapse rates.

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Supplemental material

TABLE S1 Summary of studied water sources, measured isotopic values, and estimated MRE.

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