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Classifying the water table at regional to continental scales

Tom Gleeson,[1] Lars Marklund,[2] Leslie Smith,[1] and Andrew H. Manning[3]

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[1] Water tables at regional to continental scales can be classified into two distinct types: recharge-controlled water tables that are largely disconnected from topography and topography-controlled water tables that are closely tied to topography. We use geomatic synthesis of hydrologic, geologic and topographic data sets to quantify and map water-table type over the contiguous United States using a dimensionless criterion introduced by Haitjema and Mitchell-Bruker (2005), called the water-table ratio, which differentiates water-table type. Our analysis indicates that specific regions of the United States have broadly contiguous and characteristic water-table types. Water-table ratio relates to water-table depth and the potential for regional groundwater flow. In regions with recharge-controlled water tables, for example the Southwest or Rocky Mountains, USA, water-tables depths are generally greater and more variable and regional groundwater flow is generally more important as a percentage of the watershed budget. Water-table depths are generally shallow and less variable, and regional groundwater flow is limited in areas with topography-controlled water tables such as the Northeast USA. The water-table ratio is a simple but powerful criterion for evaluating regional groundwater systems over broad areas. **Citation:** Gleeson, T., L. Marklund, L. Smith, and A. H. Manning (2011), Classifying the water table at regional to continental scales, *Geophys. Res. Lett.*, *38*, L05401, doi:10.1029/2010GL046427.

1. Introduction

[2] The character of the water table is fundamental to conceptualizing groundwater flow systems and examining the connections between groundwater, surface water, ecosystems and climate [*Fan et al.*, 2007; *Maxwell and Kollet*, 2008]. The water table is an important hydrologic interface that can modulate water, mass and energy fluxes in and between the surface and subsurface. For almost a century hydrologists have conceptualized the water table as a subdued replica of topography [*Meinzer*, 1923; *Hubbert*, 1940]. In fact, assuming that the elevation of the water table under steady-state conditions is a subdued replica of topography has been a critical assumption in both seminal papers [*Tóth*, 1963; *Freeze and Witherspoon*, 1967] and contemporary studies [*Cardenas*, 2007; *Marklund and Wörman*, 2007; *Marklund et al.*, 2008; *Jiang et al.*, 2009a, 2010] of regional groundwater systems. However the water table viewed at the regional scale should be differentiated into two types: topography-controlled water tables where the water-table elevation is closely associated with topography and recharge-controlled water tables that are largely disconnected from topography (Figure 1) [*Haitjema and Mitchell-Bruker*, 2005]. Recharge-controlled water tables are expected in arid regions with mountainous topography and high hydraulic conductivity whereas topography-controlled water tables are expected in humid regions with subdued topography and low hydraulic conductivity [*Haitjema and Mitchell-Bruker*, 2005]. Water-table type is a simple first-order characteristic of regional groundwater systems but the distribution of water-table type has not been mapped or examined at any scale.

[3] Differentiating water-table type is critical to how we conceptualize regional groundwater flow systems and may also impact our understanding of two hydrologic processes that are currently attracting significant attention: regional groundwater flow [*Cardenas*, 2007; *Gleeson and Manning*, 2008; *Schaller and Fan*, 2009; *Jiang et al.*, 2010] and the coupling of groundwater to land surface and atmospheric processes [*Liang and Xie*, 2003; *Bierkens and van den Hurk*, 2007; *Fan et al.*, 2007; *Gulden et al.*, 2007; *Niu et al.*, 2007; *Anyah et al.*, 2008; *Maxwell and Kollet*, 2008; *Miguez-Macho et al.*, 2008]. Regional groundwater flow, defined here as groundwater flow between surface watersheds (generally 10–1000 km in extent), impacts watershed budgets [*Gleeson and Manning*, 2008; *Schaller and Fan*, 2009], groundwater quality and chemistry [*Tóth*, 1999], the distribution of groundwater residence times [*Cardenas*, 2007; *Jiang et al.*, 2010], and a variety of geologic processes [*Garven*, 1995; *Tóth*, 1999; *Ingebritsen et al.*, 2006]. Numerical simulations by *Gleeson and Manning* [2008] suggest that regional groundwater flow is limited in mountainous regions with topography-controlled water tables but can be significant in regions with recharge-controlled water tables (Figure 1). The character and depth of the water table is an important control on the connection of groundwater to land surface and atmospheric processes as shown by studies that directly couple groundwater and climate model models [*York et al.*, 2002; *Maxwell et al.*, 2007; *Anyah et al.*, 2008; *Jiang et al.*, 2009b] and studies focusing on the land surface or subsurface [*Fan et al.*, 2007; *Maxwell and Kollet*, 2008; *Miguez-Macho et al.*, 2008; *Rihani et al.*, 2010]. Land surface and subsurface processes are most tightly coupled in regions with a shallow water table located less than ~5 m below ground surface [*Kollet and Maxwell*, 2008; *Maxwell and Kollet*, 2008; *Ferguson and Maxwell*, 2010; *Rihani et al.*, 2010]. In regions with shallow water tables, the water table can strongly influence soil moisture in the root zone and there can be a strong correlation between recharge, latent heat flux and water-table depth [*Fan et al.*, 2007; *Maxwell and Kollet*, 2008; *Miguez-Macho et al.*, 2008].

[4] In this paper geomatic synthesis is used to map water-table type over the contiguous United States to address two fundamental hydrologic questions: where do topography-

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[1] Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, British Columbia, Canada.

[2] Swedish Meteorological and Hydrological Institute, Norrköping, Sweeden.

[3] U.S. Geological Survey, Denver, Colorado, USA.

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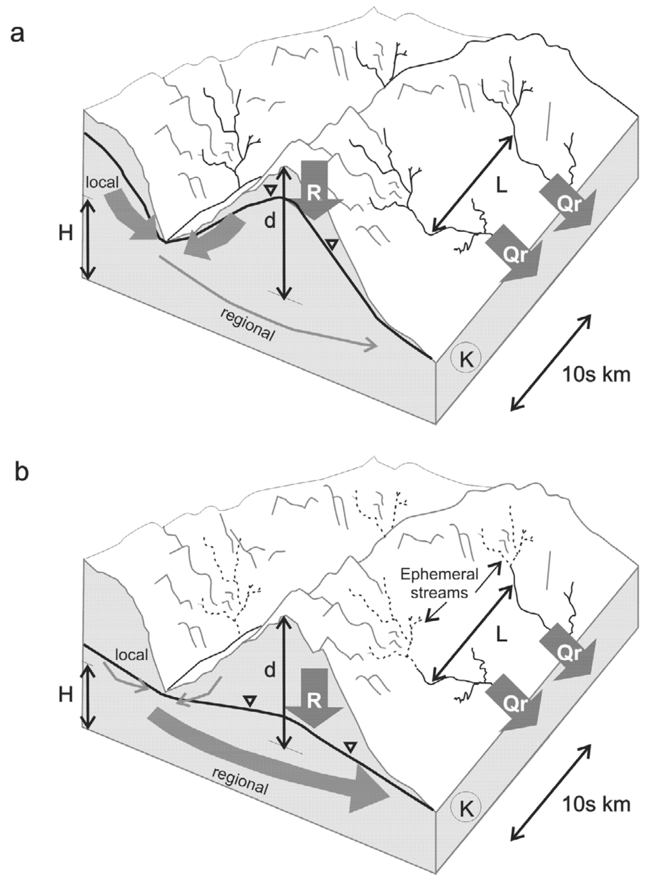

Figure 1. Regional water tables can be either (a) topography-controlled or (b) recharge controlled. The variables (H, d, R, Qr, K) are defined in the text. The water-table depth is generally deeper and more variable in the case of recharge-controlled water tables. Numerical simulations by *Gleeson and Manning* [2008] suggest that regional groundwater flow, as a percentage of the watershed budget, is limited in mountainous regions with topography-controlled water tables but can be significant in regions with recharge-controlled water tables. The arrow thickness represents the relative flux magnitude.

controlled and recharge-controlled water tables occur, and is the water-table type characteristic of certain regions or is it fragmented across the landscape? In addition, we examine the relationship between water-table type and water-table depth, which may have implications for the coupling of groundwater to surface processes and climate. Finally, we examine the relationship between water-table type and estimates of regional groundwater flow derived by *Schaller and Fan* [2009].

2. Methods and Data Sources

[5] *Haitjema and Mitchell-Bruker* [2005] derived a dimensionless criterion (herein called the water-table ratio or WTR) for differentiating topography-controlled and recharge-controlled water tables:

$$\log(\mathrm{WTR}) = \log\left(\frac{RL^2}{mKHd}\right) = \begin{cases} > 0 & \text{for topography-controlled} \\ < 0 & \text{for recharge-controlled} \end{cases} \quad (1)$$

where R (m/d) is the areal recharge rate, L (m) is the distance between surface water bodies, K (m/d) is the hydraulic conductivity, H (m) is the average vertical extent of the groundwater flow system, d (m) is the maximum terrain rise and m (unitless) is either 8 or 16, depending on the flow problem being one-dimensional or radially symmetric, respectively. Note that *Haitjema and Mitchell-Bruker* [2005] defined H in terms of average aquifer thickness. The dimensionless criterion is based on the assumptions that the Dupuit-Forchheimer approximation (i.e., no vertical groundwater flow and a relatively flat water table) is valid, and that the water table is not perched. These assumptions are considered reasonable given that we are examining the water table at regional to continental scales.

[6] The contiguous United States encompasses a broad range of geologic, climatic and topographic conditions. Defining a consistent scale of analysis is important because hydrologic fluxes such as recharge are scale dependent [*Wörman et al.*, 2007]. Scale is best defined based on watershed size (rather than an arbitrary scale such as 1:100 000) because the topographic variables in the water-table ratio (i.e., *L, d*) are watershed-based. We use the 12-digit 'subwatershed' hydrologic unit (commonly referred to as HUC12 watersheds, see http://datagateway.nrcs.usda.gov) as the scale of analysis since (1) this is smallest scale that watersheds are systematically mapped across the contiguous United States, (2) watersheds have a relatively common size in this database (~100 km^2) and (3) data for all of the variables needed for calculating the WTR (equation (1)) are available at this scale.

[7] To map the water-table ratio, spatially distributed data for each variable in the equation defining the water-table ratio is derived either from geomatic sources or representative numerical modeling that are described in detail in Text S1 and S2 of the auxiliary material and summarized in Table 1.[1] The spatially distributed data for each variable is combined into a database with the same datum (NAD83). From this database, the water-table ratio is calculated for each raster pixel using the raster mathematic tools of multiplication and division in ArcGIS. Figure 2 plots the three variables that vary most significantly in the database: recharge (*R*), hydraulic conductivity (*K*) and maximum terrain rise (*d*). The distribution of these variables is different which leads to a unique calculation of water-table ratio for each region of the USA (e.g., Southwest or Northeast). The differences in distribution also suggest that none of these variables can be used as a proxy for the other variables in this calculation. The three variables in the water-table ratio that do not significantly vary are excluded from Figure 2 (*m* and *H* are assumed constant and *L* does not vary greatly due to the methodology of watershed mapping). The absolute value of the water-table ratio for individual pixels needs to be viewed with caution due to the assumptions and uncertainties inherent in each variable as discussed in the auxiliary material. Nevertheless, the range and distribution of the calculated ratio are useful for our objective of examining continental-scale patterns and relationships. The model output (i.e., WTR) is not directly measurable but we evaluate the results by examining how the spatial distribution of the WTR is correlated to measurements such as water table depth and estimates

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL046427.

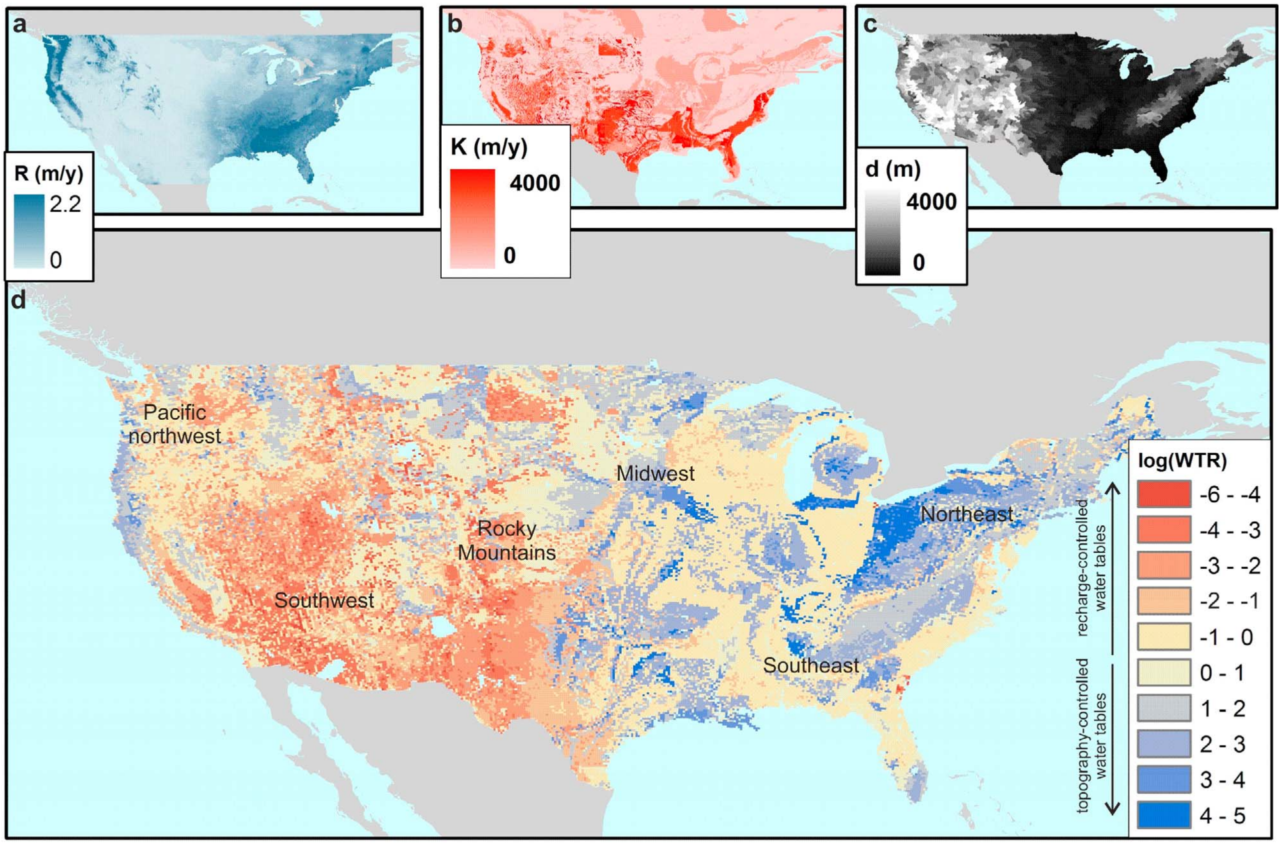

Figure 2. The water table ratio is derived from (a) recharge [*Maurer et al.*, 2002], (b) hydraulic conductivity [*Gleeson et al.*, 2011], (c) maximum terrain rise and other variables as explained in text. (d) Water table ratio over the contiguous United States expressed as log(WTR). Negative log(WTR) are recharged controlled whereas positive log(WTR) are topography-controlled.

of regional groundwater flow. The potential relationships between WTR and water-table depth and estimates of regional groundwater flow are shown conceptually on Figure 1. Equilibrium (or long-term average) water-table depth was compiled from the U.S. Geological Survey (USGS) database by *Fan et al.* [2007] into a data base of 549,616 sites. Only wells with a completion depth of <100 m were included to focus on unconfined, water-table conditions although we acknowledge that this is an imperfect filter that will include some shallow, confined aquifers. Most of these sites have only a single water level measurement recorded between 1927 and 2005. We improve the quality of the database by culling wells 1) with less than 10 observations or 2) located in areas or within 10 km of wells with documented water-table decline of >13 m [*Reilly et al.*, 2008]. This results in a database of 41,396 observations representing steady-state water-table depth over the contiguous United States that is biased towards low elevation, populated areas. *Schaller and Fan* [2009] calculated the importance of regional groundwater flow for 1555 watersheds across the United States by comparing the ratio of stream discharge (Qr) to watershed recharge (R). If the Qr:R ratio differs from 1, regional groundwater flow is either importing water to the watershed (Qr:R > 1) or exporting water from (Qr:R < 1) the watershed. Large watersheds are generally not net groundwater importers or exporters (Qr:R ≈ 1) [*Schaller and Fan*, 2009] so to examine the relationship between water-table ratio and the basin contribution to regional groundwater flow, we focus on small watersheds (<200 km^2), which is consistent with our scale of analysis (Table 1).

3. Results and Discussion

[8] Figure 2d is a map of the water-table ratio over the contiguous United States, derived from the variables in Table 1. The log-transformed water-table ratio is plotted due to the range of water-table ratio (~11 orders of magnitude). The large range indicates that water tables are distinctly recharge-controlled or topography-controlled in some regions of the USA. This result implies that the water-table ratio may be useful in characterizing different regions even given the uncertainty in the component variables. An important first-order observation is that water-table type is generally con-

Table 1. Source of Data for Calculation of Water-Table Ratio

Variable	Data Source	Vector or Raster[a]
R (m/a)	*Maurer et al.* [2002] for Figure 2 *Wolock* [2003] for Figure S4	raster (0.125°) raster (1 km)
L (m)	'HUC12' (http://datagateway.nrcs.usda.gov)	vector (89 km^2)
m (unitless)	Assume 8	-
K (m/a)	*Gleeson et al.* [2011]	vector (210 km^2)
H (m)	Numerical modeling (auxiliary material)	
d (m)	ESRI DEM	raster (1 km)

[a] Values in parentheses indicate mean polygon area for vectors and resolution for rasters.

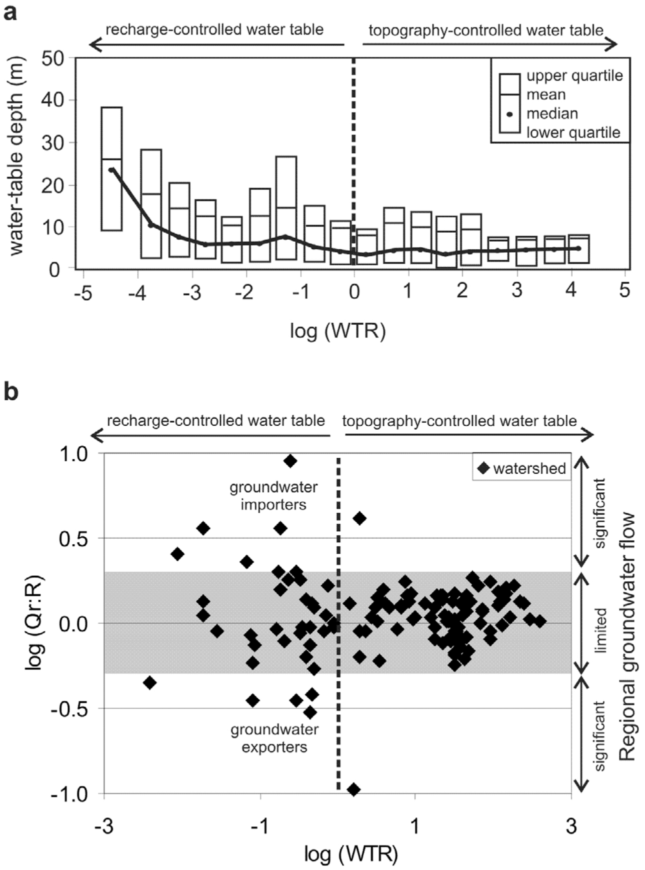

Figure 3. The relationship between water table ratio (WTR) and (a) water-table depth and (b) the ratio of streamflow (Qr): recharge [*Schaller and Fan*, 2009]. Regional groundwater flow is not considered a significant component of the watershed budget if log(Qr:R) = 0 ± 0.25 (~20% of watershed budget).

tiguous over large regions rather than fragmented across the landscape at scales greater than the HUC12 watersheds. The water table in the Southwest and Rocky Mountains is predominantly recharge controlled whereas the water table in the Northeast is predominantly topography controlled. Water tables in the Midwest and Southeast are not markedly recharge controlled or topography controlled [log(WTR) ~ 0]. The Pacific Northwest is marked by more fragmented and heterogeneous patterns of log(WTR). The consistency within regions implies that the water-table ratio is characteristic of regions. These patterns are also consistent regardless of the source of the recharge value [Figure 2; *Maurer et al.*, 2002; Figure S4; *Wolock*, 2003]. We do not examine the water-table ratio in the northern Midwest-Rocky Mountain region due to artifacts at jurisdictional boundaries embedded in the permeability map.

[9] The patterns of water-table type do not mirror any single input variable (Figures 2a–2c), implying that the water-table ratio is not dominated by a single variable at the continental scale. In certain regions the variables work in concert leading to extremely high or low water-table ratios. For example, in the Southwest and Rocky Mountains, topography (high d) and aridity (low R) both lead to low WTR whereas in the in areas of the Northeast low hydraulic conductivity, high recharge rate and moderate topography result in high WTR. Conversely, in other regions variables have opposing influence. In the mountainous areas of Pacific Northwest (i.e., Cascade Mountains), high topography and high recharge rates have opposing effects on the WTR. Since the water-table ratio is derived from six variables, speculating on the variables controlling the water-table type in each region is intriguing and the topic of ongoing research but beyond the scope of this paper.

[10] As shown in Figure 1, the water-table depth in regions with recharge-controlled water tables should be generally deeper and more variable than in regions with topography-controlled water tables [*Gleeson and Manning*, 2008]. Indeed, in regions with very low water-table ratios [log(WTR) < −3], the median water-table depth is significantly deeper than in regions with topography-controlled water tables (Figure 3a). In regions with very low water-table ratios, the variability in water-table depths is also greater as indicated by the difference between the upper and lower quartile on the box plots (~30 m). In regions with topography-controlled water tables there is less variability (~10 m difference between the upper and lower quartile on the box plots) and the median water-table depth is less than 10 m. Therefore many of the regions with topography-controlled water tables likely have characterized water-table depths of less than five metres, meaning that the water table is located in the zone where land surface and subsurface processes are most tightly coupled [*Kollet and Maxwell*, 2008; *Maxwell and Kollet*, 2008; *Ferguson and Maxwell*, 2010; *Rihani et al.*, 2010]. This suggests the WTR may be a simple, useful criterion for classifying regions of potentially strong coupling of groundwater with land surface and atmospheric processes. However, *Anyah et al.* [2008] shows that in the arid west (which is generally characterized by recharge-controlled water tables), groundwater can be an important control on local, convective precipitation suggesting this classification, if useful, could only be applied at the continental scale.

[11] Figure 3b plots the relationship between water-table ratio and basin contributions to regional groundwater flow, quantified using the Qr:R ratio thus showing the relative importance of regional groundwater flow to a watershed budget rather than quantifying an absolute flux [*Schaller and Fan*, 2009]. Significant contributions to/from regional groundwater flow are more common in watersheds with recharge-controlled water tables as indicated by substantive deviations from Qr:R = 1. Watersheds with topography-controlled water tables generally have a log(Qr:R) = 0 ± 0.25, suggesting limited contributions to/from regional groundwater flow systems. Regional groundwater is more significant in regions with a deep active groundwater flow system but herein H is assumed equal to 100 m. A deeper active groundwater flow system (e.g., 500–1000 m) would shift log (WTR) less than an order of magnitude, not significantly changing the observed relationships. *Gleeson and Manning* [2008] also examined regional groundwater flow as a percentage of recharge to a watershed. Their numerical simulations indicated that regional groundwater flow can be significant in regions with recharge-controlled water tables because the deep water tables shift the groundwater divides away from local surface water divides and decrease the length of perennial streamflow (from groundwater) in headwater watersheds [*Gleeson and Manning*, 2008]. Conversely, in watersheds with topography-controlled water tables, regional

groundwater flow is limited because the groundwater divides coincide with local surface water divides. Therefore the predictions from numerical simulations are consistent with the observed relationship between the water-table ratio and regional groundwater flow based on a synthesis of hydrologic and geomatic data.

4. Conclusion

[12] The character of the water table is a complex but fundamental feature of a groundwater flow system of any scale. We use a simple criterion, the water-table ratio, to better characterize and understand the water table over broad regions. Two fundamentally different water-table types can be defined using the water-table ratio introduced by *Haitjema and Mitchell-Bruker* [2005]: recharge-controlled water tables that are largely disconnected from topography and topography-controlled water tables that are closely connected to topography. Using geomatic synthesis of extensive hydrologic, geologic and topographic data sets, we map the water-table ratio over the contiguous United States. As expected [*Haitjema and Mitchell-Bruker*, 2005], recharge-controlled water tables are found in arid regions with mountainous topography and high hydraulic conductivity, whereas topography-controlled water tables are found in humid regions with subdued topography and low hydraulic conductivity. We show that regions have contiguous and characteristic water-table types. Water-table type is generally not fragmented in the landscape, at least not at the scale examined. Importantly, we also find relationships between water-table type and 1) water-table depth and 2) estimates of regional groundwater flow. In regions with recharge-controlled water tables, for example the Southwest or Rocky Mountains (Figure 2), water-table depths are generally greater and more variable and regional groundwater flow is generally more important. Water-table depths are generally shallow and less variable and regional groundwater flow is limited in areas with topography-controlled water tables such as the Northeast. The water-table ratio is a simple but powerful criterion for characterizing regional groundwater systems.

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T. Gleeson and L. Smith, Department of Earth and Ocean Sciences, University of British Columbia, 6339 Stores Rd., Vancouver, BC V6T 1Z4, Canada. (tgleeson@eos.ubc.ca)

A. H. Manning, U.S. Geological Survey, PO Box 25046, Mail Stop 973, Denver, CO 80225-0046, USA.

L. Marklund, Swedish Meteorological and Hydrological Institute, Folkborgsvägen 1, SE-601 76 Norrköping, Sweeden.