ground water

MODIS-Aided Statewide Net Groundwater-Recharge Estimation in Nebraska

by Jozsef Szilagyi[1,2] and Janos Jozsa[3]

Abstract

Monthly evapotranspiration (ET) rates (2000 to 2009) across Nebraska at about 1-km resolution were obtained by linear transformations of the MODIS (MODerate resolution Imaging Spectroradiometer) daytime surface temperature values with the help of the Priestley–Taylor equation and the complementary relationship of evaporation. For positive values of the mean annual precipitation and ET differences, the mean annual net recharge was found by an additional multiplication of the power-function-transformed groundwater vulnerability DRASTIC-code values. Statewide mean annual net recharge became about 29 mm (i.e., 5% of mean annual precipitation) with the largest recharge rates (in excess of 100 mm/year) found in the eastern Sand Hills and eastern Nebraska. Areas with the largest negative net recharge rates caused by declining groundwater levels due to large-scale irrigation are found in the south-western region of the state. Error bounds of the estimated values are within 10% to 15% of the corresponding precipitation rates and the estimated net recharge rates are sensitive to errors in the precipitation and ET values. This study largely confirms earlier base-flow analysis-based statewide groundwater recharge estimates when considerations are made for differences in the recharge definitions. The current approach not only provides better spatial resolution than available earlier studies for the region but also quantifies negative net recharge rates that become especially important in numerical modeling of shallow groundwater systems.

Introduction

With rapidly growing world population combined with an emerging climate change, careful allocation of existing water resources at the local, regional, and international level is becoming ever more pressing worldwide. After the polar ice cap and mountain glaciers that contain about two-third of the world's freshwater volume, groundwater is the largest more-or-less evenly distributed source of freshwater in the world (Dingman 1994). Therefore, groundwater management plays a central role in most water appraisal and allocation plans and thus in the well-being and sustainability of modern societies. Without recharge, groundwater storage would be quickly exhausted by typically fast-growing demand for it from society. Even though recharge to the groundwater plays a pivotal role in water management sustainability schemes, its temporal and spatial mean rate, not to mention its spatial distribution within a given region, is typically not known accurately enough in most cases due to reasons involving (1) spatial variability of the water-bearing aquifers' hydraulic parameters; (2) lack of continuous measurements; and (3) the inherent uncertainty in the measured values of the required variables, just to name a few.

This study is an update of previously published statewide mean annual groundwater recharge rates within

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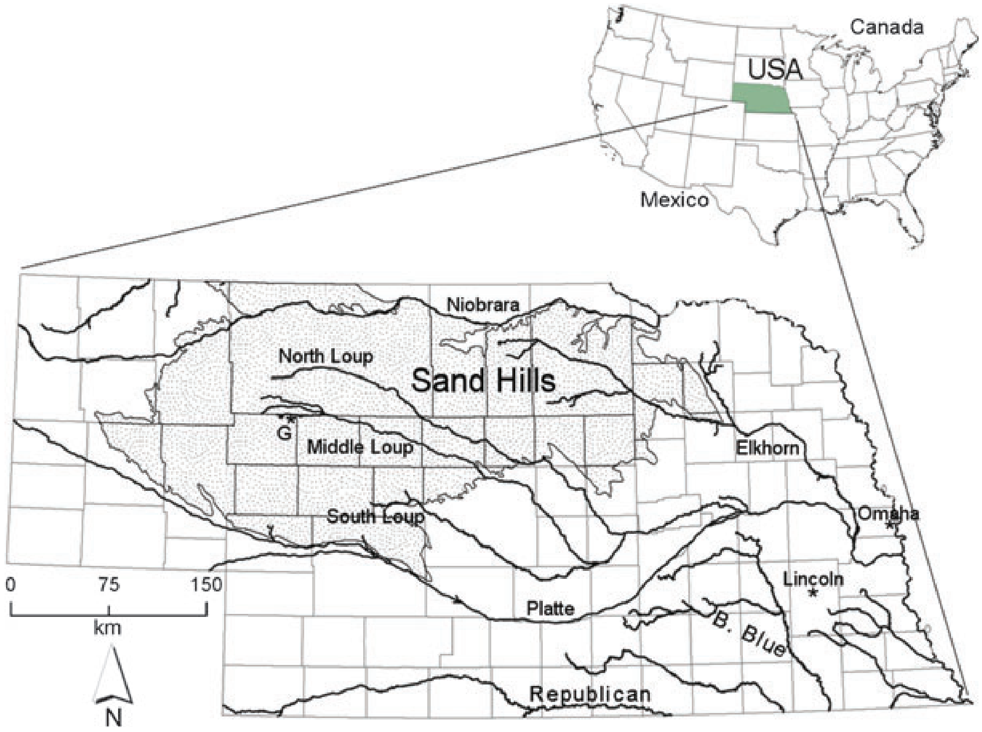

Figure 1. Location of Nebraska and the Sand Hills within. The thin lines are county boundaries. The star marks the location of the Energy Balance Bowen Ratio ET measurements of Billesbach and Arkebauer (2012) at the Gudmundsen Ranch (G).

Nebraska (Szilagyi et al. 2003, 2005), by taking advantage of the approximately 1-km resolution MODerate resolution Imaging Spectroradiometer (MODIS) data. An update is justified by the growing demand for spatially distributed groundwater recharge rates from, for example, a cooperative agreement among the states of Colorado, Nebraska, and Wyoming to address endangered species issues along the Platte River within the framework of a COoperative HYdrology STudy (COHYST at http://cohyst.dnr.ne.gov/), and from an existing multistate compact and the ensuing litigation as well as groundwater modeling involving sharing the streamflow of the Republican River among Colorado, Kansas, and Nebraska (for more detail, see http://www.republicanriver.com). Although previous studies by Szilagyi et al. (2003, 2005) relied on data from the 1961 to 1990 period, the recent study covers a decade-long time interval (2000 to 2009) following the public availability of MODIS data at the turn of the millennium. The present study differs from those of Szilagyi et al. (2003, 2005) in the type of recharge it estimates, that is, net recharge as opposed to base recharge (Szilagyi et al. 2003) and total recharge (Szilagyi et al. 2005). Net recharge (R) is defined as the net flux of water across the groundwater table, and as such can have negative values when the flux is directed away from the groundwater due to, for example, irrigation and/or groundwater evapotranspiration. Net recharge can also be defined (Crosbie et al. 2010) as the difference in total recharge (the downward flux of water reaching the water table [Healy and Scanlon 2010]) and groundwater ET.

Szilagyi et al. (2011b), employing monthly averaged MODIS daytime surface temperature (T_s) values, estimated the mean annual (2000 to 2009) net groundwater recharge for the Sand Hills region of Nebraska (Figure 1) as the difference in mean annual precipitation (P) and ET, by taking advantage that in the Sand Hills, due to its highly porous sandy soils (Bleed and Flowerday 1989; Wang et al. 2009), surface runoff (i.e., quick-storm response) is commonly negligible. Another similar recharge estimation study was recently performed for the Danube–Tisza interfluvial sand plateau region in Hungary (Szilagyi et al. 2012). The present study is a generalization of the same water-balance approach by including groundwater vulnerability (DRASTIC) code values (Aller et al. 1987) mapped for Nebraska by Rundquist et al. (1991), and previously employed for total recharge estimation by Szilagyi et al. (2005). The linear transformation of the T_s into ET values is based on the application of the Priestley and Taylor's (1972) equation for defining the evaporation rate of wet surfaces with a regional extent, in combination with the complementary relationship (Bouchet 1963) of evaporation, as formulated by Morton et al.'s (1985) WREVAP program for deriving the actual regional ET rate. Once knowing the latter (representing the mean of the spatially changing ET rates within the region), the ET-rate fluctuations around the spatial mean can be linearly related to similar fluctuations in surface temperatures provided the region is not mountainous, the land surface is vegetated, and the spatial resolution is not too fine, that is, the 1-km resolution of MODIS is almost ideal (Szilagyi et al. 2011a). For a detailed description of the ET mapping (called CREMAP from Complementary-Relationship-based Evapotranspiration MAPping) and its application for Nebraska, see Szilagyi et al. (2011a) and Szilagyi (2013).

In the present study, no individual error bounds (to express the level of uncertainty) will be calculated for the ensuing recharge estimates for two reasons: (1) they have already been specified over the Sand Hills (Szilagyi et al. 2011b), almost centrally located within the state covering about one-third of its area and yielding nearly the same range of recharge and precipitation values as to be obtained here for the entire state; and (b) the error bounds are based on broad assumptions (in the lack of rigorous region-specific validation studies) of the errors involved with the precipitation (i.e., 5%) and ET (i.e., 10%) estimation values, and thus they are only informative of the general magnitude of the ensuing recharge errors. This error was found to be in the order of 10% to 15% of the corresponding mean annual precipitation, and believed to be valid when extended across the state.

Methodology

Spatially distributed mean annual runoff (Ro, involving both quick-storm, $\mathrm{Ro_s}$, and base flow, $\mathrm{Ro_b}$, response) can be estimated as the difference in precipitation (Figure 2) and ET, provided the net lateral groundwater flow (G_n) and groundwater storage changes (ΔS) are negligible over the averaging period (2000 to 2009) and the area is underlain by an impervious layer

$$P - ET + G_n = \mathrm{Ro} + \Delta S = \mathrm{Ro_s} + \mathrm{Ro_b} + \Delta S \quad (1a)$$

$$R = P - \mathrm{Ro_s} - ET = \mathrm{Ro_b} - G_n + \Delta S \quad (1b)$$

Groundwater levels have generally been declining in many areas across Nebraska (Korus et al. 2011) during the study period due to declining precipitation and/or increasing ET rates. The lack of statewide specific yield values (to transfer groundwater-level change into water depth) prohibits the inclusion of the groundwater storage change term into the water-balance equation (i.e., into the recharge-rate estimation). Such changes are indeed negligible (<30 or 3 mm/year in water depth, assuming a 10% specific yield value) over vast areas of Nebraska, but not everywhere (Korus et al. 2011). The largest groundwater declines (in excess of 0.5 m/year) occurring in the Republican and Big Blue River basins (Figure 1) are, however, concentrated to a relatively small area. Neglecting the storage change term in the recharge estimation is most critical where its magnitude is comparable to the runoff rate, yielding an underestimation of the latter. (The same is true for the G_n term). In areas with large groundwater declines where the resulting runoff is small, net (negative) recharge, estimated as $P - \mathrm{ET}$, yields a good estimate of the storage-change term itself. As will be seen later (Figure 9), the underestimation of runoff due to the unknown storage (and G_n) term is not significant (the $P - \mathrm{ET}$ estimates are close to the USGS-published runoff rates), except at very low observed runoff values where the $P - \mathrm{ET}$ estimate may be negative. Thus, in an indirect way, groundwater-storage changes taking place during the study period are shown to indeed be negligible in the resulting recharge-rate estimation over the majority of the study area, at least at the scale of the watersheds employed.

Annual precipitation grid values came from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; PRISM Climate Group 2004) dataset, together with gridded monthly minimum, maximum air

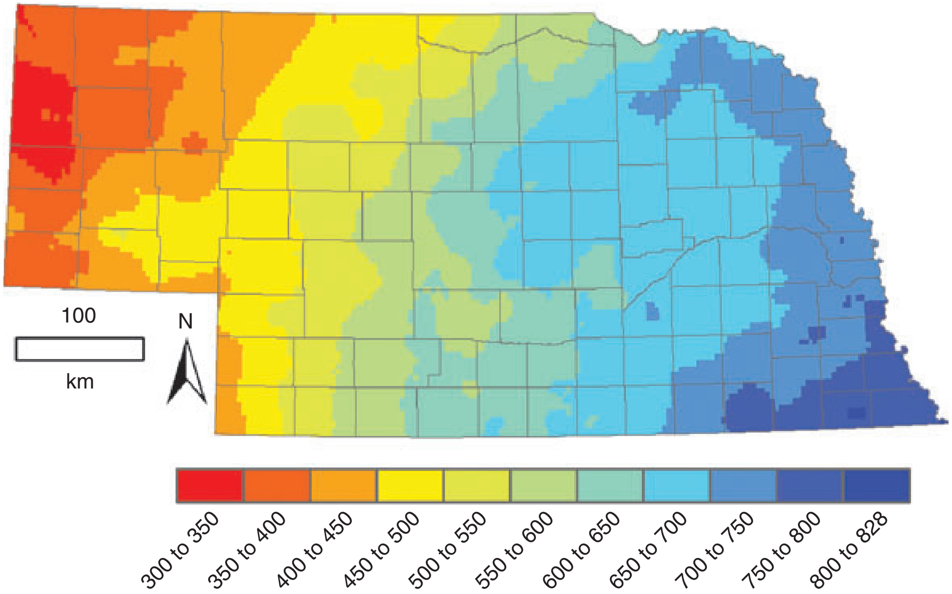

Figure 2. Period averaged (2000 to 2009) mean annual precipitation (P) rates (mm) in Nebraska. The statewide mean is 577 mm.

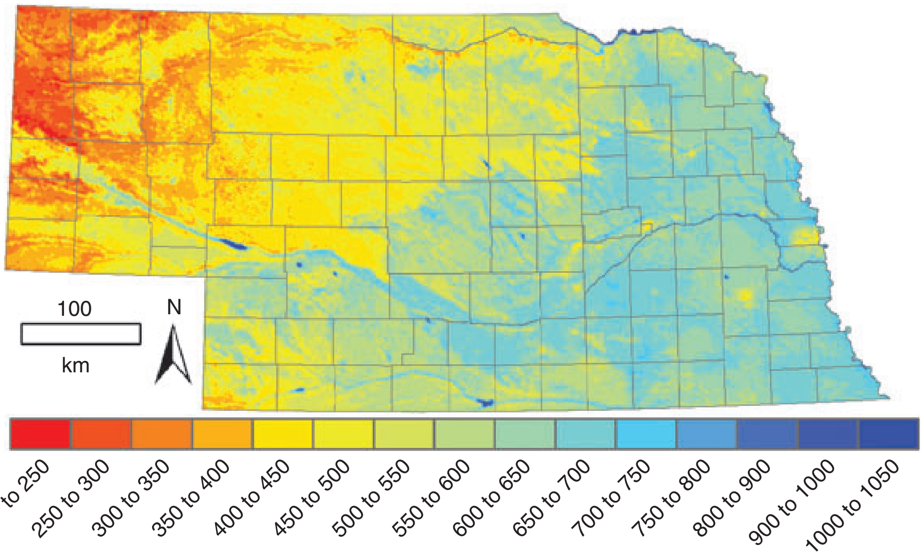

Figure 3. Period averaged (2000 to 2009) and Energy Balance Bowen Ratio-corrected mean annual ET (mm) estimates in Nebraska. The statewide mean is 536 mm.

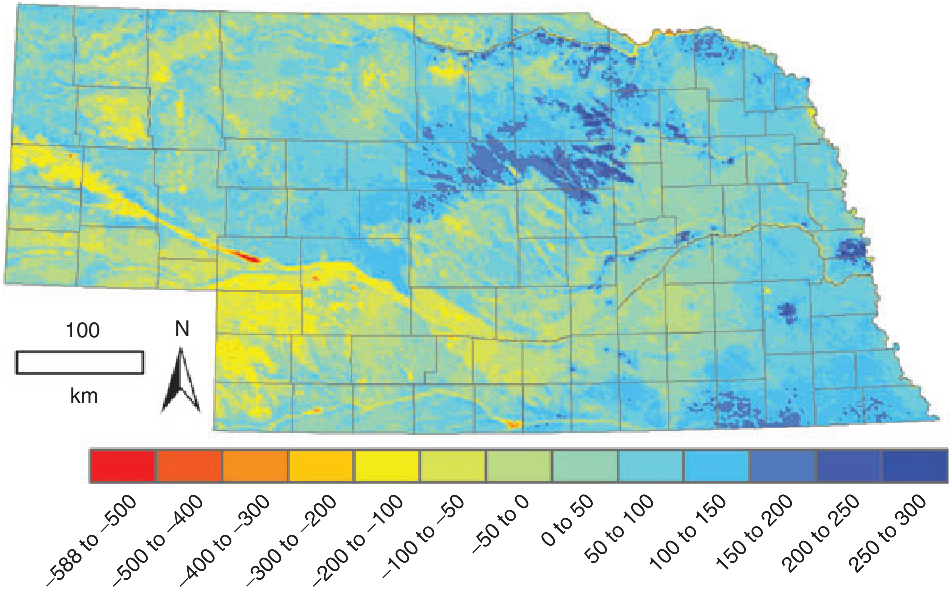

Figure 4. Period averaged (2000 to 2009) mean annual $P - \mathrm{ET}$ (mm) estimates in Nebraska. The statewide mean is 41 mm.

and dew-point temperatures. The grid values, when combined with the incident solar radiation grid data from the Global energy and water cycle experiment Continental-scale International Project's Surface Radiation Balance (GCIP/SRB; NOAA 2009), served as input to WREVAP for obtaining the regional ET rates required for the MODIS-based ET mapping. Through a comparison of multisite/multiyear Energy Balance Bowen Ratio ET measurements of Billesbach and Arkebauer (2012) in the Sand Hills, the CREMAP-derived ET rates over the Sand Hills were corrected by a constant multiplier of 0.92 in this study, similar to Szilagyi et al. (2011b), to account for about 8% overestimation of the mean annual CREMAP ET values within the region. No other regional-scale systematic over- or underestimation of the ET rates was found within the state (Szilagyi 2013), thus the remaining CREMAP ET values were employed without additional corrections. Figure 3 displays the resulting mean annual ET rates while Figure 4 the mean annual $P - \mathrm{ET}$ estimates.

At first sight, the extent of areas with negative $P - \mathrm{ET}$ values (i.e., yellow to red colors), corresponding to (but not equaling, see Equation 1b) negative net recharge rates, may be surprising. As Figure 5 demonstrates, much of these areas are connected to irrigated land (Dappen et al. 2007a), especially in the western and south-western part of the state where precipitation is the least abundant and thus irrigated water may become a significant contribution to enhanced evapotranspiration, thus increasing the cooling of the land surface detected

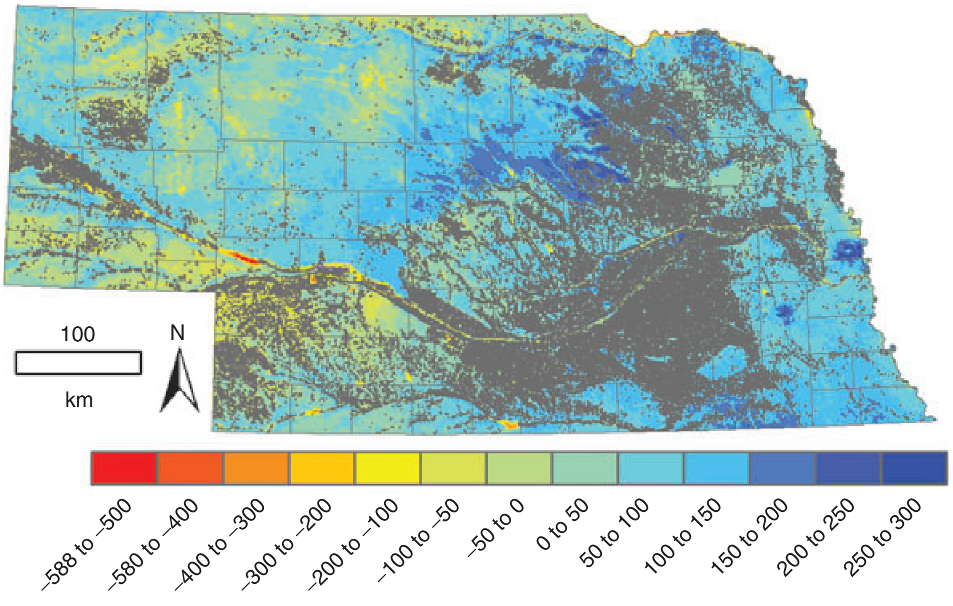

Figure 5. Extent of irrigated land (gray color, after Dappen et al. 2007a, 2007b) in Nebraska overlain the mean annual $P-\mathrm{ET}$ (mm) estimates.

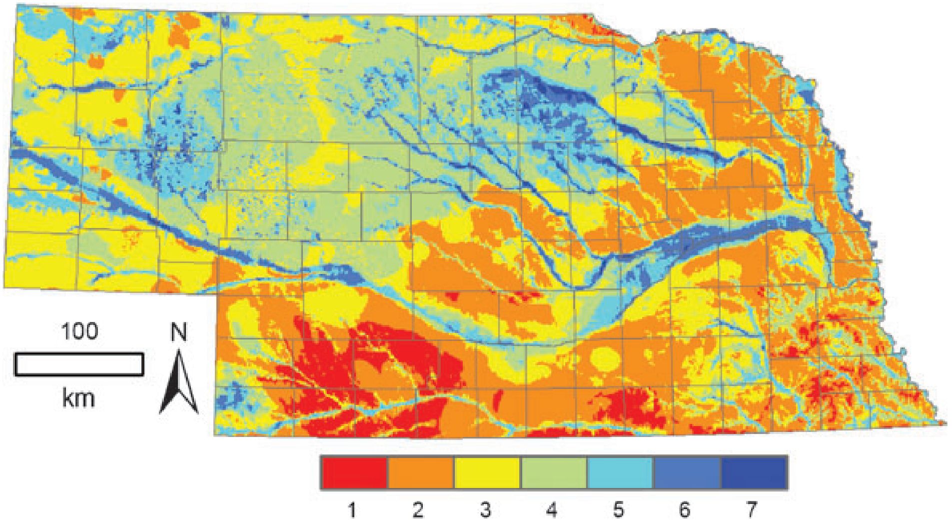

Figure 6. DRASTIC-code values for Nebraska after Rundquist et al. (1991).

by MODIS. Within the Sand Hills, on the other hand, negative $P-\mathrm{ET}$ rates predominantly relate to shallow lakes (exceeding several thousands in number) and wetlands scattered across the region. The largest runoff rates ($P-\mathrm{ET} > 150$ mm) are found in the eastern part of the Sand Hills due to elevated precipitation rates and the high-permeability sandy soils that favor infiltration and enhanced groundwater contribution to streams. The two large urban areas (as well as the smaller ones) in the south-eastern portion of the state, Omaha and Lincoln, also produce large runoff values due to their built-in environments where much of the precipitation ends up in the drainage-pipe network rather than in the soil where it would have a better chance to get evaporated back to the atmosphere.

With the help of runoff distribution and DRASTIC-code maps (Figures 4 and 6), the net recharge to the groundwater can be estimated by the application of a power function (for positive $P-\mathrm{ET}$ differences only) via first transforming the DRASTIC code values (D) into dimensionless proportionality coefficients, as

$$R = \mathrm{Ro}(D/7)^c \tag{2}$$

where the exponent, c, has to be calibrated. Note that the larger the DRASTIC-code value the more vulnerable the groundwater is to contamination and, thus assumed, the better exposed to recharge (Szilagyi et al. 2005). Calibration was aided by previously estimated base-flow indices (BFI) of Szilagyi et al. (2003) across Nebraska

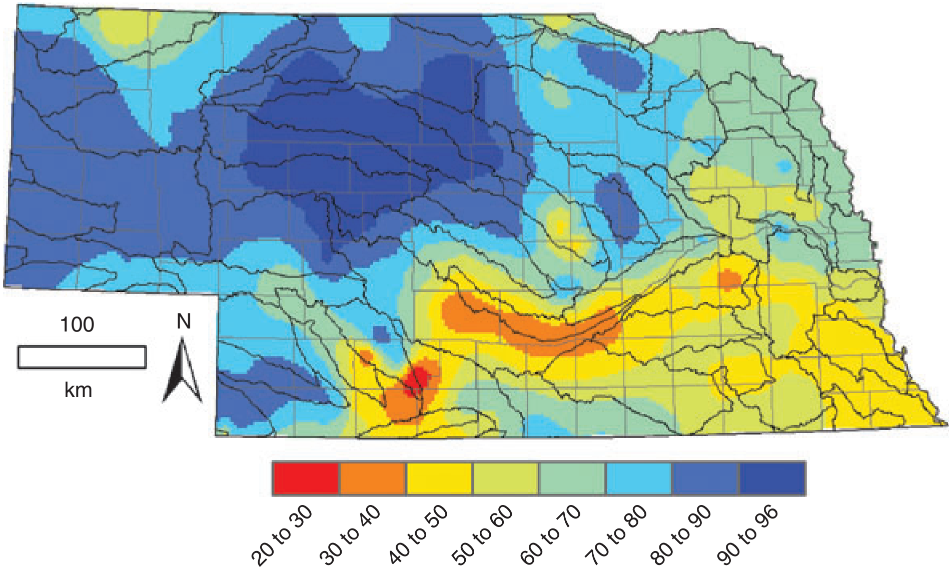

Figure 7. Distribution of the mean annual base-flow index (%) in Nebraska (after Szilagyi et al. 2003). The statewide mean is 71%. The polygons are the USGS HUC-8 level watershed boundaries.

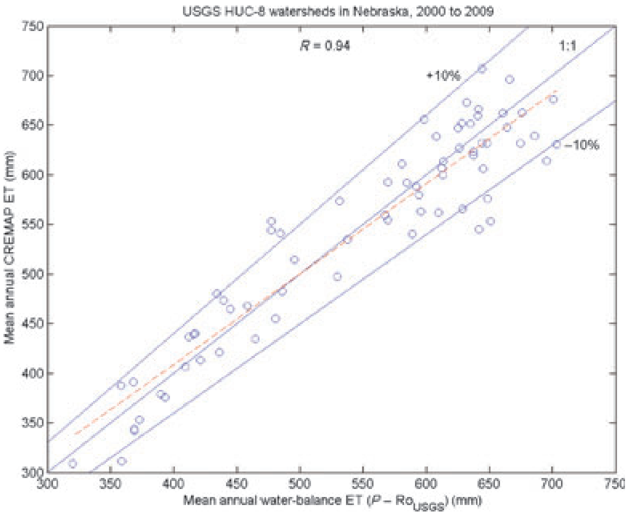

Figure 8. Regression plot of water-balance and CREMAP-estimated mean annual ET rates for the USGS HUC-8 watersheds. *R* is the linear correlation coefficient. The intermittent line is the best-fitting first-order polynomial ($y = 0.91x + 45$). Arithmetic means are 549 mm (water balance) and 545 mm (CREMAP), respectively. Sample size is 70.

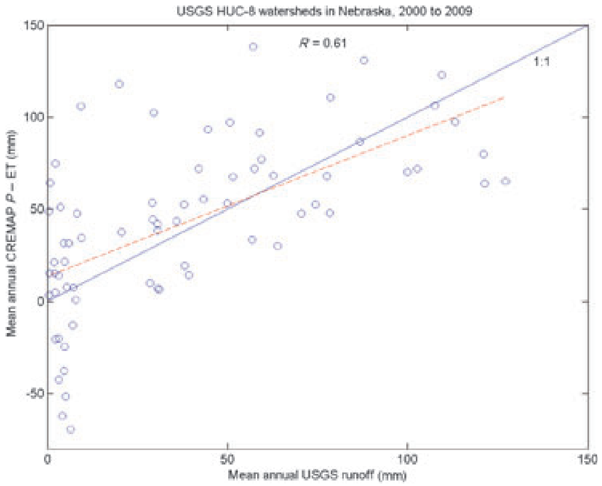

Figure 9. Regression plot of USGS-computed mean annual HUC-8 runoff and CREMAP-derived $P - \mathrm{ET}$ values. *R* is the linear correlation coefficient. The intermittent line is the best-fitting first-order polynomial ($y = 0.76x + 14$). Arithmetic means are 39 mm (USGS) and 43 mm (CREMAP), respectively. Sample size is 70.

(Figure 7). BFI is the relative contribution of groundwater (i.e., base flow) to runoff, averaged over a suitably long period.

Results and Discussion

Figure 8 displays the water-balance obtained (P minus USGS-computed runoff; http://waterwatch.usgs.gov) vs. the CREMAP-estimated mean annual ET rates (Figure 3) for the USGS HUC-8 level watersheds of Figure 7. Estimated ET rates are within 10% of the water-balance rates about 90% of the time, yielding a statewide mean (545 mm) within 1% of the water-balance mean (549 mm) value. The relationship weakens (Figure 9) when runoff is related to the difference in precipitation and estimated ET rates for at least following three reasons. (1) Many watersheds produce runoff values a magnitude smaller than their precipitation or ET rates thus significantly magnifying any errors in the P and/or ET values. For example, if ET is 500 mm/year and runoff is 50 mm/year, then a 10% error in ET will lead to a 100% error in estimated runoff. (2) For watersheds with large-scale irrigation projects where ET exceeds precipitation and runoff is small, the $P - \mathrm{ET}$ difference yields an estimate of net recharge, rather than runoff due to the significant ΔS term in Equations 1a and 1b. This is clearly discernible in Figure 9 at low USGS runoff values. (3) USGS-computed runoff may contain significant errors as well, due to discharge measurement errors as well as uncertainties in the contributing drainage area computation for flat land surfaces with a significant regional groundwater-flow system (i.e., the Ogallala aquifer) resulting in possible large differences in the surface-water and groundwater drainage areas (Szilagyi et al. 2003). For example, in the Lower Republican HUC-8 level catchment in Kansas, the mean annual (2000 to 2009) USGS-computed watershed runoff rate is 5.42 mm vs. the CREMAP-derived runoff of 99 mm (Szilagyi, unpublished data). A study by Sophocleous (2009) specified the mean annual runoff value of the Lower Republican basin (between Concordia and Clay Center, Kansas) as 106 mm over the 1977 to 1993 period. For the same period, USGS gives 38.5 mm as computed runoff (although not for the exact two gauging stations, but close to them).

Despite all these possible uncertainties, the CREMAP-estimated statewide $P - \mathrm{ET}$ difference, 43 mm/year (as the arithmetic average of the 70 catchment means), differs only by 10% from the USGS-computed runoff value of 39 mm/year.

For the calibration of the exponent, c, in Equation 2, the following objectives were set: (1) the resulting statewide mean BFI value be close to 71% (Figure 7), found previously by Szilagyi et al. (2003); (2) the mean BFI value for the Sand Hills region be close to 85% (which is the mean of the BFI values of Figure 7 averaged over the Sand Hills of Figure 1); and (c) the mean recharge value over the Sand Hills be close to 73 mm/year, a value that has been obtained by steady-state chloride mass balance data (Szilagyi et al. 2011b). Table 1 lists the calibration results for selected values of c. A value of 0.31 for c is considered optimal because Sand Hills recharge (62 mm/year) is the closest to the desired 73 mm/year rate while the two BFI means are closest to the aforementioned, automated base-flow-separation obtained values by Szilagyi et al. (2003).

Figure 10 displays the net recharge-rate distribution across Nebraska. With the help of a land-use map (Dappen et al. 2007b), urban areas could be identified (missing in the original DRASTIC map) and a DRASTIC-code value of 0.01 assigned from Equation 2 in order that the resulting urban recharge rate, according to expectations, be smaller (i.e., about 50%) than that of the surrounding agricultural land. The necessary small code value is the result of the large runoff values for urban areas. The continued spreading of the two largest cities, Omaha and Lincoln (Figure 1), between 2005 (the reference date of the land-use map) and 2009 is discernible (assuming that the land-use map is correct) in Figure 10 by the enhanced recharge rates adjacent to the two cities where the 2005 land-use classification-based DRASTIC-code adjustment could not be applied.

The net recharge-rate distribution is more-or-less similar to the total recharge distribution of Szilagyi et al. (2005): the largest rates, in excess of 100 mm/year, are found in the eastern Sand Hills as well as in eastern Nebraska, where precipitation rates are the highest. A significant difference, however, is that most of the river valleys in Figure 10 now display negative net recharge rates, ET being larger (due to the shallowness of the groundwater and widespread irrigation) than precipitation in these areas. In Szilagyi et al. (2003, 2005), base or total recharge could not be negative because of the way it was defined, being based on base-flow contribution to streamflow, which is always positive or zero and valid over the entire drainage area unlike the difference of precipitation and ET in each MODIS cell. The current statewide and Sand Hills-representative mean annual net recharge rates are 29 and 62 mm, respectively, compared with the 48-mm total recharge, previously obtained by Szilagyi et al. (2005) for both areas. Between 1961 and 1990, the statewide mean annual precipitation (employing Solar and Meteorological Surface Observation Network [SAMSON] data) and USGS-computed runoff rates were 576 and 47 mm vs. 577 and 40 mm for 2000 to 2009. Over the Sand Hills, the same rates were 525 and 56 mm vs. 534 and 47 mm in 2000 to 2009 (Table 2). Therefore, the 1961 to 1990 statewide recharge estimate (48 mm) is about the same as the USGS-computed runoff rate (47 mm), whereas in the Sand Hills it is 84% of the corresponding computed runoff rate. Note that, in Szilagyi et al. (2003), base recharge (on which total recharge estimates are based) was obtained as BFI $\cdot$ ($P - \mathrm{ET}$) in order to overcome difficulties in the aforementioned contributing drainage area computation, necessary to transfer flow rates into depth values. Regional ET for 1961 to 1990 was estimated by the current WREVAP program (relying on SAMSON data), therefore certain overestimation of Sand Hills ET (similar to the 2000 to 2009 period), and thus underestimation of recharge, is expected. Also, by the definition of total recharge, it can be larger than runoff, because it considers any water that reaches the groundwater without consideration of what

Table 1
Calibration Results for Selected Values of c in Equation 2

c	Mean Sand Hills R (mm/year)	Mean Sand Hills BFI (%)	Mean Statewide BFI (%)
0.5	56	76	58
0.4	59	81	65
0.33	61	84	70
0.32	61	84	70
0.31	62	85	71
0.3	62	85	72
0.29	62	86	73
0.28	63	86	73
0.27	63	86	74
0.2	65	90	80

R is the net recharge.

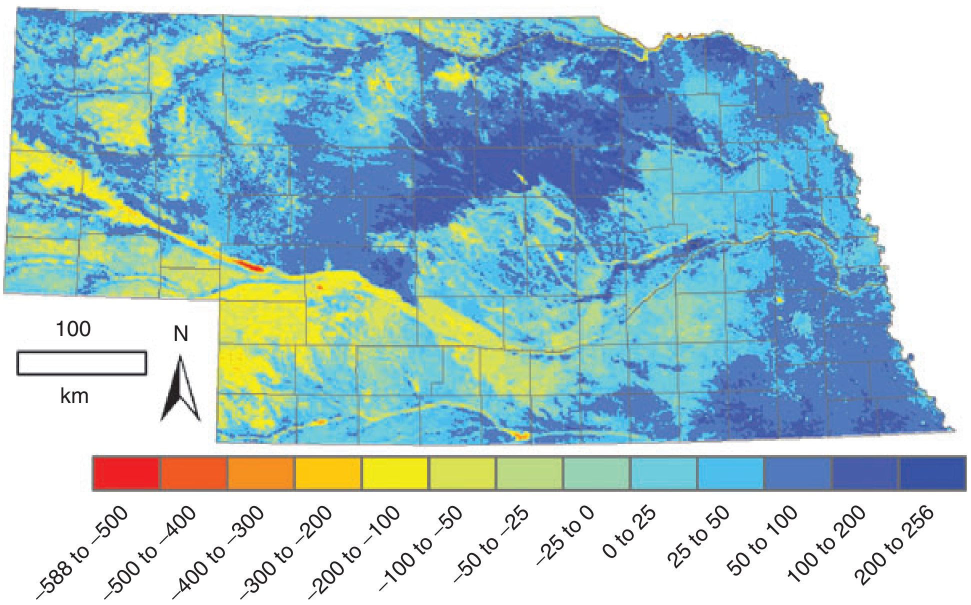

Figure 10. Period averaged (2000 to 2009) mean annual net recharge (mm) to the groundwater in Nebraska. The statewide mean is 29 mm.

Table 2
Mean Annual Region-Averaged Values (mm) of Precipitation (P), USGS-Computed HUC-8 Level Runoff (Ro), Estimated $P-\text{ET}$, and Recharge Rates (R), Total for 1961 to 1990 and Net for 2000 to 2009

	Sand Hills				Nebraska			
	P	Ro	$P-\text{ET}$	R	P	Ro	$P-\text{ET}$	R
1961–1990	525	56	40	48	576	47	65	48
2000–2009	534	47	73	62	577	40	41	29

The 1961 to 1990 values are from Szilagyi et al. (2003, 2005).

Table 3
Sensitivity of the Mean Annual Net Recharge (R) Estimates to a Systematic Error in the Precipitation (P) and ET Values

c_p	c_{ET}	Statewide R (mm/year)	Sand Hills R (mm/year)	Statewide $P-\text{ET}$ (mm/year)	Sand Hills $P-\text{ET}$ (mm/year)
1	1	29	62	41	73
1	0.95	51	82	67	96
1	1.05	6	42	14	50
1.05	1	52	85	69	100
1.05	0.95	74	105	96	123
1.05	1.05	31	65	43	76

c_p and c_{ET} are the prescribed 5% corrections to P and ET.

happens afterward (Crosbie et al. 2010), that is, whether it is evaporated back into the air or contributed to runoff as base flow. So in a hypothetical area where much of the recharged water leaves through groundwater evaporation and only little contributes to runoff (G_n and ΔS assumed negligible), total recharge can become much larger than the latter (i.e., runoff). Note that it cannot happen with net recharge because it considers ET as a possible negative flux of recharge, so in the previous example it would indeed be less (or equal) than the small generated runoff.

The current statewide recharge rate is 72% of the USGS runoff value while, in the Sand Hills, it is 15 mm higher (62 mm vs. 47 mm) than the corresponding USGS-computed runoff (Table 2). As the recent high recharge rates in the Sand Hills were verified by chloride mass balance data of Szilagyi et al. (2011b) as well as indirectly by Billesbach and Arkebauer (2012), it is suspected that not all the recharged water in the Sand Hills contributes to streams within the same region, but rather, as part of the regional Ogallala aquifer flow system, to streams (and stream reaches) already outside the Sand Hills boundary designation. This assumption certainly requires further research.

The earlier discrepancies between the recharge estimates themselves and between recharge estimates and USGS 8 level computed runoff values should not at all be surprising, especially that the precipitation station network, data, and recharge estimation methods as well as the time-periods (1961 to 1990 vs. 2000 to 2009) are all different, but most importantly, because of the inherent uncertainty in the recharge and contributing drainage area estimates.

Table 3 displays the general sensitivity of the estimated runoff and, thus, the net recharge estimates to errors in the precipitation and ET values. The mean annual precipitation values were increased by 5% to account for the generally reported systematic underestimation of the precipitation rates (Dingman 1994), while in the ET values either a 5% under- or overestimation was assumed by multiplying each mean annual PRISM precipitation and CREMAP ET value (after the Sand Hills correction) by c_{p} and c_{ET}, respectively, having assigned values of 1 and 1.05 for c_{p} and 0.95, 1, and 1.05 for c_{ET}. By choosing the statewide mean of the USGS-computed HUC-8 level runoff values as our control variable with an assumed 20% accuracy (i.e., 40 ± 8 mm), it could be decided which error-combination the recharge estimates are most or least sensitive to. As can be seen, any systematic error combination leads to significant changes in the estimated runoff (and recharge) value, except when both variables are simultaneously underestimated.

In summary, it can be stated that the present CREMAP ET-based statewide mean annual net recharge estimation method yields a spatial distribution consistent with expectations: higher recharge rates where precipitation is higher and/or the soil is highly permeable, as in the Sand Hills. It predicts low or negative net recharge fluxes for areas (1) with a shallow groundwater table with a high probability of groundwater ET, typically found in river valleys and wetlands and/or; (2) where intensive irrigation projects are widespread. The method gave a statewide mean annual net recharge rate of 29 mm, which is about 5% of precipitation and 73% of USGS-computed runoff. It is in accordance with earlier automated base-flow separation results of Szilagyi et al. (2003) that specified the statewide groundwater contribution to streamflow as 71%. The estimated values, however, contain a relatively large degree (10% to 15% of the corresponding precipitation rate) of uncertainty due to uncertainties in the required precipitation and ET values. Unlike previous statewide recharge estimates (Szilagyi et al. 2003, 2005), the current method yields net recharge rates taking into account the direction of the fluxes across the land surface as being positive or negative and that way can help regional groundwater modeling efforts of shallow groundwater systems (e.g., COHYST), where these fluxes have increased importance to model outcome and where a groundwater-model-independent determination of these fluxes is highly desirable.

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Disclaimer: The views, conclusions, and opinions expressed in this study are solely those of the writers and not the University of Nebraska, state of Nebraska, or any political subdivision thereof.

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