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RESEARCH ARTICLE

Modis-Aided Water-Balance Investigations in the Republican River Basin, USA

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Abstract

Spatially distributed monthly evapotranspiration (ET) rates over the 2000–2009 period were specified for the three states [Colorado (CO), Kansas (KS), Nebraska (NE)] sharing the Republican River basin with the help of a calibration-free ET-estimation method using Moderate Resolution (of about one km) Imaging Spectroradiometer (MODIS) data. Mean annual ET rate is 444 mm [i.e., 103% of the mean annual precipitation (P) of 430 mm] in CO, 576 mm in NE (102% of $P = 563$ mm), 540 mm (101% of $P = 536$ mm) in KS upstream of Hardy, NE; and 568 mm (95% of $P = 596$ mm) for the entire KS basin area. It is estimated that irrigation (predominantly center pivot) may lead to an additional annual ET of about 200 mm in CO and NE, and to 140 mm in part of KS that is upstream of Hardy, NE over that of native grass. The MODIS-based ET method yields estimates within 10% of water-balance derived mean annual subcatchment ET rates with correlation coefficient values of 0.99-0.96, depending on which estimate (low, average or high) of the specific yield value of the unconfined aquifer is applied in the water balance equation. The present ET-estimation method may help decision makers on how to share the Republican River flow among the neighboring states.

Keywords

Republican River basin · water balance · CREMAP ET estimates

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1 Introduction

The Republican River basin (Fig. 1) with its 64,568-km^2 drainage area is a prime agricultural region within the United States. It is shared by three states: Colorado, Nebraska, and Kansas (Fig. 1). Nebraska has the largest single share of the drainage area, 25,182 km^2 (39% of total); Colorado can claim about 20,016 km^2 (31%), and the rest, ca. 19,370 km^2 (30%), belongs to Kansas (after USDA [28], slightly modified by GIS analysis) from which about 12,913 km^2 (20%) lies upstream of Hardy, Nebraska, near the Nebraska-Kansas border. The watershed, like the surrounding region, has undergone major changes in land use and land cover over the past 50-60 years, most notably by terracing for erosion control, by reservoir constructions and by the wide-spread application of irrigation techniques, predominantly center pivots. For example, in 1950 there were only about 200 irrigation wells in the Nebraska portion of the basin, by 1985 the number had grown to 8,700, and by 2004 to about 11 thousand [15], a 55-fold increase in 55 years. During the same period the number of irrigation wells grew to about 4000 separately in Colorado and in Kansas [18].

The dominant part of the irrigated water volume ends up in the air via enhanced evaporation and transpiration rates and leaves the watershed. In fact, the effect of the massive scale of irrigation within the central prairie states has been connected [9] to enhanced July precipitation, groundwater storage and streamflow rates in the Midwestern states of e.g., Illinois, Indiana and Ohio. Increased ET rates, however, can be expected to translate into decreased streamflow rates over time under the same precipitation regime for an aquifer that has a good hydraulic connection with the streams draining it. Decreased streamflow rates have indeed been reported by Kustu et al. [8] for the High Plains aquifer, and more specifically by Szilagyi ([20, 21]) for the Republican River basin (Fig 2). Naturally, this streamflow decline integrates all the changes (natural or man-made in, e.g., climate, reservoir evaporation, land use and land cover) that have been taking place in the watershed, not only the effect of irrigation. Based on simplified water-balance modeling, Szilagyi [21] concluded that the observed streamflow decline near Hardy, NE (and thus near Junction City, KS) starting in the

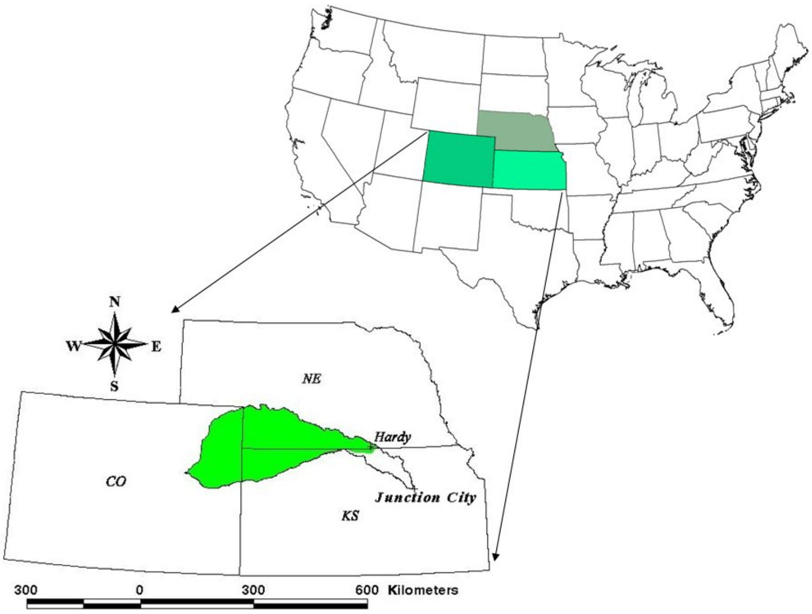

Fig. 1. Location of the Republican River watershed. The shaded area within the catchment designates drainage area upstream of Hardy, NE near the Nebraska-Kansas border.

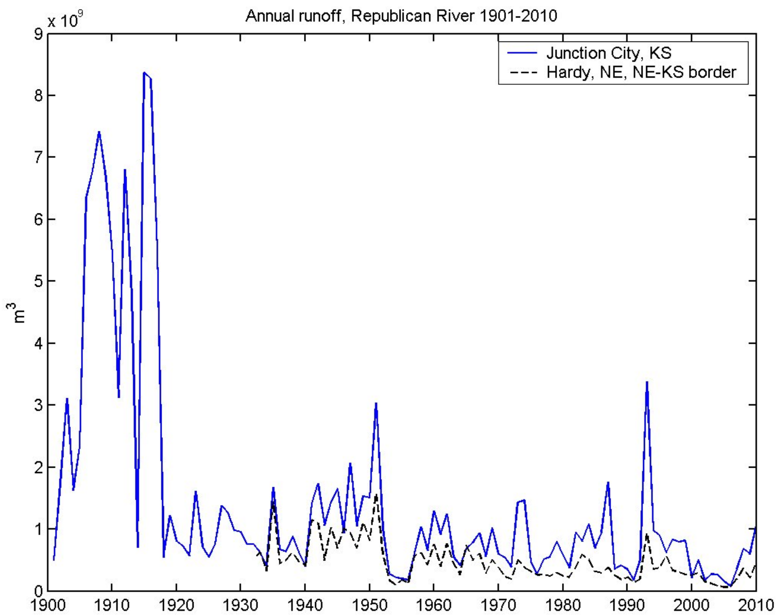

Fig. 2. Mean annual runoff volumes of the Republican River near Hardy, NE (together with the Courtland Canal irrigation diversion flow volumes at the state border nearby, the canal joining the Republican River shortly downstream of the border) and Junction City, KS (see Fig. 1).

second part of the 1950s, cannot be explained solely by naturally occurring changes in the climatic variables (e.g., change in air temperature, humidity, rainfall frequency) of the region. This is so because annual precipitation amounts across the watershed remained practically unchanged (Fig. 3) over the past seven decades (i.e., after the dust-bowl era of the 1930s) for which records are available, while upstream flow volumes declined significantly over the last 40 years or so (Fig. 4). The extreme water-rich years of the 1905-1917 period (Fig. 2) and the significant decline in flow volumes ending the period are not the focus of the present study, not the least due to the scarcity of reliable precipitation records for those years.

Ongoing interstate disputes among the three states sharing the Republican River basin focus on to what degree each state consumes Republican River streamflow. To answer this question one may draw up water balances but the water balances are strictly valid only for the drainage areas that correspond to each stream gauging station. In practice, one may not always have a high enough number of gauging stations to satisfactorily distribute the spatially varying water-balance values within a given catchment (even when one does, the measurement periods may not overlap perfectly) which becomes a problem when one wants to aggregate the water-balance values over arbitrary areas, in the present case over the drainage areas owned separately by the three states (Fig. 1). For example, many sub-catchments in Nebraska reach into Kansas and/or Colorado (Fig. 5), thus any water balance for these sub-catchments obtained by the help of stream gauging stations in Nebraska may not be representative over Kansas and/or Colorado (neither over Nebraska) because the upstream parts of these typically elongated sub-catchments may enjoy different climatic and hydrologic conditions from those of the downstream portions. This is especially true because the Republican River basin expresses high west-to-east gradients in elevation, precipitation, air temperature and humidity (Fig. 6).

The problem of horizontal extent of the sub-catchments and the resulting spatial variance of the water-balance components along them may not always be solved by simply reducing the size of the watersheds because with the decrease of subcatchment size, the relative number of available gauging stations decline sharply. In fact, the 8-digit USGS watersheds displayed in Fig. 5 are a good trade-off between spatial variance within the Republican basin in one hand and corresponding data availability and temporal coverage in the other.

In order to demonstrate the augmentation of water balance investigations, a recently developed calibration-free evapotranspiration mapping technique (CREMAP by Szilagyi et al. [23]), employing Moderate Resolution Imaging Spectroradiometer (MODIS) data, has been applied over the Republican River basin to infer how ET varies by states, sharing the watershed. Monthly CREMAP ET estimates at a spatial resolution of about one kilometer are then validated with sub-catchment water-balance data and also compared to similar estimates of a global MODIS-aided ET-estimation method by Mu et al. [13]. Finally possible explanations are sought for the observed spatial variance of ET.

2 CREMAP application

The calibration-free ET mapping (CREMAP) method of Szilagyi et al. [23] assumes a linear relationship between spatially fluctuating values of two variables around their spatial mean: the daytime surface temperature (T_s) of the vegetated land surface and the corresponding ET rate. Specification of the T_s to ET transformation requires the T_s value of a wet surface and the corresponding ET rate on top of the spatial mean value of T_s and ET. The spatial mean ET rate at a monthly basis is obtained by the WREVAP program of Morton et al. [12], while the wet surface evaporation rate (E_w) by the Priestley-Taylor equation [16].

CREMAP-derived ET estimates have been mapped for Hungary in Europe [22] and the state of Nebraska in the US [23] within the temporal coverage of MODIS (i.e., starting with 2000). They have been validated with eddy covariance and energy balance Bowen-ratio station measurements (from about a dozen different locations) plus catchment water-balance data (from half a dozen watersheds) with explained variance (R^2) typically in the range of 0.7-0.95 ([22, 23]). CREMAP ET rates have also been employed in several practical applications, such as to estimate a) spatially varying recharge rates in the interfluvial sand plateau region in Hungary [25], in the Sand Hills of Nebraska [24] as well as over the state of Nebraska [26]; (b) the recharge vs depth to groundwater relationship within the Platte River Valley of Nebraska [27].

For the application of CREMAP over the Republican River basin, the watershed has been divided into six regions (Fig. 7), due to the large variance of the climatic variables both east-to west and, to a lesser degree, north-to-south directions. The 8-day composite MODIS daytime surface temperature values for 2000-2009 were averaged for each month to obtain one surface temperature per pixel per month. Mean annual precipitation (P, required only for validation), mean monthly maximum/minimum air and dew-point temperature values were downloaded from the PRISM database [17] at 2.5-min spatial resolution. Mean monthly incident global radiation data at half-degree resolution were obtained from the GCIP/SRB site [14]. For the monthly T_s to ET mapping a spatial mean T_s value was calculated for each of the six regions with the corresponding regional ET rate obtained from WREVAP, employing regional averages of the monthly mean air and dew point temperature as well as global radiation values. For the wet surface temperature the MODIS pixel with the lowest mean annual T_s value over the Harlan County reservoir in Nebraska was chosen, the reservoir representing the largest open water surface (see Fig. 9) within the Republican River watershed, after Milford Lake near the mouth of the catchment in Kansas.

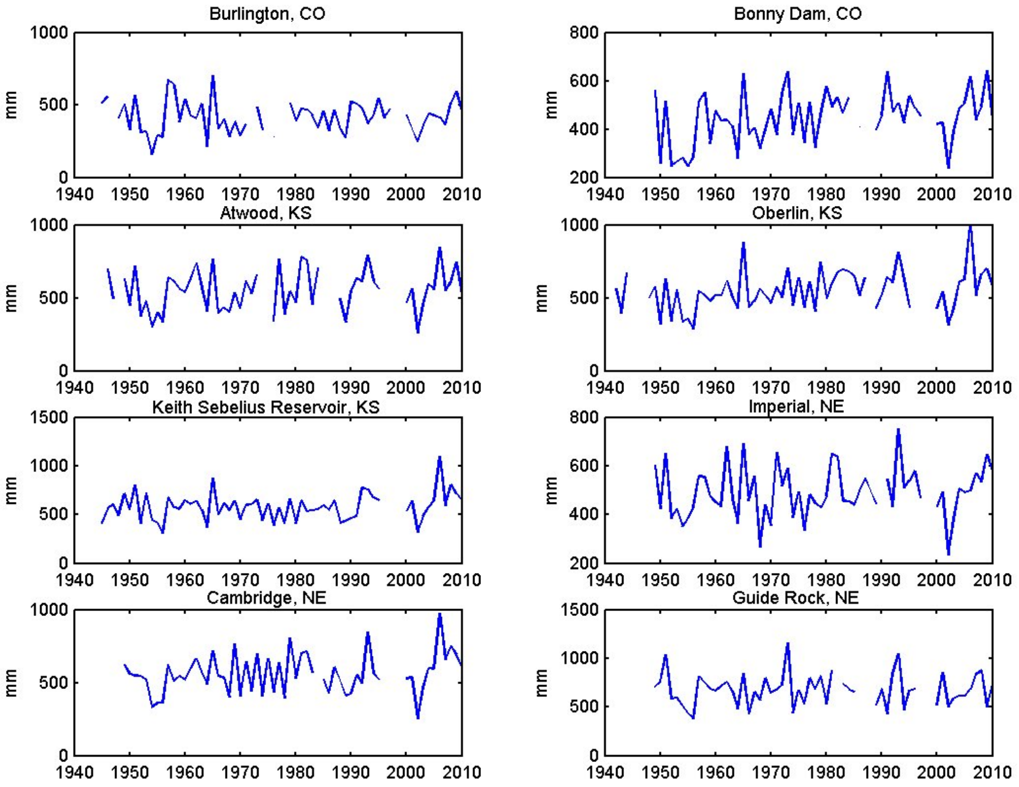

Fig. 3. Mean annual precipitation time series at selected locations (see Fig. 5) across the Republican River basin.

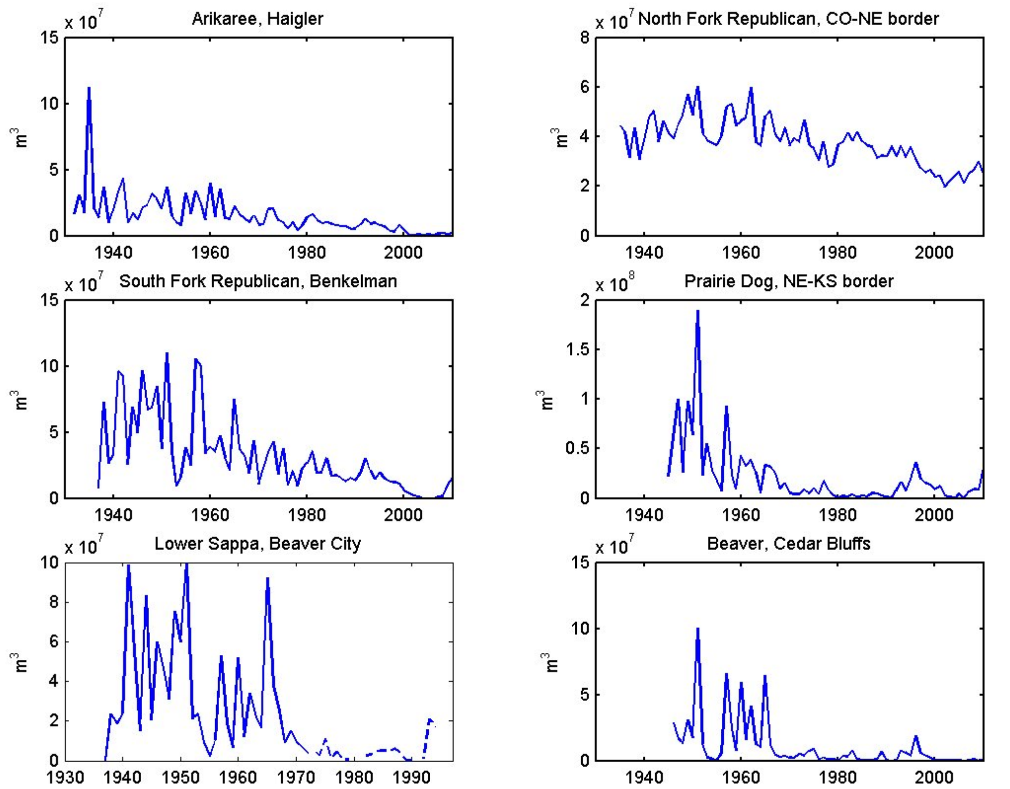

Fig. 4. Time series of annual flow volumes at selected USGS gauging stations (see Fig. 5) near the border of the three states. The intermittent line denotes estimated values from [20].

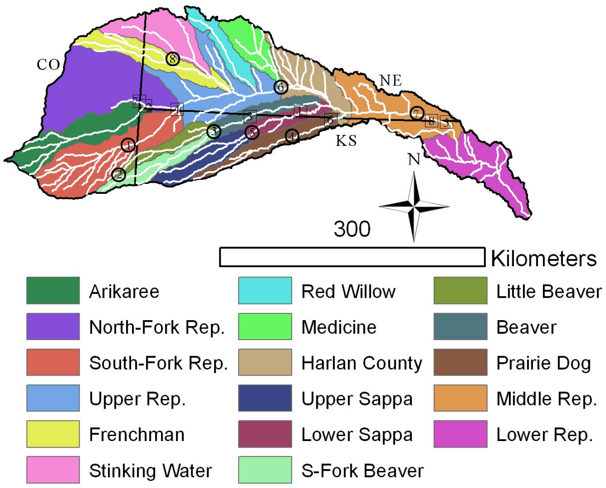

Fig. 5. Distribution of the 8-digit USGS sub-catchments within the Republican River basin. Precipitation stations (circles): 1. Bonny Dam, CO; 2. Burlington, CO; 3. Atwood, KS; 4. Keith Sebelius Reservoir, KS; 5. Oberlin, KS; 6. Cambridge, NE; 7. Guide Rock, NE; 8. Imperial, NE. Gauging stations (squares): 1. Lower Sappa, near Beaver City, NE; 2. South-Fork Republican, near Benkelman, NE; 3. Beaver near Cedar Bluffs, KS; 4. Arikaree at Haigler, NE; 5. Republican near Hardy, NE; 6. Prairie Dog near Harlan Co. Reservoir, NE; 7. North-Fork Republican at the CO-NE border; 8. Courtland Canal near Superior, NE.

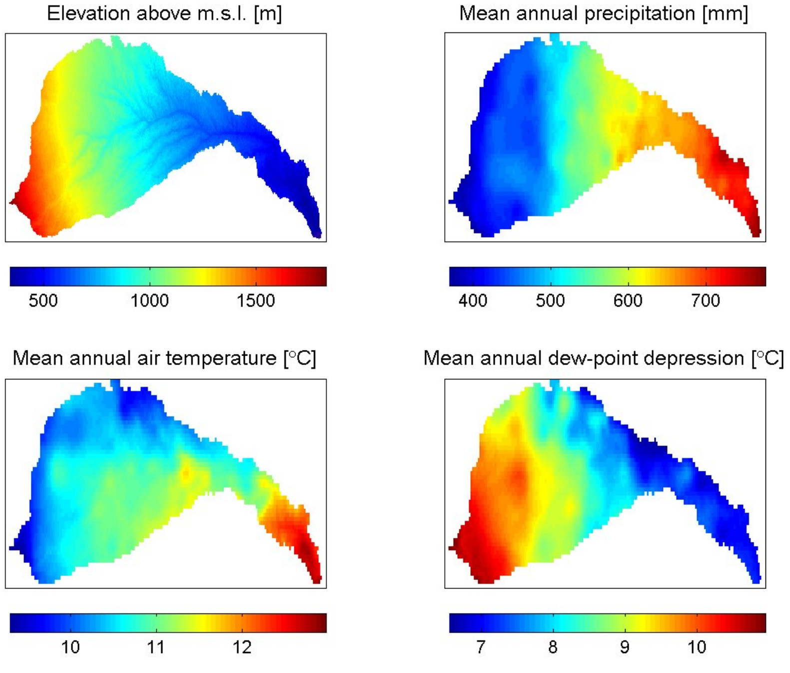

Fig. 6. Elevation of the Republican River basin from a 1-km digital elevation model as well as distribution of precipitation (2000-2009), air temperature and dew-point depression values.

Choosing a MODIS pixel over an extended water area (lake surface area is about 54 km^2) ensures that the pixel value is not contaminated by fractional non-wet areas falling into the pixel. Szilagyi et al. [23] did the same for mapping ET rates over Nebraska, employing a pixel from the largest reservoir within Nebraska, Lake McConaughy (situated outside of the Republican River basin). Kovacs [7] compared monthly MODIS T_s values over open water surfaces (large shallow lakes) with similar values over extended wetlands in Hungary and found that they were typically within 1°C, except in early spring (March-April) when lake surface temperatures were about 2-4 °C lower. This difference is mostly due to the dormancy of the vegetation in early spring with the dry leaves still attached to the stem of phreatophytes, as was found by Lenters et al. [10] in the Republican River basin as well. These are in support of the application of open water surface temperatures for the wet surface temperature values.

Because the T_s to ET transformations change by region (Fig. 7), they had to be performed multiple times for each cell employing the parameters derived for the neighboring region centers and the results weighted by an inverse-distance method to ensure a smooth ET surface without jumps at the region borders. The linear transformations were performed from March till November each year because patchy snow cover conditions may grossly violate the simplifying assumptions of the method due to the large albedo difference between snow and land. In the winter months the regional ET rate of WREVAP was kept for each region, without further disaggregation by T_s.

For validation, 8-digit USGS watershed runoff rates, *Ro* (Table 1), were derived from the USGS water resources website (http://waterwatch.usgs.gov/new/). 2005 land use and land cover information at 30-m spatial resolution for the whole basin was obtained from the Kansas Applied Remote Sensing [5] program. Groundwater elevation change data for the Spring 2000 – Spring 2010 period were provided by Korus et al. [6] for Nebraska, and by the Kansas Geological Survey [4] for Kansas. Specific yield (S_y) values for the High Plains aquifer were derived from Cederstrand and Becker [3] to transfer groundwater change (h_d) values into water depths (h_w) via $h_w = S_y \cdot h_d$. For illustration, Fig. 8 depicts the typical range of groundwater level change in the basin, from about the 1950s to 2007 [11]. The largest positive values in Nebraska are predominantly the result of irrigation-canal leakage. Note that Fig. 8 data are not used for water-balance calculations/validations since in the latter the groundwater storage change that took place during the modeled period (i.e., 2000-2009) must be included.

3 Results and discussion

Fig. 9 displays the CREMAP-derived mean annual ET rates over the Republican River basin. ET varies from about 330 mm in the western part of the catchment to about 920 mm annually, the latter over open water surfaces. The stream network pattern is discernible as high ET areas because near the streams groundwater is closer to the surface thus increasing the soil moisture in the root zone as well as letting deep-rooted vegetation to tap into the saturated zone with their root system. Also, irrigation is often concentrated in the river valleys due to almost ideal conditions (smooth, level surface, rich soils, easy access to stream water). The larger reservoirs in the basin can also be distinguished from their enhanced evaporation rates. A comparison of the annual ET rates with the land use-land cover map of Fig. 10 reveals a good spatial correspondence of irrigated crop (and open water) with elevated ET rates. Clearly, the largest continuous high ET areas are all found in Nebraska, while Kansas, with its Lower-Republican River sub-catchment area comes up second.

One obtains a better handle on the ET-enhancing effect of irrigation by looking at the ET / P (precipitation recycling) ratios (Fig. 11, expressed as percentages), since precipitation decreases significantly from east to west. The lowest ratios (75-85%) are found in the eastern portion of the watershed in Kansas, because precipitation is the most abundant there (around 700 mm/yr) within the basin as well as in the western part of it, in Colorado, over rugged terrain typically covered with native prairie grass. The largest values are concentrated in Nebraska and Colorado. These larger than unity ratios are typically connected to open water surfaces, wetlands and irrigated crops. An ET / P cell ratio larger than unity means that the cell 'consumes' more water than it receives from precipitation. For lakes and wetlands the difference is made up by naturally occurring surface runoff and/or by groundwater discharge, for irrigated crops by surface water diversions and/or groundwater pumping. The latter often results in groundwater depletions, as demonstrated in Fig. 12, where it is obvious that the largest precipitation recycling ratios occur (almost without exceptions) within the most severe groundwater depletion areas across the basin. Note the location of reservoirs, marked in Fig. 9.

The specific yield values of Fig. 13 were consequently employed for transforming the **groundwater** change that occurred in 2000-2009 into water-depth equivalent, ΔGW (Fig. 14, Table 1), to be used in the ensuing water balance calculations. Unfortunately, the groundwater-change data were available only for Nebraska and Kansas (Fig. 14). Therefore the ΔGW values by sub-catchments and by states in Table 1 must be dealt with certain caution because the groundwater maps generally do not fully cover the corresponding sub-catchment (or state) areas, thus a water-depth equivalent value calculated from partial cover and assigned for the entire sub-catchment (or state) area in question might occasionally be misleading.

Table 1 summarizes the components of the water balance equation

$$P - ET - Ro = \Delta GW \tag{1}$$

for the study period by sub-catchments and states. Note that (1) does not include lateral fluxes, such as ground-water flow. This is because groundwater fluxes are largely uncertain over the basin not the least due to uncertainties in recharge rates, which in

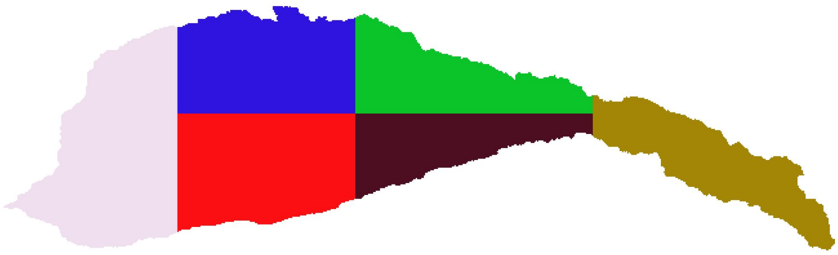

Fig. 7. Division of the Republican River watershed into distinct regions for the estimation of regional ET rates.

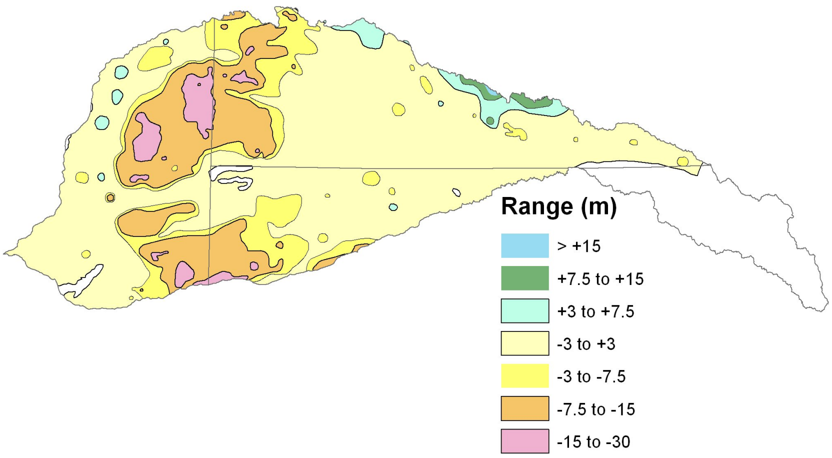

Fig. 8. Groundwater-elevation change in the Republican River basin, predevelopment to 2007.

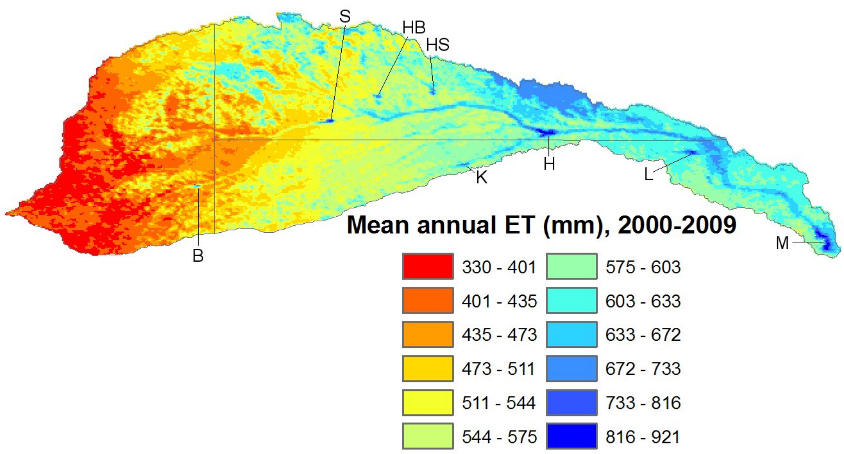

Fig. 9. Distribution of the mean annual ET rates over the Republican River basin for the 2000-2009 period. Reservoirs marked: B: Bonny; S: Swanson; HB: Hugh Buttler; HS: Harry Strunk; K: Keith Sebelius; H: Harlan County; L: Lovewell; M: Milford.

Tab. 1. Characteristics of the USGS 8-digit sub-watersheds within the Republican River basin. HUC: last two digit in the 8-digit hydrologic unit code (HUC) identification number starting with 102500; ΔGW: groundwater change in water-depth equivalent. The first ΔGW value comes from the lower boundary value of the specific discharge ranges of Fig. 15, the second from the mean of the lower and upper boundary values, while the third from the upper boundary value. All water balance variables are for the 2000-2009 period.

Name (HUC)	Drainage area (km^2)	Precipitation (mm/yr)	Runoff (mm/yr)	ΔGW (mm/yr)	ET (mm/yr)
Arikaree (01)	4465	428	0.53	-	422
North-Fork Rep. (02)	8599	433	7.02	-	453
South-Fork Rep. (03)	7147	439	0.36	-	439
Upper Republican (04)	5656	539	2.14	-13 -15 -24	545
Frenchman (05)	3534	465	5.04	-26 -32 -47	530
Stinking Water (06)	3836	474	6.34	-32 -39 -58	535
Red Willow (07)	2037	535	4.55	-26 -30 -46	563
Medicine (08)	2382	572	2.24	-7 -9 -14	575
Harlan Co. lake (09)	3624	617	2.06	2 2 2	615
Upper Sappa (10)	2616	531	0.38	-23 -26 -30	547
Lower Sappa (11)	1692	605	0.73	-1 -2 -2	581
South-Fork Beaver (12)	2027	468	0.12	-41 -47 -53	509
Little Beaver (13)	1572	490	0.12	-29 -34 -39	521
Beaver (14)	1915	591	0.42	-4 -5 -5	567
Prairie Dog (15)	2696	600	2.1	-7 -8 -9	583
Middle Republican (16)	5629	661	9.21	-6 -7 -14	638
Lower Republican (17)	5141	716	54.2	-	616
Republican River basin	64,568	531	5.13	-	533
Rep. River, CO portion	20,016	430	-	-	444
Rep. River, NE portion	25,182	563	-	-14 -17 -26	576
Rep. River, KS portion	19,370	596	-	-	568
Rep. Riv., KS portion, upstream of Hardy, NE	12,913	536	-	-20 -24 -27	540

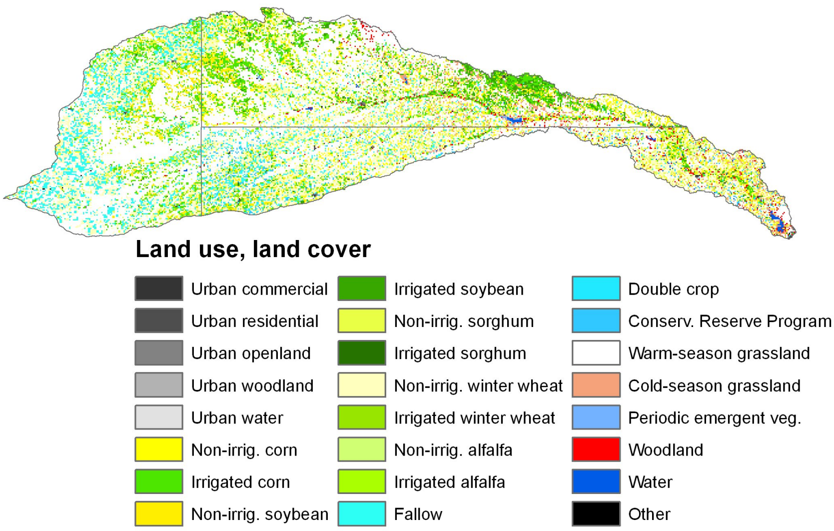

Fig. 10. 1-km resolution land-use/land-cover distribution over the Republican River basin, aggregated from 30-m resolution data.

Tab. 2. Mean annual precipitation (2000-2009) as well as estimated current and "undisturbed" ET / P ratios by states, sharing the Republican River basin.

Basin area	"Undisturbed" native prairie ET (mm)	Present ET (mm)	P (mm)	P (mm) over native prairie	ET / P (%) undisturbed	ET / P (%) present	Change in ET / P (%)
CO	430	444	430	433	99.31	103.26	3.95
NE	557	576	563	559	99.64	102.31	2.67
KS	561	568	596	591	94.92	95.3	0.38
KS upstream of Hardy, NE	536	540	536	547	97.99	100.75	2.76

turn are uncertain partly due to the dearth of accurate, spatially distributed ET rates. The present work may help with a better definition of the latter.

When comparing the water-balance components among the three states that share the basin, an interesting picture emerges. Mean annual precipitation is the most abundant in Kansas (596 mm), followed by Nebraska (563 mm) with Colorado lagging behind (only 430 mm). ET, however, is the largest in Nebraska (576 mm), followed by Kansas (568 mm), and Colorado (444 mm). While the resulting precipitation recycling ratio is 95% for Kansas, it jumps to 102% in Nebraska and 103% in Colorado. Because of the larger than unity value one is not surprised to see a general groundwater decline in the latter two states, but the same happens in Kansas as well, upstream of Hardy, NE (i.e., the KS triangle in the Figures) with a precipitation recycling index value of about 101% (P = 536 mm). Note that a larger than unity value of the precipitation recycling index is not a necessary requirement for a depletion of the groundwater reserve which can also occur when ET and runoff together is larger than P.

By combining the land use/land cover map with that of the ET rates, one could, in principle, estimate how much additional water irrigated crops use to e.g., non-irrigated crops. Such an automatic comparison must be taken with caution because a typical MODIS cell (with a size of about 1 km^2) will contain a mixture of vegetation types and still have only just one type of cover (e.g., irrigated, non-irrigated crop or native grass) assigned during the analysis, simply because of the predominance (even though slight) of that vegetation-type within the cell. The only exception is the native grass cover (warm-season), which is the predominant and most continuous vegetation cover type in each state (although in KS, downstream of Hardy, it is highly fractured), therefore the GIS-obtained mean ET value the less biased. For irrigated crops (because they often intermingle with non-irrigated ones) a better approach is to pick the largest ET rates not associated with open water or wetlands (about 620 mm in CO, 720 mm in NE, 700 mm in KS, and 670 mm in KS upstream of Hardy, NE). As a result, irrigated crops may use an additional 200 mm of water annually (47% of P) over native grass in CO, also 200 mm in NE (36% of P), and 130 mm (or 24% of P) in KS upstream of Hardy, NE (145 mm – or 25% of P – for the entire KS area, a value with high uncertainty level due to the above mentioned fractured native grass status in the Lower-Republican River sub-catchment). A similar comparison cannot be done between irrigated and non-irrigated crops due to their high level of mixing/fracturing.

When one compares the mean annual ET rates of native vegetation (430 mm in CO, 557 mm in NE, and 536 mm in KS, upstream of Hardy where native vegetation is less fractured) with precipitation rates (Table 2) over the same native vegetation, the difference becomes about 2-11 mm as runoff (assuming ΔGW is negligible, most likely true for predevelopment conditions, preceding 1960) which is ca. half of the measured mean annual runoff value of 12 mm near Hardy, NE (from Fig. 2) for 1932-1960, a period when irrigation practice was largely negligible in the region. The difference is most probably explained by the unavoidable underestimation (to unknown extent in the study) of precipitation. The uneven spatial distribution of the native vegetation cover (concentrating in the eastern portion) within KS, upstream of Hardy, NE made it necessary to replace the area-averaged P value with that taken over the native grass cover.

Brown and Caldwell (2011) estimates that in 2005 about 17% of the three Natural Resource District (NRD) areas (i.e., Upper-, Middle- and Lower-Republican NRDs), covering more than 90% of the basin area within Nebraska, was irrigated crop. If the 200 mm of the above estimated extra ET that comes from irrigated crops over that of native vegetation is distributed over the entire NE area of the basin (plus assuming that the 17% is valid for the remaining less than 10% of the NE basin and that it is also representative for the entire 2000-2009 period), one obtains about 34 mm, which when added to the estimated native ET rate of 557 mm in NE yields 591 mm, close (a difference of about 2.5%) to the already estimated mean annual ET rate of 576 mm for the Nebraska part of the basin. From this it can be surmised that the separate ET estimates for grass and irrigated crops are fairly good, provided non-irrigated crops roughly consume the same amount of water annually than native grasses, which may indeed be the case.

To further verify the accuracy of the present ET values, the sub-catchment means of the ET estimates were compared with the rest of the water balance equation terms. Note that point estimates of ET [either by eddy-covariance (EC) or Bowen-ratio methods] are not the best suited for such comparisons due to the typically large difference in the corresponding footprint areas since for point measurements it is a magnitude smaller than the MODIS-cell size. Szilagyi and Kovacs [22], however, report an EC verification of the present ET estimation approach where the instruments were located at 82 m above ground, thus the footprint area encompassed a large number of MODIS cells, and it resulted in an R^2 value of 0.95 between the multi-year measured (aggregated by month) ET values and their unbiased estimates obtained by CREMAP.

Fig. 15 is a regression plot of the ET estimates and the $P - Ro - \Delta GW$ values for the 17 sub-catchments of Table 1, and also includes the entire Republican River basin. Explained variance (R^2) is between 0.93 (with low and mean S_y values) and 0.96 (with high S_y values), depending on which S_y values of Fig. 13 are used for the ΔGW values. Without the inclusion of the ΔGW data, R^2 drops to 0.86. With high S_y values the mean annual ET is 553 mm (versus the 543 mm CREMAP estimate), with an average S_y value ET becomes 548 mm, and with a low S_y value it is 546 mm. Note that the present values are simply the arithmetic means of the first 17 values displayed in Table 1, they are not weighted by area due to the before mentioned uncertainty in the spatial extent of the measured change in groundwater-elevation values of Fig. 14 within the sub-catchments. Note also

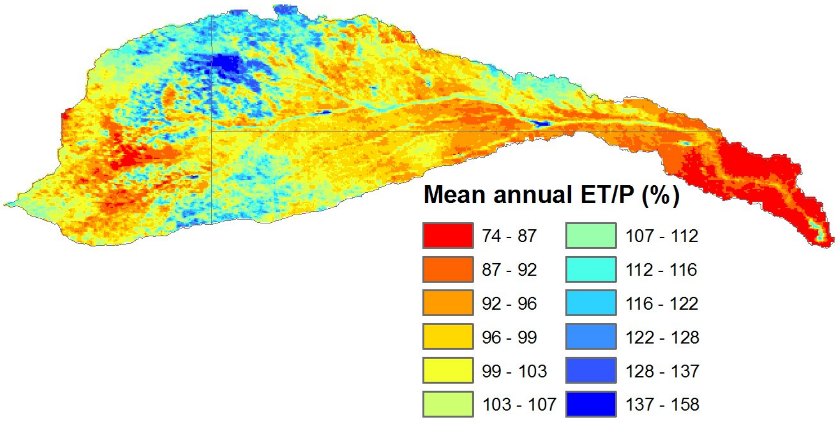

Fig. 11. Distribution of the mean annual precipitation recycling (ET / *P*) ratio across the Republican River basin.

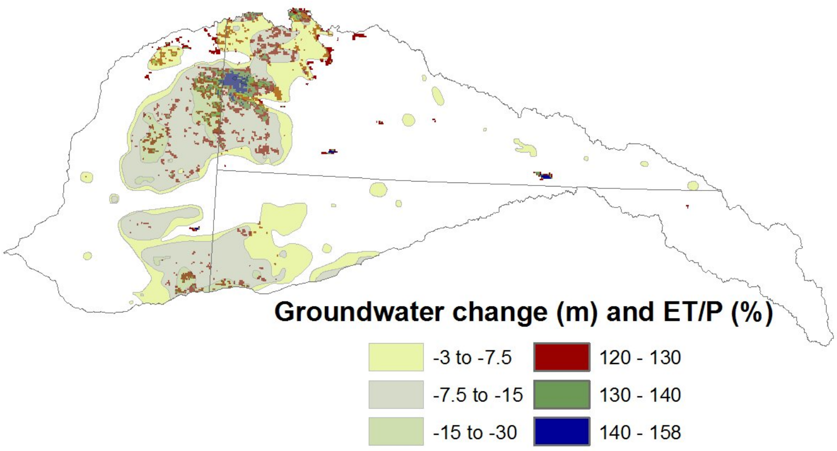

Fig. 12. Distribution of the largest groundwater decline (predevelopment to 2007) and precipitation recycling (ET / *P*) values across the Republican River basin.

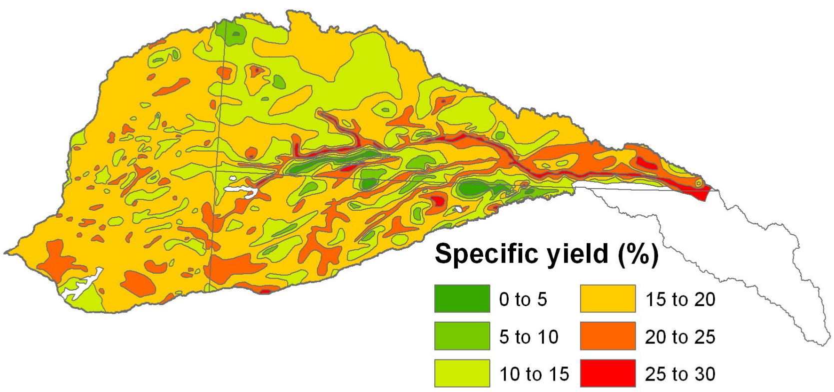

Fig. 13. Estimated specific yield values of the High Plains aquifer within the Republican River basin.

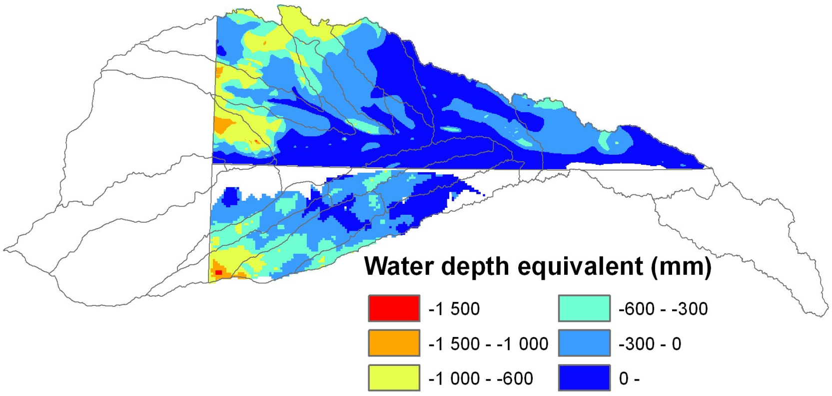

Fig. 14. Groundwater change in the 2000-2009 period as water-depth equivalent across the Republican River basin. See Fig. 5 for the identification of sub-catchments.

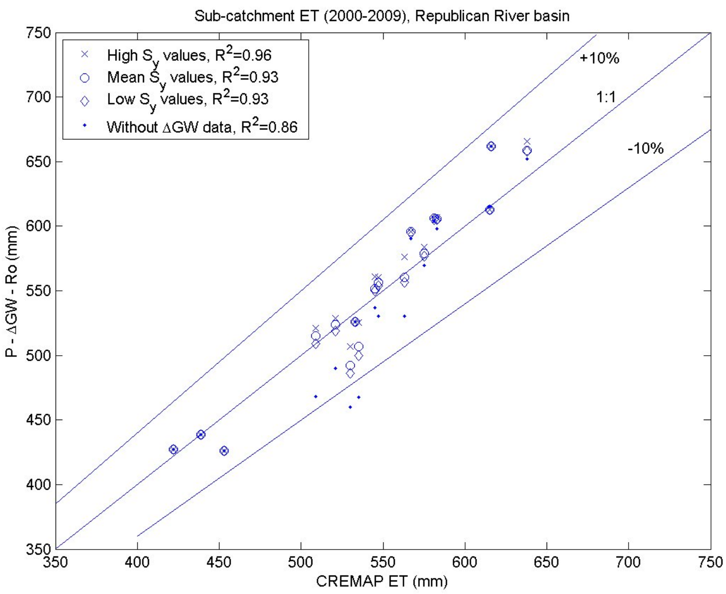

Fig. 15. Regression plot of the mean annual ET estimates versus the water-balance derived ($P - \Delta GW - Ro$) values (first 18 rows of Table 1). R^2 is explained variance, S_y is specific yield, employing the lower, upper or mean values of the range categories of Fig. 13.

that with the low S_y values the difference in the two ET means (i.e., water-balance and CREMAP derived) is about 0.5%, with the high S_y values less than 2%.

In all cases, the individual mean annual sub-catchment CREMAP ET estimate is within 10% of the water-balance derived value. The only exception is the Lower Republican sub-catchment in Kansas where CREMAP gives a mean annual runoff rate of 99 mm as the difference in P and ET for the 2000–2009 period. The USGS web-site of computed watershed runoff rates yields 5.42 mm for the same period. A study by Sophocleous [19] specified the mean annual runoff value of the Lower Republican basin (between Concordia and Clay Center, KS) as 106 mm over the 1977-1993 period. For the same period the USGS site gives 38.5 mm as computed runoff (although not for the exact two gauging stations, but rather for the sub-catchment area displayed in Fig. 5). For the 2000-2009 period, employing the gauging station discharge measurements of Concordia, KS and Junction City, KS with the corresponding published drainage area values, one obtains a mean annual runoff value of 37.44 mm which is close to the above USGS computed runoff value, suggesting that runoff may not have changed significantly between the two periods. As a tradeoff, mean annual runoff was assumed to be a magnitude higher than 5.42 mm, i.e., 54.2 mm for the Lower Republican sub-catchment in Fig. 15, a value about halfway between 5.42 and 106 mm.

Brown and Caldwell [1], employing very detailed plot-sized estimates of water consumptions of different vegetation types, found that ET was 551 mm over the three Nebraska NRDs for the 2000-2005 period. CREMAP yields a mean annual ET rate of 562 mm for the same period, a discrepancy of 2%, which is remarkable, considering the large differences in the estimation approaches.

For the Republican River basin the present estimates are clearly superior to those of a global ET estimation approach (a fairly complex one in comparison with the present method) by Mu et al. [13]. The latter yields a mean annual ET rate (2000-2009) of 315 mm for the whole basin, which is only 60% of the CREMAP value. Note that the 315 mm value does not contain the ET rates of open water bodies. From GIS analysis of the 30-m land cover/land use data, the latter has less than 0.5% of the total drainage area of the watershed, thus omission of these values cannot significantly affect the above estimate. This large underestimation shares the often mentioned property of remotely sensed data, i.e., that they convey valuable spatial patterns, but may be off in the absolute sense of the variable [2]. Indeed, the Mu et al. [13] estimates have a relatively high R^2 value of 0.74-0.76 with sub-catchment water-balance derived ET values.

4 Conclusions

Spatially distributed ET rates can be estimated with the help of a new, calibration-free ET mapping (CREMAP) approach ([22, 23]). The method requires MODIS daytime surface temperature (T_s) data and employs the Priestley-Taylor equation [16] as well as the WREVAP model [12] with air temperature, humidity and global radiation inputs for estimating the regional ET rate which is subsequently disaggregated by the T_s values. Due to its simplifying assumptions it is expected to perform best over a flat-to-rolling terrain with fairly good and varied vegetation cover. Under these conditions it is currently expected to regionally outperform most global ET estimation techniques, as it indeed significantly outperformed a recently improved and updated such ET estimation algorithm by Mu et al. [13] over the Republican River basin in the US. Since the model does not have any parameters to calibrate and requires minimal data input, it is very easy to use and readily transportable between geographic regions where the above pre-requisites are met.

With the help of CREMAP, it was found that the three states, sharing the Republican River watershed, consume different relative quantities (with respect to precipitation, P) of water as ET. On a mean annual basis over the 2000-2009 period, the largest consumer was Colorado, with its ~103% of ET / P value, followed by Nebraska with ~102% and by Kansas with a mere ~95%. The latter value changes to about 101% when the Kansas basin area upstream of Hardy, NE is considered. It has also been found that regions of the largest ET / P ratios overlapped fairly well with areas of the largest groundwater depletions. It has to be noted that a ratio less than 100% does not in itself guarantee sustainability, since groundwater may continue to decline in an area where recharge continues to be smaller than total groundwater discharge (including natural, such as e.g., baseflow to streams, and/or man-made processes, such as center-pivot irrigation) while total ET remains way below the precipitation rate.

Deviation of the current ET / P ratios from an “undisturbed” value may be indicative of the extent of accumulated (not climate-related) changes in the hydrologic cycle of the Republican River basin. An “undisturbed” ET / P ratio can be obtained by considering the ET rate of native vegetation. Table 2 lists the so-obtained “undisturbed” and current ET / P ratios with the concurrent change in the values by states. The largest change (3.95%) can be inferred to have taken place in Colorado, followed by Kansas (2.76%), upstream of Hardy, NE, with almost the same extent of change in Nebraska (2.67%).

A comparison of these values with the historical change in streamflow rates (Figs. 2 and 4) reveals an interesting picture. From the change in the precipitation recycling ratio in Table 2 one would expect the largest streamflow depletions in Colorado and roughly the same change in Kansas and Nebraska. However, the Republican River near Hardy, Nebraska and Junction City, KS exhibits the smallest decline (after the 1930s) among the eight gauging stations identified in Fig. 5. Similarly, while the Arikaree conforms to expectations, the North Fork Republican does not, even though its watershed contains the largest groundwater decline in Colorado. A possible explanation may come from differences in the regional groundwater flow contribution to streamflow by watersheds, further modified by groundwater depletions and accretions (e.g., due to canal leakage in NE), as found in Fig. 8. These net groundwater fluxes can at least partially offset the expected flow depletions as a result of increased ET rates. For example, the Brown and Caldwell [1] study estimates net groundwater flux to the Nebraska portion of the watershed to be in the order of $10^8\,m^3$ annually, which is about 40% of the mean annual Republican River flow near Hardy, NE. As a consequence, water development sustainability issues cannot be correctly addressed without inclusion of the groundwater fluxes to the Republican River basin. The present study, through an improvement of the spatially variable ET rate estimates, may help in these efforts.

The current ET estimation algorithm, due to its simplicity and calibration-free property, is expected to be used by water resources specialists with similar problems in their hands and by decision makers to better regulate existing and future water resources. While the ET estimation method may yield an inaccurate ET value for a given MODIS cell locally when the cell properties (e.g., albedo value or surface roughness) deviate significantly from the regional mean, it is expected to provide a fairly accurate ET value over a collection of MODIS cells (since with size the effect of local deviations are expected to even out), exactly what was required in the present study (i.e., the ET rates of predefined areas) and anticipated in most regional-scale water resources investigations. It can also prove useful in a) testing more complex and data intensive ET estimation methods; b) assisting with parameter calibrations of such complex methods as well as of regional groundwater models via improving their recharge estimates through improved spatially distributed monthly ET rates.

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Disclaimer

The views, conclusions, and opinions expressed in this study are solely those of the writer.

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