Towards a representative scale of the groundwater footprint based on the ecohydrological impacts of groundwater abstraction

Master thesis

by

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Abstract

Groundwater stress due to over-abstraction and associated negative effects (decreasing groundwater levels, saltwater intrusions, land subsidence, drying-out of wells, reduced baseflow, degradation of phreatic land…) are a major threat to many ecohydrological systems globally. Concepts like the groundwater footprint by Gleeson et al. (2012) aim to quantify the pressure on groundwater resources for large aquifer systems.

It has been shown (Ahner, 2017; Alley et al., 2017; Eldardiry et al., 2016) that large-scale groundwater stress calculations are not representative as a measure of sustainable groundwater use on local scale. Due to spatial heterogeneities within both the ecohydrological system and the intensity of water use, the impacts on local or regional scale can vary greatly.

This work aims to determine a representative scale for quantifying groundwater stress by considering the individual needs of local ecohydrological systems, the spatial scale on which ecohydrological impacts of groundwater abstraction occur and by identifying the scale on which changes in the water balance govern those impacts.

To achieve this, we derived environmental flow requirements and modeled the impact of groundwater abstraction on groundwater levels, phreatic land, baseflow and groundwater flow using data of an existing calibrated groundwater model for the Republican River basin (Great Plains, USA). We investigated how the effects of groundwater abstraction vary with time and scale and how sensitive the ecohydrological systems are to changes in the groundwater balance at local, regional and basin scale.

The results showed that the impact of groundwater abstraction occurred on different scales. However, the modeled impacts of groundwater abstraction on a local scale could be better explained by regional to basin scale changes in the groundwater balance rather than by local changes. Furthermore, we showed that groundwater abstraction may change the location of the groundwater drainage basin boundaries and thus the reference area to evaluate groundwater abstraction and recharge.

We conclude that our method is appropriate to find the effective scale of major pressures on the ecohydrological system and the scale of the water balance which they respond to and thus to identify a representative scale for the groundwater footprint.

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1 Introduction

Groundwater resources are under increasing pressure. Over-abstraction of groundwater and declining groundwater levels are the consequences of a water resources management that exceeds natural recharge capacities. In many ecohydrological systems, the long-term overuse of groundwater resources has caused several negative effects like water level decline, saltwater intrusions, dry-running of wells, subsidence and degradation of groundwater-dependent wetlands, riparian ecosystems and groundwater-fed surface water reservoirs.

In the last decade, different attempts have been made to quantify the pressure on global groundwater resources by calculating areal stress indices (Döll et al., 2012; Gleeson et al., 2012; Hoekstra et al., 2012; Wada et al., 2010). Gleeson et al. (2012) introduced the groundwater footprint, by means of the area-averaged annual abstraction of groundwater minus return flow divided by the recharge rate minus the groundwater contribution to environmental streamflow (i.e. environmental flow requirements) and applied it to large aquifer systems of the world. For groundwater abstraction, return flows (artificial recharge) from irrigation, and recharge, Gleeson et al. (2012) used inputs from Wada et al. (2010, 2012). Environmental flow requirements are the quantitative contribution of groundwater to surface water necessary to sustain ecosystem services (Gleeson et al., 2012; Smakhtin et al., 2004). Environmental flow requirements were computed per basin as the monthly streamflow (at the basin outlet) that is exceeded in 90 % of the simulation period. The outputs of the grid-based groundwater footprint calculations were then summarized and compared to the area of the respective aquifers.

It has been shown (Ahner, 2017; Alley et al., 2017; Eldardiry et al., 2016) that large-scale groundwater stress calculations only have a limited informative value as a measure of sustainable groundwater use on a local scale. More precisely, for an entire basin, the calculated groundwater stress might be acceptable, but due to spatial heterogeneities within both ecohydrological system and intensity of water use, the impacts on local or regional scale can still be high. Eldardiry et al. (2016) made an integrated evaluation of water stress on surface- and groundwater resources for water systems in Louisiana and pointed out the heterogeneity of water stress within one state. Ahner (2017) compared groundwater stress calculations for federal states, basins and sub-basins in Germany. The results illustrate that the selected spatial reference unit has a strong influence on the calculated level of groundwater stress. Alley et al. (2017) compared global-scale indices to regional modeling and illustrated that there is a scaling problem of global scale indices and provided evidence for the limited informative value for complex hydrological systems with intensive use.

Bredehoeft (2002) claims that determining sustainable groundwater use cannot be accomplished by using simple groundwater balances and groundwater recharge as a reference volume. According to his findings, the parameter that determines the available amount of groundwater is capture which responses dynamically to processes in the aquifer systems and can only be approximated with groundwater modeling. While generally questioning the idea of using the water balances as a measure of sustainable groundwater use he does not take into account groundwater as an important source of environmental streamflow.

This points out that the underlying concepts of sustainable groundwater use differ greatly among the various approaches for the assessment of available groundwater resources. Gerten et al. (2013) and Pastor et al. (2014) criticize global water assessments as they are often purely anthropocentric and neglect environmental flow requirements leading to an overestimation of the water quantity available for human consumption. Pastor et al. (2014) therefore demands a full acknowledgment of nature as an independent water user and an assessment of the water resources needs of ecohydrological systems on local scale.

However, the definition of the groundwater-resources-needs of natural systems is difficult as ecohydrological systems react dynamically on a changing resources availability.

The illustrated problems show that in order make the groundwater footprint applicable on all scales we need to account for: (i) the specific local environmental flow requirements, (ii) consider the scale on which the impacts of groundwater abstraction occur and (iii) identify the scale on which changes in the water balance govern those impacts.

To achieve this, we investigate what the negative ecohydrological effects of groundwater abstraction have been over time and how they scatter comparing different hydrological scales. Do the modeled negative effects of groundwater abstraction correlate best with the stress index at local, regional or basin scale? Furthermore, we discuss which assumptions have to be made and which parameters of the water balance need to be considered for quantifying groundwater stress.

2 Methodology

2.1 Study area

The analysis is based on the modeling results (cell-by-cell groundwater balances and hydraulic head results) of the Republican River Groundwater Model (2003) (Figure 1). It covers an area of about 91345 km² of which about 56575 km² belong to the Republican River basin. The Republican River basin is a drainage system originating in the high plains and is intersecting the states of Colorado, Nebraska and Kansas. It is fully underlain by the Ogallala aquifer, a heterogeneous sandstone formation that forms the largest groundwater system in North America. The river basin contains shallow alluvial aquifers that are hydraulically strongly connected to the Ogallala aquifer. Together they serve as the primary water source in the basin (Bureau of Reclamation, 2016).

Prior to the 1940s, the water balance of the Republican River basin was only insignificantly influenced by human activity. With the construction of surface water channels in the 1940s, water from the South Platte River was imported to the Republican River basin and acted from then onward as a significant source of recharge in the north-eastern part of the basin. Between 1948 and 1957 several dams (Harlan County Lake, Bonny Reservoir, Swanson Lake, Hugh Butler Lake, Harry Strunk Lake, Keith Sebelius Lake, Enders Reservoir) were constructed in the basin to serve as flood protection, wildlife habitat, and for surface water irrigation and recreational purposes (Bureau of Reclamation, 2016; Republican River Compact Administration, 2003). Beginning in the 1950s well pumping started to increase rapidly until the mid-1970s. From then onward it established itself on a high level continuing to be a major stress in the basins' water balance. Recharge increased simultaneously with increased groundwater pumping due to its application for irrigation purposes (Republican River Compact Administration, 2003).

2.2 Design of the Republican River Groundwater Model

The Republican River Groundwater Model (2003) is a 2D transient single-layer model bounded below by the impermeable Pierre Shale. It models hydraulic head, water balance and baseflow at specific locations for the Republican River basin, High Plains, USA (simulation period 1918-2000). The model has a spatial discretization of one square-mile and monthly stress periods. As aquifer parameters it uses specific yield information obtained from USGS investigations and calibrated hydraulic conductivities.

Steady state recharge or initial conditions are an average of the 1918 to 1940 recharge, adjusted with a global multiplier of 0.75 to replicate the long-term upward trend in hydrographs observed in the western part of the model domain. It assumes no well pumping, and only precipitation as a source of groundwater recharge prior to 1940.

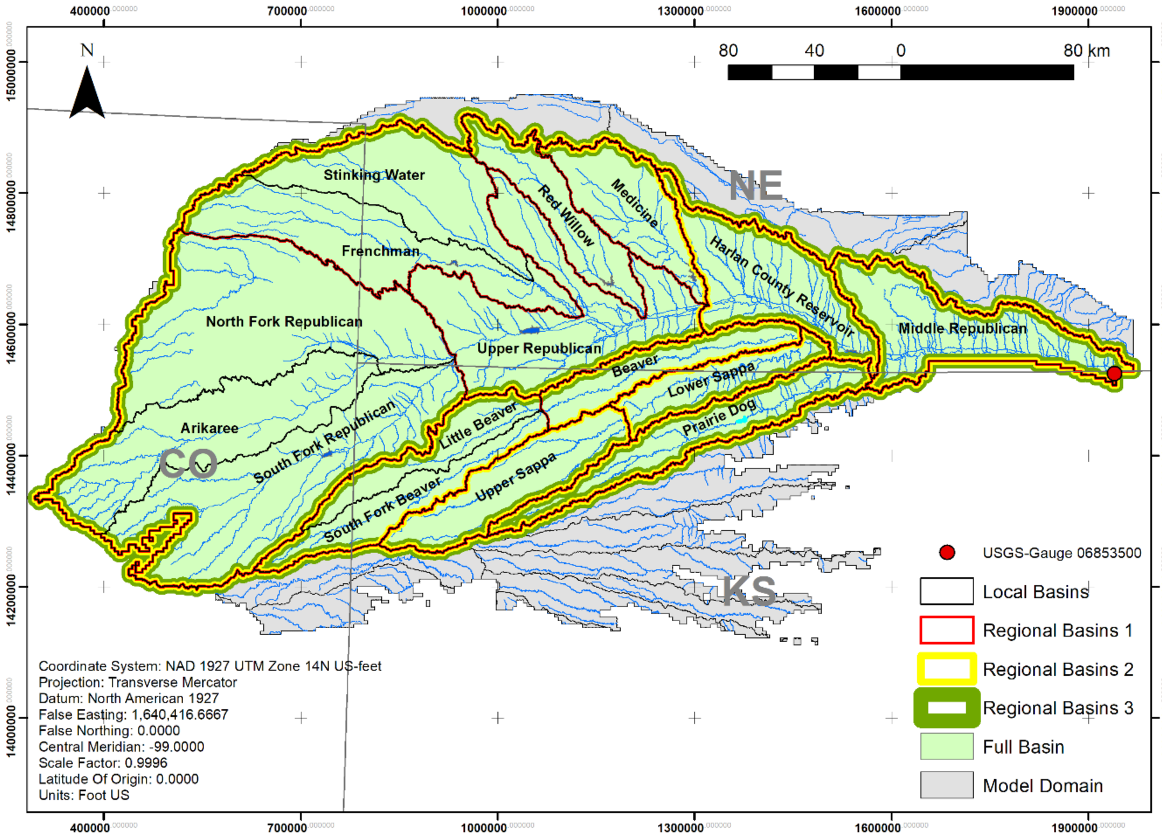

Figure 1: Map of the Republican River Groundwater Model domain. The map shows the hydrological basin scales used for the analysis of groundwater balance and ecohydrological indicators: local basins (framed in black, labeled by name), regional basins (framed in red, yellow and green) and the full Republican River basin (green area). Marked in red is the gauge at the basin outlet near Hardy, NE (USGS-gauge 06853500).

For the transient Republican River Groundwater Model, total recharge was calculated as the sum of precipitation recharge (calculated by kriging the annual precipitation of stations in the basin), surface and groundwater irrigation recharge and canal leakage. Well pumping rates, surface and groundwater irrigation recharge, canal leakage and corresponding locations were obtained from state databases. Evapotranspiration was modeled based on monthly data obtained from climate stations in the basin and a set of sub-basin factors that vary with year and sub-basin. The implementation of streams in the model was based on USGS stream network data.

The model was calibrated using 350233 water level records from 10835 sites which were obtained from the Ground Water Site Inventory (GWSI) maintained by the United States

Geological Survey (USGS). Baseflow calibration was based on 65 independent hydrograph separation analyses (Pilot Point method) (Republican River Compact Administration, 2003).

For our analysis, we applied some minor adjustments to the original Republican River Groundwater Model input files (see Appendix II). The model was executed with USGS MODFLOW-2005 (v.1.12.00) double precision mode (convergence criterion: head change criterion = 0.001 ft., residual criterion = 0.1 ft^3).

We used USGS Zone Budget (v.3.01) to calculate water balances for zones and composite zones associated with surface water basins intersecting the model domain (see Figure 1). Zone Budget accomplishes this by merging the cell-by-cell water balances according to location-based zones, which we defined in a zone-file. The defined zones (Local Basins; see Figure 1), correspond to the HU-8 sub-basins of the USGS Watershed Boundary Dataset (Watershed Boundary Dataset, 2017). For the composite zones, the sixteen HU-8 sub-basins contributing to the Republican River were merged according to the stream network order and form different levels of regional basins (Regional Basins 1-3; see Figure 1). The composite zone that consists of all sixteen zones corresponds to the entire share of the Republican River basin intersecting the model domain (Full Basins; see Figure 1).

2.3 Calculation of the groundwater footprint

We calculated the groundwater footprint (Eq.1) as

$$GF = \frac{W}{(R^{*} - E)} \qquad \text{(Eq.1)}$$

where W is total groundwater pumping, R^* is the accumulated natural (precipitation) and artificial (channel leakage, surface- and groundwater irrigation) recharge to groundwater and E is the environmental flow requirement (i.e. groundwater contribution to environmental streamflow). In contrast to the approach of Gleeson et al. (2012) the groundwater footprint is not given as an area but as the share of the annually renewed groundwater resources used up by groundwater pumping. The groundwater footprint is thus dimensionless.

All terms of the equation correspond to the spatial scales illustrated in Figure 1. We extracted the input values for W and R^* directly from the zonal water balances. For the approximation of environmental flow requirements, we used the steady state value for net-leakage from model cells to the corresponding stream reaches, henceforth referred to as modeled baseflow. To make the resulting environmental flow requirements and groundwater footprint more comparable to the methodology used by Gleeson et al. (2012), we determined Q50- and Q90- baseflow

(Smakhtin et al., 2004) for the Republican River basin at Hardy, NE (USGS-gauge 06853500, see Figure 1) close to the outlet of the model domain. Q50- and Q90- Baseflow values where calculated as the 4-year-median of monthly mean discharge (Period 1960-2000).

2.4 Determining the ecohydrological impacts of groundwater abstraction

We investigated the effects of groundwater abstraction with a set of ecohydrological indicators: Mean hydraulic head change, change of potential phreatic land area, area with a drawdown > 10 m, modeled baseflow and inter-basin groundwater flux. We acknowledged that groundwater abstraction can also cause other negative effects in the natural system like subsidence or saltwater intrusions. However, they were not addressed in this study. We assumed the pre-1918 (steady-state) conditions as the "natural" ecohydrological status of the basin, serving as the reference value to identify the respond of the ecohydrological indicators.

We defined the ecohydrological indicator for the potential occurrence of phreatic land as the area where the water level is between 3 m below and 3 m above the topographic surface. It is expressed as the annual-mean discrepancy from the steady state conditions in percent. For this, we converted the monthly Modflow head output file to raster files (resolution: 1-mile^2), resampled and compared them to a digital elevation model (National Elevation Dataset, 2017). We reclassified the resulting monthly raster files to identify the pixels in the desired value range.

Additionally, we monitored the impact on groundwater levels with two indicators. The first monitored the monthly mean hydraulic head change for each defined basin scale. The change is expressed as the annual-mean discrepancy from the steady state conditions in meters. As a second indicator, we calculated the area were a water level decrease of more than 10 m compared to steady conditions is observed. It is expressed as the annual-mean discrepancy from the steady state conditions (= 0) in percent.

For baseflow observation, we took the monthly modeled baseflow for each defined basin scale (see Figure 1). It is expressed as the annual-mean discharge in cubic-meters per second.

We used the inter-basin groundwater flux, expressed in cubic-meters per second, to monitor whether the watershed boundaries of the basins change over time. It is calculated by subtracting the inflow of groundwater above the zonal watershed boundaries from the outflow.

2.5 Time and scale-dependent system characterization

We conducted the analysis for the spatial scales: local basins, regionally merged basins (regional basins 1, regional basins 2, regional basins 3) and the full basin of the Republican River (see Figure 1). They correspond to the same zones and composite zones that were used as the spatial reference for the calculation of zonal groundwater balances with USGS ZoneBudget (see section 2.3).

As a first step, we conducted a timeseries analysis of the groundwater footprint and the defined ecohydrological indicators to identify overall trends for the Republican River basin. For this, we calculated the annual means for the groundwater footprint and the ecohydrological indicators based on the monthly modeled values for each stress period.

To identify spatial variations of the groundwater footprint and ecohydrological indicators, we plotted groundwater footprint and ecohydrological indicators calculated for local, regional and basin scale against the corresponding basin area for selected times. We selected the times for which the spatial variations of groundwater footprint and ecohydrological indicators are displayed, according to significant turning points (parameter peaks or onsets) identified from the timeseries in Figure 2.

Furthermore, we calculated Pearson correlation coefficients (r) of the ecohydrological indicators with the corresponding groundwater balances of well pumping (W) over recharge (R^*) for local, regional and full basin scale after the employment of increased groundwater pumping (period: 1950-2000) to gain insight on which scale the modeled ecohydrological indicators can be explained best by the groundwater balance. The Pearson correlation coefficient (r) [-1-1] is a measure for the degree of linear relationship between two variables. The relationship between the coefficient of determination (R^2) and the Pearson correlation coefficient (r) is $R^2 = r^2$. We assumed a direct response of ecohydrological indicators on changes in the Republican River water balance if the hydrological system can be considered closed. The median of the r coefficients for each local basin was calculated to identify the overall trend.

3 Results

3.1 Temporal variations of groundwater footprint and ecohydrological indicators

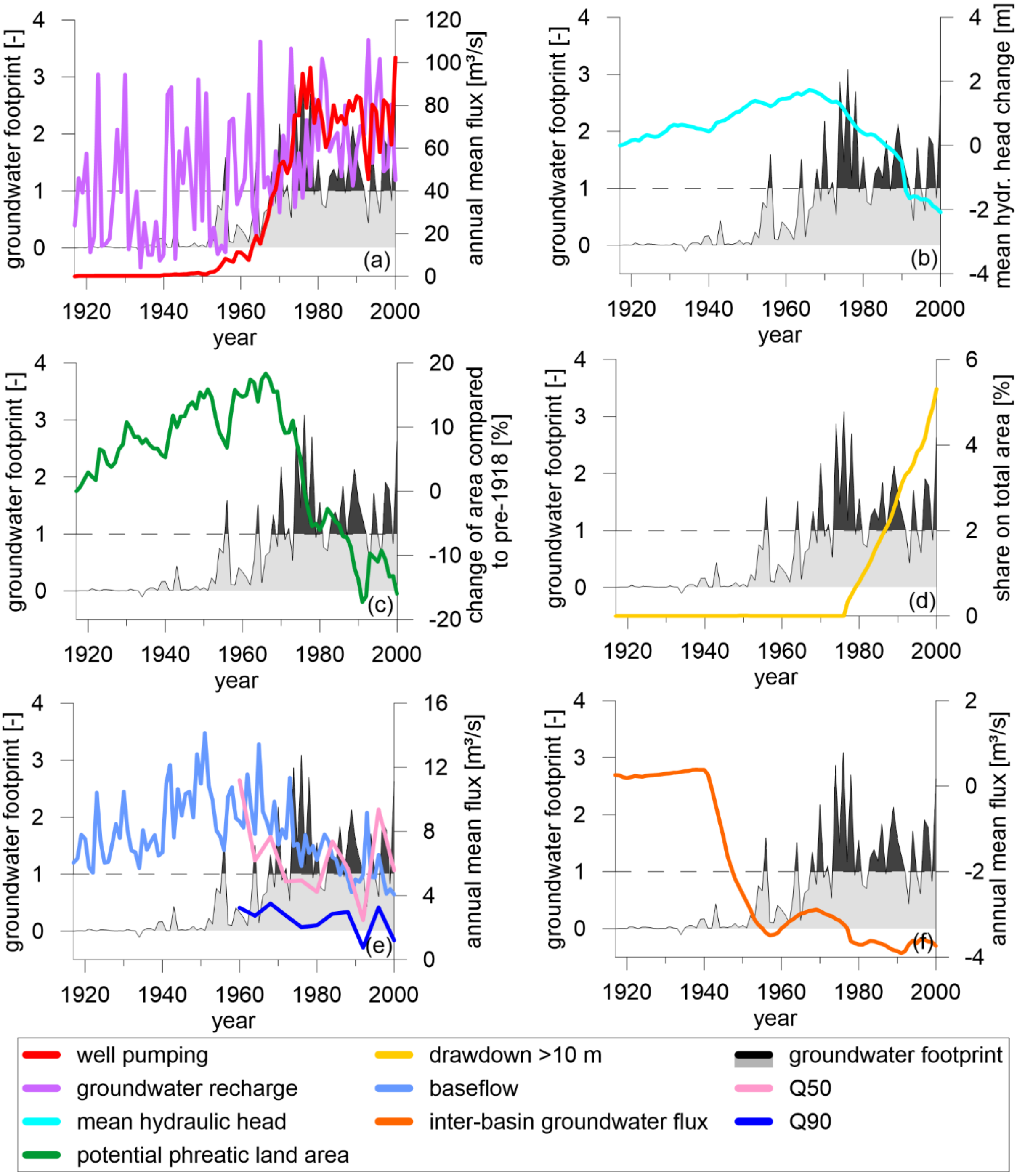

Figure 2: Annual mean variations of (a) the groundwater footprint and the ecohydrological indicators ((b) mean hydraulic head change; (c) change of potential phreatic land area; (d) share on total area with a drawdown > 10 m; (e) modeled baseflow; (f) inter-basin groundwater flux) in the Republican River basin for the modeled period (1918-2000). In black is marked where the groundwater footprint exceeds the critical value of 1. Q50 and Q90 (e) for the Republican River basin at Hardy, NE (USGS-gauge 06853500) close to the outlet of the model domain. Q50 and Q90 values where calculated as the 4-year-median of monthly mean discharge (Period 1960-2000).

While showing strong interannually variability, the calculated groundwater footprint in the Republican River basin generally followed an upward trend exceeding the critical value of groundwater footprint = 1 for the first time in the 1950s and reaching its peak in the mid-1970s at a value of about 3. From then until 2000 the critical value of 1 was exceeded in most of the years. Figure 2a shows that the annual mean well pumping rate (W) started to increase rapidly in the 1950s and remains stable from the mid-1970s at a level of 100 m^3/s and 40 m^3/s. The annual mean groundwater recharge rate (R*) followed a general upward trend while showing high inter-annual variations between 4 m^3/s and 110 m^3/s until the 1970s and afterwards between 30 m^3/s and 110 m^3/s. Years of low annual mean groundwater recharge rate (R*) coincide with high annual mean well pumping rates.

The timeseries of modeled change of the annual mean hydraulic head compared to pre-1918 (steady-state) conditions (Figure 2b) showed an increase of hydraulic head until the late 1960s to about 2 m above steady state conditions, followed by a strong decline of about 4 m until 2000.

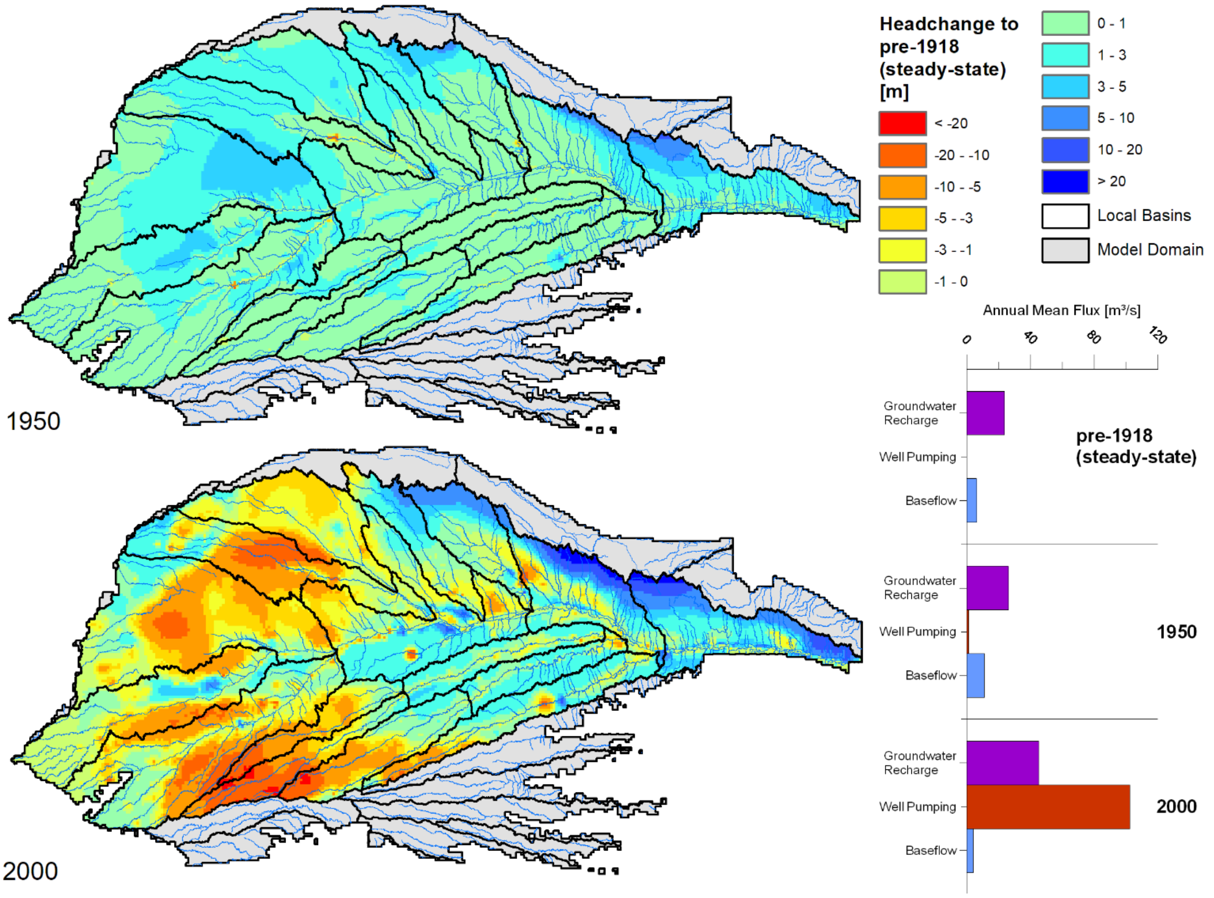

Figure 3: Map of hydraulic head change compared to pre-1918 (steady-state) conditions for December 1950 (upper left) and December 2000 (lower left). Bar-chart of the annual mean rate of groundwater recharge, well pumping and baseflow for pre-1918 (steady-state) conditions, 1950 and 2000 (lower right).

Figure 3 illustrates the change of hydraulic head compared pre-1918 (steady-state) conditions for December 1950 (upper left) and December 2000 (lower left) within the Republican River basin. For 1950 we found that the hydraulic head remained stable in the major part of the basin.

Along the northeastern border of the Republican River basin hydraulic head increased up to 10 m. Strong drawdowns were spatially limited to a few locations within the South Fork Republican, Medicine and the Frenchmen local basins. For 2000 we found strong and widely spread hydraulic head decreases of up to 20 m in the west (local basins: Stinking Water, Frenchmen, North Fork Republican) and decreases partly exceeding 20 m the southwest of the Republican River basin (local basins: Arikaree, South Fork Republican, Little Beaver, South Fork Beaver, Upper Sappa). Along the northeastern boundary of the Republican River basin the hydraulic head increased up to more than 20 m (local basins: Medicine, Harlan County Reservoir, Middle Republican). Furthermore, locally limited hydraulic head increases of up to 20 m occurred predominantly in the Upper Republican and Arikaree local basin. The bar chart of the annual mean rates for groundwater recharge, well pumping and baseflow (Figure 3, lower right) shows that the overall increase of hydraulic head observed in 1950 coincides with an increased baseflow, and the overall decrease of hydraulic head modeled for the year 2000 coincides with a decrease of baseflow, a moderately increased groundwater recharge and a strong increase of well pumping.

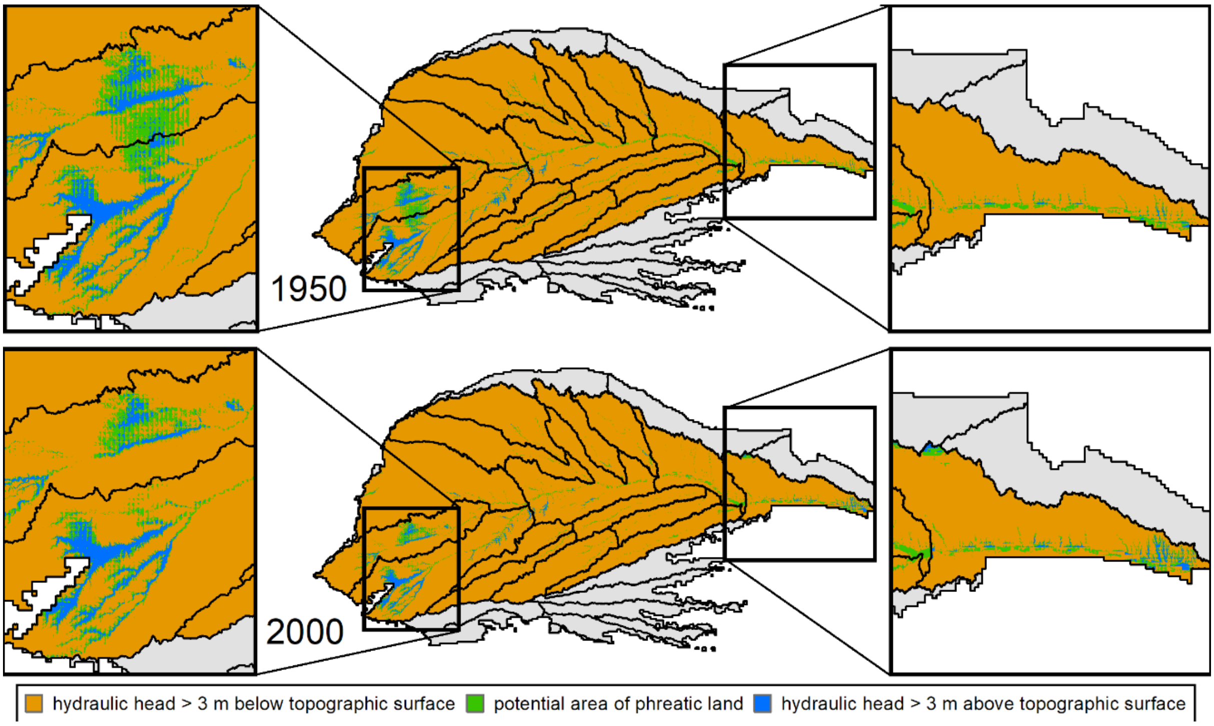

Figure 4: Potential area of phreatic land in the Republican River basin prior to the onset of increased groundwater abstraction (December 1950) and for the end of the modeled period (December 2000).

The timeseries of modeled potential area of phreatic land (Figure 2c) increased about 20 % until the late 1960s compared to pre-1918 (steady-state) conditions, followed by a strong decrease to about -18 % until 2000. The decrease of potential area of phreatic land in the Republican River basin between the onset of increased groundwater abstraction (1950) and the end of the modeled period (2000) is shown in Figure 4.

The first drawdown > 10 m compared to steady state conditions (Figure 2d) was modeled for the mid-1970s which then spread out continuously to about 5.5 % of the total area in 2000. The onset of drawdown > 10 m was falling together with the year where the maximum groundwater footprint of about 3 (1976) for the Republican River basin was modeled.

Figure 2e shows the strong inter-annual variations of the annual mean modeled baseflow. Starting off with a discharge of 6 m^3/s for steady state conditions, it reached the maximum of about 15.2 m^3/s in 1950. After 1950, the annual mean of modeled baseflow declines to about 4.1 m^3/s. The calculated 4-year-median Q50- and Q90- baseflow values (Figure 2e) for the period 1960 till 2000 are in line with the downward trend of the modeled baseflow. During the observation period Q50 declined from 11.4 m^3/s to 5.8 m^3/s, and Q90 from 3.2 m^3/s to 1.7 m^3/s. The downward trend observed for the modeled baseflow coincides with the upward trend in the modeled groundwater footprint.

Inter-basin groundwater flux (Figure 2f) remains stable at a level of about 0.2 m^3/s until the 1940s and then significantly decreased to a level of about -3.3 m^3/s in the 1950s. Another distinct decrease happened in the late 1970s, with the inter-basin groundwater flux reaching a new stable state of about -3.7 m^3/s.

3.2 Spatial variations of groundwater footprint and ecohydrological endicators

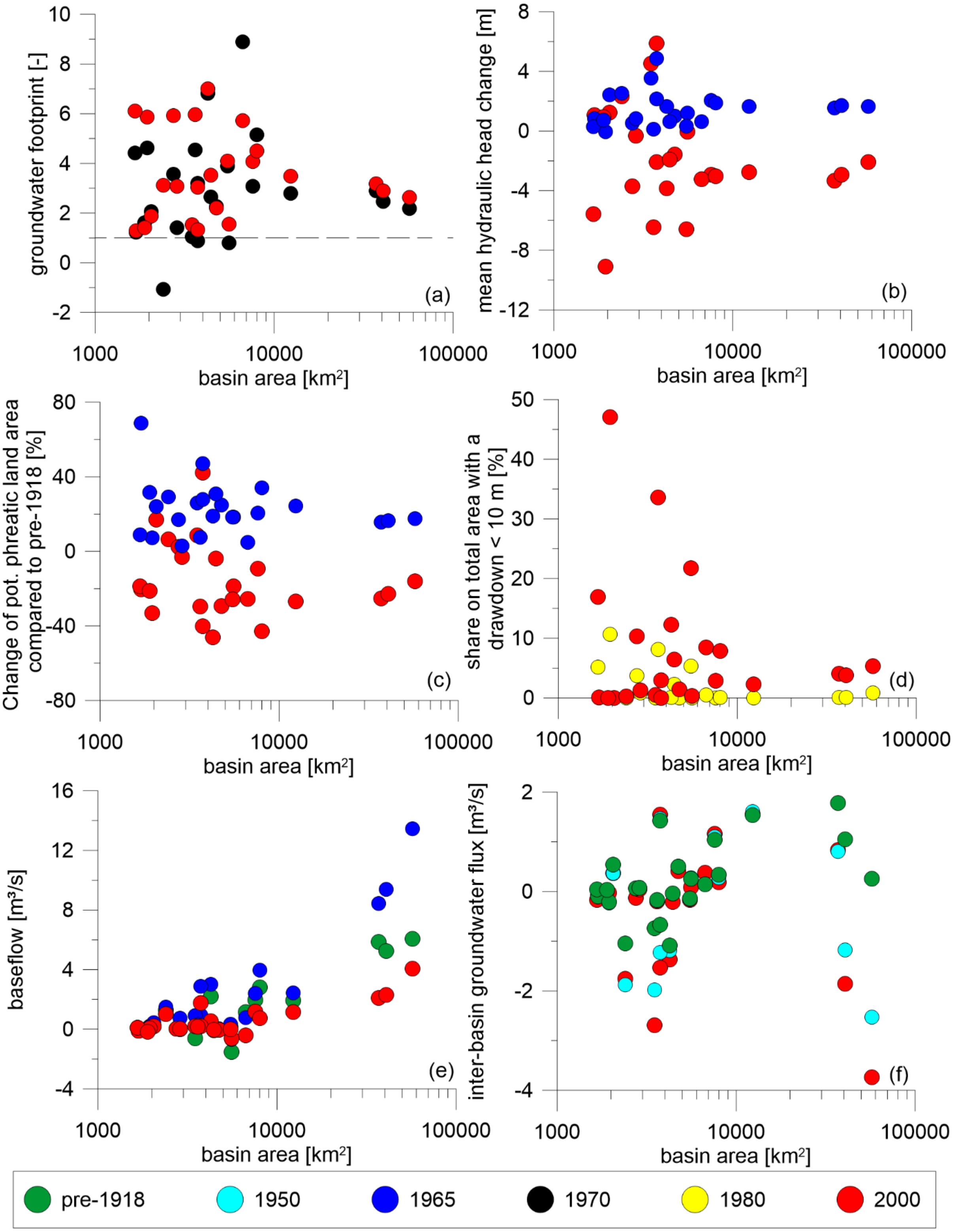

Figure 5: Spatial variations of (a) the groundwater footprint and the ecohydrological indicators ((b) mean hydraulic head change; (c) change of potential phreatic land area; (d) share on total area with a drawdown > 10 m; (e) modeled baseflow; (f) inter-basin groundwater flux). Each point represents the state of one local basin (scale = 1550 to 7462 km^2), regional basins (scale =3478 to 40245 km^2) or the full basin (56576 km^2).

Figure 5a illustrates the heterogeneity of the groundwater footprint on different scales. Negative values (local basin: Medicine for the year 1970) are calculated if the environmental flow requirements derived from steady state modeled baseflow exceeds the modeled groundwater recharge (R^*) for the same year. For the year 1970 the critical groundwater footprint value of 1 was exceeded on most scales with groundwater footprint ranging from -1 to about 9. For the year 2000 the groundwater footprints showed compared to 1970 conditions a higher mean groundwater footprint but a smaller range of 1.2 to 7.

The annual mean hydraulic head changes compared to steady state conditions for 1965 displayed in Figure 5b showed, with a range from +0.2 m to +2.3 m, a comparably homogeneous increase throughout the entire basin. For the year 2000 the changes of hydraulic head scattered more, ranging from an increase of +6 m to a decrease of -9.2 m. We modeled the strongest head increase in hydraulic head for the local basins Medicine (+2.2 m), Harlan County Reservoir (+4.5 m) and Middle Republican (+6 m) in the east of the Republican River basin and the strongest head decrease for the basins Upper Sappa (-3.9 m), South Fork Beaver (-9.2 m) and Little Beaver (-5.6 m) in the south of the Republican River basin for 2000.

The area of potential phreatic land for 1965 displayed in Figure 5c increased compared to steady state conditions in the entire basin. On the local scale the increase ranged between 2.6 % to 68.8 %. For the year 2000 the area of potential phreatic land decreased in all basins compared to 1965 and in most basins compared to steady state conditions. On the local basin scale the change of potential phreatic land area compared to steady state conditions scattered between an increase of 42 % and a decrease of 46 %. For the year 2000 we modeled the strongest increase of potential phreatic land for the local basins Red Willow (+16.9 %) and Middle Republican (+42 %) in the east of the Republican River basin and the strongest decrease of potential phreatic land for the local basins Frenchman (- 46 %), Stinking Water (-40.2 %) and South Fork Beaver (- 33 %).

According to the results presented in Figure 5d drawdown greater than 10 m was found only in some of the local basins. For the year 1980 drawdown greater than 10 m was present in the basins Upper Sappa (3.7 %), South Fork Beaver (10.6 %), Little Beaver (5.1 %). For the year 2000 drawdown greater than 10 m increased for the local basins Upper Sappa (10.3 %), South Fork Beaver (47 %) and Little Beaver (16.9 %). Additionally, more than 5 % of the total area of the local basins South Fork Republican (8.5 %) and Frenchman (12.2 %) had a drawdown greater that 10 m. For the other local basins, the area with a drawdown exceeding 10 m was 0 or below 5 % of the total area.

Figure 5e shows that the strongest change of modeled baseflow was found on basin (6.05 m^3/s in steady state to 4.07 m^3/s in 2000) and regional scale. On local scale change of modeled baseflow was mainly observed for the basins North Fork Republican (1.96 m^3/s in steady state to -1.18 m^3/s in 2000), South Fork Republican (1.15 m^3/s in steady state to -0.43 m^3/s in 2000), Upper Republican (-1.52 in steady state to -0.61 m^3/s in 2000), Frenchman (2.2 m^3/s in steady state to 0.56 m^3/s in 2000) and Harlan County Reservoir (-0.63 in steady state to 0.2 m^3/s in 2000).

For the inter-basin groundwater flux (Figure 5f) we observed the most severe changes on the watershed boundaries of the full basin. Major changes of inter-basin groundwater flux on local scale are limited to the basins Frenchman (-1.09 m^3/s in steady state to -1.37 m^3/s in 2000), Medicine (-1.04 m^3/s in steady state to -1.75 m^3/s in 2000), Harlan County Reservoir (-0.74 m^3/s in steady state to -2.69 m^3/s in 2000) and Middle Republican (-0 .67 m^3/s in steady state to -1.53 m^3/s in 2000).

3.3 Correlations of local ecohydrological indicators and groundwater balance at local, regional and basin scale

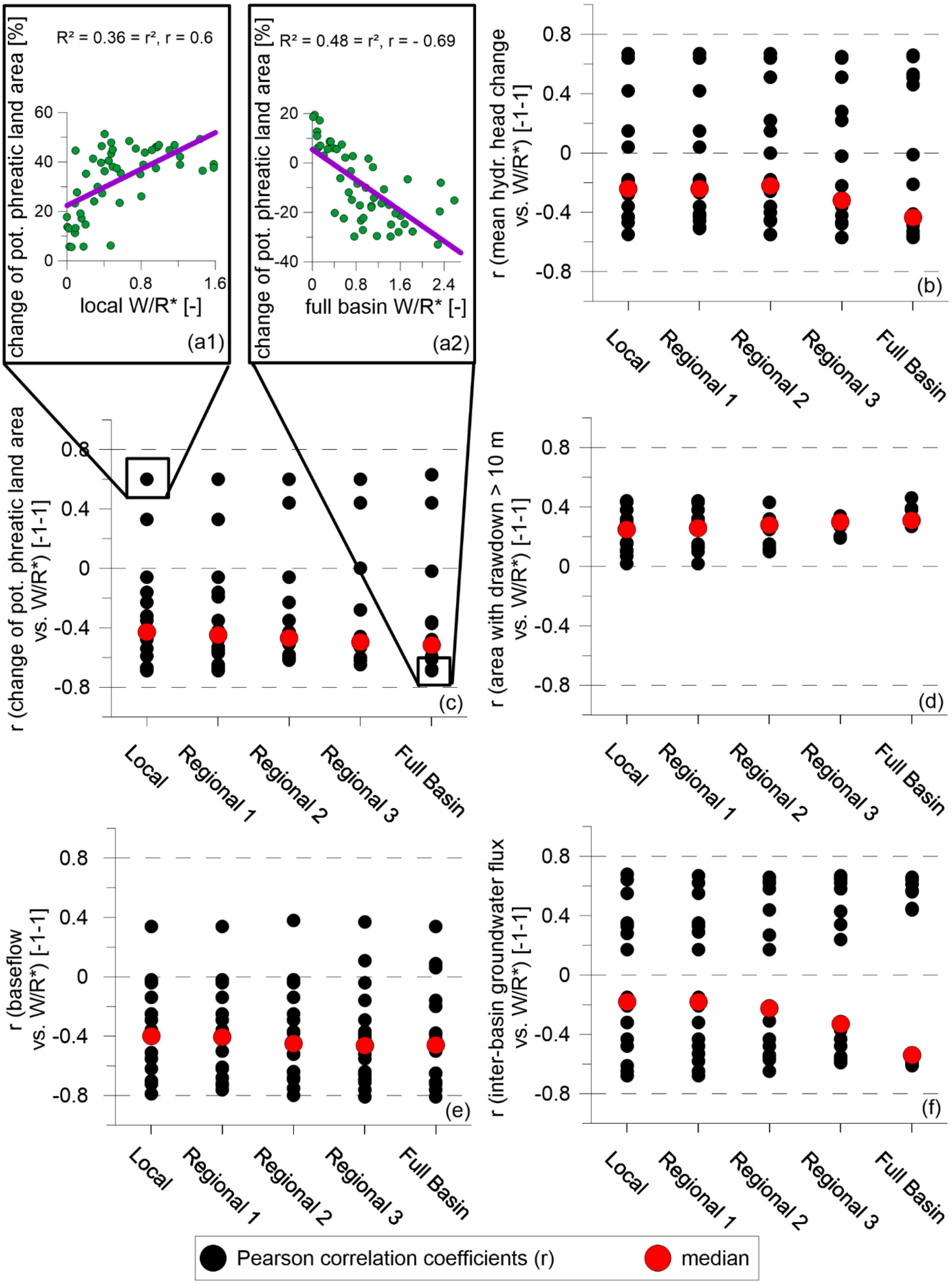

Figure 6: Exemplary correlation of an ecohydrological indicator with the local and the full basin water balance (a1, a2). Pearson correlation coefficients of locally modeled ecohydrological indicators ((b) mean hydraulic head change; (c) change of potential phreatic land area; (d) area with a drawdown greater than 10m; (e) modeled baseflow; (f) inter-basin groundwater flux) with the groundwater balance at local,

regional and basin scale after increasing groundwater pumping in the 1950s until 2000. The red dots display the median of the Pearson correlation coefficients for each scale. The scales of the x-axis (Local, Regional 1-3, Full basin) are defined in Figure 1.

For the Pearson correlations of local hydraulic head change with groundwater balance at different scales (Figure 6b) we found a positive and a negative correlation trend. Positive correlations for local basins were found where a hydraulic head increase coincides with an increasing groundwater balance value and are dominantly found in the east of the model domain (Local basins: Medicine, Harlan County Reservoir, Lower Sappa, Beaver, Middle Republican). Negative correlations were found where a hydraulic head decrease coincides with an increasing groundwater balance value (Local basins: Arikaree, North Fork Republican, South Fork Republican, Upper Republican, Frenchman, Stinking Water, Red Willow, Upper Sappa, South Fork Beaver, Little Beaver, Prairie Dog). However, the median trends towards better correlation of local hydraulic head change with groundwater balance at full basin-scale (median r = -0.435).

For the Pearson correlation of local change of phreatic land area with groundwater balance at different scales (Figure 6c) we also found two opposing correlation trends. The positively correlating local basins (Red Willow, Middle Republican) are located in the east of the model domain. The other basins show negative correlations (Local basins: Arikaree, North Fork Republican, South Fork Republican, Upper Republican, Frenchman, Stinking Water, Red Willow, Upper Sappa, South Fork Beaver, Little Beaver, Prairie Dog) or no lineal correlation (Harlan County Reservoir). The median trends towards better correlation of local change of phreatic land area with groundwater balance at full basin-scale (median r = -0.515).

For the Pearson correlation of local modeled baseflow with groundwater balance at different scales (Figure 6e) we found a positive correlation for the local basin Upper Republican. The other local basins showed negative correlations (Local basins: Arikaree, North Fork Republican, South Fork Republican, Upper Republican, Frenchman, Stinking Water, Red Willow, Upper Sappa, South Fork Beaver, Little Beaver, Prairie Dog) or no lineal correlation (Harlan County Reservoir, Prairie Dog). The median trends towards better correlation of local modeled baseflow with groundwater balance at regional-basin-3 scale (median r = -0.465).

For the Pearson correlation of local area with drawdown greater than 10 m with groundwater balance at different scales (Figure 6d) we found positive correlations for all local basins. The median trends towards better correlation of local area with drawdown greater than 10 m with groundwater balance at full basin-scale (median r = 0.31).

The Pearson correlation of local modeled inter-basin groundwater flux with groundwater balance (Figure 6f) at different scales trends towards better correlation of local modeled inter-basin groundwater flux with groundwater balance at full basin-scale (median r = -0.54). However, we found positive and negative correlations. Positive correlations occurred where more water is export than imported (Local basins: North Fork Republican, South Fork Republican, Stinking Water, Red Willow, Medicine, Lower Sappa, South Fork Beaver) negative where more water is imported than exported (Local basins: Arikaree, Upper Republican, Frenchman, Harlan County Reservoir, Upper Sappa, Little Beaver, Beaver, Prairie Dog, Middle Republican).

4 Discussion

4.1 What have been the negative ecohydrological effects of groundwater abstraction over time?

The general upward trend of the groundwater footprint revealed the increased development of groundwater resources starting in the 1950s in the Republican River basin and reaching a peak in the 1970s. From then onwards, the critical groundwater footprint value of 1 was exceeded in most years.

The mean hydraulic head and area of phreatic land area moderately increased simultaneously with increasing water imports from the South Platte River to the eastern part of the Republican River basin in the 1940s. In the mid-1960s hydraulic head and phreatic land area peaked and then strongly decreased coinciding with the rapidly increasing groundwater abstraction.

Drawdowns of more than 10 m compared to steady state conditions first appeared in 1976, coinciding with the highest modeled groundwater footprint of about 3.

The modeled baseflow mirrors the evolution of the groundwater footprint in the Republican River basin, which resulted in a decrease of about 30 % for the year 2000 compared to pre-1918 (steady-state) conditions.

The inter-basin groundwater flux reveals the increasing water imports to the basin starting with construction of irrigation channels in the 1940 which derivate water from the South Platte River towards the Republican River basin. The resulting rise of local groundwater levels of more than 20 m close to watershed boundary of South Platte River and Republican River (see Figure 3) lead to a steep hydraulic gradient and thus increased groundwater flow towards the Republican River basin. Another slight increase in water imports can be identified for the 1970s coinciding with strong groundwater drawdowns in the south of the basin. Those observations are an indication of how changing hydraulic conditions as caused by extensive well pumping or water imports can result in an enlargement of the groundwater basin. The dynamic response of the groundwater basin boundary on changing hydraulic conditions itself alters the reference scale for the evaluation of the groundwater footprint parameters and the groundwater contribution to baseflow.

4.2 How do these effects depend on spatial scale?

In general, the ecohydrological indicators showed high heterogeneities among the local basins. We found that a decrease of hydraulic head and of area of phreatic land was present in most local basins, while a drawdown higher than 10 m only occurred in some basins and thus is a local problem. However, in those local basins, up to 46 % of the total area were affected.

The comparison of modeled baseflow for various scales showed that baseflow is dominantly altered in local basins belonging to the northern regional basin (see Figure 1: Regional-Basin-3). Modeled baseflow showed changing water exchange rates between groundwater and streams for some local basins. In the upstream basins of North Fork Republican, South Fork Republican, and Frenchman, modeled baseflow strongly decreased and resulted in influent stream conditions for the North Fork Republican, South Fork Republican local basins. As the consequence of the reduced baseflow generation, the stream flow in downstream basins decreased and thus effected the ecohydrological system on a regional scale.

The inter-basin groundwater flux which was modeled for different spatial scales, showed that the strongest changes occurred along the boundaries of the Republican River basin. Fluxes between local basins remained stable. Exceptions are the local basins in the eastern part of the Republican River basin with increased hydraulic heads due to the water imported from the South Platte River and the Upper Sappa, South Fork Beaver and Little Beaver local basins in the south of the Republican River basin where the strongest areal drawdown was modeled.

4.3 Do the modeled negative effects of groundwater abstraction correlate best with the stress index at local, regional or basin scale?

Due to the water imports from the South Platte River we cannot make a valid statement on the relationship of the water balance and the ecohydrological indicators on a local scale for the eastern part of the Republican River basin as the hydrological system cannot be considered as closed. The western part is dominantly governed by regional to full basin changes in the water balance.

The Pearson correlation coefficient of groundwater balance and ecohydrological indicators is showing a slight trend towards better linear correlations with the basin scale balance, though the difference between local, regional and basin scale are, for most correlations, relatively small ($< |0.1|$).

The overall high correlation of groundwater balance with inter-basin groundwater flux indicates that the watershed boundaries change in accordance with a change in the W / R* ratio.

The groundwater footprint and the ecohydrological indicators showed high heterogeneities on the local basin level. The effects of groundwater abstraction appearing on local scale however could be explained better with regional to full basin changes in the groundwater balance than with changes in the local groundwater balance.

4.4 Which assumptions have to be made and which parameters of the water balance need to be considered for quantifying groundwater stress?

We showed that the ecohydrological indicators that were used are sensitive to water management measures (i.e. water imports/exports from South Platte River). Therefore, correlations with the groundwater balance are only valid for closed systems or a groundwater balance that accounts for those external factors.

According to Bredehoeft (2002) determining sustainable groundwater use cannot be accomplished by using simple groundwater balances and groundwater recharge as a reference volume and can only be approximated with groundwater modeling. In his work stream leakage is considered a source of groundwater recharge, however the importance of groundwater contribution to environmental stream flow is neglected.

Our modeled baseflow proved that due to increasing groundwater use, baseflow can become a source of groundwater recharge and compensate for the lack of water in the groundwater balance. However, the groundwater footprint has a more holistic approach, aiming on a sustainable groundwater use under consideration of the contribution of groundwater necessary to sustain environmental stream flow. Following this idea, surface water cannot be considered for compensation of missing natural groundwater recharge as it changes the amount of water available for environmental flow requirements. In addition, the calculated Pearson correlations showed that locally modeled ecohydrological indicators can be explained well by the water balance trending towards better correlations with the regional scale water balance (median r baseflow = -0.465) or the basin scale water balance (mean head change median r = -0.435; area of potential phreatic land median r = -0.515; drawdown median r = 0.31; inter-basin groundwater flux median r = -0.54).

The groundwater footprint considers Q90 Baseflow for the observed period to estimate environmental flow requirements. It is however much lower than the modeled baseflow (see Figure 2). The calculated Q50 however shows comparable discharge rates. As ecohydrological systems react dynamically on a changing resources availability we consider Q90 as too low to account for environmental flow requirements. Additionally, in a hydrologically undisturbed system a single long-term estimate of baseflow of the Q50/Q90 can be considered adequate to estimate environmental flow requirements as it represents the natural ecohydrological conditions of the watershed. In a system under water stress, the natural ecohydrological conditions are disturbed. As the long-term baseflow estimation is intended to represent the natural flow conditions, Q50/Q90 cannot be applied over a period where baseflow is already altered due to water stress. A crucial step to a valid estimate of baseflow and environmental flow requirements is therefore the determination of the natural steady-state conditions of the ecohydrological system.

4.5 Limitations of the study

Water imports limit the informative value of the calculated Pearson correlations on the causality of water balance and ecohydrological impact indicators on local scale as has been shown for the eastern part of the Republican River basin.

The computed and observed negative groundwater footprints values result if the environmental flow requirements exceeds the GW Recharge in this period. As the environmental flow requirements value is a long-term mean on baseflow, natural baseflow variations are not included in the approach.

5 Conclusions

In this study we tried to identify a representative scale for the groundwater footprint based on the ecohydrological impacts of groundwater abstraction. We calculated the groundwater footprint and environmental flow requirements for various hydrological scales and defined a set of ecohydrological indicators. Our analysis is based on zonal groundwater balances and hydraulic head data derived from a long-term high-resolution groundwater model of the Republican River basin (Great Plains, USA). We modeled what the effects of groundwater abstraction have been over time and how they vary spatially. Finally, we computed Pearson correlations to identify the scale on which changes in the water balance correlate best with local changes of baseflow and other ecohydrological indicators.

We find that, to observe ecohydrological impacts, we need to identify what was the status of the ecohydrological indicators under “natural” conditions and compare them to their status for the examined time period. In addition, the choice on what is seen as the “natural” state of the system directly influences the groundwater footprint by determining the environmental flow requirements. Calibrated long-term groundwater models like the Republican River Groundwater Model (Republican River Compact Administration, 2003) allow estimates of the “natural” conditions with steady state modeling and are thus valuable for water management and planning of mitigation strategies for ecohydrological systems.

The impact of groundwater abstraction for the defined ecohydrological indicators occurred on different scales. However, the modeled impact on the ecohydrological indicators mean head change, phreatic land, drawdown, inter-basin groundwater flux on local scale could be better explained by basin scale changes in the groundwater balance rather than by regional or local changes. Baseflow however correlated best with changes in the water balance on the regional-3 scale.

Pearson correlations can be used to identify whether the modeled local ecohydrological effects can be explained best by the local, regional, or full basin groundwater balance and thus to determine a representative scale for the calculation of the groundwater footprint. It is furthermore a method to see how local scale basins are hydraulically interconnected.

However, as ecohydrological indicators are sensitive to water management measures (i.e. water imports/exports, reservoirs), the correlations with the groundwater balance are only valid for closed systems or a groundwater balance that accounts for those external factors.

Overuse of Groundwater resources, as has been shown for the Republican River basin, may change the borders of the groundwater drainage basin due the inversion of hydraulic gradients. The influence of changed groundwater drainage basins borders on baseflow has to our knowledge not yet been studied for the Republican River basin. As the groundwater drainage basin changes in size also the reference area to evaluate groundwater abstraction and recharge changes. Those additional sources and sinks must be considered and incorporated in groundwater footprint calculations. Modelling helps to identify changed groundwater drainage basin boundaries.

With our findings we identified the effective scale of major pressures on the ecohydrological system and the scale of the water balance to which the ecohydrological indicators respond. The presented approach is thus appropriate to identify a representative scale for the groundwater footprint.

References

Ahner, B.: Assessing Groundwater Stress: An approach of measuring groundwater stress based on sub-national statistical data, Delft, The Netherlands. [online] Available from: https://www.un-igrac.org/resource/assessing-groundwater-stress-approach-measuring-groundwater-stress-based-sub-national, 2017.

Alley, W. M., Clark, B. R., Ely, D. M. and Faunt, C. C.: Groundwater Development Stress: Global-Scale Indices Compared to Regional Modeling, Groundwater, doi:10.1111/gwat.12578, 2017.

Bredehoeft, J. D.: The Water Budget Myth Revisited: Why Hydrogeologists Model, Ground Water, 40(4), 340–345, doi:10.1111/j.1745-6584.2002.tb02511.x, 2002.

Bureau of Reclamation: Republican River Basin Study Full Report. [online] Available from: https://www.usbr.gov/watersmart/bsp/docs/finalreport/republican/republican-river-basin-study-final-report.pdf (Accessed 20 October 2017), 2016.

Döll, P., Hoffmann-Dobrev, H., Portmann, F. T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G. and Scanlon, B. R.: Impact of water withdrawals from groundwater and surface water on continental water storage variations, J. Geodyn., 59–60(6), 143–156, doi:10.1016/j.jog.2011.05.001, 2012.

Eldardiry, H., Habib, E. and Borrok, D. M.: Small-scale catchment analysis of water stress in wet regions of the U.S.: an example from Louisiana, Environ. Res. Lett., 11(12), 124031, doi:10.1088/1748-9326/aa51dc, 2016.

Gerten, D., Hoff, H., Rockström, J., Jägermeyr, J., Kummu, M. and Pastor, A. V: Towards a revised planetary boundary for consumptive freshwater use: Role of environmental flow requirements, Curr. Opin. Environ. Sustain., 5(6), 551–558, doi:10.1016/j.cosust.2013.11.001, 2013.

Gleeson, T., Wada, Y., Bierkens, M. F. P. and van Beek, L. P. H.: Water balance of global aquifers revealed by groundwater footprint, Nature, 488(7410), 197–200, doi:10.1038/nature11295, 2012.

Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E. and Richter, B. D.: Global Monthly Water Scarcity: Blue Water Footprints versus Blue Water Availability, edited by J. A. Añel, PLoS One, 7(2), e32688, doi:10.1371/journal.pone.0032688, 2012.

National Elevation Dataset: National Elevation Dataset (NED) - 1 arc-second DEM, Publ. by USGS [online] Available from: https://viewer.nationalmap.gov (Accessed 15 September 2017), 2017.

Pastor, A. V., Ludwig, F., Biemans, H., Hoff, H. and Kabat, P.: Accounting for environmental flow requirements in global water assessments, Hydrol. Earth Syst. Sci., 18(12), 5041–5059, doi:10.5194/hess-18-5041-2014, 2014.

Republican River Compact Administration: Republican River Compact Administration Groundwater Model. [online] Available from: http://www.republicanrivercompact.org/ (Accessed 26 April 2017), 2003.

Smakhtin, V., Revenga, C. and Döll, P.: A pilot global assessment of environmental water requirements and scarcity, Water Int., 29(3), 307–317, doi:10.1080/02508060408691785, 2004.

Wada, Y., van Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S. and Bierkens, M. F. P.: Global depletion of groundwater resources, Geophys. Res. Lett., 37(20), n/a-n/a, doi:10.1029/2010GL044571, 2010.

Wada, Y., van Beek, L. P. H. and Bierkens, M. F. P.: Nonsustainable groundwater sustaining irrigation: A global assessment, Water Resour. Res., 48(6), doi:10.1029/2011WR010562, 2012.

Watershed Boundary Dataset: Watershed Boundary Dataset (WBD) for {HUC1025}, Publ. by USDA-NRCS, USGS EPA [online] Available from: http://datagateway.nrcs.usda.gov (Accessed 15 September 2017), 2017.

Appendix I: Tables

Table 1: Name, hydrological unit number, intersecting US-states and size of local basins within the Republican River basin.

Local basin name	Hydrological unit number	States	Area [km^2]
Arikaree	10250001	CO,KS,NE	4630
North Fork Republican	10250002	CO,KS,NE	7462
South Fork Republican	10250003	CO,KS,NE	6613
Upper Republican	10250004	KS,NE	5581
Frenchman	10250005	CO,NE	4265
Stinking Water	10250006	CO,NE	3747
Red Willow	10250007	NE	2055
Medicine	10250008	NE	2401
Harlan County Reservoir	10250009	KS,NE	3491
Upper Sappa	10250010	KS	2747
Lower Sappa	10250011	KS,NE	1691
South Fork Beaver	10250012	CO,KS	1928
Little Beaver	10250013	CO,KS	1550
Beaver	10250014	KS,NE	1896
Prairie Dog	10250015	KS,NE	2867
Middle Republican	10250016	KS,NE	3652

Appendix II: Changelog for the Republican River Groundwater Model

1. Converting of model input files with programs USGS MF2KtoMF05UC
2. Rewriting input files with USGS FloPy (v.3.2.6)
3. Modflow input-file adjustments:
    a. EVT package for MODFLOW-2005
        i. IEVTCB from UNIT 42 to UNIT 40 (write cbc-water balance to unit)
    b. DRN package for MODFLOW-2005
        i. IDRNCB from UNIT 43 to UNIT 40 (write cbc-water balance to unit)
    c. STR package for MODFLOW-2005
        i. ISTCB1 from UNIT 41 to UNIT 40 (write cbc-water balance to unit)

Declaration of Authorship

I hereby confirm that I have written the attached thesis on my own and that I did not use any resources than those specified above. This work has not been previously submitted, either in the same or a similar form to any other examination committee and has not yet been published.

Göttingen, January 23, 2018