

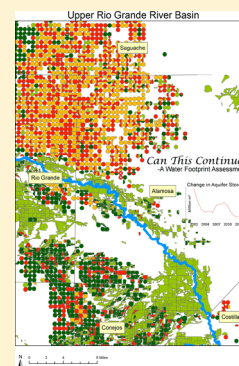
Consumptive Water Use Analysis of Upper Rio Grande Basin in Southern Colorado

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S Supporting Information

ABSTRACT: Water resource management and governance at the river basin scale is critical for the sustainable development of rural agrarian regions in the West. This research applies a consumptive water use analysis, inspired by the Water Footprint methodology, to the Upper Rio Grande Basin (RGB) in south central Colorado. The region is characterized by water stress, high desert conditions, declining land health, and a depleting water table. We utilize region specific data and models to analyze the consumptive water use of RGB. The study reveals that, on an average, RGB experiences three months of water shortage per year due to the unsustainable extraction of groundwater (GW). Our results show that agriculture accounts for 77% of overall water consumption and it relies heavily on an aquifer (about 50% of agricultural consumption) that is being depleted over time. We find that, even though potato cultivation provides the most efficient conversion of groundwater resources into economic value ($\text{m}^3 \text{ GW}/\$$) in this region, it relies predominantly (81%) on the aquifer for its water supply. However, cattle, another important agricultural commodity produced in the region, provides good economic value but also relies significantly less on the aquifer (30%) for water needs. The results from this paper are timely to the RGB community, which is currently in the process of developing strategies for sustainable water management.



INTRODUCTION

Water and energy use are two important resource-use issues of the century as there are limits to the extent that humanity can continue to increase its appropriation of fossil fuel resources and freshwater from the natural environment.¹ Further, water and energy interdependencies and supply constraints have been recognized by researchers to pose significant risks that can potentially and unintentionally shift overall impacts geographically and temporally.^{2,4} In this context, proper quantification of fresh water resources needed for the environment as well as human made products (e.g., agricultural produce) and processes (e.g., power plant cooling) across nations and subregions is the necessary first step toward addressing water use issues.^{2,3} Water Footprint (WF)^{3,6,7} is an approach that provides a useful framework to quantify freshwater usage along the entire supply chain.⁵ WF has been used to assess both direct consumptive water use and indirect embodied water content of individual products such as milk and clothes,⁶ as well as to assess entire nations and the global system.^{8,9} However, this paper, which pulls certain concepts from WF, focuses only on consumptive water use of a regional system with the aim to provide data and analysis for both consumers of water from the river-basin as well as water managers.^{10–13} Note that this analysis is based on water consumption as opposed to the more conventional water withdrawal metric, in that a consumptive water use metric recognizes the interconnectedness of the hydrologic cycle and appropriately allocates evaporation, return flows, irrigation inefficiencies, and other withdrawn but “unused” water.³

The San Luis Valley (SLV) or Upper Rio Grande Basin (RGB), is a high altitude agricultural valley in South Central Colorado that covers roughly 21 000 km² (8000 square miles). It has an average elevation at the valley floor of 2300 m (7600 ft.) above sea level with an average annual precipitation of 222 mm (9 in.). It is a snowmelt driven hydrologic system, with the majority of the water into the SLV coming from river and stream flows from the surrounding mountain ranges. Hay production and pasturelands utilize some of the snowmelt, but much of it flows into the massive aquifer that underlies the entire valley, a portion of which is pumped back for irrigation. It is also important to note that not all of the water that flows into the RGB is “owned” by the region. Two major interstate compacts, the Rio Grande Compact (1938)¹⁵ and the Amended Costilla Creek Compact (1963),¹⁴ require the SLV to allocate water to downstream states based on the annual snowmelt. This precious water supply in this high desert region is what allows the SLV to be one of the nation’s key producers of potatoes, alfalfa, and the first place in North America to grow quinoa. Barley is another important crop grown in the region, and SLV is the main supplier to Coors Brewing Company. Because of SLV’s limited population, isolated location, and the fact that its natural watershed boundaries coincide closely with its political boundaries made this region a good study area to test regional sustainability analysis.^{16–18}

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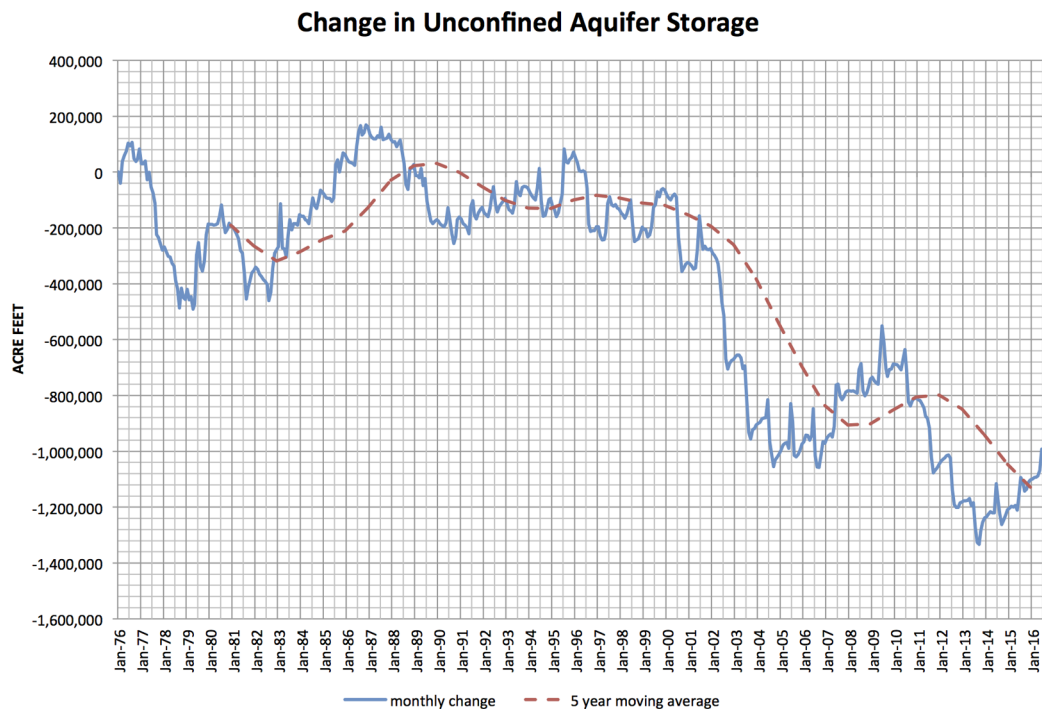


Figure 1. Change in storage of the unconfined aquifer in RGB over time (Source: Davis Engineering, 2016, Change in Unconfined Aquifer Storage; Commissioned by the Rio Grande Water Conservation District <http://www.rgwcd.org>, <http://www.daveng.com>).

The impacts of groundwater pumping on surface water flows in the region have been recognized and the extreme drought of 2002 brought the situation to the forefront. A robust groundwater¹¹ model, developed by Colorado Division of Water Resources (CDWR), shows that continuous and increasing depletion of the aquifer (*as monitored since the late 1970s by Davis Engineering* (see Figure 1)) has affected surface water flows over the last ten years and impacted agriculture which relies on those flows. This region specific model provides a complete water balance and describes consumptive water use in the region that includes return flows, crop shortages, and native vegetation.²² Because agriculture is the major economic activity in the region, the community has recognized the importance of working toward sustainable management of the region's water resources on which its economy relies heavily.¹⁹ The community recognized the importance of water and demanded legislation from the state that requires sustainable water management, namely Senate Bill 04-222²⁰ signed in 2004, which is currently being implemented. As part of this bill, the Colorado Division of Water Resources (CDWR) has promulgated well rules and regulations and submitted them to the Colorado Water Court in the Fall of 2015.²¹ The purpose of this legislation is to ensure the prior appropriation system is upheld, given the now apparent impacts of groundwater pumping on surface water flows. The priority system, or prior appropriation system, is based on the "first in time first in right" concept of western water law, which appropriates surface water rights to the first person to divert the water for beneficial use. The RGB's surface water was fully appropriated by 1900, but as groundwater at that time was thought to be delinked from the surface water system, the state continued to issue well permits for groundwater pumping until the 1970s. The new legislation requires repayment of injurious depletions to senior surface water rights holders due to groundwater pumping.

Another major component of the well rules and regulations, and in some regard the most interesting due to the major drop in the aquifer levels that took place during the 2002 drought (Figure 1), is the requirement that the confined aquifer be maintained at the average historic levels similar to the time period of 1978 to 2000. This is the first legislation of its kind in the country and may set a precedent for future sustainable aquifer management and related legislation across the country. The State Engineer's Office and the CDWR's Division 3 Engineer, who administers the Rio Grande Basin, is responsible for managing and enforcing the groundwater rules. Also allowed under the legislation is the formation of groundwater management subdistricts of the Rio Grande Water Conservation District (RGWCD). These entities are tasked with managing their water use, replacing injurious depletions to the senior surface water rights holders through replacement water, financial water saving incentive programs, and restoring and maintaining a sustainable aquifer within the parameters of the legislation.²¹

Simultaneously, Governor John Hickenlooper issued an Executive Order in 2013 requiring the Colorado Water Conservation Board (CWCB) to develop a statewide water plan. Each of the state's nine river basins host a conservation roundtable composed of water users and stakeholders in each region. The roundtables were each tasked to develop Basin Implementation Plans (BIP). The Rio Grande Basin Roundtable (RGBRT) was tasked with developing a BIP for RGB (23). The BIP lays out projects, goals, and priorities for the basin's future. The BIP was published in the summer of 2015 and focuses on achieving a balance of competing water needs through cooperative management of water resources.²³ The BIP outlines detailed plans and allocated funds to help manage water resources. The BIP presents ways to improve soil health to increase water holding capacity, improving streamflow forecasting, irrigation improvements, head gate and ditch

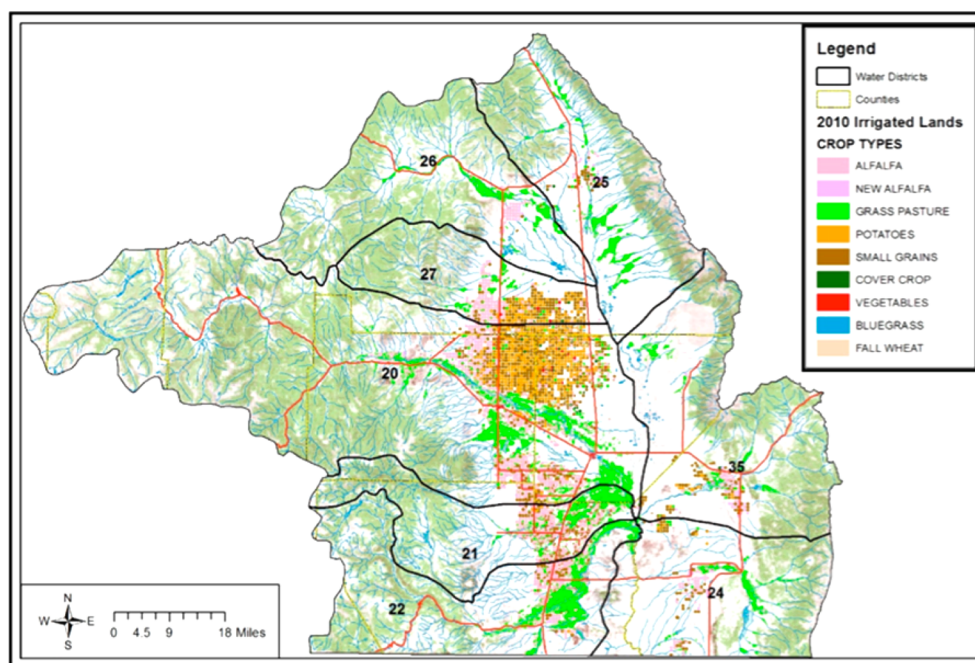


Figure 2. Geospatial representation of crop production in the SLV.²⁷

restoration projects, and the Rio Grande headwaters restoration project. It also emphasizes the importance of maintaining a healthy stream corridor to achieve efficient compact deliveries at the state line. The BIPs from across the state, each of which focused on their individual basins, informed the Colorado Water Plan, which was delivered to the Governor in November of 2015 and will highly influence water use in the state (www.Coloradowaterplan.org). This unique regional context required the development of SLV specific methods, models and data to understand and address the problem. In an attempt to fill information and data gaps, we present a robust and descriptive baseline consumptive water use analysis (CWU). This model will be available as a resource to assist local decision makers who are continuing to develop plans and implement actions toward sustainable water use in the RGB.

MATERIALS AND METHODS

Our analysis utilizes the concept of tracking the origin (source) of water be it effective rain (green water) or rivers and streams (blue water).^{24,25} In the present study, we also divided the blue water into surface and groundwater components due to the unique hydrologic features of the SLV region. We characterize the water consumption in SLV into the following three categories: Crops, Livestock, and Municipal/Industrial use; and we consider the following three water sources: effective precipitation (green water), surface water runoff (blue water surface/snowmelt), and ground water from the aquifer (blue water ground) (see [Supporting Information Table S1](#)). The gray water component, which represents water needs for pollutant discharge and dilution, was not considered in this study due to lack of region specific data and interest. Because this research focuses on the water consumption patterns of the region itself, we only considered water originating within the basin and did not account for any upstream-embodied water of imported goods and services. In this way, the analysis is different from the traditional Water Footprint methodology.

The consumptive water use (CWU) calculations adapted for the RGB are shown below:

$$CWU_{RGB} = CWU_{green} + CWU_{blue}$$

$$CWU_{green} = CWU_{green_crops} + CWU_{green_livestock}$$

$$CWU_{blue} = CWU_{surface} + CWU_{ground}$$

$$CWU_{surface} = CWU_{surface_crops} + CWU_{surface_livestock} + CWU_{surface_M\&I}$$

$$CWU_{ground} = CWU_{ground_crops} + CWU_{ground_livestock} + CWU_{ground_M\&I}$$

A unique aspect of the presented regional consumptive water use assessment is that we first estimate the total consumptive water use in the basin using a local groundwater model, and then we derive the Consumptive Water Content (CWC) of each crop from this overall CWU making the results highly specific to the region. The CWC represents the quantity of water needed to produce an unit of a good or service.^{3,26} This level of regional specificity was possible due to the close collaboration of our research team with the Colorado Division of Water Resources (CDWR), and the use of regional data from CDWR's central database (HydroBase) that contains real-time, historic, and geographic data related to water resources in Colorado. We used the Rio Grande Decision Support System (RGDSS) groundwater model,^{22,27} which is specifically calibrated for this region, and were able to develop a robust, region-specific accounting that does not rely on global averages (which is typical of consumptive water use studies).

Crop Water Use of RGB. Calculation of crop water consumption were performed within the Colorado crop consumptive use model (StateCU) component of the RGDSS and considered all of the area in Water Division 3.²⁸ StateCU, as applied in the RGDSS, models the water budget of

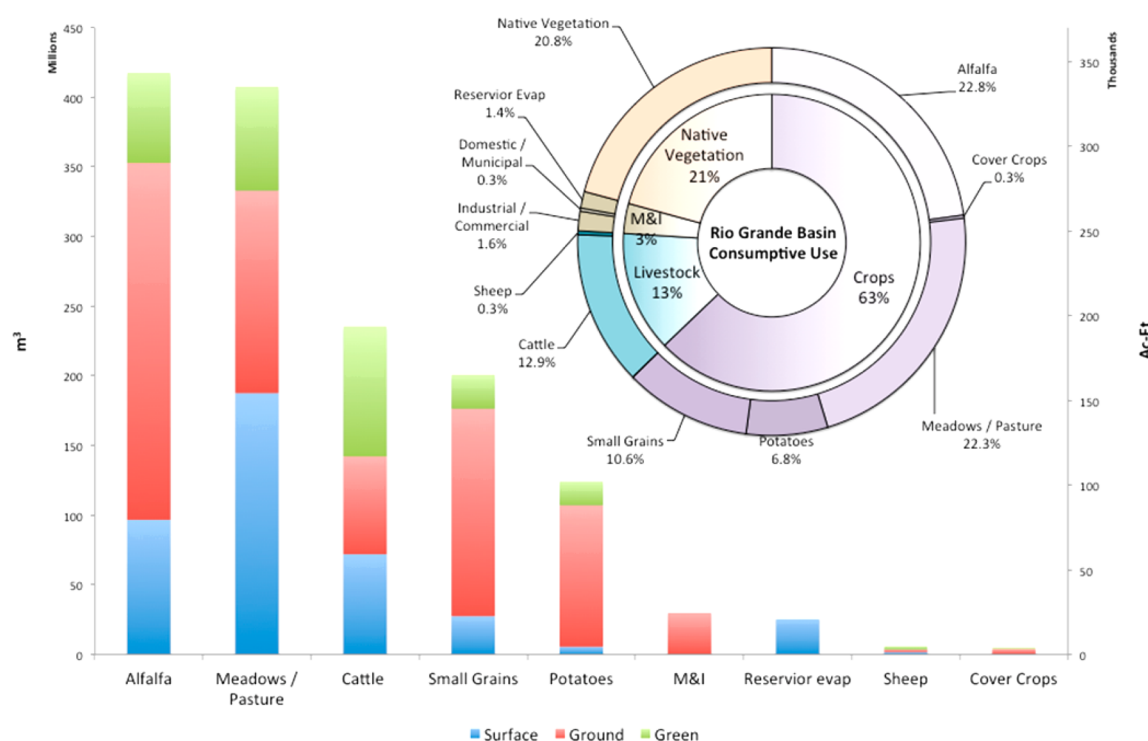


Figure 3. Average annual water allocation in the SLV from 2000 to 2010. (1 Ac-ft. = 1233.5 m³).

a ditch service area by calculating the quantity of water consumed by different crops using a modified Blaney-Criddle method with locally calibrated crop coefficients. In addition, local data related to temperature, precipitation, rooting depths, growing season start and end dates, available water content of soils, irrigated acres, cropping patterns, surface and ground-water diversions, ditch conveyance and irrigation application efficiencies were supplied as inputs into the StateCU model. Data were developed and maintained within HydroBase²² as part of RGDSS efforts.

We assessed the four major crops cultivated in the region (Figure 2): alfalfa, potatoes, small grains (mainly barley) and meadows/pasture grass on a monthly time step for years 2000 to 2010. They were assessed for potential evapotranspiration, effective 217 precipitation (EF), and the remaining irrigation water requirement (IWR).

Much like the global crop consumptive water use model (CROPWAT), which many studies use to estimate crop water consumption, the StateCU model is used to estimate the effective precipitation and the amount of irrigation water consumed by the crops.^{6,10,11} Using a local consumptive water use model (StateCU) coupled with a local groundwater model (RGDSS) is unique and critical because there may be times when precipitation and irrigation water supplies are insufficient to meet the entire crop demands, and for these instances there is a shortage that may be met if the groundwater table is within the crop's root zone. The RGDSS groundwater model simulates the groundwater table and the associated crop demand shortage, and if the water table is within the crop-rooting zone, the groundwater model automatically meet the crop water demand through sub irrigation (direct groundwater consumption from crop roots). Further, there may be times when all water supplies fall short of meeting the full crop demands, which may affect crop yields. Crop yield data were obtained at the county level through the National Agricultural

Statistics Service (NASS)²⁹ and are presented in Table S2 (see [Supporting Information](#)).

Due to the difference in the evaluation methods of this research and StateCU, i.e. this research by crop and StateCU by ditch service area, we post processed the StateCU results to quantify the individual crop consumptive water use amounts. The analysis utilizes information from the Alamosa climate station as an approximation for the remainder of Water Division 3 to evaluate crop demands, and then normalizes the crop demands back to the Water Division 3 StateCU model results. By combining the post processing results from the StateCU model and crop yield data²⁹ we were able to determine the CWC_{green} , $CWC_{surface}$, and in combination with the RGDSS groundwater model, the CWC_{ground} for each of the major crops.

Livestock Water Use of RGB. We calculated the consumptive water use of livestock ($CWU_{livestock}$) in the SLV by multiplying the consumptive water content (m³/ton live weight) of each livestock ($CWC_{livestock}$) type by the production quantity in the RGB (see [Supporting Information S3](#)). The three major water uses needed for calculating the $CWC_{livestock}$ are drinking water requirement (DWR), service water requirement (SWR), and feedwater requirement (FWR).¹⁰ SWR is a measure of the small amount of water used for keeping and maintaining the animals. The DWR and SWR were estimated using global annual averages from Mekonnen and Hoekstra's³⁰ analysis of livestock water footprints for grazing animals. In addition, under consumptive water use of livestock we also include the water embodied in the feed that the livestock eat (FWR), as this water also originates in the basin. The FWR, which accounts for 99% of the grazing livestock CWU , was calculated based on local consumptive water content of the feed crops grown in the region (see [Supporting Information Table S4](#)) coupled with the amount and feed conversion efficiency (FCE) of each type of feed consumed by the livestock. FCE is a

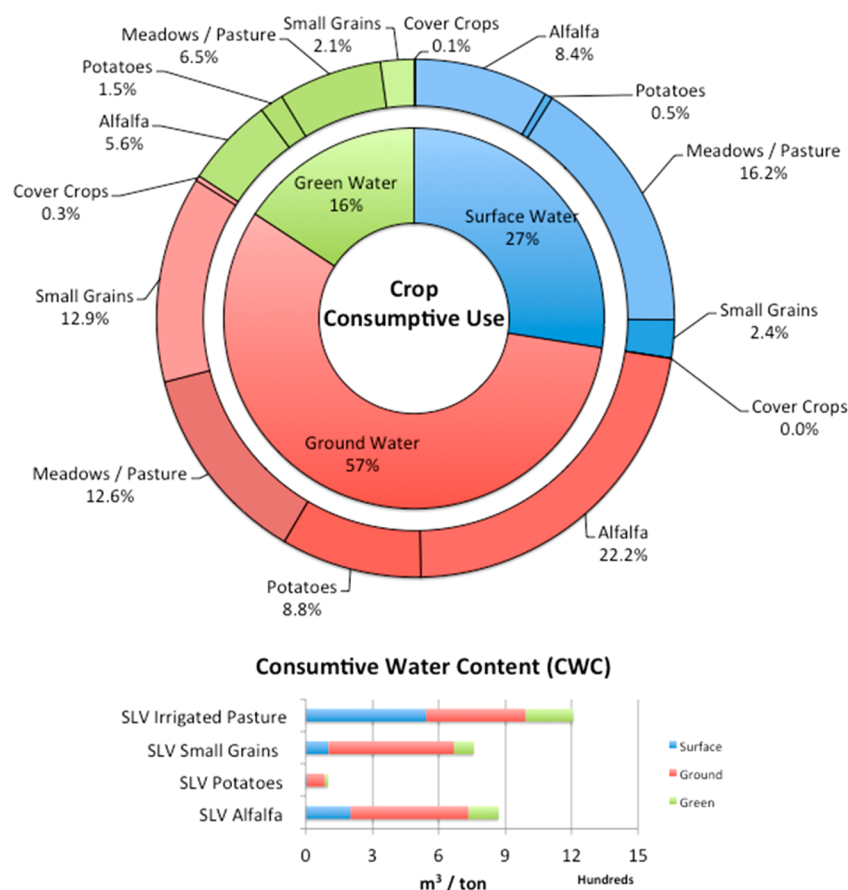


Figure 4. Crop water use allocated between $CWU_{\text{green-crops}}$, $CWU_{\text{surface-crops}}$, and $CWU_{\text{ground-crops}}$ as well as the consumptive water use content of each crop.

measure of the quantity of feed needed to produce a certain quantity of output.

$$FWR = \sum FCE_f \times VWC_f$$

f = feedtype

$$FCE = \frac{DMI}{\text{liveanimalweight}}$$

DMI = drymatterintake

A daily dry matter intake (DMI) of 3% of the body weight for adult cattle and 1.5% for calves and grazing sheep in accordance with Mekonnen and Hoekstra³⁰ and confirmed by the local extension office and a local rancher was used.^{31,32} Total forage consumption values were based on the assumption that all feed requirements needed by the livestock were satisfied through local resources, as is the practice in the region. Public grazing lands in the region has the capacity to support the herd of cattle and sheep spending 3 months of the year on dry land pasture,^{33–35} 5 months grazing on private irrigated pasture and meadows, and 4 months eating baled hay grass and/or hay alfalfa.^{31,32} The total livestock headcount was obtained from NASS and because the FWR of hogs originate from outside the region, and their population is small (see [Supporting Information Table S3](#)), they were not included in this study. Typically, ranchers in the SLV do not finish cattle or sheep locally but tend to export live animals; therefore, we used ton live animal as the unit for livestock production instead of the more conventional unit of kg meat.

Municipal and Industrial Water Use of RGB. We calculated the consumptive water use of the municipal and industrial sector ($CWU_{\text{M\&I}}$) based on input data used in the RGDSS groundwater model on a monthly time step for the period of 2000 through 2010. The value for M&I water consumption was based on the total pumping and return flows for all nonirrigation high capacity wells within the RGDSS model domain, which covers the entire region. In addition to groundwater pumping, this sector also includes consumptive water use from reservoir evaporation of surface water. It is important to note that the manufacturing and industrial sector in the SLV represents only ~1% of the overall economy.¹⁹

RESULTS AND DISCUSSION

Total Consumptive Water Use of RGB. An examination of the results shows that RGB's consumptive water use is dominated by agricultural activities. Crops account for 63% of the CWU of the valley, followed by livestock at 13% and municipal and industrial use accounting for only 3%. In addition, non-agricultural native vegetation accounts for about 21% of the overall consumptive water use in the valley (Figure 3). The total consumptive water use (in million m^3) was separated into green water, surface water, and groundwater (See Figure 3). By breaking up the blue water CWU (CWU_{blue}) into two components: CWU_{ground} and CWU_{surface} , we were able to analyze, in fine detail, how the various water users draw upon specific water sources (ground vs surface water).

From Figure 3 we see that alfalfa is the largest overall user of water followed by meadows and pasture and then cattle. It is

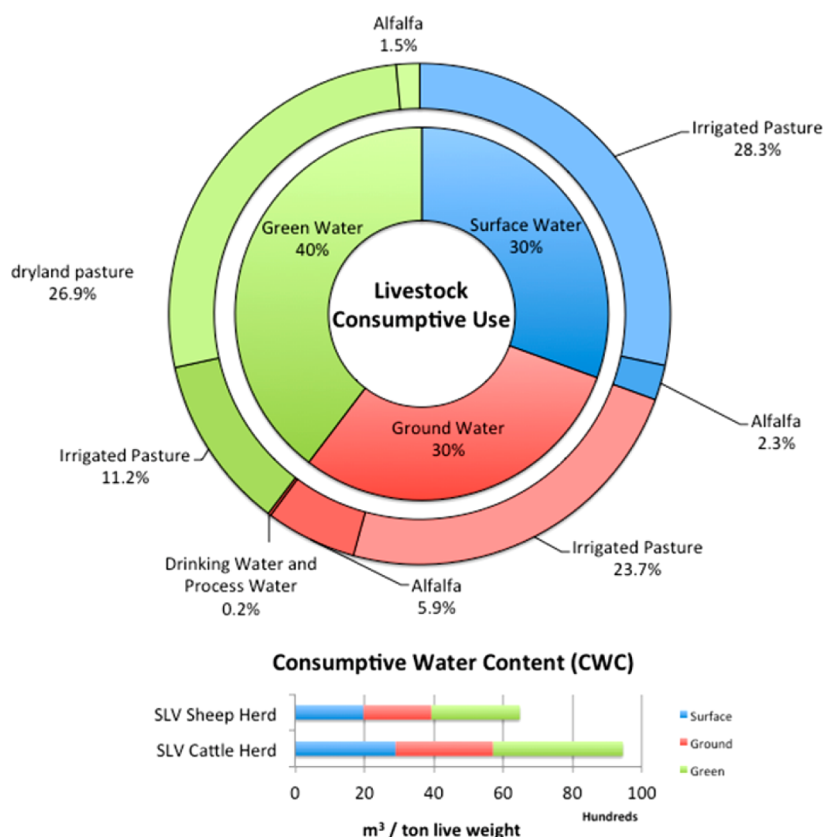


Figure 5. Livestock consumptive water use ($CWU_{livestock}$) for SLV allocated between $CWU_{green-crops}$, $CWU_{surface-crops}$, and $CWU_{ground-crops}$ as well as the consumptive water use content. Cattle represent 98% of all livestock CU in the region.

important to note that meadows and pasture are useful for much more than just grazing cattle, as demonstrated by the fact that even after allocating the water needed for raising forage for cattle and sheep, the remaining meadows are still one of the largest overall contributors to the CWU in the RGB. This relatively large water use is due in part to the fact that the majority of irrigation water used for meadows and pasture is surface water that is diverted for agricultural uses during early spring and summer, in accordance with prior appropriation system. In many locations, surface water is diverted from rivers or streams onto the fields to grow grass where ranchers graze cattle, store hay for the winter, and export haylage (baled grasses). In addition to providing grazing land, meadows also sustain a vast and complex network of wetlands, native habitat, and species diversity.

Crop Consumptive Water Use of RGB. Overall, 57% of crop water requirement is provided by ground water, 27% is provided by surface water, and 16% is from effective precipitation during the growing season (Figure 4). Alfalfa is the largest consumer of ground water in the Valley whereas meadows/pasture is the largest consumer of surface and green water. The blue water portion (BWP), which combines surface water and groundwater needed for all crops in the valley accounts for about 85% of the CWU_{crops} . This blue water for crops is much higher than the global average of 19%,²⁶ indicating that the region is much more reliant on irrigation in comparison to other regions. In addition, our finding that 57% of the CWU_{crops} comes from groundwater resources has a profound and direct bearing on the long-term sustainability of the aquifer (a key requirement of the new well rules and regulations).

Livestock Consumptive Water Use of RGB. The livestock consumptive water use considers water needed for feed crops, drinking water, and service water. In the RGB, 98% of the water needs for livestock can be attributed to the feedwater requirements (FWR). Figure 5 presents a breakdown of the $CWU_{green-livestock}$, $CWU_{ground-livestock}$, and $CWU_{surface-livestock}$ in the Valley. Overall, 40% of the livestock water needs are met by green water, 30% by ground and surface water. Livestock are able to utilize the sparse green water that falls in the region through dry land pasture grazing in the summer months. This, along with meadows and pasture grazing, is why we see such a large green water percentage for the livestock CWU. The majority of the surface and groundwater portion of the $CWU_{livestock}$ goes to raising irrigated pasture for grazing and winter hay feed.

Agricultural Products. Table 1 compares the CWC, Total CWU, and water source percentages for each of the major agricultural products in the region. Further, we define the groundwater intensity as a measure of the quantity of groundwater needed per ton or per dollar revenue of agricultural products. The dollar value for agricultural products sold in Colorado was obtained from the USDA²⁹ using the previous 5-year average and was used to calculate the groundwater intensity in dollars/ m^3 (see Supporting Information Tables S3 and S4).

Results indicate that, when we use revenue as the index, potatoes have the highest efficiency in converting groundwater into dollars followed by sheep and cattle. Efficient conversion of ground water resources to dollars captures two major issues related to the valley, economy and a depleting aquifer. Potatoes are efficient at producing high yields (17 tons/acres) and hence

Table 1. Comparison of Major Agricultural Products in the Region from Multiple Perspectives. (1 Ac-ft. = 1233.5 m³)

	CWU Content - SLV (m ³ t ⁻¹)	CWU Valley Wide (million m ³)	surface water portion (SWP) %	ground water portion (GRD-WP) %	green water portion (GRD-WP) %	ground water use/\$ revenue (m ³ GW \$ ⁻¹)
alfalfa	871.2	417.5	23.1	61.3	15.5	2.61
potatoes	100.4	124.3	4.5	81.7	13.9	0.41
small grains	758.5	200.8	13.7	74.1	12.2	2.26
live cattle	9529.9	237.6	30.6	29.8	39.7	1.69
live sheep	6535.4	5.9	30.1	30.4	39.5	1.54

have a low groundwater use per dollar revenue. However, this is offset significantly by the fact that they require the highest groundwater portion (81%) per ton of crop (Table 1). This is in contrast to sheep and cattle, which are second in efficient conversion of groundwater resources into dollars but also have the lowest groundwater portion (~30%) per ton of any of the agricultural products in the region. Further, the current consumption of blue water for crops and livestock (almost all of which is exported) results in a net displacement of 1120 million m³/year (908 thousand ac-ft.) in the form of virtual water flows (calculated as area under the “blue water CWU crops and feed” curve of Figure 6) of surface and groundwater.

Blue Water Scarcity. We use Blue Water Scarcity (BWS)^{3,10} as a metric to understand water sustainability of the region. BWS occurs anytime the WF_{blue} exceeds the Blue Water Availability (WA_{blue}) (See Figure 6).

$$WA_{\text{blue}} = \text{Runoff} - \text{EFR} - \text{InterstateCompactDeliveries}$$

$$\text{EFR} = \text{EnvironmentalFlowRequirements}$$

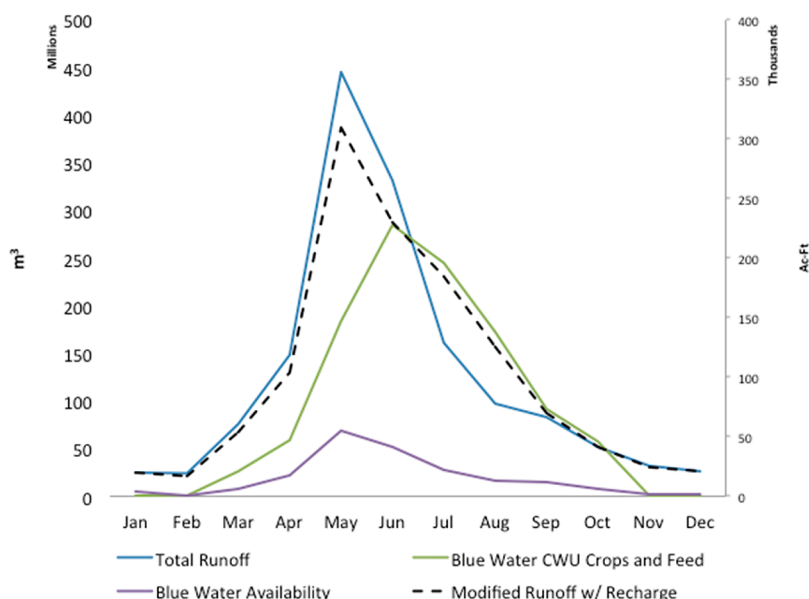
We obtained monthly average runoff from mountains into the basin for years 2000–2010. Data were composed of gauged and ungauged inflows and provided by RGDSS. Figure 6 shows

the average natural runoff curve and a modified runoff curve. The modified runoff curve accounts for farmers using the aquifer as a reservoir, which is a local practice, and was based on monthly recharge data from RGDSS. Farmers direct their surface water allocations into “recharge pits” at the corners of their fields so water can infiltrate into the aquifer. To estimate the WA_{blue} curve, both the interstate compact water that is owed to downstream states, and the Environmental Flow Requirements (EFR) were subtracted from the total runoff. Because region specific data were not available for EFR, we used 80% of the total runoff to be allocated to stream and ecosystem services as proposed by Hoekstra et al.^{3,10} Finally, the monthly average blue water CWU of crops and feed over the 10-year period was also graphed.

RGB experiences Blue Water Stress, which is the difference between CWU_{blue} and WA_{blue}, during seven months of the year. This resource overutilization causes severe damage to the ecosystem of the region.^{10,36} In addition to ecosystem service damages, the RGB has been experiencing Water Shortage in the form of aquifer mining during two months of the year. Water Shortage occurs anytime CWU_{blue} exceeds the total runoff. The evidence for this includes the observation that the bulk of the natural runoff occurs in May and June, but the spike in CWU occurs between June and August. This local Water Shortage can be seen whenever the modified runoff w/recharge curve drops below the WF curve in Figure 6. Even with the use of recharge pits, the RGB has been experiencing Water Shortage, mainly in July and August, of about 41 million m³ annually. To make matters worse it is predicted that the natural runoff in spring will shift from June to May in a changing climate scenario.^{23,37}

Once CWU_{blue} exceeds runoff, it does not take long to see the effects. Water Shortage due to dry conditions and over-pumping has caused a major dip in the aquifer (see Figure 1).

The aquifer is likely to be further affected by climactic changes; some of these effects are apparent today. The aquifer is recharged by surface water runoff, which infiltrates to the groundwater through rivers and streams, rim recharge, flood irrigation and state issued recharge decrease. A dry regime, which is predicted by climatologists, will reduce snowpack and

**Figure 6.** Monthly water availability and monthly water use (2000–2010) (1 Ac-ft. = 1233.5 m³).

subsequently limit the aquifers ability to bounce back from the annual groundwater pumping.³⁷ Senate Bill 04-222 and the groundwater rules and regulations, requires water users in the region to maintain aquifer levels similar to the average levels between the years 1978 and 2000. This is already a difficult task and will be even more challenging under a changing climate.^{38,39} It is predicted that stream flows at the upper gauges will decrease by approximately one-third between now and 2100.^{23,37}

Looking Forward. RGB is a microcosm of many dry regions across the globe where water demand exceeds supply, and drought due to a changing climate is adding stress to the already over appropriated systems. This CWU analysis developed for RGB can provide valuable information and perhaps management models for other areas facing similar challenges.

This is a complex system and just making irrigation more efficient may not be the answer. Along the riparian corridors, diverted water used for growing meadows and pasture sustains a variety of wetland types that are invaluable for waterfowl, wildlife, and recreation and other ecosystem services. These seasonal wetlands account for a substantial portion of the wetlands in the region.²³ While flooding land during the growing season may not sound like an “efficient” use of water, it provides an important service as these lands provide habitat for native and sensitive species as well as grazing land for livestock.^{23,40,41} In addition, it is important to sustain a “wet sponge” along the river corridor, so that Rio Grande Compact water deliveries can be managed. If river corridor zones were permanently dry by change of use, it would cause a substantial challenge to the State’s ability to meet compact requirements. This situation was experienced during the 2002 drought and subsequent years. On the other hand, through our analysis, we see that native vegetation consumes significant amounts of water, which affects the regions ability to maintain a sustainable aquifer. It will be important for future regional water use analyses to allocate water toward ecosystem services and environmental flow requirements. Much work has been done in the area of quantifying ecosystem services and these methodologies could be applied to river basins such as RGB^{42–45}

Maintaining a sustainable aquifer is of utmost importance in the region. Managing the use/loss while maintaining the agricultural heritage and economy of the region is important. However the aquifer is being continually depleted by heavy extraction of groundwater for agricultural purposes. The results indicate that agricultural products, like sheep and cattle, that convert groundwater to revenue efficiently, do not rely heavily on groundwater, and utilize the scarce green water through dry land grazing, can be an opportunity for the region to move toward sustainable water management. This opportunity is somewhat constrained due to space limitations for dryland pasture grazing and the potential for ongoing drought. Alternative grazing practices, such as cover crop grazing, will need to be employed if the number of livestock were to increase.

A variety of soil health management practices implemented by an active group of farmers and ranchers are showing promising results. These include the use of cover crops, compost application, alternative pest and weed control practices, reduced tillage, grazing animals on green manure, and more. These are part of a larger strategy to improve soil health (as measured by increased organic matter in the soils, water-holding capacity, soil fertility and other metrics) and

reduce the need for pumped water to maintain soil moisture for growing crops. This is a field of growing interest in the community and holds promise for reducing pumping while sustaining viable agricultural production. It is our hope that this region specific CWU assessment framework can aid this and other basins in their pursuit for sustainable water resource management. The proposed framework could be replicated in other basins provided region specific data and models are available.

■ ASSOCIATED CONTENT

§ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: [10.1021/acs.est.6b01711](https://doi.org/10.1021/acs.est.6b01711).

- (a) A description of green, ground and surface water types; (b) Data on area, production, yield and market value of agricultural products (PDF)

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Notes

The authors declare no competing financial interest.

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