

Article

Modelling Development of Riparian Ranchlands Using Ecosystem Services at the Aravaipa Watershed, SE Arizona

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Abstract: This paper describes how subdivision and development of rangelands within a remote and celebrated semi-arid watershed near the US–Mexico border might affect multiple ecohydrological services provided, such as recharge of the aquifer, water and sediment yield, water quality, flow rates and downstream cultural and natural resources. Specifically, we apply an uncalibrated watershed model and land-change forecasting scenario to consider the potential effects of converting rangelands to housing developments and document potential changes in hydrological ecosystem services. A new method to incorporate weather data in watershed modelling is introduced. Results of introducing residential development in this fragile arid environment portray changes in the water budget, including increases in surface-water runoff, water yield, and total sediment loading. Our findings also predict slight reductions in lateral soil water, a component of the water budget that is increasingly becoming recognized as critical to maintaining water availability in arid regions. We discuss how the proposed development on shrub/scrub rangelands could threaten to sever imperative ecohydrological interactions and impact multiple ecosystem services. This research highlights rangeland management issues important for the protection of open space, economic valuation of rangeland ecosystem services, conservation easements, and incentives to develop markets for these.

Keywords: hydrology; watershed modelling; water resources; scenario planning; sustainable management; ecosystem services

1. Introduction

Ranchlands in the western United States are often used to raise livestock and grow various crops. They are typically composed of a combination of privately-owned land and regulated grazing leases on adjacent Federal or State allotments. In recent decades, rapid population growth and associated cultural paradigms have incurred land-use change [1], including remote and arid rural landscapes in the United States and Mexico borderlands [2,3]. Large historical cattle ranches get subdivided into exurban landscapes and housing developments, or ranchettes, which fragment rangelands with construction of roads and buildings [4]. Subdivision and development of large ranches can have a variety of impacts on rangeland ecosystems, including the potential for increased nonnative plant and

animal species [5,6], soil disturbance, changes in prescribed fire or managed wildfire, and fragmented wildlife habitat and travel corridors [7].

Development of rangelands is also known to affect the function and character of local hydrology in terms of changes to (i) peak flow, (ii) total runoff, (iii) quality of water, and (iv) hydrologic amenities, defined as the appearance of a river [8]. Ellingson [9] proposed three watershed management approaches for protecting the base flow of a river: (i) Artificial recharge to the aquifer; (ii) low-flow augmentation using runoff impoundments; and (iii) restricting development. He suggested studies to test the feasibility of these activities could be best conducted using calibrated rainfall-runoff or groundwater flow models. In arid and semi-arid rangelands, biological diversity is closely linked to the availability of water, and reducing the effects of land development on stream ecosystems is a conservation priority. In the southwestern US, conservationists, ranchers, and forest workers are trying to promote both environmental and economic sustainability on rangelands [10,11]. A mutual goal is to balance production and conservation on interconnected landscapes and maintain cultural and biological diversity for future generations.

Historically, there has been a lot of research to understand the repercussions of varied land-use within watersheds. Leopold [8] presented an application that forecasts conditions expected with urbanization, which would explore scenarios based on different management options. Hydrology and sedimentation models, coupled with urban growth or restoration scenarios, can be applied to compare long-term water availability and tradeoffs in management practices [12–16]. Villarreal et al. [3] developed future land-use scenarios in the binational Santa Cruz watershed, located on the border of Arizona, United States, and Sonora, Mexico, to examine how biodiversity patterns are impacted by land use change. The scenarios identified possible unintended consequences that may result from the future implementation of regional conservation plans and portrayed some tradeoffs. For example, Perkl et al. [17] coupled urban growth simulations with models of wildlife corridors to examine how species migration might be adversely affected by development, and found that projected growth could be mitigated to have less harmful impacts.

Rangeland and riparian areas in the southwest were heavily impacted by livestock grazing in the 19th and early 20th centuries [18,19]. Overgrazing affected a wide range of ecosystem services, and the debate over the relative ecological footprint of grazing vs. development (i.e., “cattle vs condos”) continues to this day [6,20,21]. On one hand, because livestock are mobile, their footprint can be large and affect a wide range of ecosystems (both upland and riparian) and ecosystem services [19]. Livestock trample and compact soils, causing erosion in both the uplands and riparian areas, with impacts often lasting years after grazing pressure has subsided [22]. While the footprint of exurban development may be more discrete, building may cause more direct habitat loss and fragmentation for wildlife [23]. Bestelmeyer and Briske [24] suggest assessing and managing tradeoffs among ecosystem services to guide adaptation and transformation in rangelands.

Hydrologic ecosystem services describe the way ecosystems affect water resources, where ecohydrological impacts on water quantity, quality, location, and timing, are portrayed in terms of availability for humans [25–27]. Rangelands provide a suite of ecosystem services, including forage for livestock production, habitat for wildlife, biodiversity, open space, carbon sequestration, fresh water supply, and cultural services [10]. Norman et al. [14] outlined an approach to visualize declining surface-water flows in unincorporated communities located within a 150-mile swathe of the border between the US and Mexico. Socially and environmentally vulnerable communities may be more receptive to incentive-based policy tools than more affluent communities.

Food production from a rangeland-based industry is in decline, pressured by poor economic returns, increased regulations, an aging rural population, and increasingly diverse interests of land owners [10]. However, there are numerous other goods and services provided by rangelands that can supply societal demands, such as clean water, pollinator services, and food supplies. Payment for Ecosystem Services (PES) programs can compensate or subsidize landowners for producing or maintaining environmental services [28]. With proper incentives and economic benefits, rangelands

can provide both historical and more unique goods and services [10]. PES may be particularly suited to rural ranching communities and ranchettes in the US–Mexico borderlands [29].

The Aravaipa Watershed in southeastern Arizona, USA, contains Federally-protected perennial creek flows and wilderness areas, and culturally important rangelands, approximately 135 km north of the US–Mexico border. Some Aravaipa Valley ranches have recently (between 2004–2008) split off privately-owned parcels. According to the Aravaipa Watershed Conservation Alliance (AWCA; personal communication), approximately 300 ~16 ha lots are currently being considered for conversion to ranchettes, with associated roads, plumbing, well-excavation, and electrical expansion imminent. Additionally, county taxes are delinquent on some of these lots and many are currently re-listed for sale at this time. While these ranches were subdivided and sold during the real-estate boom, it is the local contention that the properties have subsequently lost value. The goal of this research is to help qualify and document the value, aside from realty dollars, associated with hydrologic ecosystem services lost or gained from varying land-management strategies, that might be vetted for PES incentives.

2. Methods

We describe our study area, followed by the two main components of research. First, we applied a daily time step hydrological model to simulate 36 years of rainfall and runoff, and developed estimates of watershed response spatially, to examine the water budget. Second, we modified the land cover input of the model to simulate how low-density development of ranchettes on some private lands might affect the expected hydrological response within the watershed and how ecosystem services may respond to these changes.

2.1. Study Area

Aravaipa Canyon lies astride Graham and Pinal Counties, Arizona, USA, just south of and adjacent to the San Carlos Apache Reservation (Figure 1). The ~140,000 ha watershed is removed from urban centers and access is limited by topography and lack of roads. Increasing livestock and mining developments began in the 1890s and by the 1920s, mining thrived, goat and human populations surged, and livestock roamed the open range [30].

In 1980, the advocacy group Defenders of Wildlife expressed concern about the effects of increased water demand in Aravaipa [9]. Renowned ichthyologist Wendell Minckley [31] suggested that monthly flows varied between 0.28–0.71 cubic meters per second (cms) while maintaining an average of 0.42 cms, and the US Bureau of Land Management (BLM) applied to the Arizona Department of Water Resources (ADWR) for a permit to appropriate this average to sustain fish, wildlife, and recreation [32]. Adar and Neuman [33] suggested that to preserve the habitat of the canyon, the recharge area at the east entrance to the Canyon must be conserved.

In 1984, Congress designated ~2711 ha of the lower Canyon and surrounding area a “wilderness area” (P.L. 98-406, 98 Stat. 1485) and then expanded this to ~8094 ha in the Arizona Desert Wilderness Act of 1990 (H.R.2570 - 101st Congress (1989–1990)). The BLM manages the Aravaipa Canyon Wilderness while allowing for limited primitive and unconfined recreation (Figure 1). In 1989, the third instream flow permit (Number 33-87114) in Arizona’s history was issued at Aravaipa, effectively protecting the average monthly flow of 0.42 cms required (~0.28 cms for fish and wildlife and ~0.14 cms for recreation) from appropriation by subsequent junior surface water claimants. This protected natural conditions and flow of Aravaipa Creek based on Federal and State water rights [34].

Currently, privately-owned land within the watershed (~21,793 ha) includes 18 ranches that also hold Federal and/or State allotments and leases for livestock grazing (Figure 1). Among the public lands present, only Aravaipa Canyon itself is not grazed as an allotment [32]. Management of the leased acreage is divided by the following agencies: State Trust ~53,343 ha, US Forest Service ~34,383 ha, BLM ~28,021 ha, The Nature Conservancy (TNC) ~3642 ha, and some smaller parcels managed by the San Carlos Apache Tribe and other Indian tribes, with allotments ~1755 ha (Figure 1). The amount of forage authorized on BLM allotments in the Aravaipa area is 9306 Animal Unit Months (AUMs) [32].

In general, most of these ranches have reduced numbers of cattle compared to 20 years ago, due to long term drought and reduced carrying capacity.

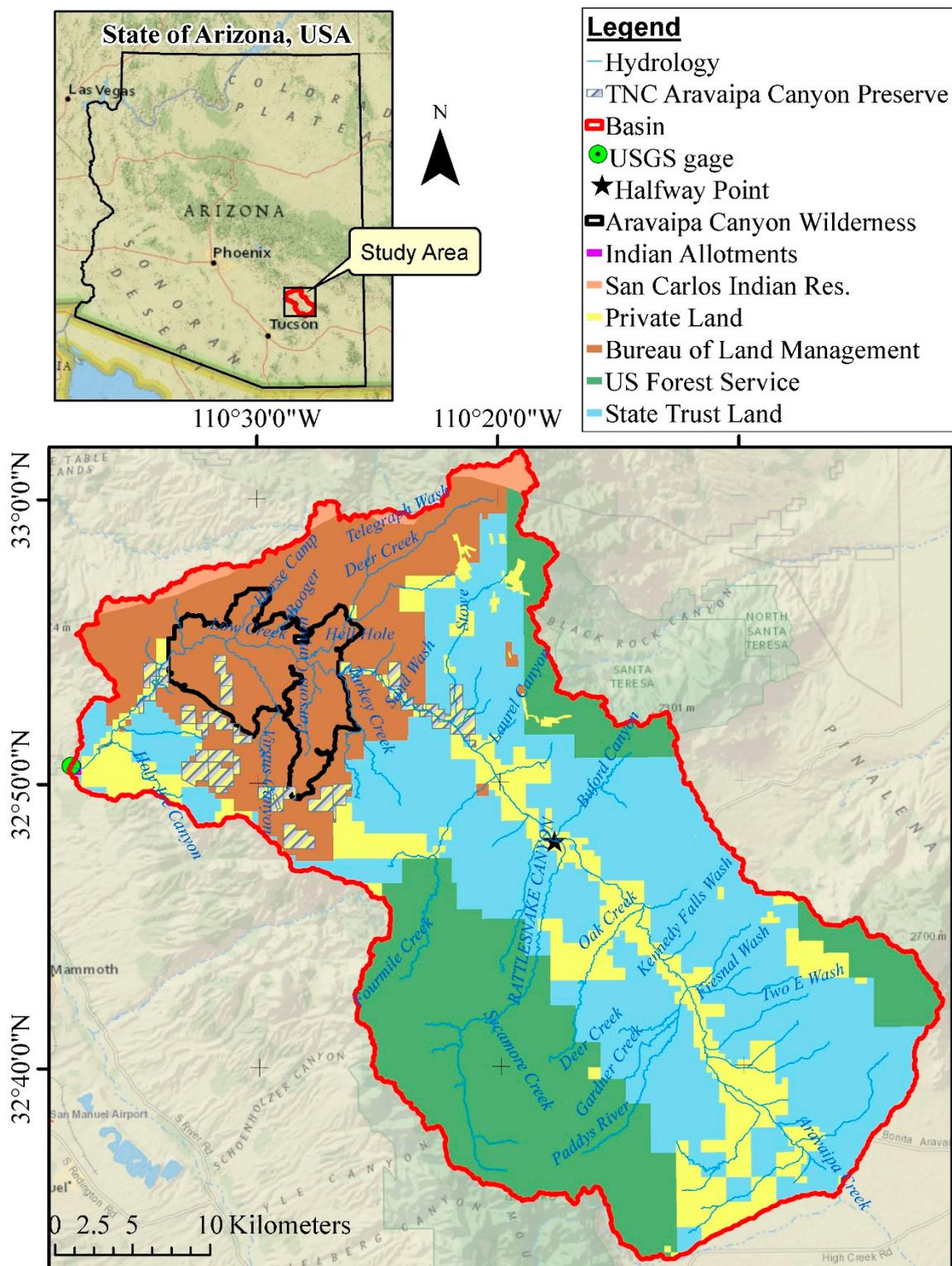


Figure 1. Location of the Aravaipa Watershed Basin (red outline) within the State of Arizona, the landownership, major streams, USGS gaging station, and Wilderness boundary.

Conservation incentives authorized by the 2002 Farm Bill include donated and purchased conservation easements by national non-governmental organizations such as TNC [10]. TNC prioritizes

balancing the needs of people and nature to ensure that conservation is a critical outcome in economic development. Conservation-easement agreements usually hinder development and support on-going stewardship of natural resources by ranchers and other private landowners [10]. TNC maintains a goal to ensure the long-term protection of the Aravaipa Creek stream system.

In 1991, Hadley et al. [30] noted that due to abundant water with little usage in Aravaipa, a watershed conservation organization was unnecessary, but given a need to coordinate upstream and downstream practices and erosion control, it might be desirable. In response to the shared goal to preserve and sustain Aravaipa Valley's natural landscapes by means of watershed and rangeland restoration, the Aravaipa Watershed Conservation Alliance (AWCA) formed in 2016, joining nonprofit groups, private landowners and agency staff. In 2017, AWCA engaged the USGS to consider how watershed models could be used to simulate surface-water runoff and recharge under various land-use conditions to demonstrate how people can affect the future of their water resources [35]. AWCA is interested in understanding how low-density residential development on privately owned portions of ranches in the upper watershed could affect ecosystems and water supplies.

2.1.1. Environmental Setting

The climate is semi-arid; annual precipitation ranges from 36 to 71 cm. Aravaipa Creek, a tributary of the San Pedro River, runs south to north, through Klondyke and then west, where it enters Aravaipa Canyon (Figure 1). It is mostly ephemeral (has flowing water for brief periods in response to rainfall), but is normally dry from the headwater to the intersection with Stowe Gulch [9]. From this intersection to the west, where there is a USGS stream gage station (#09473000 Aravaipa Creek near Mammoth; Figures 1 and 2), Aravaipa Creek is perennial, but again becomes ephemeral downstream of that.

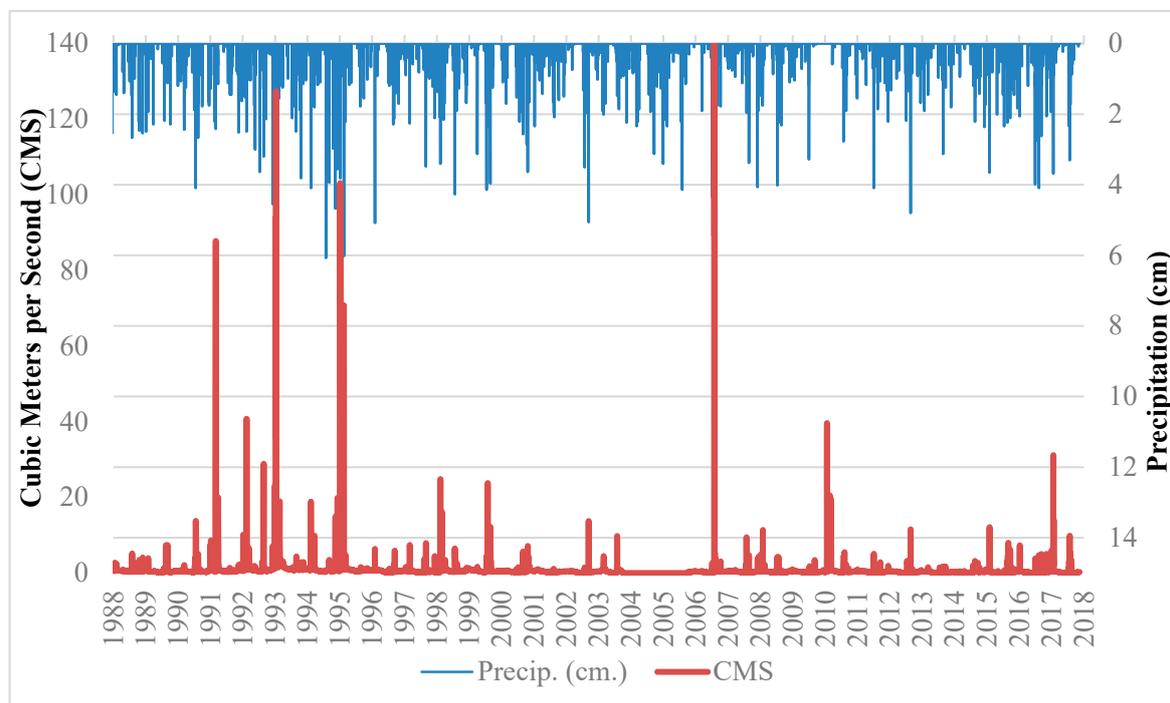


Figure 2. Rainfall-runoff response portrayed in hyetohydrograph at USGS stream gage station #09473000, Aravaipa Creek near Mammoth Springs.

The gaging station has been in operation since 1987, operated through the cooperation of Pinal County and the USGS AZ Water Science Center Tucson Field Office. At the gage, discharge measurements average ~0.62 cms. Ellingson [9] suggests the runoff ratio is ~3.3% with springs sustaining the creek during drier periods.

Groundwater moves from recharge areas in the high-elevation mountain blocks and along the mountain fronts towards Aravaipa Creek on the central valley floor (Figure 3a), and hence downgradient to the discharge area near the confluence with Stowe Gulch [9,36,37]. The underground water moves up to 396 m/day [9,30]. Groundwater recharge and discharge at springs is likely dependent on precipitation [32]. Ellingson [9] estimated ~2.4% (14.3 MIL m³) of the watershed's annual precipitation reaches the groundwater reservoirs. Other groundwater recharge estimates from infiltrating precipitation and runoff range from 8.6 MIL m³ to 20.6 MIL m³ [38]. Adar and Neuman [33] applied a model that shows lateral recharge from the pediments and the tributary Stowe Gulch Basin to be the main source of replenishment to the water table aquifer (~77 mm of deep percolation per year over approximately 111 km² of the basin). Lateral flows are critically important in dry seasons, with some upward leakage from the underlying confined aquifer [33].



(a)



(b)



(c)



(d)

Figure 3. Photographs of (a) upper watershed, (b) narrow and deep basin, (c) “Aravaipa Spring” and (d) mainstem of creek.

Small rural communities exist in the riparian corridor at both ends of the watershed and use the instream flow for irrigation, stock watering, and household use [39]. The narrow and deep Aravaipa basin (Figure 3b) was formed by displacement of the valley downward, relative to the mountains on each side, along normal faults forming the graben structure seen today [9,33]. Three of the Arizona “Sky Islands” mountain ranges border Aravaipa basin: (i) Santa Teresa (north-eastern), (ii) Pinaleno (southeastern), and (iii) Galiuro (southwestern).

Along the upper mainstem of Aravaipa Creek, the river is situated in mostly sedimentary deposits, consisting of loosely- to firmly-consolidated gravel, sand and silt, local clay, gypsum, marl, limestone, diatomite, and some intercalated basalt flows and felsic tuff beds [40]. The location of “Aravaipa Spring” and the beginning of perennial flow is controlled by the presence of bedrock (Figure 3c). Aravaipa Creek flows from its headwaters northwest to its confluence with the San Pedro River on younger alluvium [9]. Along the central axis of the valley, the young alluvium is separated from old alluvium by low permeability layers. Here the young alluvium provides a shallow water table unconfined aquifer and the old alluvium forms a confined aquifer [36,41]. The older alluvium abruptly ends near the top of the canyon, where a fault has displaced the Hellhole Conglomerate down against the relatively impermeable volcanic rocks. This structure forces water in the confined aquifer upward, and is responsible for the perennial flow found in Aravaipa Creek [9] (Figure 3d).

2.1.2. Ecosystem Services

The Millennium Ecosystem Assessment [42] was the first to systematically define ecosystem services. Even before this assessment, Hadley et al. [30] described some goods and services in the Aravaipa Canyon being provided by nature. Goods included food, crops, fuelwood, fish, game, furs and minerals and services such as diluting and cleansing polluted air and water, filtering and chemically transforming harmful mining residuals, manufacturing and supplying plant nutrients (from photosynthesis and soil supplies), and conditioning microclimates. While some of these more tangible resources have obvious economic and social value, some are yet to be quantified. The Millennium Ecosystem Assessment [42] grouped ecosystem services into four categories: (i) provisioning; (ii) regulating; (iii) supporting; and (iv) cultural.

Provisioning ecosystem services are the products that humans obtain from ecosystems including water, food, and habitat for wildlife. “Any desert canyon with permanent water, like Aravaipa, will be as full of life as it is beautiful” [43]. The abundance of water (rain and soil moisture) determines the abundance of crops and rangeland. A critical provisioning service to rangelands includes management practices that maintain ecological functions or restore functions to systems that have been degraded [10].

Regulating ecosystem services maintain the quality of air and soil, provide flood control, or pollinate crops. Flooding, like erosion, can be important for ecosystems but regulation is important [44]. While air and water quality enhancement have clear implications for human use, they also contribute to the quality of habitation of critical fish and wildlife species. Ecosystem services in the Canyon that benefit wilderness and wildlife are barely understood and largely unquantified [39]. The effects of land clearing and cultivation, livestock, mining and road building on soils have not been well documented in Aravaipa [30], yet the current inhabitants express great interest in protection of the environment.

Supporting ecosystem services are those that provide living spaces for plants and animals as well as maintain their diversity. Along the riparian zone, where water is available to support them, cottonwood, Arizona walnut, alder, willow, mesquite, box elder, and other vegetation grow to provide habitat for more than 200 species of birds, 46 species of mammals, 46 reptilian species, and 8 amphibian species that reside in the wilderness area [34], and the Aravaipa watershed and riparian corridor have been identified as important breeding habitat for the Federally threatened yellow-billed cuckoo [45]. Depth to water table sets the upper limit of a riparian species’ elevation, while ability to tolerate scour may set the lower limit [32]. In 1966, seven native fish species were documented at Aravaipa, the densest native population in the state [46]. The perennial nature of the water supply supports this habitat. Fish habitat is controlled by patterns of erosion, sediment transport, and deposition, which

in turn are functions of precipitation, runoff, and bed load volume [46]. Flood magnitudes vary over a period of hours along with corresponding changes in turbidity, while water temperatures can change from ~16–40 °C annually [46,47].

Cultural services are nonmaterial benefits or experiences that people obtain from ecosystems. Aravaipa has great value as an aesthetic resource and beauty is abundant [30]. A variety of outdoor recreationists use the ecosystem for hiking, hunting, picnicking, birding, horseback riding, primitive camping, off-highway vehicle driving, geocaching, and playing in the stream [32]. In fact, the canyon is such a popular destination for outdoor enthusiasts, that the BLM turned to a permit system to limit the number of visitors and reduce human impacts to the area. Moore et al. [34] found that water was rated by visitors as the most important attribute in the recreational setting of Aravaipa Canyon. Weber and Berrens [39] discussed that the instream flow allocation for recreation represents significant worth to society. And the rural or ranching cultural history values are plentiful. At Aravaipa Canyon, the relatively small floodplain discouraged large human settlements that grew up along other Arizona perennial rivers and the rugged terrain provided sanctuaries for wildlife and reduced extinction rates [30]. The enormous biodiversity provides services that have yet to be fully characterized, such as species that provide habitat for pollinators or species with medicinal value. Effects that the loss or degradation to environmental factors, such as in soil nutrient wealth and depth to bedrock or water, would have on biodiversity are unknown.

2.2. Hydrological Model Application

The Soil and Water Assessment Tool (SWAT) is a semi-distributed model, jointly developed by USDA Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research, a part of the Texas A&M University System [48]. It is a long-term yield model, that uses daily average values as input. SWAT has been applied to predict the effect of land use, management practices, and climate change on water, sediment, and agricultural chemical yields in small- to large-scale watersheds with varying soils, land use, and management over extended periods of time [48,49]. It is oft used in assessing erosion control, non-point source pollution control, and best management in watersheds [13,14,16,50–54].

In watershed-modeling studies, flow is often calibrated at the watershed outlet. However, in arid and semi-arid watersheds, flow characteristics vary throughout the watershed and is often discontinuous for most of the year, except during large flood events. In a SWAT calibration at the nearby Santa Cruz River Watershed, calibration was performed at 7 monitoring stations throughout the watershed to improve model reliability [53]. Results portray that each station required different variations of controlled parameters to match flow predictions in the model at that site. However, when the model was calibrated at only the watershed outlet, flow predictions at the other monitoring stations proved inaccurate. Uncalibrated watershed models have been used in a number of applications for assessing relative change [55,56]. Uncalibrated physically based models can also be used with some confidence in identifying the trends and directions of changes in watershed response due to changes in watershed conditions and are a valuable aid in identifying where conservation efforts might be focused to offset impacts from LULC [53,56,57]. In this study, we use the uncalibrated model for assessing the relative change in hydrology and associated ecosystem services resulting from conversion of rangeland to housing development.

SWAT Model Development and Parametrization

We obtained soils, topography and land-use data from various sources and organized them in a geodatabase. Soils were mapped by the USDA Natural Resources Conservation Service (NRCS) at a scale of 1:12,000, in the Soil Survey Geographic Database (SSURGO) data [58]. The USGS National Land Cover Database is a 16-class land-cover classification based on the Landsat Enhanced Thematic Mapper+ (ETM+) from 2011 at a spatial resolution of 30 m [59]. A 10 m digital elevation model (DEM) was input into SWAT to delineate watershed boundaries, where stream channels were constricted to represent ~722 ha. The USGS gage was identified as the outlet to drain to, creating a total area of

139,296 ha to be modeled. All geospatial data were trimmed to represent the study area and converted to a common Universal Transverse Mercator (UTM) projection.

SWAT model requires continuous slope values to be discretized into multiple classes (3) with limits 0%–10%, 10%–30%, and >30%. The watershed was subdivided into 734 discrete hydrologic response units (HRUs), within 117 sub-basins. We defined the weights of the HRU thresholds equally to represent 10% over sub-basin, land use, and soil areas. The model was run for 36 years, starting in 1981, with daily rainfall derived runoff estimated using the curve number method.

At first, we used an observed/measured rainfall dataset of 2 gages for the watershed to drive the rainfall in the model but found our biased data capture skewed the precipitation distribution. There is always uncertainty attributed to the precipitation input, and even when a watershed is heavily gaged, it is hard to document all the storms that might occur and not over-extrapolate. We simulated weather using the weather generator in SWAT with multiple gages simulated for the watershed and it created inaccurate estimates of higher precipitation in the western side of the watershed, which tapered to the east. The SWAT weather generator portrayed the same bias as the real rain gage dataset, which was ultimately driven by the weather generator. It was unable to capture the high-elevation precipitation we knew to be occurring in the Pinaleño and Galiuro Mountain ranges, but instead depicted high rainfall towards the outlet. This is very different from what land managers see on the ground, where the upper watershed in the southwest is grassland and oak savanna, indicating more precipitation, while the area to the northwest, where the USGS gage is located, is in saguaro cacti and creosote shrublands, a drier regime.

In order to resolve the error in spatially distributed precipitation as extrapolated by the SWAT model from station (point) data, we downloaded 35 years of daily weather raster data (precipitation) available at a 4 km spatial scale from PRISM (<http://www.prism.oregonstate.edu>). The PRISM Climate Group [60] gathers climate observations from a wide range of monitoring networks, with quality-control measures, and develops spatial climate datasets that portray short-term and long-term climate patterns. We used the centroid of each PRISM grid cell to create a proxy “station” for use in SWAT. We selected stations that best represent the spatial and climatic variability of this watershed, based on topography and local knowledge. PRISM grid points were mostly supplemented for the areas where the observed meteorological station was scarce and not representative of the actual precipitation due to spatial heterogeneity of topography and rainfall along that northern part of the watershed. All SWAT model input parameters are improved given actual physical knowledge of the watershed, which is true for most physically-based models [61]. After some trial and error, 20 virtual “gages” scattered within the watershed with additional gages around it appear to portray the elevation associated spatial patterns evidenced in the climate normal pattern, with one gage per ~70 km² of watershed area. The data were formatted appropriately to use as weather data input (Figure 4).

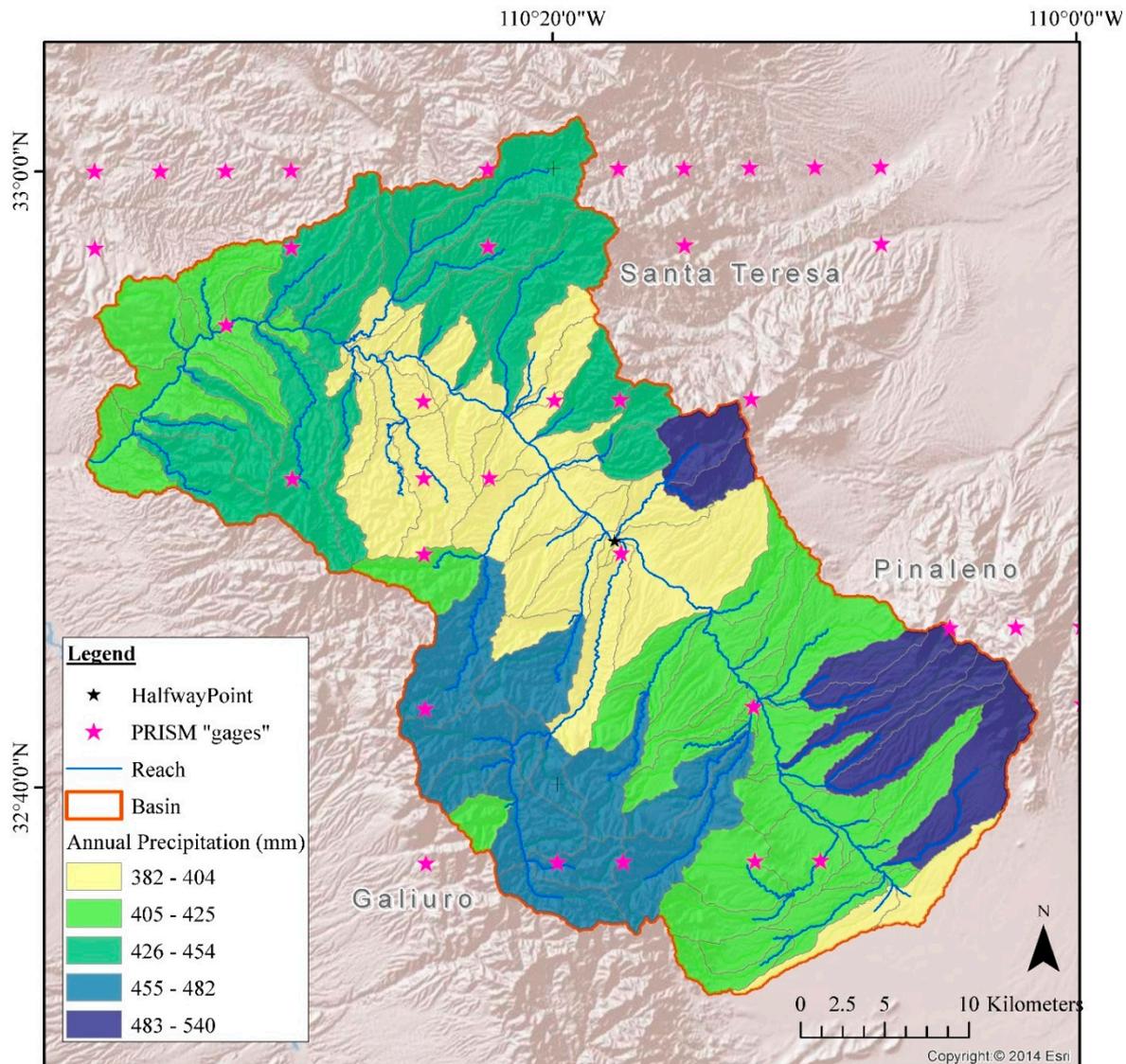


Figure 4. Distribution of precipitation based on synthesized gage dataset to represent daily rainfall summarized to 2016 annual values.

2.3. Scenario Assessment

The use of watershed hydrologic models, designed specifically to simulate surface and near-surface processes, can aid in visualizing potential effects of land management decisions on surface-water hydrology and the groundwater system. Logsdon and Chaubey [44] developed mathematical indices to represent ecosystem service quantities using the outputs SWAT. We consider the provisional and regulatory ecosystem services they describe: Fresh water provisioning, food provisioning, fuel provisioning, erosion regulation and flood regulation, to compare ecosystem services within a watershed, given two different land management scenarios.

In Aravaipa, some land owners are dividing ranches into ranchettes and developing the riparian area to supplement incomes (Mark Haberstich personal observation 2018). In order to simulate this land-change scenario, the National Land Cover Database (NLCD) data from 2011 was downloaded and mapped for the watershed (Figure 5, top). To simulate conversion of ranchland to ranchettes, all pixels falling within privately-owned parcels in the upper watershed were changed to “Developed” to reflect potential land cover changes (Figure 5, bottom). Developed, Open Space areas were defined as a mix of constructed materials, but mostly vegetation, where impervious surfaces account for less than 20% of

total land cover [59]. The SWAT model was then applied to both the baseline and developed scenarios and differences between the two were assessed.

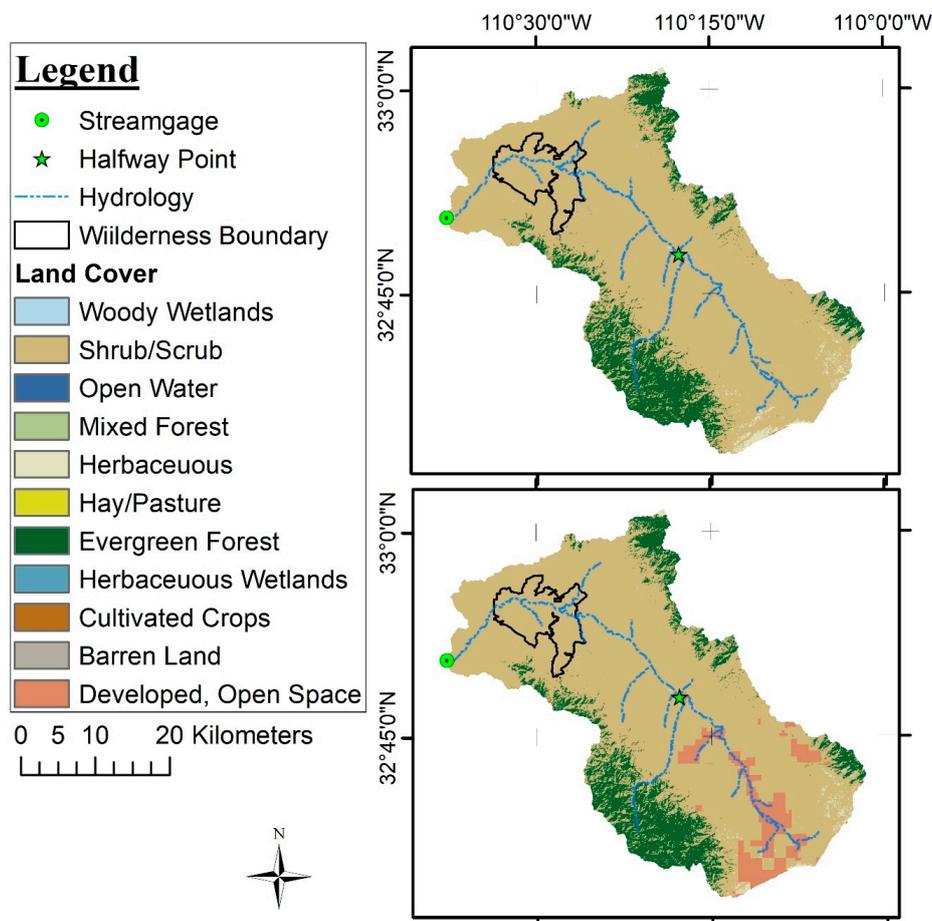


Figure 5. Current (top) and developed (bottom) land use inputs for SWAT (Soil and Water Assessment Tool) scenario assessment, modified from the NLCD [59].

When interpreted by the SWAT model, this created an increase in low-density urban land use and an almost equivalent decrease in Range-Brush along the riparian area (in privately owned lands), affecting ~5600 ha (4% of the total watershed area).

3. Results

The analyses and maps include a halfway point in the Aravaipa Creek watershed, near the centroid of the polygon (UTM: 12N 563257, 3627291; Figure 1). We designated this to look at the impacts directly below where our changing land-use is set to occur. We compare it with the outlet of the entire watershed (USGS Gaging Station) to discern how those immediate impacts are diffused over time and space. It is noted that the model has not simulated a change in land use at a specific time frame but rather, examines what the land use change would look like at any year of the iteration. Obviously, this did not occur in the past, but is meant to portray the impacts of such a change into the future, based on the previous climate record.

In examining the model results for both daily and monthly simulations for the 36-year simulation (1981–2016), we present the ending yearly totals from 2016, a relatively normal year precipitation-wise, to examine changes in discharge and concentration of sediment. Spatial variations on the landscape are portrayed for percolation, surface water runoff, water yield, evapotranspiration and sediment yield. The differences between the current land use and the proposed ranchette development are compared. Additionally, the average annual results for both scenarios are discussed.

3.1. Discharge

Results show simulated increased surface discharge on the landscape in the main channel or reach files. This is represented as increased daily streamflow in the reaches downstream, where simulated average annual flow is increased by ~0.04 cms at our halfway point and ~0.03 cms at the USGS gaging station (Figure 6).

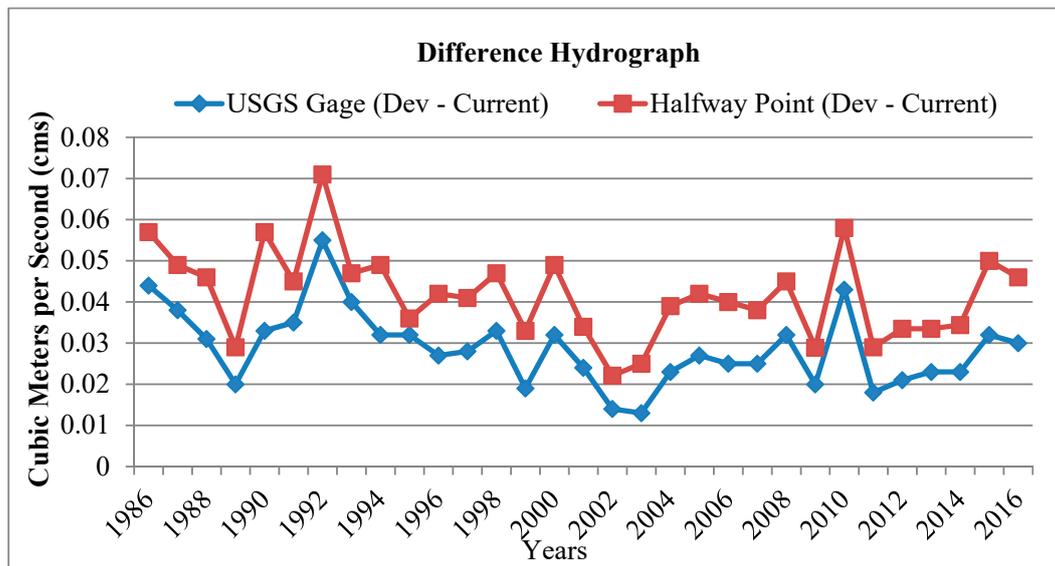


Figure 6. Difference in discharge between Current and Developed scenarios, at Watershed Halfway Point and USGS Gaging Station, from uncalibrated SWAT model iterations.

3.2. Sedimentation

The simulated increased sediment yield extends into the river, represented as increased concentration of sediment in the reach during the timestep, accessed in SWAT output files and described in the main channel or reach files. Simulated sediment concentration average is increased by ~0.19 mg/kg (ppm) at our halfway point but is negligible at the USGS gaging station (Figure 7).

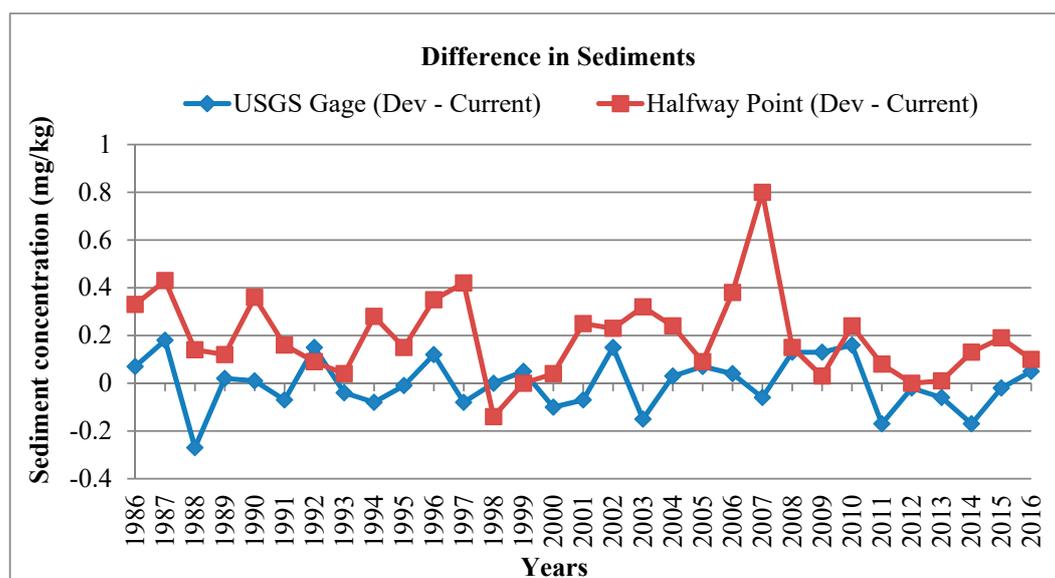


Figure 7. Difference in sediment concentration between Current and Developed scenarios, at Watershed Halfway Point and USGS Gaging Station, from uncalibrated SWAT model iterations.

3.3. Spatial Distribution

Most important to the individual land managers was the effect that development might have on their ranches, portrayed by SWAT output variables describing sub-basins. Modeling shows most change occurs in the upper watershed where the development occurred (Figure 8). Changes in evapotranspiration show both increases and decreases. Percolation decreases in the upper watershed and increases on the lower watershed, especially around Aravaipa Spring. Without knowledge of the groundwater aquifer boundaries feeding into the spring discharge and well table connectivity, it is hard to say how this affects water users. Surface-water discharge and water yield increases in the upper watershed based on the scenario change. Sediment yield increased there as well as in downstream sub-watersheds.

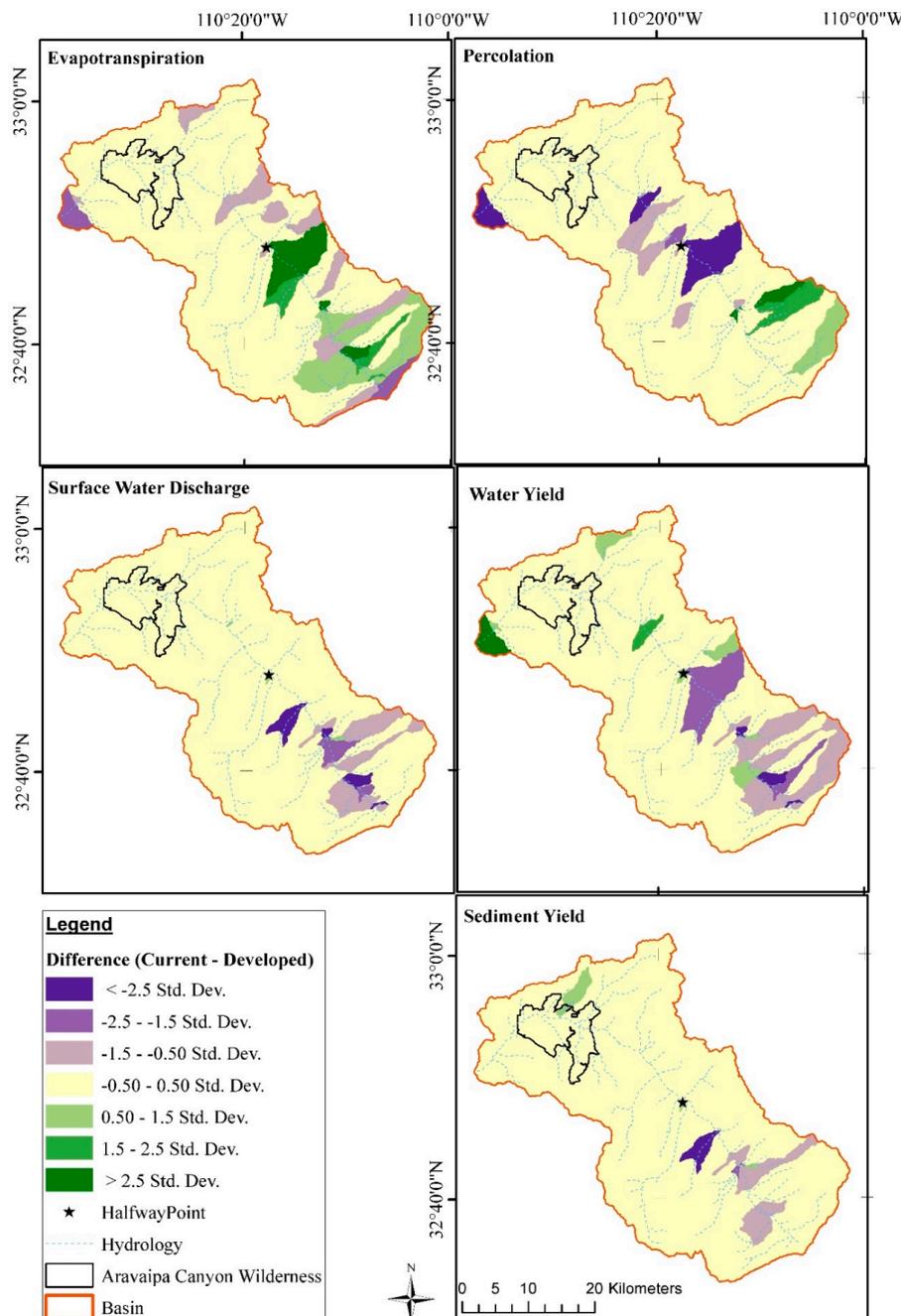


Figure 8. Difference in results between Current and Developed scenarios, from uncalibrated SWAT model iterations, where values above standard deviation (Std. Dev.; purple) show increased, and values below Std. Dev. (Green) depict decreases.

3.4. Basin-wide Change

In comparing the output files from each simulation, there are some notable changes in average annual basin stress values, including a small increase in surface-water runoff and yield, and total sediment loading, along with a small decrease in lateral soil discharge and ET, based on the increased development (Table 1). As expected, the changes look less significant at the basin scale when compared at the sub-basin scale, where changes are more significant. There are also changes in average annual basin nutrients, based on the increased development, especially noted are the increase in nitrogen and decrease in phosphorus.

Table 1. Differences in average annual basin output values between Current and Developed scenarios.

| | Current | Developed | Difference | Units | % Change |
|---------------------------------|---------|-----------|------------|-------|----------|
| PRECIP | 425.4 | 425.4 | 0 | MM | 0 |
| SURFACE RUNOFF DISCHARGE (Q) | 18.13 | 18.99 | 0.86 | MM | 5 |
| LATERAL SOIL Q | 83.02 | 82.71 | −0.31 | MM | 0 |
| TOTAL WATER YIELD | 104.09 | 104.71 | 0.62 | MM | 1 |
| GROUNDWATER (SHALLOW AQUIFER) Q | 2.3 | 2.35 | 0.05 | MM | 2 |
| DEEP AQUIFER RECHARGE | 0.63 | 0.64 | 0.01 | MM | 2 |
| PERCOLATION OUT OF SOIL | 12.68 | 12.84 | 0.16 | MM | 1 |
| TOTAL AQUIFER RECHARGE | 12.7 | 12.86 | 0.16 | MM | 1 |
| EVAPOTRANSPIRATION | 311.3 | 310.6 | −0.7 | MM | 0 |
| TOTAL SEDIMENT LOADING | 2.47 | 2.52 | 0.05 | T/HA | 2 |

4. Discussion

We used an uncalibrated SWAT model for assessing relative change in hydrology and associated ecosystem services resulting from conversion of rangeland to housing development. Watershed modelling efforts often calibrate flow at the watershed outlet to improve model reliability. However, arid land discharge varies greatly from site to site within a watershed, due to intermittent and ephemeral flows, climate, etc., and calibration at one location does not extend reliability upstream or downstream [53]. Uncalibrated watershed models are useful for assessing relative change and comparing scenarios [55,56].

Results of introducing ranchettes portray slight reductions in lateral soil water and ET. The importance of lateral flows and bank storage to maintaining water availability in arid lands is becoming better understood [62,63]. For example, Schreiner-McGraw and Vivoni [64] deemed the connectivity along hillslope-channel pathways an essential control on the streamflow generation and groundwater recharge in arid regions. As a watershed is urbanized and vegetation is replaced by impervious surfaces, the area where infiltration to groundwater can occur is greatly reduced, compromising soil-water storage capability. As the model used is uncalibrated, we feel it important to note that usual calibration for this river system and nearby rivers would start with removing most of the lateral flow component [14,16,53,54,57,65,66]. This is because arid lands do not support a great amount of soil water-moisture transfer. The threat of residential development further reducing more of this flow suggests impacts to all associated water availability. In the following paragraphs we discuss in more detail some of the possible implications of urbanization on the ecosystem services of the Aravaipa watershed.

The Millennium Ecosystem Assessment [42] ecosystem services categories can be examined in relationship to local SWAT results of our scenario analyses (Table 2). The Local Response portrayed in Table 2 is based on comparing results between Current and Developed scenarios, derived from the uncalibrated SWAT model iterations. In some cases, an obvious increase or decrease is documented. In others, which we have not investigated in this research, we want to point out the potential change in

service that could be expected. Freshwater provisioning considers both the quality and quantity of water. Given our scenario assessment, we see an increase in discharge and sedimentation, thereby diminishing water quality in the higher flows. Freshwater provisioning services are compromised by land-use change. Food and fuel provisioning from crops and from grasslands for livestock and wildlife forage would likely decrease as rangeland is converted to low-intensity residential [44].

Table 2. Cross-walking ecosystem services, SWAT outputs and local response based on results between Current and Developed scenarios, from uncalibrated SWAT model iterations.

| Category | Ecosystem Service | SWAT Output | Local Response |
|--------------|--|---|----------------|
| Provisioning | Water | SURFACE RUNOFF Q | Increase |
| | Water | TOTAL AQ RECHARGE | Increase |
| | Food (crops/rangeland) | ET | Decrease |
| | Food (crops/rangeland) | NUTRIENTS in Soil | Decrease |
| | Fuel | ET | Decrease |
| Regulating | Soil-Moisture | LATERAL SOIL Q | Decrease |
| | Water quality | TOTAL SEDIMENT LOADING | Decrease |
| | Erosion control | TOTAL SEDIMENT LOADING | Decrease |
| Supporting | Flood control | SURFACE RUNOFF Q | Decrease |
| | Habitat (in-stream) | <i>Dependent on Water Provisioning and Water Quality Regulating</i> | <i>Change</i> |
| | Habitat (on land) | <i>Dependent on Food (crops/rangeland) Provisioning</i> | <i>Change</i> |
| Cultural | Habitat (on land) | <i>Dependent on Erosion Control Regulating</i> | <i>Change</i> |
| | Recreation (hiking, hunting, birding) | <i>Dependent on Water Provisioning</i> | <i>Change</i> |
| | Intrinsic (biodiversity, societal value) | <i>Dependent on Water Provisioning</i> | <i>Change</i> |
| | Historical | <i>Dependent on Water Provisioning</i> | <i>Change</i> |

Land use and land cover have a great impact on patterns of infiltration and rainfall runoff. Vegetation can slow runoff, allowing water to seep into the ground. Impervious surfaces, usually associated with development, increase overland flow rates, limiting the potential to infiltrate the surface and contributing to more flash floods and high flow events [67]. In arid rangeland environments where vegetation is already sparse, the change from natural upland vegetation to developed lands has had a considerable impact on flooding, for example in Nogales, Sonora, and Mexico [12,67–70]. In the Aravaipa Watershed, regulating services of erosion and flood control are also impacted by the proposed land-use change scenario. Specifically, we found that erosion control is diminished in the upper watershed and flood control is decreased in the lower watershed. These changes to erosion and flood control can also produce feedbacks that affect connected ecosystems services; for example, increased runoff can lead to channelization that decreases vegetation/habitat and increases sedimentation and erosion downstream [71].

Supporting ecosystem services (e.g., primary production, nutrient cycling) are those that provide living spaces for plants and animals as well as maintain their diversity. Seven native fish species depend on the water supply [46,47]. It is unclear if these supporting ecosystem services would be compromised by the slight changes in turbidity, patterns of erosion, sediment transport, and deposition that impact water temperatures, but important for land managers like TNC, whose mission is to "Manage for Biodiversity". Additionally, as sediment increases in the stream, so do some of the nutrients from the

nearby agricultural fields. This is potentially hazardous to stream inhabitants. The soils and nutrients are also important to consider keeping on the landscape as organic material is important for farming and ranching land. Development of rangelands is likely to have a large impact on ecosystem services of the rangelands, where altered watershed processes can affect the distribution and cycling of nutrients and soil health and lead to reduced ET and overall vegetation productivity.

Cultural services important at Aravaipa are also related to water availability, where [34] found it to be the most important attribute in the recreational setting of Aravaipa Canyon. Instream flow is one way to monitor the provisioning of this cultural service [39]. Instream flows are protected at an average monthly flow of 0.42 cms for fish, wildlife and recreation. The current mean annual discharge at the outlet of the watershed is 0.48 cms. Our scenario modelling predicts that conversion of privately-owned ranches to ranchette-type developments would increase discharge by ~0.03 cms, keeping it within State and Federal requirements.

As a first response, it is easy to consider the increase in surface runoff as a positive thing for dry regions. Many people support management via tax dollars to remove vegetation from arid lands, and enhance river flow [72]. However, higher peak flows can create unwanted flooding and the associated increase in concentrated sediments pose risk to downstream habitats [12,66,68–70]. Endangered species in the canyon have temperature and turbidity preferences that might be adversely affected by such changes. The proposed conversion of land use threatens supporting ecosystem services, dependent on ecological processes and related to biological diversity as well as regulating ecosystem services, such as the provision of carbon sequestration, preventing soil erosion, and controlling of floods.

Bank storage offers the potential to hold water with returns to the stream occurring over a period of days or weeks, which can reduce flood peaks and later supplement stream flows [73]. Norman and Niraula [66] and Norman et al. [63] found that bank storage and lateral flow can be improved in arid land watersheds intentionally, by installing erosion control structures to slow and store water. The potential to guide land-use plans to enhance lateral flows, develop perched aquifers, and recharge groundwater aquifers is of utmost importance in Aravaipa and arid lands in general. The subsequent increases in available surface water from bank storage supports the suite of ecosystem services in the Aravaipa watershed and may be used to offset some of the expected watershed changes if the area is developed. Modeling can be used to identify areas at risk that should be considered for more protection to ensure desired ecosystem services are sustained into the future.

Adar and Neuman [33] identified recharge at Stowe Gulch as critically important, especially during dry seasons, to support annual discharge through the Aravaipa Spring. Likewise, according to the spatial distribution of SWAT model results, Stowe Gulch and other locations may be considered crucial to recharge the aquifer and should be considered for protection from change. Urban development by ranchette creation could alter these sites. While the effects of ground water withdrawals (pumping, etc.) are significant and need to be considered by management, we do not discuss them in this research. Our model does not consider withdrawals, but increased withdrawals from the upper basin for agriculture, domestic use, or inter-basin transfer, could pose additional threat to flow in Aravaipa Creek [32].

In running the SWAT model, the soil parameters (Ksat, soil-water holding capacity, etc.) are likely creating anomalies given the lack of survey effort in the National Forest, a recurring hardship for watershed modelling [66]. Rivers in semi-arid regions are less predictable than those of rivers in humid regions because flow is tied to highly variable spatial and temporal patterns of precipitation. There is always uncertainty attributed to the precipitation input for models unless a watershed is heavily gaged, and even then, it is hard to not over-extrapolate. We examined three different precipitation inputs for the SWAT model: (i) the measured rainfall for the watershed was biased by gage locations and skewed the outputs as such; (ii) the SWAT weather generator simulation didn't improve the precipitation patterns beyond the measured data; and (iii) PRISM-generated "virtual" rain gages created relatively accurate rainfall distribution based on the land management personnel's long-term observations and followed patterns observed in the elevation derived normal. This new "virtual" rain

gage approach could improve SWAT modelling in many areas characterized by comparatively high, spatially heterogeneous precipitation patterns.

In the SWAT model, water that infiltrates the surface is divided into multiple layers for routing and moves through the soil via “lateral flow” or unsaturated flow. SWAT models calibrated in southeastern Arizona are normally manipulated to reduce the lateral flow component drastically, to best mimic arid land processes and lack of bank storage (soil of stream bed and banks that stores water) [53,54,57,63,66,71]. Typically, a model is calibrated against observed streamflow data and parameters are adjusted until observed streamflow equals model streamflow [48]. This should allow the model to accurately mimic the actual watershed processes and estimate movement of sediment, nutrients, and pesticides from a watershed. We consider the potential to calibrate the model to derive more accurate estimates of volume, but the uncalibrated version of the model allows for qualitative analysis of variations in input. Our model portrays ~4.3% of precipitation allocated to runoff and ~19.5% predicted to flow through lateral soil discharge, creating total water yield ~24% of precipitation. About 73% of the precipitation is absorbed into the water cycle as ET in our model predictions and ~3% goes to total aquifer (shallow + deep) recharge. These uncalibrated water budget estimates are only slightly higher than previous estimates by Ellingson [9], who suggested that ~3.3% of precipitation supports surface runoff and ~2.4% of the watershed’s annual precipitation reaches the groundwater reservoirs.

5. Conclusions

Sustainable land management depends on reconciling supply and demand for ecosystem services by different stakeholders. Demand for ranchettes has allowed many ranchers to liquidate small portions of their property and make more money than they would grazing. In addition to the conservation easements available to protect privately owned rangeland, it would be worthwhile to consider economic valuation of rangeland ecosystem services and incentives to develop markets for these. This study the portrays differences in predicted water budgets (vs. absolute values of stream flow) based on varied land use. The conversion of rangeland to low-density exurban ranchettes will have a variety of effects on the hydrology of the area and, ultimately, on the ecosystem services provided to the inhabitants and visitors of the area.

In terms of ecosystem services, flows in the Aravaipa watershed are critical for (i) provisioning of water for food and livelihoods; (ii) regulating environmental quality; (iii) supporting habitat and biodiversity; and (iv) supporting cultural and recreational opportunities for people. This analysis uses a watershed modeling approach to simulate the effect of ranchette development on the Aravaipa watershed to weigh potential effects and associated trade-offs between ecosystem services. The proposed anthropogenic modification on shrub/scrub rangelands could disconnect imperative ecohydrological interactions, causing increases in water provisioning services in the near-term that might decline in the long-term. Associated decreases in food (crops/rangeland), fuel and soil-moisture provisioning services would be expected. Similarly, decreases in water quality, erosion-control, and flood-detention regulating services would be expected to decrease based on this scenario. Secondary effects, dependent on these, would cause changes in habitat (both in-stream and on land) supporting services and recreation, intrinsic, and historical cultural services.

This research is a valuable first step to try to integrate land-use planning and ecosystem dynamics, but more valuation of costs and benefits is needed. It is important to consider all the tradeoffs in values of rangelands, for meat production, wildlife, water, open space, and aesthetics associated with developing ranchettes on arid rangelands. An exciting byproduct of this analysis is the creation of a valuable substitute for weather data input to SWAT models where elevation changes and lack of precise, real-world data exist by using gridded PRISM data to create virtual weather stations.

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