

EVALUATING HYDROLOGICAL RESPONSE OF FUTURE LAND COVER CHANGE SCENARIOS IN THE SAN PEDRO RIVER (U.S./MEXICO) WITH THE AUTOMATED GEOSPATIAL WATERSHED ASSESSMENT (AGWA) TOOL

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Abstract—Long-term land-use and land cover change and their associated impacts pose critical challenges to sustaining vital hydrological ecosystem services for future generations. In this study, a methodology was developed to characterize potential hydrologic impacts from future urban growth through time. Future growth is represented by housing density maps generated in decadal intervals from 2010 to 2100, produced by the U.S. Environmental Protection Agency (EPA) Integrated Climate and Land-Use Scenarios (ICLUS) database. ICLUS developed future housing density maps by adapting the Intergovernmental Panel on Climate Change (IPCC) social, economic, and demographic storylines to the conterminous United States. To characterize hydrologic impacts from future growth, the housing density maps were reclassified to National Land Cover Database 2006 land cover classes and used to parameterize the Soil and Water Assessment Tool (SWAT) using the Automated Geospatial Watershed Assessment (AGWA) modeling system.

INTRODUCTION

Scenario analysis provides the capability to explore pathways of change that diverge from baseline conditions and lead to plausible future states or events. Scenario analysis has been used in studies related to environmental decision support to assist in evaluating policy or management options, such as in the Colorado River Basin (USDI 2012). Most approaches are designed to analyze alternative futures related to decision options, potential impacts and benefits, long-term risks, and management opportunities (Steinitz and others 2003, Kepner and others 2012, March and others 2012). The technique provides a dynamic and flexible way to evaluate policy or management options and is frequently combined with process modeling intended to bridge the gap between science and decision making across a broad range of spatial and temporal scales (Liu and others 2008a and 2008b, Mahmoud and others 2009).

The objective of this study is to develop and demonstrate a methodology to integrate a widely used watershed modeling tool with an internally consistent national database of alternative futures which can then be scaled to regional watershed applications. The focus of the study is to explore cumulative impacts of housing densities parsed out at decadal intervals to the year 2100 on a hydrological ecosystem consisting primarily of ephemeral and intermittent waters.

Ephemeral waters are extremely important in the arid west as a key source of groundwater recharge (Goodrich and others 2004). They provide important near channel alluvial aquifer recharge to support aquatic ecosystems in downstream perennial and intermittent streams (Baille and others 2007) and also provide critical ecosystem services (Levick and others 2008). Based on the National Hydrography Dataset; 94, 89, 88, and 79 percent of the

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streams in Arizona, Nevada, New Mexico, and Utah, respectively, are intermittent or ephemeral (Alexander and others 2015).

For the purpose of this study, the results are restricted to the San Pedro River, U.S./Mexico (Fig. 1). The intent is to quantitatively evaluate hydrologic impacts of future developments at the basin scale, which intrinsically addresses the cumulative impact of multiple housing development projects. The study area encompasses the Arizona portion of the watershed (9,800 km²). The San Pedro River flows 230 km from its headwaters in Sonora, Mexico to its confluence with the Gila River near the stream gage (USGS 09473500) at Winkelman, AZ. It is nationally known as one of the last free-flowing rivers in the Southwest. It has significant ecological value, supporting one of the highest numbers of mammal species in the world and providing crucial habitat and a migration corridor to several hundred bird species. Vegetation ranges from primarily semi-desert grassland and Chihuahuan

desert scrub in the Upper San Pedro to primarily Sonoran desert scrub and semi-desert grassland in the Lower San Pedro. The Upper San Pedro is home to the San Pedro Riparian National Conservation Area (SPRNCA). It was designated as the first National Conservation Area for riparian protection by Congress in 1988. The SPRNCA protects approximately 64 km of river and is administered by the U.S. Department of the Interior, Bureau of Land Management (Kepner and others 2004, Bagstad and others 2012).

METHODS

The Automated Geospatial Watershed Assessment (AGWA; Miller and others 2007; <http://www2.epa.gov/water-research/automated-geospatial-watershed-assessment-tool> and <http://www.tucson.ars.ag.gov/agwa>) tool is the key hydrological modeling system utilized in this study to identify areas that are most sensitive to environmental degradation as well as areas of potential

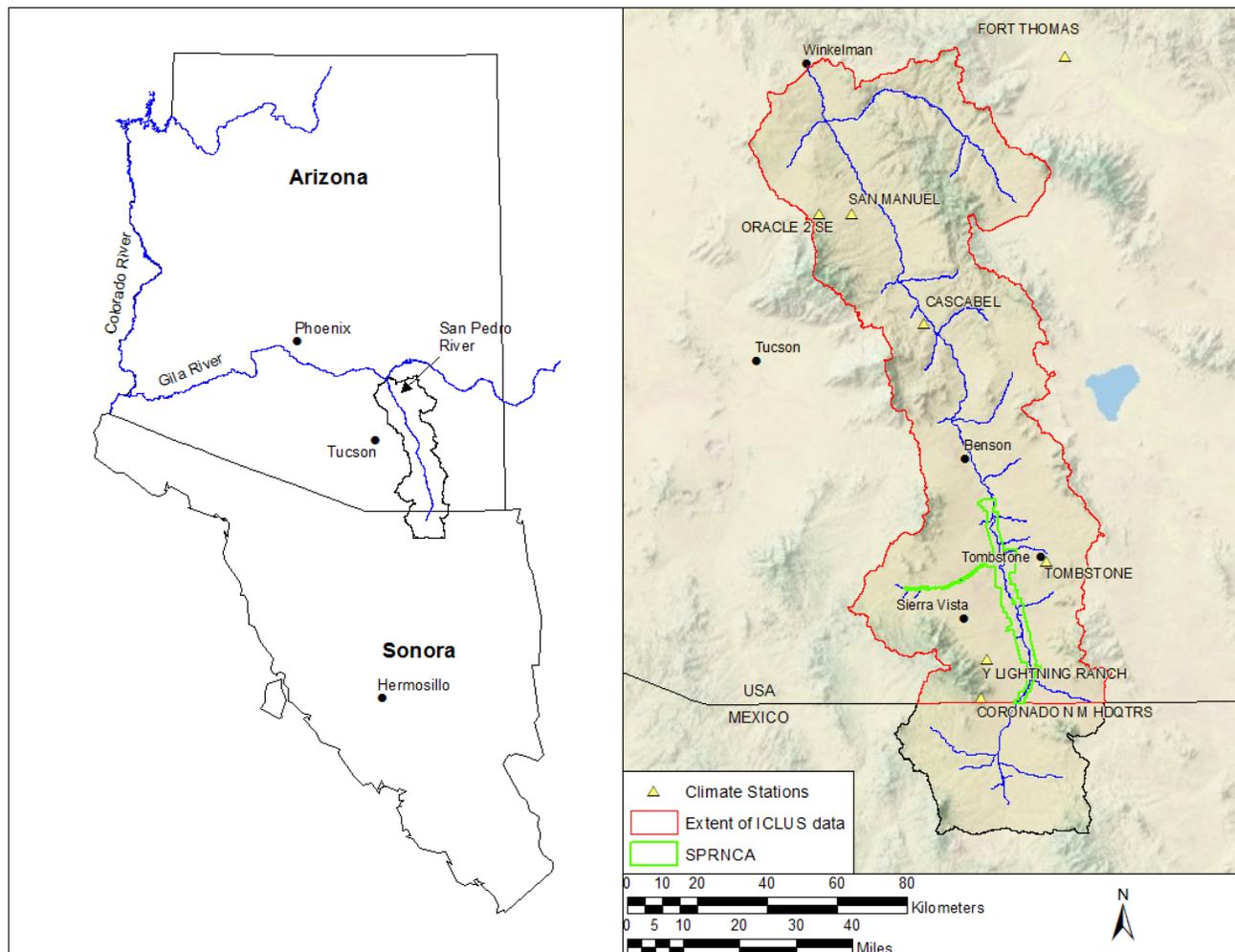


Figure 1—Location Map of the Study Area Contrasting the Extent of the ICLUS Data Used in the Future Scenarios to the San Pedro Watershed.

mitigation or enhancement opportunities, and thus inform restoration, permitting, and water management strategies. AGWA is recognized as one of the world's primary watershed modeling systems (Daniel and others 2011) providing the utility to generate hydrologic responses at the subwatershed scale and spatially visualize results for qualitative comparisons.

The AGWA tool was used to model the San Pedro Watershed with the SWAT model. The AGWA tool is a user interface and framework that couples two watershed-scale hydrologic models, the KINematic Runoff and EROsion model (KINEROS2; Semmens and others 2008) and the Soil and Water Assessment Tool (Arnold and others 1994), within a geographic information system (GIS). The coupling of hydrologic models and GIS within the AGWA tool performs model parameterization, execution, and watershed assessment at multiple temporal and spatial scales, and visualization of model simulation results. Current outputs generated through use of the AGWA tool are runoff (volumes and peaks) and sediment yield, plus nitrogen and phosphorus with the SWAT model. Simulations were parameterized using a 10m digital elevation model (DEM) and derived flow direction and accumulation, modified State Soil Geographic (STATSGO) soils, seven precipitation stations, and the 10 land cover datasets produced by combining the National Land Cover Database/North American Landscape Characterization Project (NLCD/NALC) digital land cover datasets with the decadal ICLUS datasets.

The approach is a multi-step process. First, the watershed border is defined to ensure that data are obtained for the entire study area. Digital land cover data is converted into a format compatible with AGWA and reflecting the available scenario options into the future. Next, soils and precipitation data for the study area are located and extracted. Finally, AGWA is used to delineate subwatersheds as comparative units and parameterize and run the Soil and Water Assessment Tool (Neitsch and others 2002; Srinivasan and Arnold 1994) for the baseline condition and future land cover/use scenarios. The Integrated Climate and Land-Use Scenarios (ICLUS; Bierwagen and others 2010; EPA, 2009; EPA, 2010) project data were identified as an ideal dataset for projecting basin-wide development into the future. The ICLUS national-scale housing-density (HD) scenarios are consistent with the Intergovernmental Panel on Climate Change (IPCC 2001) Special Report on Emissions Scenarios (SRES; Nakicenovic and Swart 2000) greenhouse gas emissions storylines and they are available in 10-year increments until 2100.

To define the project extent, the project watershed is delineated in AGWA and given a buffer distance of 500 meters. The watershed is delineated using a 10-meter

DEM that has been hydrologically corrected to ensure proper surface water drainage. In the United States (and for basins extending into Mexico), the U.S. Geological Survey's (USGS) The National Map Viewer and Download Platform (<http://nationalmap.gov>) provides the National Elevation Dataset (NED; <http://ned.usgs.gov/>) source data. The digital land cover available for this study is derived from two sources. The National Land Cover Database 2006 (Fry and others 2011) was used in combination with the North American Landscape Characterization Project (EPA, 1993) to capture classified digital land cover of known accuracy (Kepner and others 2000, Kepner and others 2003, Skirvin and others 2004).

Because the 2006 NLCD and 1992 NALC datasets have different classifications, the NALC land cover was reclassified to match the NLCD land cover. The reclassified NALC dataset of Mexico is then combined with the 2006 NLCD dataset of the U.S. resulting in a derived NLCD dataset that covers the entire project extent. The ICLUS HD data is combined with the NLCD/NALC data to project future development by decade to 2100. The ICLUS data have five categories of housing density representing rural, exurban, suburban, urban, and commercial/industrial.

The ICLUS database produced 5 seamless, national-scale change scenarios for urban and residential development. The A2 Scenario is characterized by a high fertility rate (average number of children that would be born to a woman over her lifetime) and low net international migration; it represents the highest U.S. population scenario gain (690 million people by 2100). The Base Case (BC) and Scenario B2 are the middle scenarios, with a medium fertility rate and medium to low international migration. Differences between BC and B2, as well as A1 and B1, reflect how housing is allocated – sprawl vs. compact growth patterns. As a result of this distinction, the county populations in urban and suburban areas generally grow faster than in rural areas in the base case, but the experiences of individual counties vary. A1 and B1, with low fertility rates and high international migration are the lowest of the population scenarios. The primary difference between these scenarios occurs at the domestic migration level, with an assumption of high domestic migration under A1 and low domestic migration under B1. The effect of different migration assumptions becomes evident in the spatial model when the population is allocated into housing units across the landscape. The national Baseline forecast for 2100 is 450M people and B1 could be lower at 380M people. The A2 Scenario results in the largest changes in urban and suburban housing density classes and greater conversion of natural land-cover classes into new population centers, or urban sprawl. The largest shift from suburban densities to urban occurs in 2050 – 2100 for the A-family

scenarios (Bierwagen and others 2010). The ICLUS scenarios were developed using a demographic model to estimate future populations through the year 2100 and then allocated to 1-hectare pixels by county for the conterminous U.S. (EPA 2009, EPA 2010). The final data sets provide decadal projections of both housing density and impervious surface cover from the 2000 baseline year projected out to the year 2100.

The NLCD data has different land cover classes, a different projection, and is at a different resolution (30m) than the ICLUS data (100m); therefore the ICLUS data were pre-processed for use in this project. Preprocessing includes clipping the ICLUS data to the boundary of Arizona, projecting the ICLUS data to UTM Zone 12 NAD83, reclassifying the ICLUS data to NLCD classes and resampling the ICLUS data from 100m to 30m. The resulting dataset was then merged with the NLCD dataset so the ICLUS data replaced the NLCD data if there was a change in land cover. The reclassification scheme was determined based on housing density definitions, which were different between the two datasets. As a result the “Rural” land cover type in the ICLUS data was defaulted to the NLCD class present at that location. This methodology was incorporated into a tool in ArcToolbox in ArcGIS for easy conversion of the ICLUS datasets.

In this example, only Scenario A2 (corresponding to storyline A2 in the SRES) of the ICLUS data was used for example analysis, however all five ICLUS scenarios (A1, A2, B1, B2, and BC) were used in the final analysis (Burns and others 2013). Ten land cover datasets per scenario (50 total) are produced from the combination of the NLCD/NALC datasets and the ICLUS datasets, representing the change in landscape attributed to population and development changes by decade from 2010 to 2100. For each scenario, the dataset from 2010 is used as the project baseline to which the successive decadal datasets are compared. Soils data for the U.S. were obtained from the Natural Resources Conservation Service (NRCS) - National Cartography and Geospatial Center’s (NCGC) State Soil Geographic (STATSGO; USDA-NRCS 1994) database. Soils data for Mexico were obtained from the San Pedro Data Browser (Kepner and others 2003, Boykin and others 2012). The soil types were matched and redefined to equivalent STATSGO soil types. Precipitation data obtained from the National Climatic Data Center (NCDC; <http://www.ncdc.noaa.gov/>) were used to drive the SWAT model in AGWA. Climate stations within or near the San Pedro Watershed were reviewed for periods of record and completeness of the dataset. The review produced a total of seven climate stations in Arizona with the recorded precipitation needed for the SWAT model (Fig. 1). The period of record is from 1971-2001.

RESULTS

All scenarios resulted in an increase to the Human Use Index (HUI) metric averaged over the entire watershed. HUI (adapted from Ebert and Wade, 2004) is the percent area in use by humans. It includes NLCD land cover classes “Developed, Open Space”; “Developed, Low Intensity”; “Developed, Medium Intensity”; “Developed, High Intensity”; “Pasture/Hay”; and “Cultivated Crops”. The ICLUS A2 Scenario resulted in the largest increase of the HUI, 2.21 percent in year 2100 for the entire watershed (Fig. 2 and Table 1).

Similarly to the increases in HUI over the entire watershed, both simulated runoff and sediment yield increased at the watershed outlet over time for all scenarios; Scenario A2 experienced the largest percent change in surface runoff and sediment yield, 1.04 and 1.19 percent, respectively (Figures 3 and 4; Tables 2 and 3). Percent change was calculated using the following equation:

$$\frac{([decade_i]-[base_i])}{[base_i]} \times 100 \quad (1)$$

where $[decade_i]$ represents simulation results for a decade from 2020 through 2100 for a given scenario (i) and $[base_i]$ represents the baseline 2010 decade for the same scenario.

Figure 5 depicts the percent change of HUI, channel sediment yield, and subwatershed surface runoff from 2010 to 2100 for Scenario A2. The changes in HUI relate well to the changes in sediment yield and surface runoff. The figures show the impact of growth locally on one level with the subwatersheds and in greater detail with the explicit percent change in the growth areas.

DISCUSSION

Hydrologic impacts of future growth through time were evaluated by using reclassified ICLUS housing density data by decade from 2010 to 2100 to represent land cover in AGWA. AGWA is a GIS tool initially developed to investigate the impacts of land cover change to hydrologic response at the watershed scale to help identify vulnerable regions and evaluate the impacts of management. AGWA allows for assessment of basin-wide changes and cumulative effects at the watershed outlet as well as more localized changes at the subwatershed level.

ICLUS datasets were used for a number of reasons including their availability (<http://cfpub.epa.gov/ncea/global/recordisplay.cfm?deid=205305>). Reclassification was necessary to convert from housing density classes

HUI Change 2010-2100 (Entire Watershed)

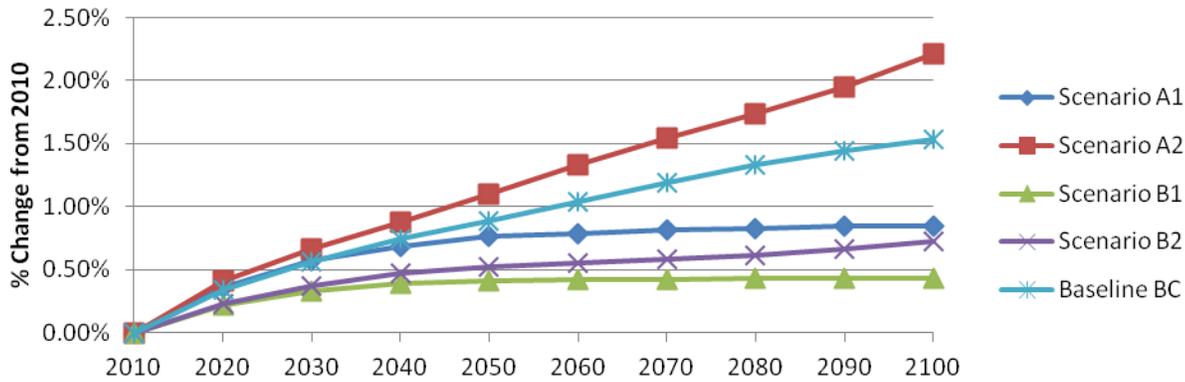


Figure 2—Watershed Average Human Use Index (HUI) for All Scenarios.

Change in Surface Runoff 2010-2100 (Entire Watershed)

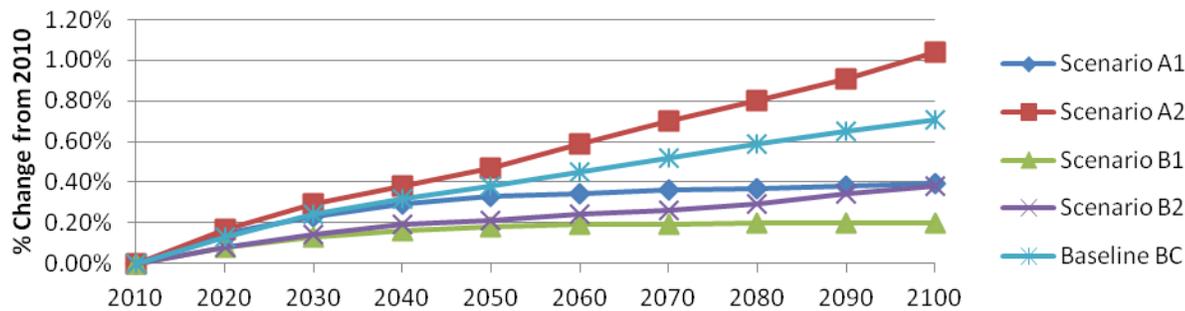


Figure 3—Watershed Average Percent Change in Surface Runoff for All Scenarios.

Change in Sediment Yield 2010-2100 (Watershed Outlet)

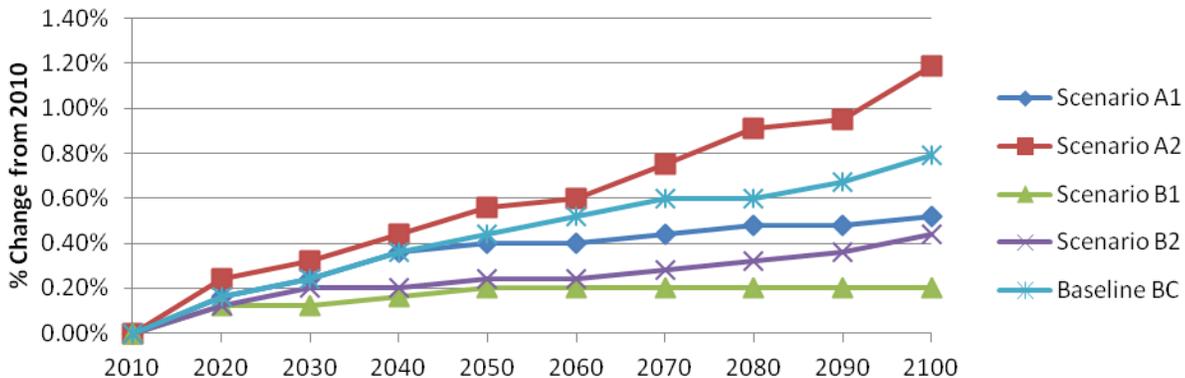


Figure 4—Watershed Average Percent Change in Sediment Yield for All Scenarios.

Table 1—Change in Human Use Index for All Scenarios (2010 - 2100)

	HUI Base	Change in Human Use Index from base								
	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Scenario A1	5.23%	0.36%	0.57%	0.69%	0.76%	0.79%	0.81%	0.83%	0.84%	0.85%
Scenario A2	5.09%	0.41%	0.66%	0.88%	1.10%	1.33%	1.54%	1.73%	1.95%	2.21%
Scenario B1	5.15%	0.22%	0.33%	0.39%	0.41%	0.42%	0.43%	0.43%	0.43%	0.43%
Scenario B2	5.09%	0.23%	0.37%	0.47%	0.52%	0.55%	0.58%	0.61%	0.66%	0.73%
Baseline BC	5.12%	0.34%	0.57%	0.74%	0.89%	1.04%	1.19%	1.33%	1.44%	1.54%

Table 2—Change in Surface Runoff for All Scenarios (2010 - 2100).

	Surface Runoff Base	Percent Change in Surface Runoff from Base								
	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Scenario A1	42.98 mm	0.15%	0.23%	0.29%	0.33%	0.34%	0.36%	0.37%	0.38%	0.39%
Scenario A2	42.95 mm	0.17%	0.29%	0.38%	0.47%	0.59%	0.70%	0.80%	0.91%	1.04%
Scenario B1	42.96 mm	0.08%	0.13%	0.16%	0.18%	0.19%	0.19%	0.20%	0.20%	0.20%
Scenario B2	42.96 mm	0.08%	0.14%	0.19%	0.21%	0.24%	0.26%	0.29%	0.34%	0.38%
Baseline BC	42.96 mm	0.13%	0.24%	0.32%	0.38%	0.45%	0.52%	0.59%	0.65%	0.71%

Table 3—Change in Channel Sediment Yield for All Scenarios (2010 - 2100).

	Sediment Yield Base	Percent Change in Sediment Yield from Base								
	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Scenario A1	25220 t	0.16%	0.24%	0.36%	0.40%	0.40%	0.44%	0.48%	0.48%	0.52%
Scenario A2	25200 t	0.24%	0.32%	0.44%	0.56%	0.60%	0.75%	0.91%	0.95%	1.19%
Scenario B1	25210 t	0.12%	0.12%	0.16%	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%
Scenario B2	25200 t	0.12%	0.20%	0.20%	0.24%	0.24%	0.28%	0.32%	0.36%	0.44%
Baseline BC	25200 t	0.16%	0.24%	0.36%	0.44%	0.52%	0.60%	0.60%	0.67%	0.79%

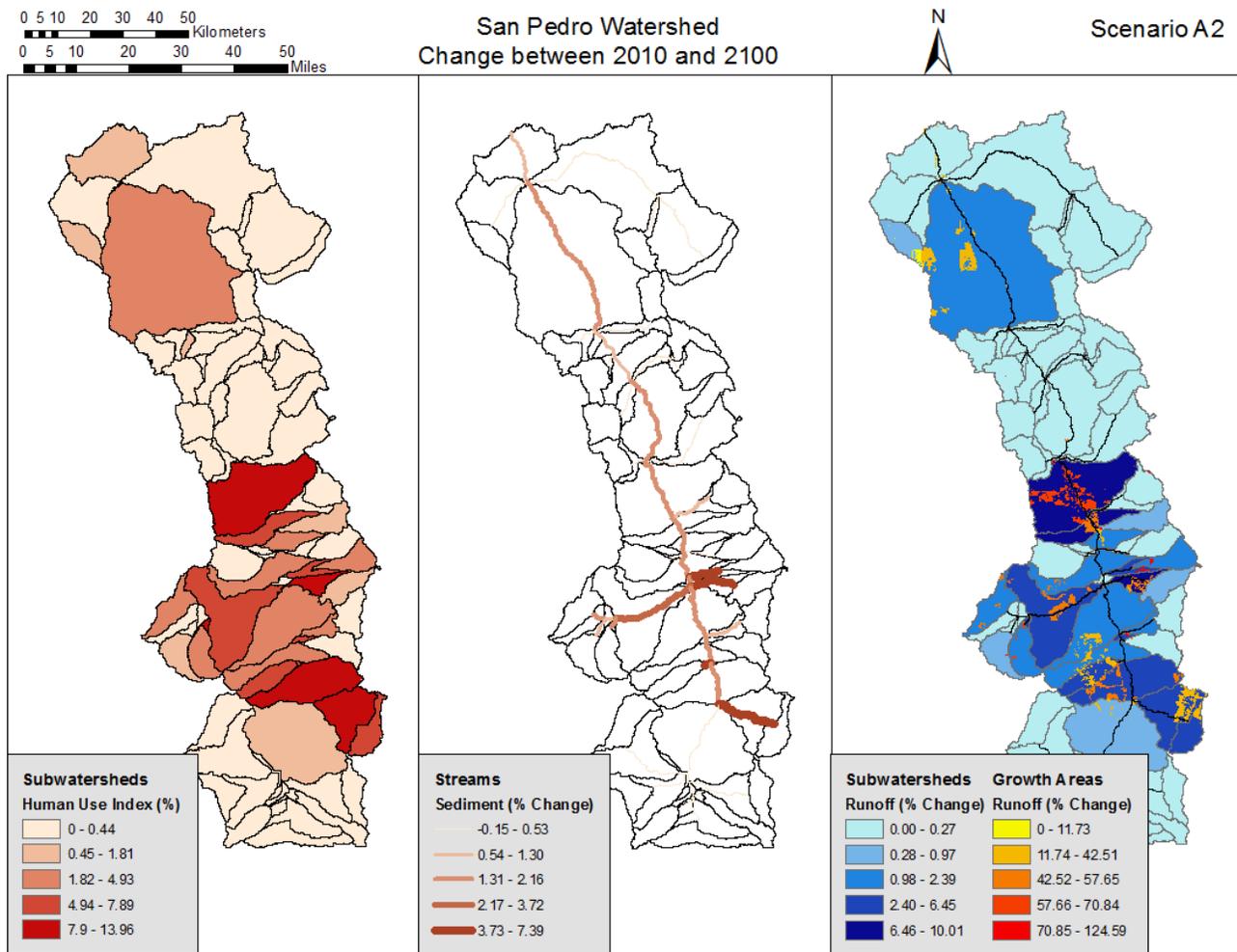


Figure 5—Change in Human Use Index (HUI), Sediment Yield, and Surface Runoff (both Average and Explicit) in Percent from 2010 to 2100 for Scenario A2.

to “developed” type classes in the 2006 National Land Cover Database. All land cover classes of the NLCD are supported in AGWA via look-up tables which allow for translation of land cover classes into hydrologic parameters necessary to parameterize the hydrologic models.

The results produced by the AGWA-SWAT modeling represent a qualitative assessment of anticipated hydrologic change resulting from the ICLUS A1, A2, B1, B2, and BC scenarios. Historic rainfall and climate data are used to drive the SWAT model, so anticipated climate change is not accounted for in the results, although climate change may amplify or reduce the results presented here. Quantitative assessments of anticipated hydrologic impacts resulting from the ICLUS scenarios would require calibration for the baseline (2010) for each scenario and additional information to parameterize future decades, including but not limited to the design and placement of flood mitigation measures (detention basins, riparian buffers, water harvesting, recharge wells, open

space infiltration galleries, etc.) that would be a required component of any future development.

The methodology presented herein uses HUI as an easily quantifiable metric for land cover change resulting from urban growth; however it does not distinguish between different types of human use. Different types of human use, ranging from “Developed, Open Space” to “Developed, High Intensity” to “Cultivated Crops” have different hydrologic properties associated with them, so despite the observed relationship between increasing HUI and increasing surface runoff and sediment yield in the results, HUI cannot be used as a surrogate for actual hydrologic modeling, which more closely captures the actual land cover properties and the complex interactions and feedbacks that occur across a watershed.

The greatest changes in surface runoff occur in subwatersheds where the change in HUI was also greatest; accordingly, the smallest changes in surface runoff occur in areas where the change in HUI was smallest. Sediment

yield in the channels is largely driven by surface runoff, so channels immediately downstream of subwatersheds with high changes in HUI and surface runoff experience the largest changes in sediment yield. The results emphasize the importance of investigating localized impacts to natural resources at appropriate scales as the impacts at the subwatershed scale and below can be much greater than at the basin scale. They also highlight the effective modulation of local changes by large undevelopable areas. At the subwatershed scale, unacceptable hydrologic impacts may be observed that would not otherwise be captured at the basin scale if development was occurring basin-wide. Instead, basin-wide impacts are effectively averaged out by undevelopable lands. Thus any interests in cumulative effect should be addressed at the subwatershed versus basin scale for this western watershed or others like it which contain large tracts of land in the public domain, and are therefore not subject to direct urbanization impacts.

CONCLUSIONS

Changes in land cover/use under the A2 Scenario result in the greatest hydrologic impacts due to a higher population growth rate and a larger natural land cover conversion rate. The results of the analyses for all scenarios over the 2010 – 2100 year period (Tables 2 and 3) indicate changes in the range of 0.2 percent (B1 Scenario) to 1.04 percent (A2 Scenario) on average surface runoff across the watershed, and changes in the range of 0.2 percent (B1 Scenario) to 1.19 percent (A2 Scenario) on sediment yield at the watershed outlet.

Local changes to hydrology and sediment delivery at the subwatershed level and below are relevant because at those scales the impacts tend to be much more significant. Additionally, since the hydrologic impacts are tied to changes in land cover, and because the San Pedro Watershed has large amounts of land that cannot be developed, the hydrologic impacts at a watershed scale are expected to be limited. The localized impact of development found in this study may be representative for much of the western arid and semi-arid U.S., where 47.3 percent of the 11 coterminous western states (AZ, CA, CO, ID, MT, NV, NM, OR, UT, WA, and WY) is managed as federal public lands by the Bureau of Land Management, Fish and Wildlife Service, National Park Service, U.S. Forest Service and the Department of Defense (Gorte and others 2012). Despite the constraints that limit developable areas, hydrologic changes at the watershed scale are still expected to occur.

Simulated increases in percent change of surface runoff and sediment yield closely tracked increases in the HUI metric; consequently growth and development should be moderated to prevent large increases in surface runoff

and sediment yield, which could degrade water quality from sediment and pollutant transport, erode and alter the stream channel, degrade or destroy habitat, decrease biological diversity, and increase flooding. The effects of growth may be magnified or mitigated by climate change, though this is not accounted for in this analysis.

Scenario analysis is an important framework to help understand and predict potential impacts caused by decisions regarding conservation and development. For the EPA and other stakeholders, hydrologic modeling systems (e.g. AGWA) integrated with internally-consistent national scenario spatial data (i.e. ICLUS) provide an important set of tools that can help inform land use planning and permitting, mitigation, restoration, and water management strategies.

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