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Simulated Changes in Runoff and Sediment in Developing Areas near Benson, Arizona

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Abstract

Residential and commercial development is occurring with unprecedented speed throughout the American Southwest. It is projected that from 1995 to 2025, the population in the six Southwestern states of California, Nevada, Arizona, New Mexico, Utah and Colorado will increase by more than 50%, while the remainder of the country is projected to grow only 10 to 15%. More recently the Arizona Department of Commerce has projected the state's population will increase three-fold in the next several decades. This scale and rapid pace of development presents special challenges to the review and permitting process as required under Section 404 of the Clean Water Act (CWA) and the National Environmental Policy Act (NEPA). Many of the areas undergoing rapid development are in arid and semiarid regions whose watersheds and associated streams exhibit ephemeral or intermittent flow. The standard process for CWA permitting associated with new development rarely considers the special attributes and circumstances encountered in these environments. In addition, rapid urbanization can present a challenge in assessing the cumulative impacts of development on watersheds and landscapes when permitting is conducted piecemeal over multiple parcels in the same region.

Geospatial tools are needed to enable the rapid assessment of proposed developments to identify circumstances that may require more in-depth analysis. The Automated Geospatial Watershed Assessment (AGWA) tool is a GIS-based interface for the well established Soil and Water Assessment Tool (SWAT) and Kinematic Runoff and Erosion Model (KINEROS2) watershed models, and is capable of such assessments (see http://www.tucson.ars.ag.gov/agwa/ and/or http://www.epa.gov/esd/land-sci/agwa/). In this study AGWA was applied to an 8,200-acre study area proposed for development located near Benson, Arizona. Pre- and proposed post-development land-cover conditions were simulated using KINEROS2 through the AGWA interface and subjected to several design storms. Changes in runoff and sediment yield due to the proposed changes in land cover were computed for five watersheds encompassing the study area and extending to the main-stem of the San Pedro River. The largest average changes in runoff volume (~ +413%) and sediment yield (~ +231%) across the five watersheds occurred for the two-year, one-hour design storm. For the 10-year, one-hour design storm these changes in runoff and sediment yield were reduced to roughly +23%.

This analysis represents a preliminary, qualitative assessment of anticipated hydrologic change resulting from proposed development in the Benson area. Results definitively indicate that the proposed land-use changes will result in significant alteration of the hydrologic regime both within and downstream of the impacted watersheds where they empty into the San Pedro River. Quantitative predictions of these impacts would require substantial additional information that is not presently available for the ungauged study-area watersheds. Insufficient information on the design and placement of flood mitigation measures (detention basins, riparian buffers, water harvesting, recharge wells, open space infiltration galleries), for example, did not allow this study to assess the impacts of such structures on runoff changes. In addition, a larger-scale analysis of development within the San Pedro River Basin would be necessary to ascertain cumulative impacts to the river and identify areas of critical concern.

Introduction

The study area is located near Benson, Arizona, in the San Pedro Valley, and represents approximately thirteen (13) square miles of an overall development envelope described by the

City of Benson General Plan. Development in the study area will convert the land uses of approximately 8,200 acres of previously undisturbed land that drains directly into the San Pedro River (Figure 1). The San Pedro River is nationally known as being one of the last free-flowing rivers in the Southwest. It is a critical migration corridor for hundreds of bird species and serves as important habitat for many other regionally-declining species of plants, fish, and wildlife. Just a few miles upstream from the proposed development is the San Pedro Riparian National Conservation Area (SPRNCA). The first RNCA (Riparian National Conservation Area) designated in the country, the SPRNCA was created in 1988 to protect nearly 40 miles of river and riparian area, and its biological, educational, recreational and cultural resources. Although not federally protected as an RNCA, the San Pedro River downstream (north) of the study area also contains many of the same highly valued attributes and is critical to maintaining the ecological integrity of upstream areas.

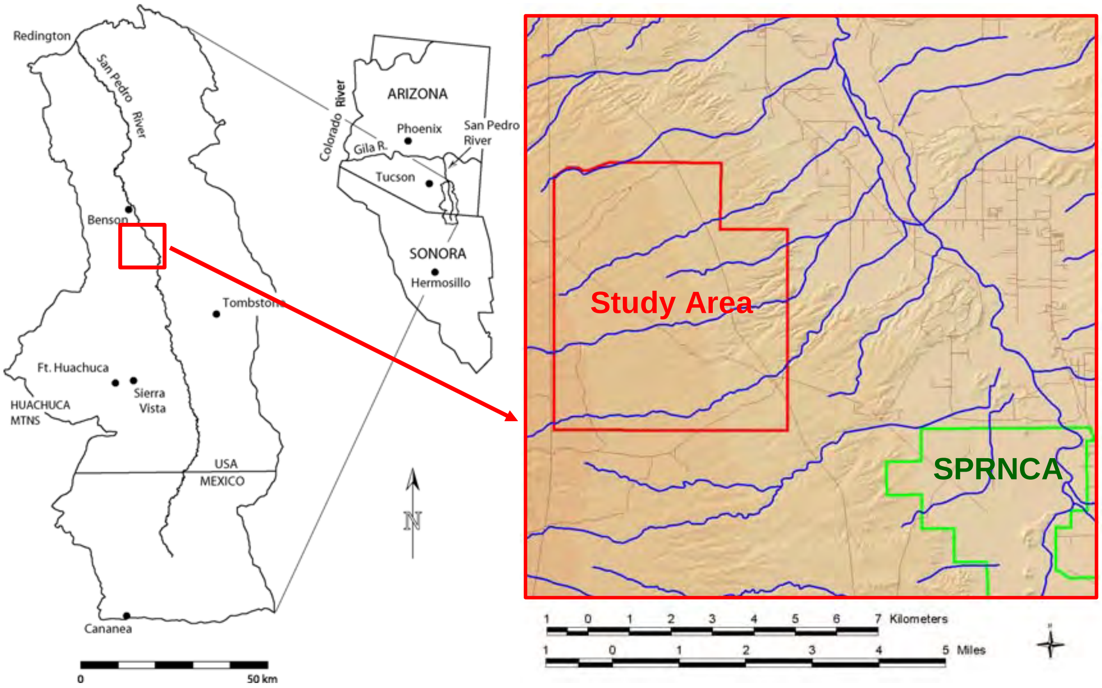

Figure 1. Location Map of the study area, near Benson, Arizona.

The U.S. Environmental Protection Agency's (EPA) 404(b)(1) Guidelines (Guidelines) are the substantive environmental criteria used in evaluating permit applications to the U.S. Army Corps of Engineers (USACE) to discharge dredged or fill material into waters of the United States, including wetlands, under Section 404 of the Clean Water Act. No discharge of dredged or fill material shall be permitted if there is a practicable alternative which would have less adverse impact on the aquatic ecosystem, so long as the alternative does not have other significant adverse environmental consequences.

To determine the impact of a proposed project on the aquatic ecosystem, the Guidelines require an analysis of the direct, indirect, secondary and cumulative impacts to the aquatic ecosystem (40 CFR 230.11(g)(1)(h)). According to the Guidelines, "the terms *aquatic environment* and *aquatic ecosystem* mean waters of the United States, including wetlands, that serve as habitat for interrelated and interacting communities and populations of plants and animals" (Part 230.3(c)), and the definition of "waters of the United States" includes tributaries. The condition of an aquatic ecosystem may be better understood by examining the hydrology of the watershed. For example, communities of plants and animals depend on the aquatic environment for nutrients and shelter. Changes to the hydrology of that environment, such as increases or decreases in flow or sediment volumes, can have serious impacts on the aquatic ecosystem and the health of those communities.

This study examines the effects of development on the hydrology of a particular portion of the San Pedro River watershed. The results disclose changes to the hydrologic regime that are attributable to modifications in land cover. Changes include the impairment of water resources due to increases in stormwater runoff and sediment yield during frequent, small storm events. This study reveals change as a result of individual discharge and through the cumulative effect of numerous changes to the environment in multiple adjacent watersheds.

Methods

A land-use map of the study area was used to define land-cover types of proposed development zones (Figure 2). A geo-referenced image (jpg) of the proposed development map was converted into a polygon map (shapefile) through on-screen digitizing in ArcView 3.x (Figure 3). The 1992 National Land Cover Dataset (NLCD) grid was used as the predevelopment baseline condition (Figure 4). The NLCD was modified using the polygon map of the proposed development to create a land-cover grid of the study area and adjacent land (Figure 5). The proposed land-use map identified ten land-cover types. These were consolidated into five land-cover types to correspond with the NLCD land-cover designations (see Table 1). The conversion of the park/open space land-use designation to the NLCD herbaceous/grassland land-cover class was made in the absence of any knowledge about how these areas will be managed. This is a conservative representation in that grassland contributes far less runoff and sediment than the existing natural vegetation. The "Jurisdictional Waters" land use designation falls within the modeled AGWA/KINEROS2 channel network and does not represent any change from predevelopment conditions.

Table 1. Conversion of developed land-use designations to NLCD land-cover types.

Land-use designation under proposed development	NLCD land-cover type
Low density residential	Low intensity residential
Medium density residential	High intensity residential
Recreation Center	High intensity residential
Right-of-way	High intensity residential
Golf course	Urban/recreational grasses
Commercial/High density residential	Commercial/Industrial/Transport
School	Commercial/Industrial/Transport
Park/Open Space	Grasslands/Herbaceous
Jurisdictional Waters	not classified; AGWA creates channels based on the DEM topography
Proposed Impact Areas	no specific classification, incorporated into adjacent land cover

The AGWA tool (Miller et al., 2007) and its component hydrologic model, KINEROS2 (Smith et al., 1995), were used to model 5 small watersheds encompassing the footprint of the proposed development area (Figure 6). The outlets for each of these five adjacent watersheds were located at the San Pedro River so that potential impacts to the river, such as changes to runoff or sediment delivery, could be determined. Simulations were performed for pre- and post-development conditions, using 2-year-1-hour, 5-year-1-hour and 10-year-1-hour design storms. STATSGO (State Soil Geographic) soils data and a 10-meter Digital Elevation Model (DEM) were used to provide soil and topographic inputs for the modeling. The AGWA version used was agwa_beta_b.avx, for ArcView 3.x. A significant advantage of the AGWA system is that spatially distributed modeling results can be mapped back onto the watershed for rapid identification of "hot-spots" where more extreme localized changes in runoff and sediment yield occur. This capability may aid in the identification and design of remediation measures to lessen the impacts of proposed development. In this study the functionality is used primarily to illustrate and convey the modeling results.

Recent studies on the interactions between ecological and hydrological processes have indicated that increased surface runoff and/or sediment yield can result in harmful impacts to the aquatic ecosystem (Wilcox and Newman, 2005). These impacts may include more frequent and severe flooding, stream channel adjustment, stream bank erosion, water quality degradation from sedimentation and contaminant transport, habitat destruction and decreased biological diversity (Dorworth and McCormick, 2005). Therefore, for the purpose of this study, unfavorable impacts are considered to be any increase in surface runoff and/or sediment yield.

It should be noted that without detailed development plans we did not have site-specific information on planned post-construction topography, channelization/channel dimensions, channel sediment grain-size distributions, or the location and dimensions of flood-detention structures. Post-construction topography, channelization, and flood-detention structures were thus omitted from this analysis. Natural channel dimensions were estimated from hydraulic-geometry relations derived in the nearby USDA-ARS Walnut Gulch Experimental Watershed, located near Tombstone, which is also in the Upper San Pedro Basin (Miller et al., 2003). Channel sediment grain-size distributions were also estimated based on observations in Walnut Gulch. While observational information would be very useful it is not essential to make rapid initial assessments such as this one. Much more detailed modeling and incorporation of these features would be warranted at the next level of assessment if sufficient concerns and potential hot-spots are identified in the initial assessment. In addition, it would be desirable to have observed runoff and sediment-yield data within, or at the outlets of the watersheds being modeled to enable pre-development calibration and validation of the simulation models employed. When this type of data is lacking, which is commonly the case, it is important to judge the differences in pre- and post-development simulation results in terms of the ordinal relative change instead of quantitative impacts.

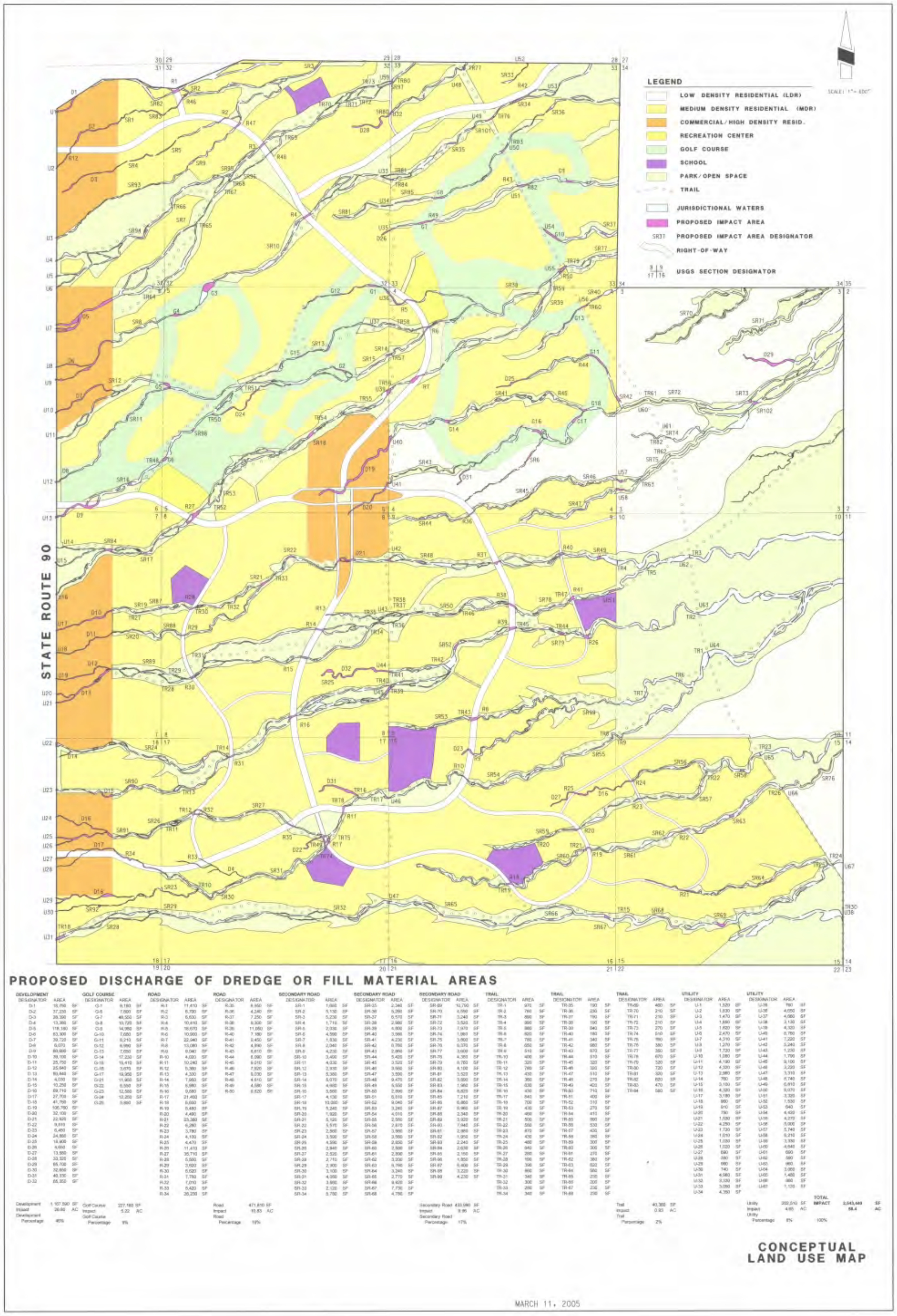

Figure 2. Conceptual Land Use Map, provided by permit applicants, March 11, 2005.

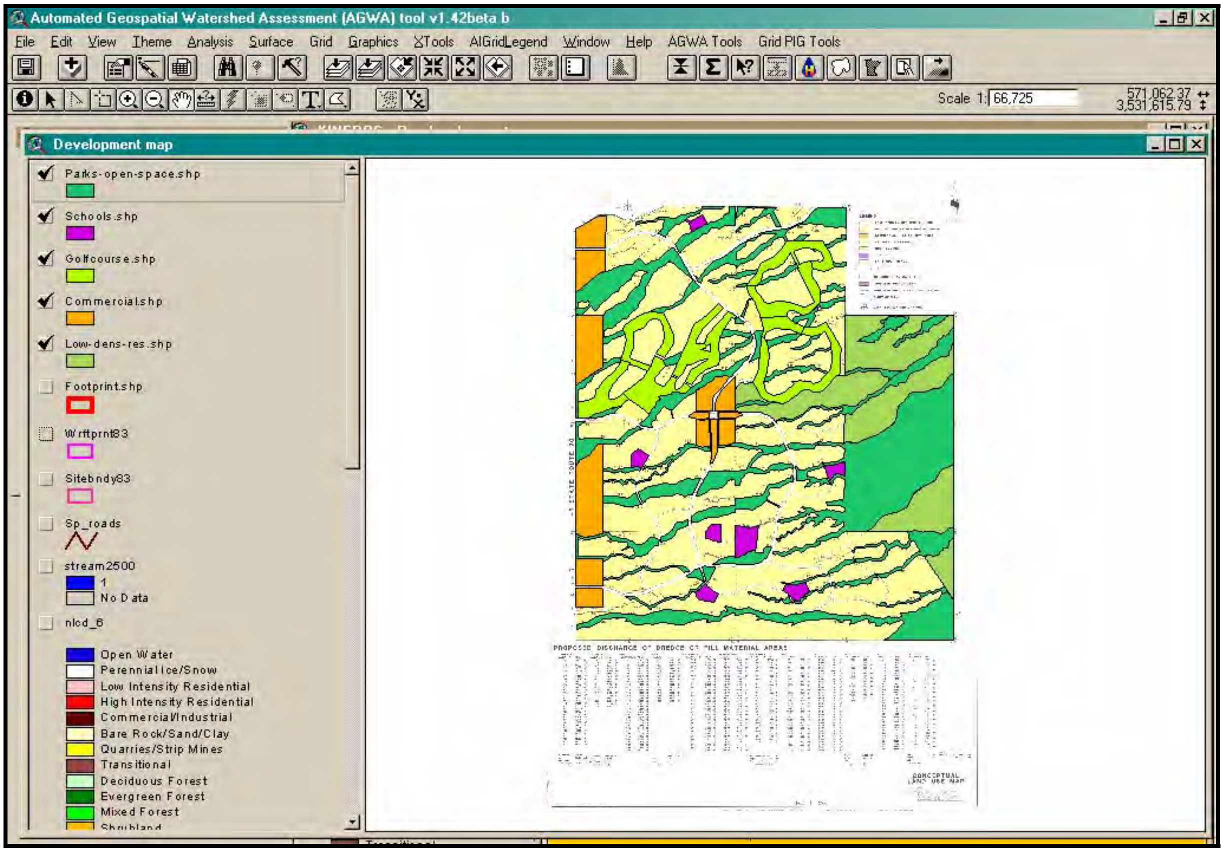

Figure 3. Digitized proposed land uses of the study area near Benson, Arizona, in ArcView.

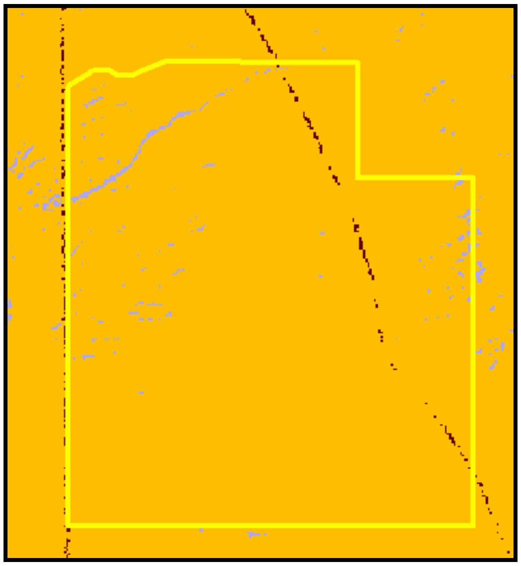

Figure 4. Predevelopment conditions, 1992 NLCD land cover. Yellow outline is the study area footprint. Legend is same as in Figure 5.

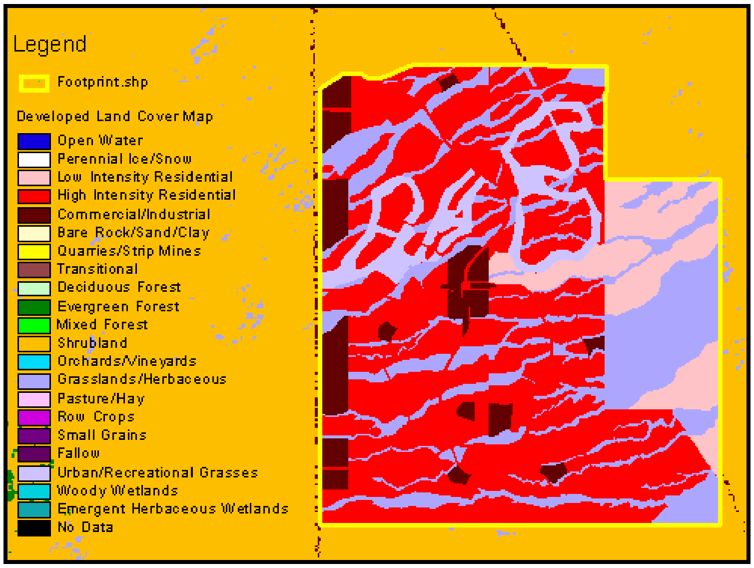

Figure 5. Developed conditions, modified 1992 NLCD land cover. Yellow outline is the study area footprint.

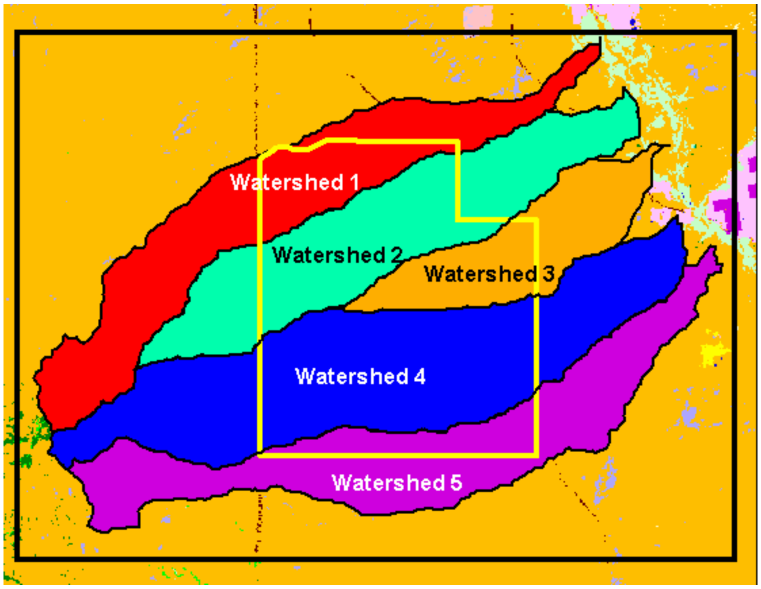

Figure 6. AGWA delineated watersheds encompassing the study area (yellow outline) and extending to the San Pedro River (not shown; light green land cover indicates riparian areas). Land-cover area analysis was conducted within the dark black rectangular outline.

Results

The proposed development resulted in a change in area for six different land-cover types (Table 2). The area totals shown in the table are for a rectangular area surrounding the small watersheds (Figure 6). The largest changes were a decrease in shrubland and an increase in residential land.

Both simulated runoff and sediment yield increased at the watershed outlets as a result of the proposed development (Tables 3 and 4, and Figures 7 through 12). Table 5 shows the percent change at the San Pedro River for each rainfall event on each watershed, and as the average change for all five watersheds. All changes were computed using the following equation:

$$\frac{[(developed)-(undeveloped)]}{(undeveloped)}\times 100$$

in which (developed) and (undeveloped) represent the simulation output being considered, in this case runoff or sediment yield. For the two-year, one-hour event, average runoff and sediment yield increased 413% and 231%, respectively (Table 5). For the five- and ten-year events the percentage change was lower. For the ten-year, one-hour event, the average relative change over the five watersheds was an increase of 23% for both runoff and sediment yield. The smaller relative increases in runoff and sediment yield for the larger design storms occurs because storm inputs become relatively more dominant as compared to land cover variability in watershed and sediment response with increasing storm size.

Table 2. Change in land-cover type from pre-developed condition to developed, near Benson, Arizona.

	Predevelop (1973)		Developed (2005)		change	
Land Cover Type	m2	ha	m2	ha	m2	ha
Low Intensity Residential	12,600	1.3	3,254,900	325.5	3,242,300	324.2
High Intensity Residential	0	0.0	17,579,300	1757.9	17,579,300	1757.9
Commercial/Industrial/Transport	475,200	47.5	2,855,500	285.6	2,380,300	238.0
Shrubland	153,528,300	15352.8	120,230,200	12023.0	-33,298,100	-3329.8
Grasslands/Herbaceous	1,889,400	188.9	9,735,700	973.6	7,846,300	784.6
Urban/Recreational Grasses	1,800	0.2	2,251,700	225.2	2,249,900	225.0

Table 3. Simulated runoff and sediment yield at the San Pedro River (watershed outlets) with Pre-development conditions for each watershed, near Benson, Arizona.

		Pre-development					
watershed	watershed	2yr1hr event (18.47 mm)		5yr 1hr event (23.09 mm)		10yr 1hr event (28.67 mm)	
number	area (ha)	runoff (mm)	sed yld (kg/ha)	runoff (mm)	sed yld (kg/ha)	runoff (mm)	sed yld (kg/ha)
1	1717.01	0.05	23.62	0.88	415.23	3.13	2718.35
2	1701.69	0.13	38.65	1.21	345.26	3.83	1512.76
3	873.45	0.16	80.96	1.30	567.59	4.22	1929.52
4	2553.50	0.03	14.03	0.74	213.06	2.88	881.41
5	1755.11	~0.00	~0.00	0.57	199.88	2.58	1581.84

Table 4. Simulated runoff and sediment yield at the San Pedro River (watershed outlets) with Developed conditions for each watershed, near Benson, Arizona.

		Developed					
watershed	watershed	2yr 1hr event (18.47mm)		5yr 1hr event (23.09 mm)		10yr 1hr event (28.67 mm)	
number	area (ha)	runoff (mm)	sed yld (kg/ha)	runoff (mm)	sed yld (kg/ha)	runoff (mm)	sed yld (kg/ha)
1	1717.01	0.23	82.24	1.29	669.30	3.84	3712.86
2	1701.69	0.23	66.35	1.48	406.46	4.30	1734.13
3	873.45	0.42	189.69	1.86	724.75	4.91	2129.77
4	2553.50	0.37	80.17	1.56	417.74	4.28	1138.48
5	1755.11	0.05	24.14	0.80	284.38	3.03	1994.51

Table 5. Percent change at the San Pedro River for each rainfall event, for each watershed and as an average of all 5 watersheds, near Benson, Arizona.

watershed	watershed	2yr 1hr event (18.47mm)		5yr 1hr event (23.09 mm)		10yr 1hr event (28.67 mm)	
number	area (ha)	runoff	sed yld	runoff	sed yld	runoff	sed yld
1	1717.01	345	248	46.0	61.2	22.5	36.6
2	1701.69	83.8	71.6	22.1	17.7	12.2	14.6
3	873.45	154	134	42.8	27.7	16.5	10.4
4	2553.50	1070	471	111	96.1	48.8	29.2
5	1755.11	134,000	8,650,000	40.1	42.3	17.3	26.1
avg % all watersheds		[†]**413**	[†]**231**	**52.4**	**49.0**	**23.4**	**23.4**

[†] Note: Average excludes results from Watershed 5 due to essentially zero (0) flow prior to development which results in very large percent change.

Figures 13 through 18 illustrate the percent change in runoff and sediment yield for the individual watershed planes and stream channel segments as simulated with AGWA/KINEROS2, and illustrate the variable nature of changes within the watersheds – i.e. some areas experience a major decrease in runoff because they have been converted to grass/park, while other areas experience a major increase due to conversion to impermeable surface (roads, pavement, houses, etc.). Note that the tables and figures presented above show percent change at each watershed outlet, which includes the effects of channel transmission losses (infiltration or groundwater recharge), and therefore show different values than the individual model-element results pictured in Figures 13 through 18.

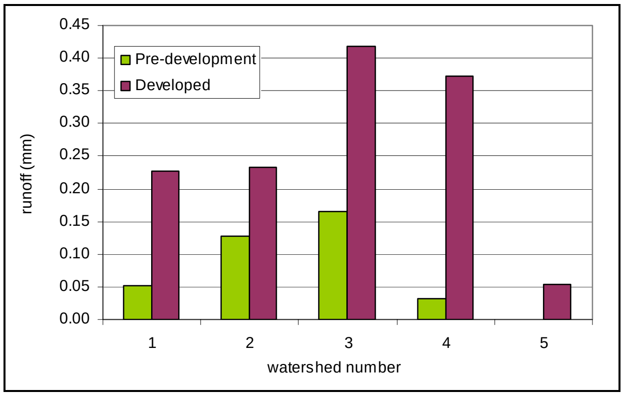

Figure 7. Simulation Results, Runoff, 2-year 1-hour design storm, pre-development & developed conditions, near Benson, Arizona.

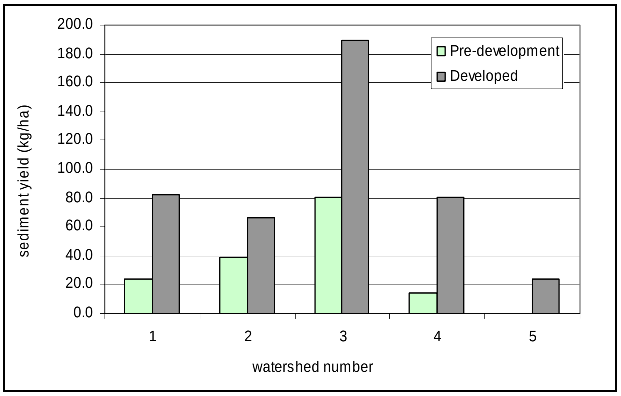

Figure 8. Simulation Results, Sediment Yield, 2-year 1-hour design storm, pre-development & developed conditions, near Benson, Arizona.

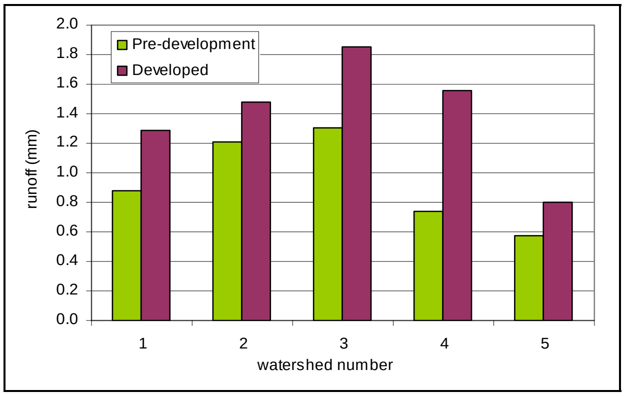

Figure 9. Simulation Results, Runoff, 5-year 1- hour design storm, pre-development & developed conditions, near Benson, Arizona.

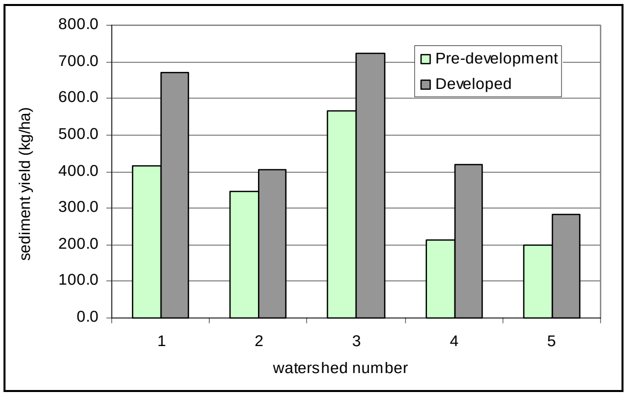

Figure 10. Simulation Results, Sediment Yield, 5-year 1-hour design storm, pre-development & developed conditions, near Benson, Arizona.

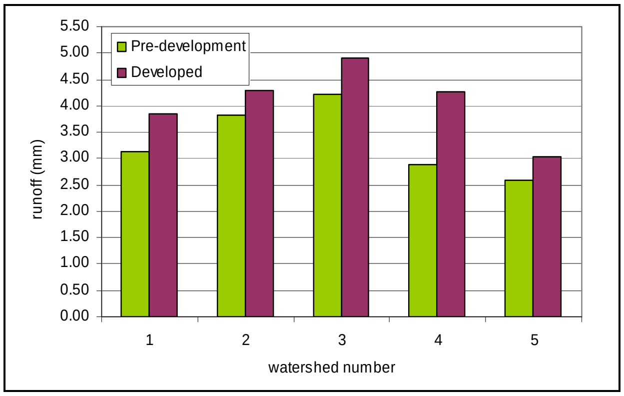

Figure 11. Simulation Results, Runoff, 10-year 1-hour design storm, pre-development & developed conditions, near Benson, Arizona.

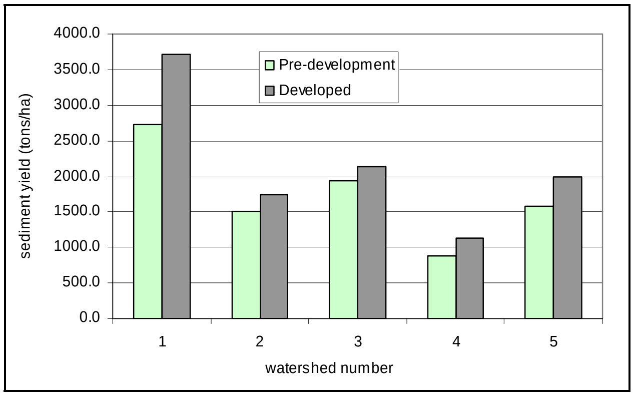

Figure 12. Simulation Results, Sediment Yield, 10-year 1-hour design storm, pre-development & developed conditions, near Benson, Arizona.

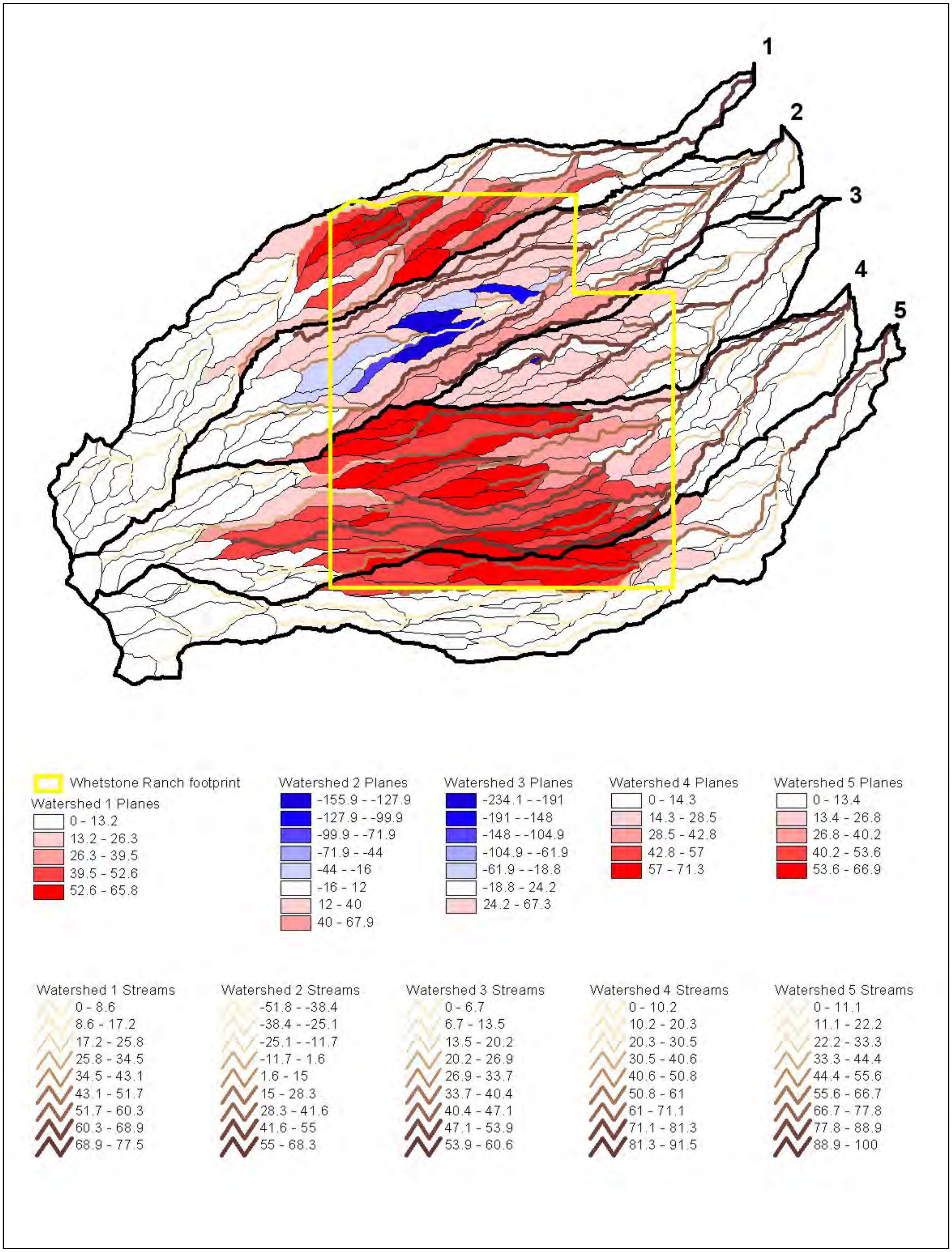

Figure 13. Percent change in runoff, 2-year 1-hour design storm, near Benson, Arizona.

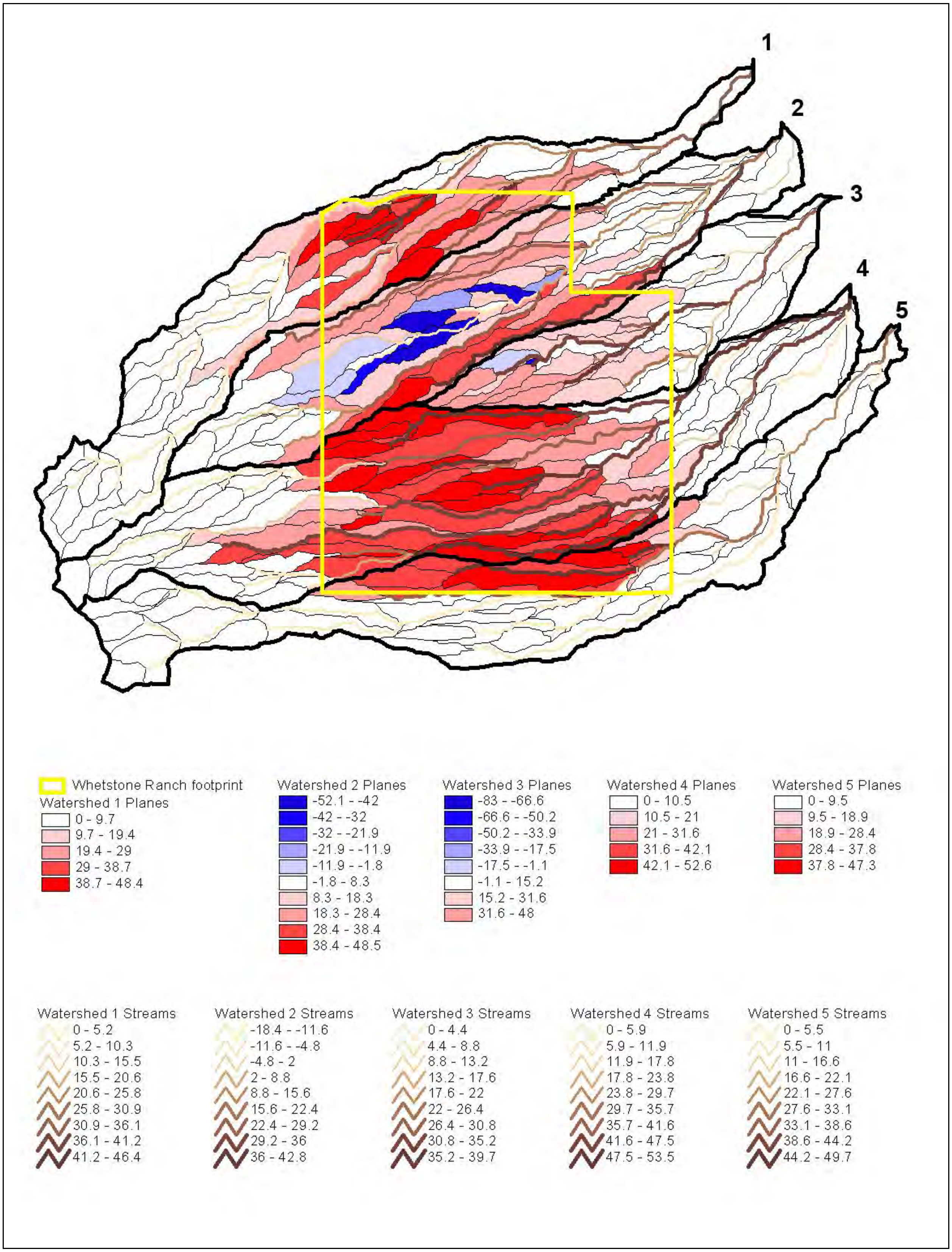

Figure 14. Percent change in runoff, 5-year 1-hour design storm, near Benson, Arizona.

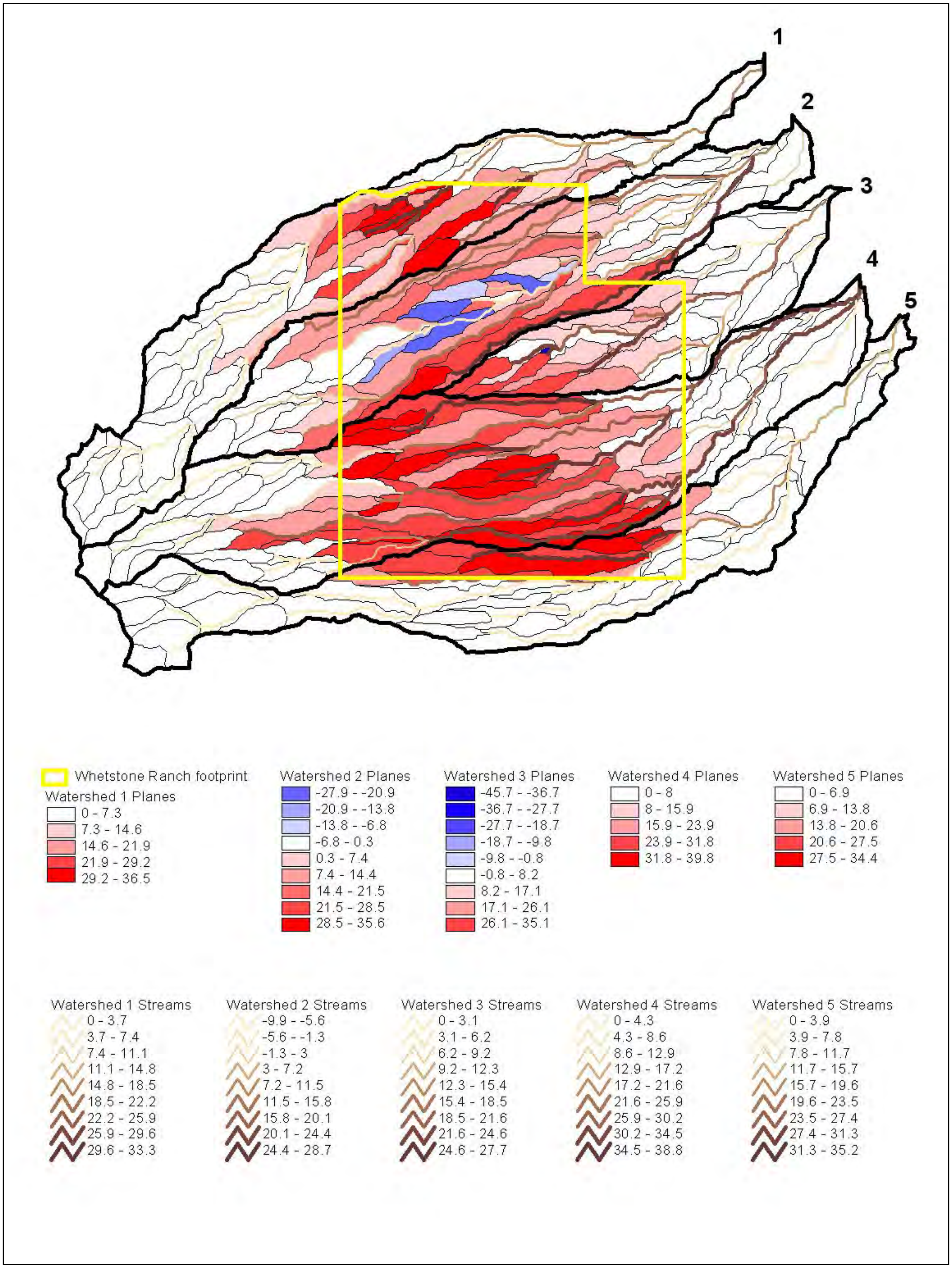

Figure 15. Percent change in runoff, 10-year 1-hour design storm, near Benson, Arizona.

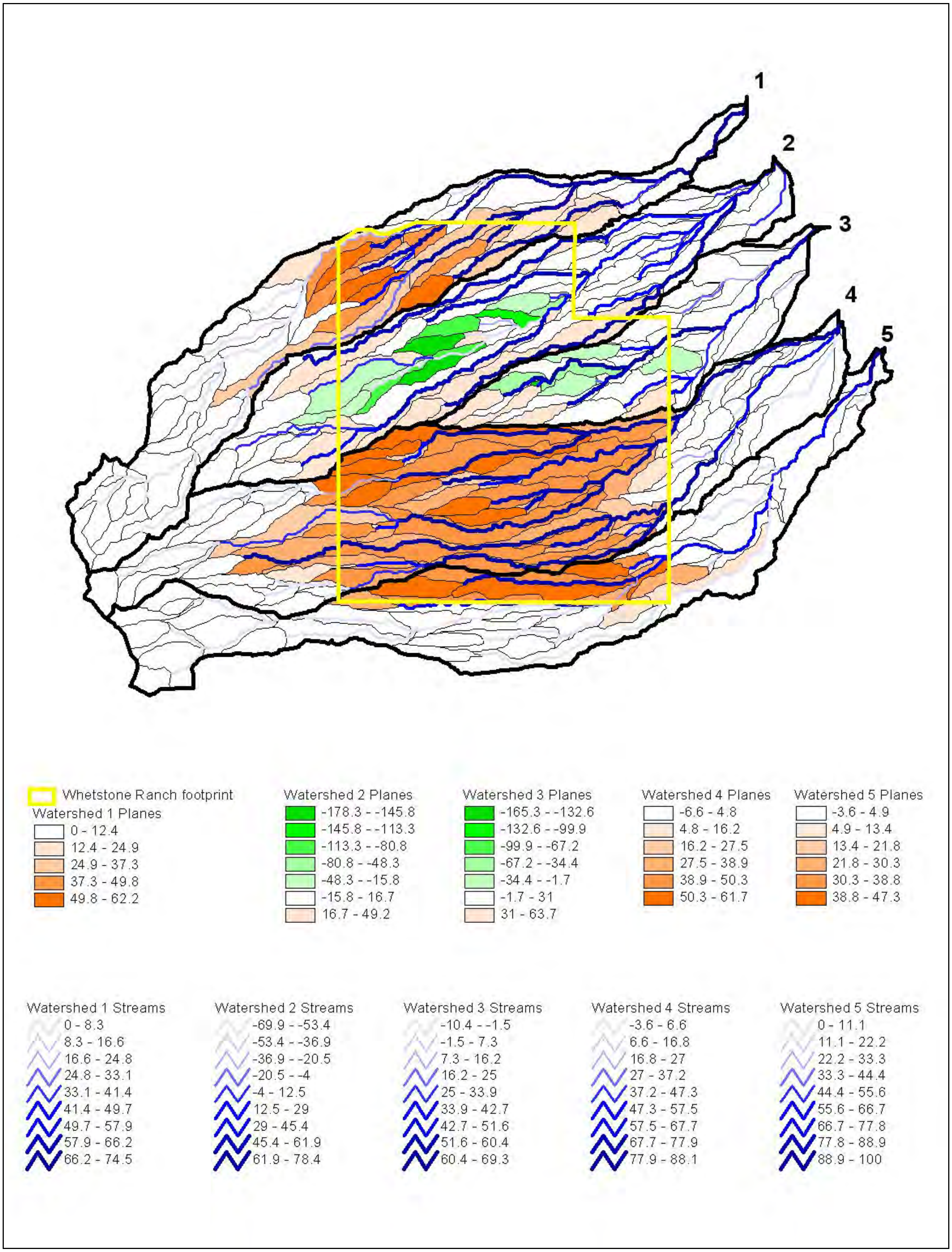

Figure 16. Percent change in sediment yield, 2-year 1-hour design storm, near Benson, Arizona.

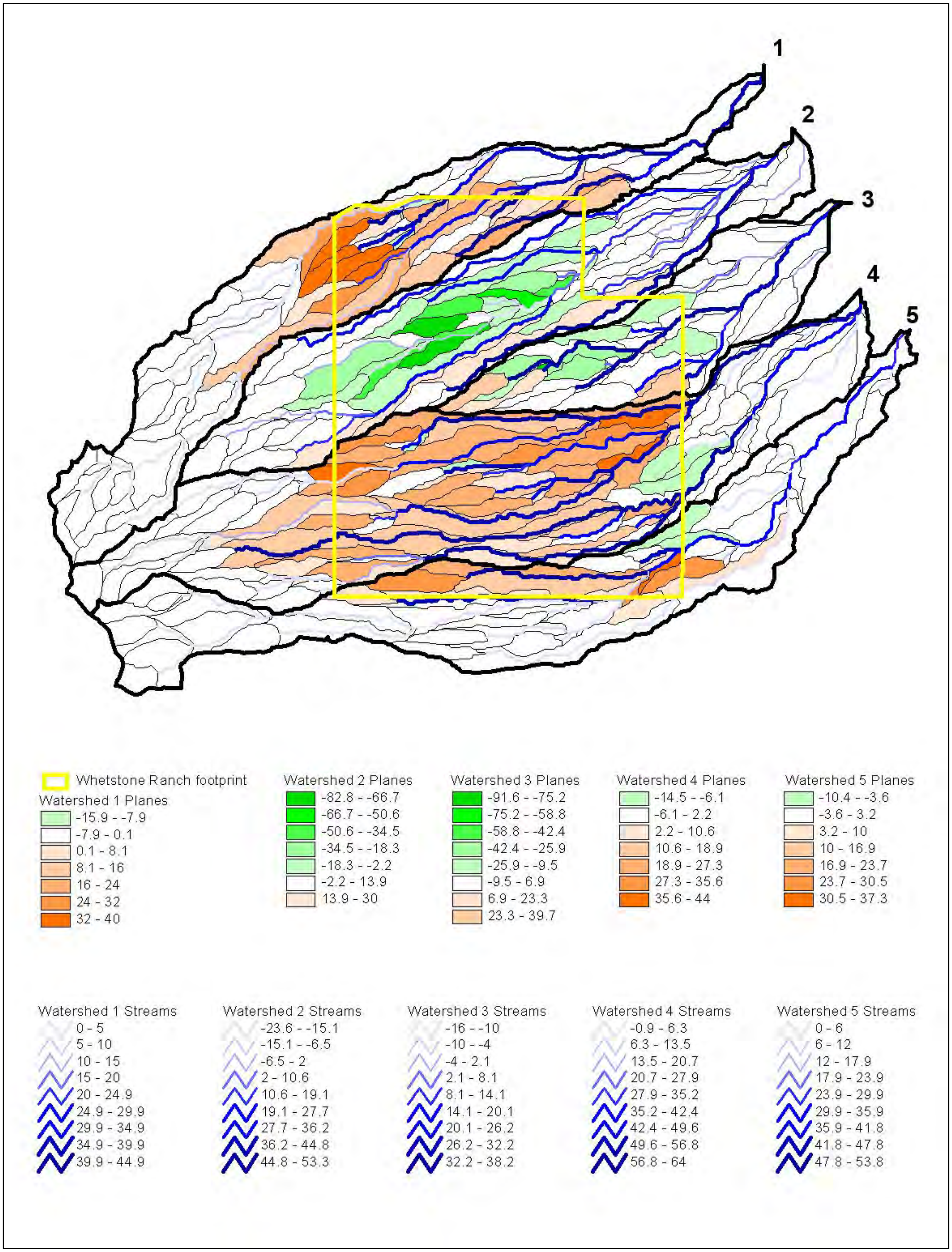

Figure 17. Percent change in sediment yield, 5-year 1-hour design storm, near Benson, Arizona.

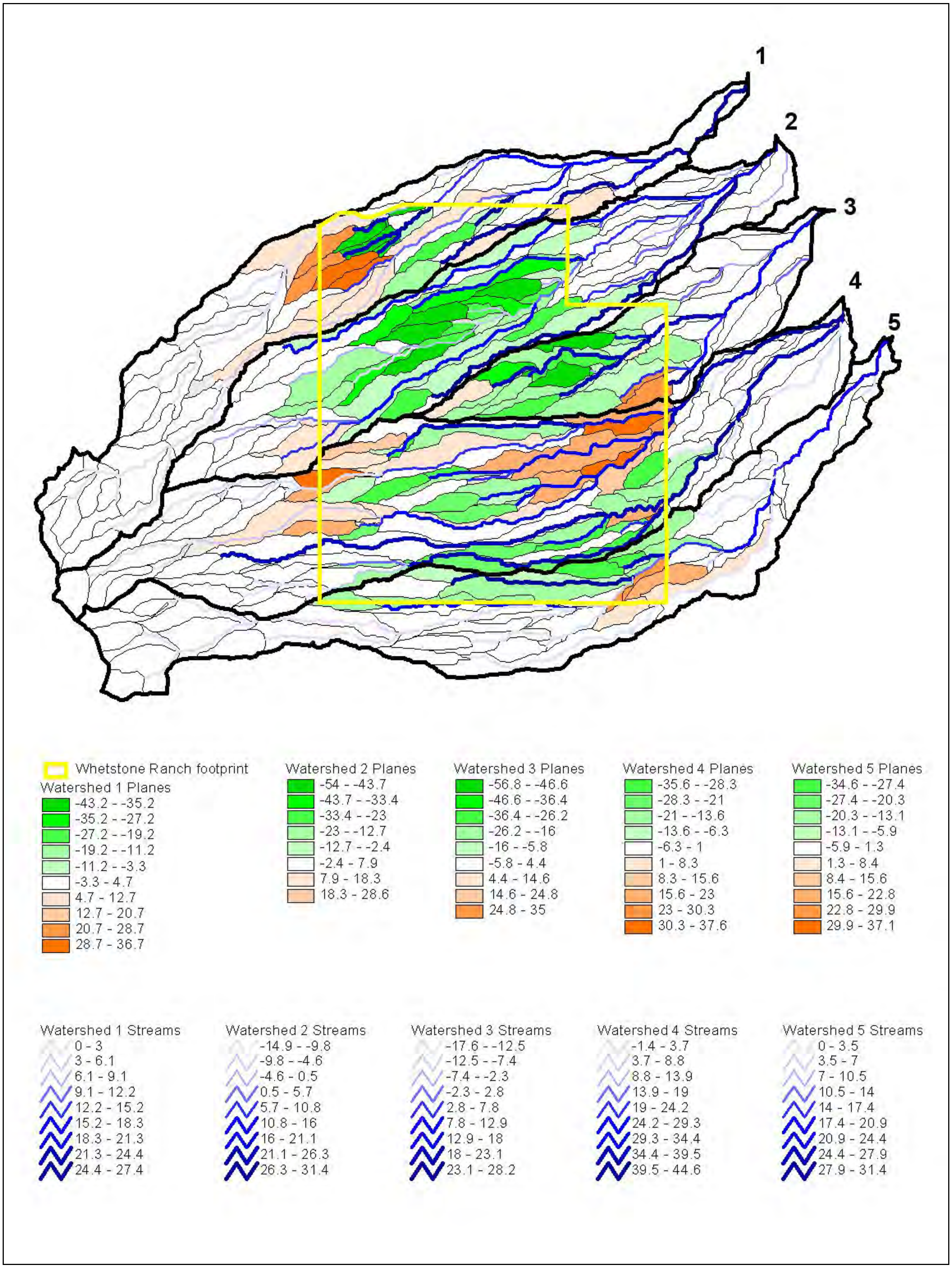

Figure 18. Percent change in sediment yield, 10-year 1-hour design storm, near Benson, Arizona.

Discussion

Simulation results are presented for relative changes in runoff and sediment yield due to a proposed development at the outlets of five watersheds where they flow into the San Pedro River just downstream (north) of the San Pedro Riparian National Conservation Area. The proposed development resulted in substantial relative changes in runoff and sediment yield as predicted by the AGWA/KINEROS2 rainfall-runoff-erosion model. Consistent with established principles, the relative changes are largest for the smallest design storms and decrease with increasing design-storm size (Tables 3 and 4, and Figures 7 through 12). In all cases, net runoff and sediment yield increased at the watershed outlets due to urbanization and more impermeable surfaces.

Predicted changes at the watershed outlets are substantially greater than those predicted within the watershed. For instance, for the 2-year-1-hour event in Watershed 4, the maximum percent increase in runoff from an upland overland flow element (modeled as overland flow planes) is approximately 71% (Figure 13); however, the percent increase in runoff at the watershed outlet is approximately 1,072% (see Table 5, Watershed 4, 2-year-1-hour event). A considerable portion of the larger predicted changes at the watershed outlets can be attributed to the dynamics of ephemeral flow in the channel network: sediment on initially dry channel beds represents a reservoir that must be filled/saturated before significant flow can occur. Under predevelopment conditions, the 2-year-1-hour event is just enough to fill the void spaces in channel-bed sediment, overcome transmission losses, and cause a small but measurable flow at the watershed outlet. Following development, the same event produces a great deal more runoff at the watershed outlet because increased impervious upland surfaces produce more surface discharge and little additional water can be absorbed by the channel-bed sediments.

Figures 13 through 18 illustrate the simulated changes in runoff and sediment yield for each plane and stream segment. The greatest relative increases in runoff occurred in areas of highest density urbanization, where impermeable surfaces dominate land cover. The greatest relative decreases occurred in portions of Watershed 2 in the north-central part of the site approximately where the golf course is to be located. Grass or turf will produce less runoff and sediment than native shrubland. Additional analyses of the soil, topographic, and pre- and post-development land cover in these areas are warranted to further elucidate reasons for the large simulated changes. This can be undertaken using AGWA by rediscretizing the model into smaller elements for more detailed analysis, but would also require field measurements to support the analysis.

Changes in sediment yield from upland surfaces show a different response pattern than does runoff after development. For the 2-year, 1-hour event sediment yield decreased under the developed conditions only in those areas experiencing runoff decreases. As rainfall increased, however, simulated sediment yields decreased in areas with increasing runoff. The explanation for this lies in the fact that impervious surfaces are treated as non-eroding in the model. For smaller events the increase in runoff and associated hydraulic erosion has a larger effect on sediment yield than the fractional reduction of the erodible area due to development, so sediment yield increases. As runoff increases become proportionally smaller for larger, less frequent events, the reduction of erodible area becomes more significant and can result in decreased sediment yield despite increasing runoff. Of course, during construction, grading large areas of bare soil has the potential for causing markedly higher erosion and offsite sediment yields if containment measures are not taken.

These are preliminary results from a rapid initial assessment of the hydrologic changes likely to result from some of the development being proposed near Benson, Arizona. As such, they can be interpreted as a qualitative representation of the expected impacts to water and sediment flows in the San Pedro as a result of the proposed development. Other important endpoints, such as transmission losses from ephemeral stream channels should also be evaluated, but require inputs that were unavailable for this analysis. Transmission loss from runoff in ephemeral streams has been shown to be an important mechanism for groundwater recharge in the San Pedro Basin (Goodrich et al., 2004; Coes and Pool, 2005). Depending on the proposed level of channel fill and lining in the development, channel recharge could be significantly altered.

In most cases, local and state regulations require that increases in downstream flooding due to development be mitigated without permanently impounding water, which may impact downstream water rights. Typically, detention ponds are constructed within defined drainage channels to temporarily hold flood waters and release them more gradually to reduce the peak runoff rate to some specified pre-development level. In Arizona, once water enters a stream (ephemeral, intermittent or perennial) it is subject to water rights adjudication. However, if the increases in runoff due to urbanization are handled before they enter a defined channel they may be retained without impacting downstream water rights. This opens up opportunities for handling flood-waters resulting from development in more innovative ways to attempt to mitigate the impacts of development on runoff and sediment. Methods such as home and subdivision scale water harvesting, riparian buffers, infiltration galleries, and installation of numerous recharge wells (already used on a large scale in Chandler, AZ) may offer viable alternatives to the typical practice of concrete lined channels within a subdivision to control erosion and downcutting, draining into flood detention structures. The AGWA model is currently capable of modeling the relative impacts of detention ponds and riparian buffers but would need more development and verification to treat strategies such as water harvesting and recharge wells.

Insufficient information on the design and placement of detention structures did not allow this study to assess the mitigating impacts of such structures on runoff changes. With further AGWA development a suite of mitigation features, such as those discussed above, could be available to the planner/developer to readily assess combinations of mitigation features in terms of numbers and spatial watershed locations. Approximate costs of these features could be estimated and incorporated into AGWA to enable rough cost/benefit analysis of various mitigation scenarios.

As noted above, a more detailed assessment would warrant additional field measurements to better parameterize the model. For example, significant improvements in model estimates would be obtained from incorporating the full complement of hydraulic structures (e.g. water-detention basins, culverts, etc.) and channel modifications anticipated in the proposed design. In addition, more specific information on channel geometry, runoff and precipitation would also improve the results. This information was not available and thus not accounted for in the present analysis. Finally, the availability of detailed design plans would enable the implementation of the KINEROS2 urban-element feature that explicitly accounts for runoff and sediment movement over various configurations of pervious and impervious surfaces, and would improve estimates of water and sediment yield from the urbanized areas.

Conclusions

The hydrologic response resulting from pre- and post-development scenarios for an area near Benson, AZ, was evaluated using AGWA, a GIS tool developed to integrate landscape information with hydrologic process models for the assessment of watershed impacts. This type of assessment allows rapid evaluation of likely changes in surface runoff throughout a basin, as well as the cumulative downstream change as widely distributed tributary impacts are felt in the main channel. In this fashion, it is possible to assess the vulnerability of potentially sensitive areas to basin-wide and site-specific development alternatives. For the purpose of this study, negative impacts are considered to be any increase in surface runoff and sediment yield (Kepner et. al., 2004). Expected adverse environmental consequences from such increases may include degraded water quality from sediment and pollutant transport, erosion and alteration of the stream channel, habitat destruction, decreased biological diversity, and increased flooding. The hydrologic modeling results indicate that significant increases in both runoff and sediment yield are likely at the San Pedro River main-stem under the development scenario.

Despite the qualitative nature of this analysis, several important conclusions can be drawn from the results. The proposed development will profoundly alter the hydrology for five watersheds with a total area of 86 square kilometers (33.2 square miles). Those watersheds all flow directly into the San Pedro River within a few miles downstream (north) of the San Pedro Riparian National Conservation Area, and will have a significant impact on the hydraulic and sediment regimes in this river reach.

As expected, flows are most substantially increased for the smaller, more frequent rainfall events. As event magnitude increases and frequency decreases, the impacts of land-use change (increased flow) become small relative to the volume of rainfall, and changes in runoff due to development are less significant. Increases in sediment yield are also most significant for the smaller, more frequent rainfall events. As event magnitude increases, changes in sediment yield become smaller and in some cases negative, indicating less erosion despite higher runoff. For all events there is a simulated average net increase in runoff and sediment yield at the San Pedro River.

For the smaller, more frequent events, predicted change at the San Pedro River is much greater than on the upland surfaces directly impacted by development. In arid and semi-arid regions characterized by ephemeral stream systems there is a threshold below which rainfall and associated runoff are absorbed entirely before reaching the watershed outlet. With the installation of impervious surfaces, development has the effect of reducing that threshold such that a lesser amount of rainfall is necessary to generate runoff at the watershed outlet. In the present analysis the 2-year 1-hour design storm just exceeds this threshold prior to development, but substantially exceeds it after development. The net result is that more frequent and larger runoff events can be expected from the project area, which has also been commonly associated with channel incision and increased sediment yield downstream.

As noted above this is due to the non-linear nature of runoff response in arid and semiarid watersheds (Goodrich, et al., 1997) due, in part, to the thresholds to overcome in runoff generation due to ephemeral channel transmission losses, and the scale dependency where runoff response becomes more non-linear as watershed scales increase. This is in direct contrast to watershed response in more humid regions where runoff response typically becomes more linear as watershed size increases.

Scenario analysis can help better understand and visualize how today's decisions regarding conservation and development cumulatively act to change the future. The combination of both landscape analysis and hydrological modeling can be widely applied on a variety of landscapes, watersheds and regions, and provides an important tool to assess Section 404 permitting under the CWA and NEPA compliance. The use of scenario analysis coupled with hydrologic process models thus allows stakeholders and decision-makers, such as the U.S. EPA and the USACE, to assess the relative impacts of several alternative sets of options, and thus represents an important tool to help make better-informed choices to protect the physical, chemical, and biological integrity of waters of the United States.

We further recommend that Region IX of the U.S. EPA and the Los Angeles District of the USACE consider evaluating the cumulative environmental impacts of multiple proposed projects for the San Pedro River via scenario analyses. This examination should include recommendations for improving "Standard Operating Procedures" in the regulatory permitting process, including minimum standards for data and analyses required for permit applications. The full implementation of a regional web-based modeling, decision support and planning tool such as DotAGWA would greatly benefit such an effort.

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