DETERMINING WATERSHED BOUNDARIES AND AREA USING GPS, DEMS, AND TRADITIONAL METHODS: A COMPARISON

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Defining a watershed's boundary is critical for understanding the movement of water across the landscape. In the past, hydrologists defined watersheds using topographic map features such as contour lines, stream networks, and traditional surveys. However, the more advanced current techniques for defining watershed boundaries use Geographic Information Systems (GIS) in conjunction with Digital Elevation Models (DEMs; Maidment 1999). GIS is an important tool in resource management today. Because of its precision and accuracy, we expect the Global Positioning System (GPS) to be more appropriate for delineating watershed boundaries and calculating area than traditional forestry field methods of using a compass and chain. We also expect GPS surveyed boundaries to be more precise than those determined using DEMs, because DEMs rely on 10 m topographic intervals, which can lead to faulty results, especially in areas with small elevation differences.

After "selective availability" was removed from GPS technology in May of 2000, potential point location error without differential correction dropped from 100 to 3 m. According to Oderwald and Boucher (2003), this indicates that a single point observation on average is within approximately 3 m of its true location. In contrast, on a 1:24,000 topographic map, a 0.5 mm pencil line is 12 m wide (Oderwald and Boucher 2003).

In our study, we chose not to apply post-processing differential correction to our data for three reasons. First, users may not have access to base stations to differentially correct their data or may not have the expertise to do so. Second, low-end, consumer-grade GPS units may not offer the option of differential correction. Third, we assume that for areas greater than 20 hectares (ha) in size cumulative error is insignificant due to the randomness distribution of the horizontal error distance (which averages between 3 and 4 m for each point; Wilson 2000).

DEMs are digital representations of surface elevations laid out over the landscape. A DEM is produced from digitized map contours, spot elevations, and hydrography overlays or from manual scanning of aerial photographs (Elassal and Caruso 1983; Maidment and Djokic 2000). DEMs are valuable because they provide managers with the same information as contour maps, but in a digital format suitable for processing by computer-based systems rather than in an analog format (Cho and Lee 2001). The accuracy of DEMs for use in watershed delineation depends mostly on their cell size and resolution. The smaller the cell size the greater the resolution; therefore, smaller watersheds require a smaller cell size to accurately represent the watershed area. According to Maidment and Djokic (2000) for most hydrologic and geomorphic modeling applications 10 m DEMs are sufficient. Currently, the USGS has DEMs with 30, 100, 500, and 1000 m cell sizes available for the United States. A 30 m DEM means that each cell covers an area of 30 m x 30 m (Maidment 1999). Higher resolution DEMs such as 5 and 10 m are more readily available from state governments and the USGS through its

partner ATDI (http://www.atdi-us.com; accessed March 2004).

From October 2002 through January 2004, two large, four medium, and three small watersheds were mapped using a hand-held GPS receiver. The two large watersheds—Watershed 20 (Bar M) and Watershed 19 (Woods Canyon)—as well as three small sub-watersheds (85, 86, and 87) within Watershed 19 are located in the Beaver Creek Experimental Watershed in central Arizona (Figure 1). The four medium-sized watersheds—the East and West Forks of Castle Creek and the North and South Forks of Thomas Creek—are in eastern Arizona (Figure 1). The objective of this study was to compare watershed area and boundary determined using a GPS (without post-processing differential correction of data) with watershed parameters determined using traditional methods of area calculation, and with watersheds determined using DEMs in GIS.

STUDY AREAS

The Forest Service had established experimental watersheds in Arizona to determine the amount and sustainability of water yield produced from various silvicultural practices. Twenty pilot watersheds were set up by the USDA Forest Service between 1957 and 1962 in the Beaver Creek Experimental Watershed, which is located within the Coconino National Forest of northern Arizona (Figure 1). Of the 20 watersheds, 18 range in size from 27 to 824 ha. The remaining two watersheds, Bar M (Watershed 20) and Woods Canyon (Watershed 19), are much larger and are located in the ponderosa pine forest ecosystem, encompassing 6620 and 4893 ha, respectively (Baker and Ffolliott 1999). The four mid-sized watersheds are located 14–25 km south of the town of Alpine in the Apache-Sitgreaves National Forest in eastern Arizona (Figure 1). The West and East Fork experimental watersheds of Castle Creek were established in 1955 and are 354 and 458 ha in size, respectively. The East Fork was subject to preharvest prescribed burning (Gottfried and DeBano 1988). The North and South Forks of Thomas Creek, established in the mid 1960s, are 184 and 221 ha in size, respectively (Dietrich 1980; Ffolliott and Gottfried 1991).

METHODS

The original identification and mapping of the study watersheds involved several steps. The boundary of each watershed was roughly delineated on a topographic map to install a flume at the mouth of each watershed. Following flume installation, the boundary of each watershed was flagged, beginning at the lowest elevation and ending at the highest elevation. Upon marking the boundary, in the Beaver Creek watersheds trees were painted at eye level with yellow paint to make the boundary permanent and visible from a substantial distance in any direction. At Thomas Creek, trees were painted with white paint. In the absence of trees, the paint marks were applied to rocks or stumps. Next, surveyors used traditional forestry surveying techniques to map the boundaries. Beginning at the stream gauging equipment, surveyors measured short segments of the boundary using a 2-chain steel tape while correcting for slope using a clinometer. With a compass, the bearing of each segment was taken and plotted on a Reinhardt Redy Mapper (a hard plastic board with imprinted grid and compass bearings). The Castle Creek watersheds were not delineated on the ground.

Field Methodology

In the Beaver Creek Experimental Watershed we used the paint markings made by surveying crews in the late 1950s as guides to locate ridge points, and we followed these when we delineated the watershed boundaries with our GPS receiver. Originally trees had been marked in close proximity to one another, however not all the trees and markings exist today. Some of the marked trees have since died, burned, or been harvested, or their markings have faded away as a result of exposure to sunlight. Wherever we encountered gaps between marked trees, we depended on the topographic features of the

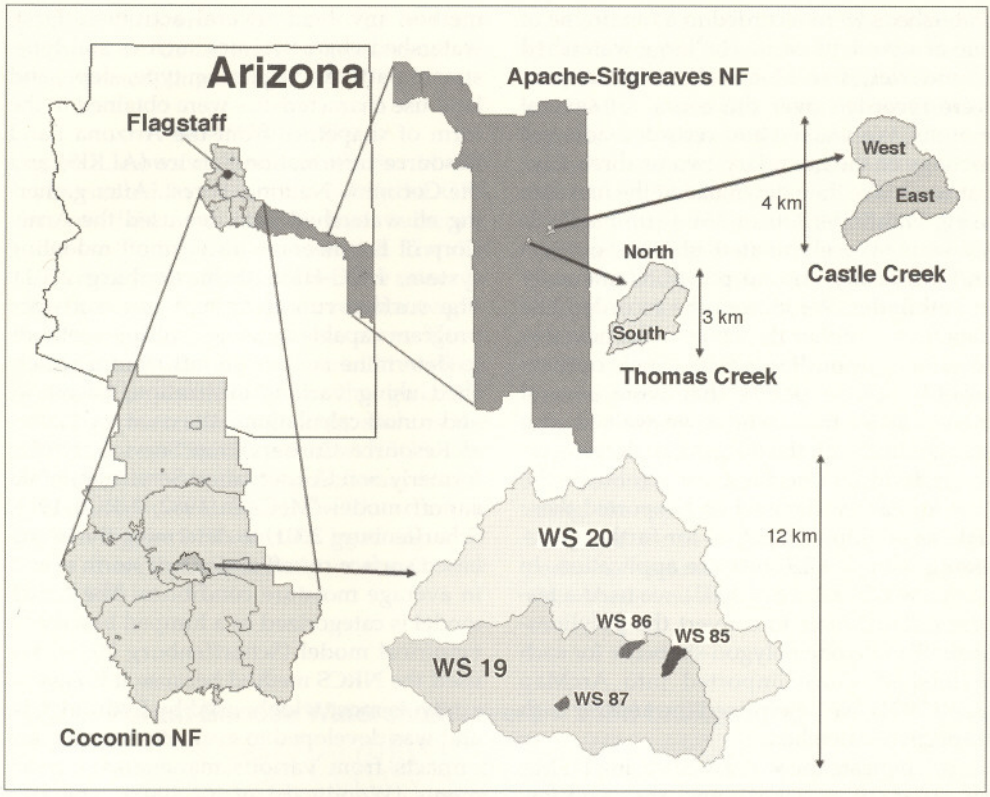

Figure 1. Location of study watersheds within the Coconino and Apache-Sitgreaves National Forests in Arizona.

landscape to delineate the watershed boundary. The longest unmarked boundary line we encountered was approximately 500 m on a well-defined ridgeline. In the Castle Creek watersheds we relied on a distinct ridge as well as a compass and a topographic map with 5-foot contour intervals that circumscribed the watershed boundary. In the Thomas Creek watersheds, we used a combination of topographic features, marked trees, a compass, and a topographic map with 5-foot contours on which the watershed boundary had been marked, to determine the actual watershed boundary on the ground. The beginning and ending location of the survey of each watershed was the respective gauging station of that watershed.

GIS/GPS Methodology

We used a Trimble GeoExplorer3 handheld GPS receiver to record our position along the boundary and to record line data in a kinematic mode. GPS data were recorded in Universal Transverse Mercator (UTM) format and were projected using the North American Datum (NAD) of 1927. The typical distance between each recorded point on the line was about 5 m, but varied up to a maximum of 30 m. The GPS receiver recorded points every few seconds, depending on reception. Reception, in turn, depended on the topographic features and canopy closure (Karsky 2001), which varied from 0 to 100 percent. In rare cases we had to wait several minutes before a point was recorded. The boundaries of small and medium sized

watersheds were recorded in a timeframe of one or two days each. The large watershed boundaries, Bar M and Woods Canyon, were recorded over the course of several months. We walked and recorded adjacent sections of the boundary two or three days per week. We then downloaded the line data using Pathfinder Office 2.90 (Trimble 2002) software. We eliminated obvious outliers and artificially created polygons manually in Pathfinder. We viewed the recorded line data files on either the same or the next day to eliminate outlier points. Such outliers would include points that were several meters away from where we walked in a straight line with the GPS. After cleaning up the individual line files, we combined the files for each watershed and exported these data as polyline shapefiles for further processing using a GIS software application. In ArcView GIS 3.3 (ESRI 2003), we used a feature called Xtools to convert the polylines-shapefile into one polygon-shapefile for each watershed. Once imported into ArcMap (ESRI 2004), we determined the area for each respective watershed.

To delineate the watersheds using DEMs, we used 10 m DEMs and the ArcView CRWR Preprocessor (Maidment and Djokic 2000; ESRI 2002). DEMs were obtained from the Arizona Regional Image Archive (ARIA) and projected in UTM NAD 1927. All DEMs were merged using the map calculator to create one complete DEM for analysis. A stream shapefile obtained from the Arizona Land Resource Information Service was burned into the DEM and appropriate steps were followed in the CRWR Preprocessor to fill sinks, compute the flow direction and flow accumulation grids, construct the basic stream network, segment streams into stream links, find link outlets, delineate the watersheds, and vectorize the stream and watershed grids. After the above steps were completed, sub-watersheds were merged to create the specific watersheds of this study.

Determining Discharge Using HEC-HMS

Determining the discharge from all watersheds and their respective areas from each method involved several activities. First, watershed characteristics such as soil type, stream patterns, vegetation type, slope, and land use characteristics were obtained in the form of shapefiles from the Arizona Land Resource Information Service (ALRIS) and the Coconino National Forest. After gathering all watershed data, we used the Army Corp of Engineers surface runoff modeling system, HEC-HMS (Scharffenburg 2001). The surface runoff system is a software program capable of using multiple methods to determine surface runoff from a watershed using various infiltration, baseflow, and runoff calculations. We used the Natural Resource Conservation Service (NRCS; formerly Soil Conservation Service) rainfall-runoff model (McCuen 1982; NRCS 1986; Scharffenburg 2001) to determine the event-based surface runoff under two storm events in average moisture conditions. The NRCS model is categorized as a lumped based and empirical model (Scharffenburg 2001). We used the NRCS method because it is easy to apply, is most widely used by hydrologists, and was developed to evaluate downstream impacts from various management treatments (Woodward et al. 2002). The two events that we used to generate runoff were 25 and 100 yr return period storms covering the entire watershed area. We used the SCS type II 24 hr rainfall distribution pattern for the 25 and 100 yr storms, and the storm depths were determined to be 6.8 and 8.5 cm of precipitation respectively (U.S. Army Corp of Engineers 2000).

RESULTS

The results of this study are threefold. First, we have established the boundaries of the watersheds in a GIS format that has been derived using various methods. Second, we compared the watershed areas determined using our GPS method to the areas determined using traditional cartographic methods as well as to the areas calculated using the computer analysis of DEMs. We also compared the results of computer analysis to the traditional method of determining watershed areas. Third, we used the HEC-HMS surface-runoff software to de-

termine differences between the various methods of delineating a watershed, in terms of modeling output.

Area Discrepancies

Figure 2 shows a section of the Bar M GIS layer created in this study using the GPS data overlaid with a GIS layer currently inuse by the USDA Forest Service. The differences between the two layers are minor in most instances but can easily reach a magnitude of 50 ha or more in some areas. These discrepancies also have a cumulative effect on the entire watershed. Even though DEMs used by government agencies, such as the USDA Forest Service or the USGS, are developed to National Map Accuracy Standards (Longley et al. 2001), the 10 m contour lines in Figure 2 fit our GPS layer arguably better than those currently in use by the Forest Service.

Another example of area discrepancy is given in Figure 3, which shows the difference between a layer we created using a 10 m DEM and our GPS layer. Here the GPS layer is very close to the traditionally determined boundary. However, according to the DEM layer, Woods Canyon should include a section of approximately 200 ha, which it does not. This discrepancy probably results from the DEM's failure to capture the less than 10 m elevation difference between the boundaries.

We encountered another major area difference while creating our DEM layers for sub-watershed 85. Here the DEM created two separate watersheds for the area that had been determined to be one watershed using the traditional methods (Figure 4). However, for the purpose of our area comparisons, we combined the area of these two watersheds into one.

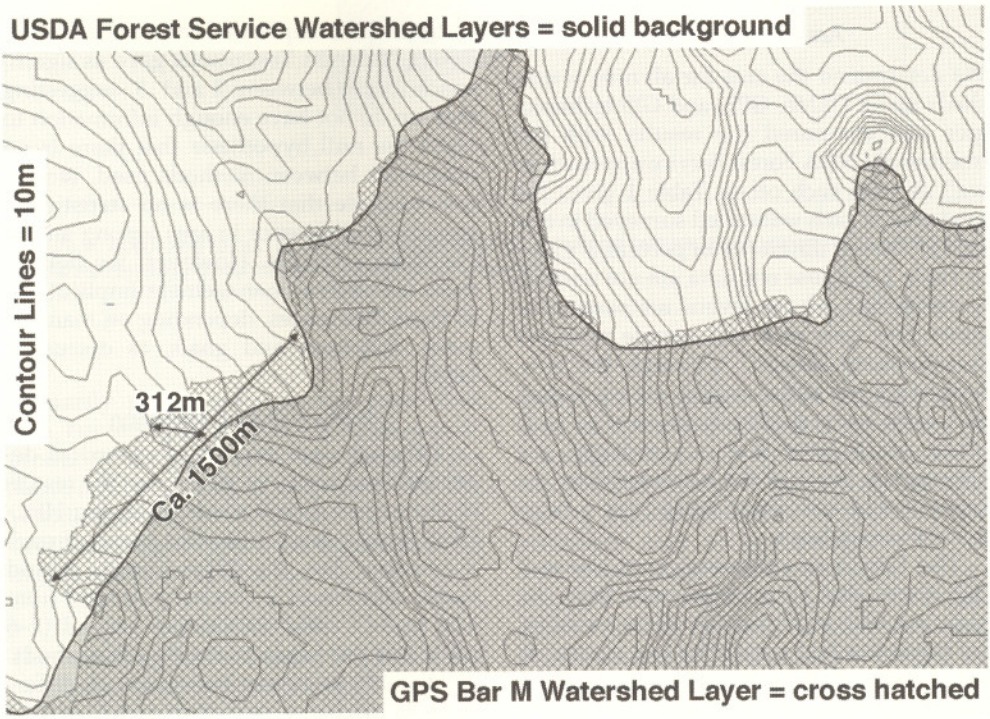

Figure 2. Comparison of a portion of the Bar M watershed with a USDA Forest Service GIS layer; 10 m contour interval derived from USGS digital elevation model.

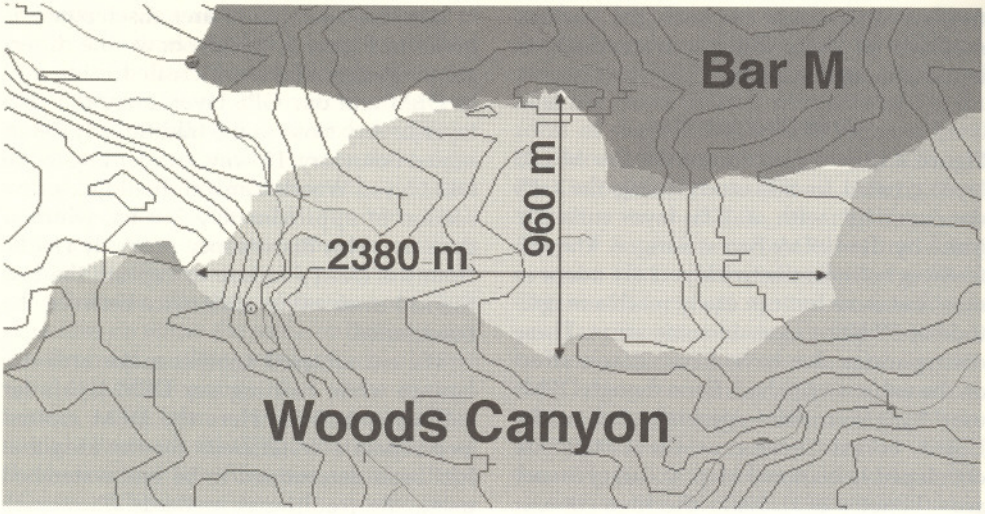

Figure 3. According to our 10 m DEMs, an area of ca. 200 ha should be included in our GPS layer of the Woods Canyon watershed. Even the Woods Canyon gauging station does not fall within the DEM layer.

Area Calculations

We determined the area for all nine watersheds using DEMs, GPS, and GIS technologies and compared the results with the traditional USDA Forest Service approach as well as with each other. Table 1 gives the total area of each watershed surveyed in this study. The net difference in percent is given in Table 2. Because our data are not normally distributed, we ran several nonparametric equivalent tests of a one sample repeated measurement design. Although the subwatersheds are nested within one watershed and some watersheds are adjacent to each other, we believe that our statistics are appropriate because the measurements are separate and watershed areas have a functional independence.

The Friedman procedure tests the null hypothesis that k variables come from the same population; in our case these variables are the watershed areas. The test statistic is based on these ranks. We also performed the Kendall's W, the Wilcoxon rank tests, and a multi-response permutation procedure for a block design (MRBP) based on Euclidean distance for unreplicated randomized block design (Table 3). Test results gave us significance values between .2 and .5, suggesting that we do not have enough information to reject the null hypothesis that there is no difference between methods used. Hence, we conclude that there is no statistically significant difference in area among any of the three methods. However, we believe there are several management implications to these differences, depending on management objectives and goals, as discussed below.

Surface Runoff Modeling

Although each method of watershed delineation produced varying areas, the results of the surface runoff modeling using HEC-HMS show a small difference in runoff peak discharges. For the 25 yr return period storm, differences in discharge ranged from 0.06 to 0.17 cubic meters per second (2–6 cubic feet per second) among all methods. For the 100 yr return period storm differences in discharge ranged from 0.23 to 0.53 cms (8–19 cfs) among all methods of area delineation. The difference in discharge was

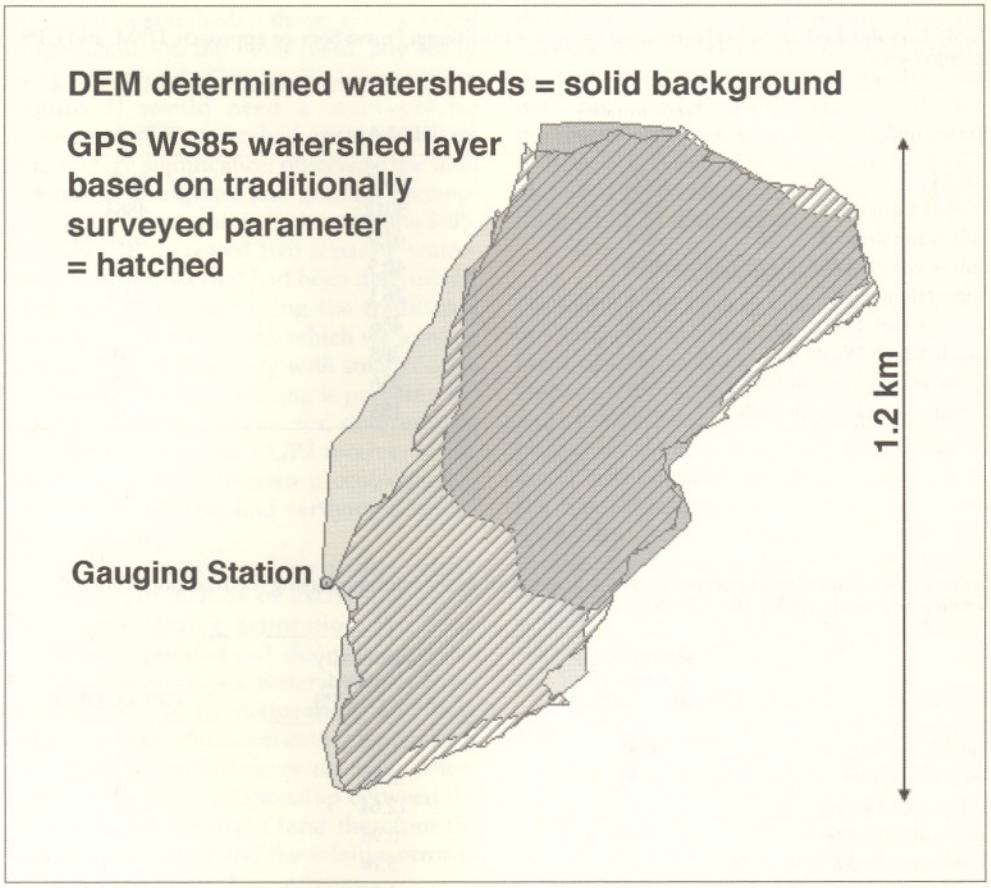

Figure 4. According to our 10 m DEMs, watershed 85 should be two separate watersheds, whereas traditional surveying techniques suggest one watershed.

primarily proportional to the watershed area. For example, watersheds 85, 86, and 87 produced discharge at the lower end of the above discharge ranges, whereas the Bar M, Woods Canyon, Castle Creek, and Thomas Creek watersheds produced discharge at the higher end of the discharge ranges.

DISCUSSION

The results in Tables 1 and 2 show that depending on the size of a watershed it may be advantageous to incorporate GPS technology into the watershed survey procedure. Using a GPS receiver allows for a faster, less complicated estimate when calculating the area of a watershed and determining its boundary. Training field users to collect uncorrected GPS data has a steep learning curve; the equipment is inexpensive and relatively easy to use compared to the traditional forestry field methods of using a compass and chain. Collecting GPS data allows ground truthing of watersheds and avoids adding additional area or leaving out area, which may be the case when using DEMs to determine watersheds. In our study the size of the errors seems relatively constant with respect to watershed size, so

Table 1. Watershed areas (ha) estimated using the traditional Forest Service approach, DEM, and GPS technologies.

Watershed	Traditionally Calculated Area	DEM Area	GPS Area
Bar M	6621	6641	6662
Woods Canyon	4893	5017	4884
Sub-watershed 85	70.4	64.2	61.5
Sub-watershed 86	40.9	40.9	40.5
Sub-watershed 87	23.5	26.1	22.3
Castle Creek East	458	456	467
Castle Creek West	354	398	364
Thomas Creek South Fork	221	236	230
Thomas Creek North Fork	184	185	191

Table 2. Net difference in percent between watershed areas estimated using the traditional Forest Service approach, DEM, and GPS technologies.

Watershed	Traditionally Calculated Area vs. DEM	Traditionally Calculated Area vs. GPS	GPS vs. DEM
Bar M	–0.31	–0.62	–0.31
Woods Canyon	–2.52	0.19	2.65
Sub-watershed 85	8.82	12.64	4.19
Sub-watershed 86	–0.07	0.98	1.05
Sub-watershed 87	–11.21	5.16	14.71
Castle Creek East	0.35	–1.86	–2.22
Castle Creek West	–12.39	–2.94	8.41
Thomas Creek South Fork	–6.58	–4.12	2.31
Thomas Creek North Fork	–0.54	–3.59	–3.03

Table 3. Test statistics indicating similarity between watershed areas estimated using the traditional Forest Service approach, DEM, and GPS technologies.

Test	p-Value	Traditional Method	DEM	GPS
MRBP	.228	6.98	3.49	10.69
Wilcoxon	.495	11.56	15.89	14.56
Friedman	.236	1.67	2.44	1.89
Kendall's W	.236	1.67	2.44	1.89

for large watersheds, these errors seem insignificant. On the other hand, any study using the Woods Canyon gauging station (Figure 3) would need a more precise measurement of watershed area, regardless of monetary significance; otherwise the data become meaningless. The greatest discrepancy we found was in sub-watershed 85. Here the DEM created two separate watersheds for the area that had been determined to be one watershed using the traditional methods. In this instance, which we assume to be a problem primarily with smaller scale watersheds, ground truthing is probably the most reliable technique for determining boundaries. Carrying a GPS receiver while doing so, in turn, is also a cost-effective method of recording and verifying a watershed boundary.

Another concern we have is that certain methods may include or exclude topography or area during delineation. Wu et al. (2003) have pointed out that not only size but also the relief of a watershed can affect the accuracy of its delineation, and they advise caution when delineating watersheds that are small with little or no relief. There may be a negative relationship between the steepness of the terrain (and therefore the watershed divides) and the relative error in measuring watershed boundaries.

The discrepancies in the Woods Canyon watershed delineation using the different methods (see Figure 3) are caused by the flat terrain, and suggest that more precise methods are needed in flat terrain, or in places where watershed divides are low. There may not be a significant correlation between overall watershed relief and the relief of the watershed divides at certain scales.

This study compares the use of the traditional topographic method, DEMs, and GPS to delineate watershed boundaries and derive their areas. However, future comparisons of watershed area should include absolute (rather than net) differences in watershed area size and their effects on watershed water balance. Although each method produced slightly different watershed areas, the difference in runoff modeling using the various watershed areas for model input seemed small. Even so, scientists and land managers need to use special care during the modeling process, and should be aware of how a watershed area was determined and what potential pitfalls exist according to the method of delineation.

ACKNOWLEDGMENTS

We thank Scott Walker and Steve Andariese of Northern Arizona University's Department of Geography and School of Forestry, respectively, for their technical help in the use of GIS; Jonathan Long and Ruihong Huang for their reviews; and Steve Overby and Geoff Seymour for their assistance in the field. Funding for this study was provided by Arizona State Prop. 301, the Bureau of Forestry Research, and the USDA McIntire-Stennis funding as well as the USDA Forest Service Rocky Mountain Research Station in Flagstaff, AZ.

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The Colorado Plateau II

BIOPHYSICAL, SOCIOECONOMIC, AND CULTURAL RESEARCH

Edited by Charles van Riper III and David J. Mattson

The University of Arizona Press

Tucson

This volume is based on research presented at the Seventh Biennial Conference of Research on the Colorado Plateau. This conference was held at Northern Arizona University, Flagstaff, Arizona, and organized by the U.S. Geological Survey Southwest Biological Science Center, Colorado Plateau Research Station and the Center for Sustainable Environments at Northern Arizona University. The primary sponsors of this conference were the U.S. Geological Survey, U.S. National Park Service, U.S. Bureau of Land Management, and Northern Arizona University.

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This book is printed on acid-free, archival-quality paper.
Manufactured in the United States of America

10 09 08 07 06 05 6 5 4 3 2 1

Library of Congress Cataloging-in-Publication Data
Conference of Research on the Colorado Plateau
(2001–) (7th : 2003 : Northern Arizona University)
The Colorado Plateau II : biophysical, socioeconomic, and cultural research / edited by Charles van Riper III and David J. Mattson.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-0-8165-2526-3 (hardcover : alk. paper)
ISBN-10: 0-8165-2526-9 (hardcover : alk. paper)
1. Natural history—Research—Colorado Plateau—Congresses. 2. Natural resources—Research—Colorado Plateau—Congresses. 3. Natural resources—Colorado Plateau—Management—Congresses. 4. Colorado Plateau—Research—Congresses. I. Van Riper, Charles. II. Mattson, David J. (David John) III. Title.
QH104.5.C58C66 2003
333.73′16′097913–dc22
2005013439

This book was published from camera-ready copy that was edited and typeset by the volume editors.