Estimating Channel Morphologic Properties from a High Resolution DEM

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Abstract

Channel morphology plays a critical role in the understanding and interpretation of the hydrologic and geomorphic characteristics of an area. Traditional techniques for determining channel width, depth, and cross-section area are time consuming and may not be truly representative of the spatial variability within a watershed. A method for extracting channel morphologic properties from a high resolution digital elevation model (DEM) is presented. Interferometric synthetic aperture radar data was used to build a high resolution digital elevation model for the USDA-ARS Walnut Gulch Experimental Watershed. While a fully automated technique proved elusive, a quasi-automated system using a geographic information system and expert opinion was successful in estimating channel shape properties. This integrated technique was not as effective in estimating channel depth, but estimated values of channel width were highly correlated with field observations.

Introduction

This paper presents the preliminary results of an investigation into the automated extraction of channel morphologic properties from high resolution digital elevation models. A quasi-automated approach was used to extract cross-section profiles on an ephemeral stream system at numerous sites that had been previously manually surveyed. A geographic information system was used to extract terrain information from the terrain model, which was then subjected to manual interpretation to determine the bank locations, after which the average channel morphologic properties of width, depth, and cross-section area were determined.
Results indicate a high correlation between observed and estimated width, with slightly poorer results for channel depth and area. These findings will be used as the basis for the development of a fully automated system in which channel properties may be extracted from high resolution terrain models.

The accurate estimation of channel dimensions is a critical element in many hydrologic and geomorphic investigations. Process-based hydrologic models that simulate the various components of processes controlling runoff, such as transmission losses, may require that the channel width and depth be known in order to accurately simulate runoff (Smith et al. 1995). For example, Table 1 illustrates the impact of channel width on runoff and sediment yield using the Kinematic Runoff and Erosion Model (KINEROS) (Smith et al 1995).

Detachment and transport of sediment within a stream channel is a function of the energy associated with water moving through a channel reach, and modifications to the estimated channel width may alter the prediction as to whether a given reach will be aggrading or degrading for a given stream flow. Likewise, geomorphic studies that seek to determine the short- and long-term fluxes in sediment and potential for bank failure of alteration in channel planform, require inputs related to channel width and depth.

The hydraulic relationships between channel morphology and runoff were first explored by Leopold and Maddock (1953) in which exponential equations were developed between channel morphologic properties and runoff characteristics. Channel geometry has been used for indirectly estimating streamflow. Because of variability in recording and the possibility for measurement errors in determining channel depth, Hedman and Osterkamp (1982) focused on the relationship between streamflow and channel width and reported relationships between streamflow and channel width for areas of similar climates within the Western United States. By taking into account the shear stress distribution within the channel,

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Table 1. Impact of systematically changing channel width on hydrologic simulations using KINEROS.

	Multiplier of channel width						
	0.7	**0.8**	**0.9**	**1**	**1.1**	**1.2**	**1.3**
Runoff	12.76	8.41	4.07	0.00	-3.85	-7.31	-10.52
Sediment yield	3.88	2.60	1.30	0.00	-1.30	-2.38	-3.37
Peak Runoff	11.90	8.13	4.12	0.00	-4.12	-8.01	-11.97
Transmission Losses	-10.82	-7.13	-3.46	0.00	3.19	6.06	8.70

Osterkamp et al. (1983) further explored the relationships governing streamflow and channel geometry and derived the exponents for the width, depth, and velocity factors as used in hydraulic geometry. Other researchers have found the variables of width and depth to display a large variance, while cross-sectional area displays a strong relationship to flow distance (Miller et al. 1996).

In support of such investigations, a field campaign is typically undertaken in which channel cross-sections are surveyed using either hand-held means or more sophisticated surveying equipment. Such techniques have been shown to be relatively robust, although a degree of subjectivity and error are embedded in the estimation of bank height and location of break points along a given profile. Ephemeral streams are relatively easy to survey when dry, but the nature of runoff in such areas often leads to uneven or indistinct channel forms. Perennial streams may provide a more stable and uniform profile, but are challenging to survey as the surveyor must navigate through inundated areas.

A significant drawback to field investigations of channel morphology is the amount of time necessary to carry out such a campaign. For example, Miller et al. (1996) manually surveyed over 300 channel sections using primarily a line-level and rod approach, with an average of 2.4 profiles per section, in support of a joint watershed / channel morphology project. This field work consumed approximately 40 field days and often required more than one scientist. Using a total station requires a minimum of two people and can consume more time due to increased set-up and mobility constraints. In sum, field-based channel morphology investigations are both time-consuming and costly in terms of manpower and equipment.

Significant advances in hydrologic model development have been made with respect to developing linkages between geospatial data and the parameterization of geomorphic and hydrologic models using geographic information systems, or GIS (Arnold et al. 1994, Miller et al. 2002). In general, these GIS-based linkages rely heavily upon users for the estimation of channel morphologic and hydraulic properties; several do not attempt to utilize channel morphology in the simulation of runoff and avoid the difficulties associated with acquiring intensive field-based data.

An alternative approach to utilizing GIS for the estimation of channel morphology is presented here. A high resolution DEM was acquired using interferometric synthetic aperture radar (IFSAR) at a 2.5 m resolution. Channel profiles were extracted from the DEM at the same locations surveyed by Miller et al. (1996) and compared to the field observations. A methodology for extracting the channel profiles for estimation of channel width, depth, and cross-section area is presented. Results show a high correlation between the observed data and those derived from the DEM.

The objective of this project was to develop a quasi-automated approach to determining channel morphology from a high-resolution DEM using a GIS. Following Miller et al. (1996) it was hypothesized that the estimation of channel width would be in relatively close agreement with the observed values, while the estimation of depth would be less reliable. This approach is intended to provide a basis for a fully automated GIS-based technique for generating spatially distributed estimates of channel width and depth for support of hydrologic and geomorphic modeling.

Description of the Study Area

The USDA - Agricultural Research Service Southwest Watershed Research Center administers the Walnut Gulch Experimental Watershed. Located in southeastern Arizona, Walnut Gulch encompasses the city of Tombstone and contributes runoff to the San Pedro River. Approximately 148 km^2 in size, the watershed is located on the pediment between the Dragoon mountains and the San Pedro River. Climate in this region is semi-arid, with the majority of the rainfall occurring during summer monsoon rainfall, primarily as a result of high-intensity localized convective events (Renard et al. 1993).

Walnut Gulch is within the transition zone between Chihuahuan and Sonoran deserts. Vegetation is a mixture of grasslands (in the upper, eastern portion of the watershed) and shrub-steppe (dominant in the lower, western section). Soils in the watershed are primarily sandy loams, and the stream beds are a mixture of sands and gravels with high infiltration capacities.

The terrain is primarily composed of rolling topography with a dendritic stream network. In some areas relatively shallow depth to bedrock and small-scale faulting exert geologic control over the channel pattern and morphology. A majority of the watershed overlies deep alluvial outwash from the Dragoon mountains. However, igneous and exposed sedimentary rocks form the Tombstone Hills and form much of the southern boundary of the watershed.

Methods

A quasi-automated methodology was employed in the estimation of channel morphologic properties from a high resolution IFSAR DEM. The IFSAR model was built using data collected from a mission flown in the year 2000. Radar backscatter was acquired using low-flying aircraft and a terrain model was generated with a 2.5m resolution. Since no averaging or smoothing was performed on the raw DEM occasional errors in elevation are present. At a larger scale, the cumulative errors cause problems for continuity in the terrain surface and make hydrologic modeling difficult, but at the cross-section scale these data are appropriate, since spurious elevation may be readily identified and excluded from the analysis.

Cross-section profile locations from the field campaign of Miller et al. (1996) were input into a GIS. These cross-sections were located by Miller et al. (1996) using a 0.5 m resolution ortho-rectified aerial photography. In the current effort these section locations were transformed into linear (arc) features using ArcGIS. The aerial photographs were geo-rectified and input as grid features into the GIS and served as background imagery to ensure the correct placement of the profiles.

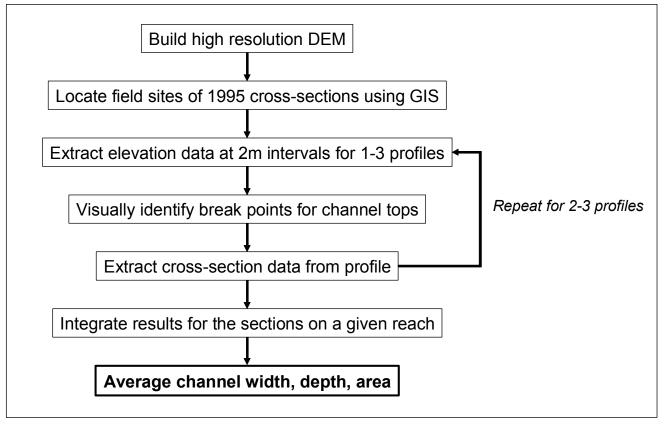

Figure 1. Generalized methodology for extracting channel dimensions using a combined GIS and graphical technique.

In order to capture the variability in channel morphology found within a given stream segment, multiple cross-section profiles were measured at each site. Channel morphologic features were extracted for each profile, and the results averaged to create a composite, or representative, cross-section. Figure 1 shows the generalized approach used to create the composite cross-sections.

Once the individual profiles were built as line features in the GIS they were intersected with the 2.5 m IFSAR DEM. Elevation points at 2 m intervals along the profiles were determined from the DEM. In this way, a three-dimensional representation of the profiles was built and these data were exported into a spreadsheet. A long-term goal of this ongoing research is to automate the determination of the channel banks for the purpose of isolating the exact channel width and depth. However, in this effort an interactive approach was taken to demonstrate the feasibility of using DEM data for channel morphologic investigations. Data exported from the GIS were imported into a spreadsheet and used to create cross-section profile in graphical format (Figure 2).

Field investigations typically rely on indicators such as slope breaks, changes in bed or bank materials, a shift in vegetative type, debris lines, and bank staining may be used to determine bankfull depth (Osterkamp et al. 1983, Gordon et al. 1992). Evidence indicative of a constructive, rather than destructive process is preferable in the determination of bank height; in the southwestern United States channel processes are governed by rapid and violent runoff events, and many of the channels on Walnut Gulch are actively degrading and therefore not in equilibrium.

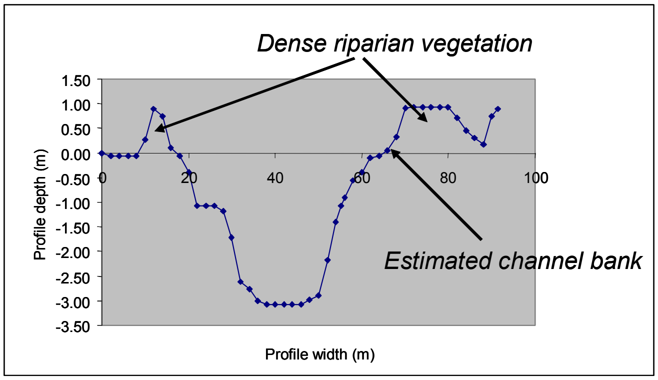

Figure 2. Example of channel profile extracted from DEM. In this example the channel bank is obscured by dense riparian vegetation that obscures the true elevation of the land surface.

A significant drawback to using a GIS is the inability to estimate whether a channel is stable or to accurately depict the correct location of a channel bank. In systems such as Walnut Gulch, where repeated incision has developed stream segments with multiple overbank deposits, bank height is often a subjective interpretation. Using a GIS increases the subjectivity in estimating bank location and introduces error. In the case of high frequency IFSAR such as was used in this experiment, dense vegetation often reflected the radar pulse and obscured the true ground elevation. Figure 2 illustrates this problem; in this case a relatively thick vegetative cover at the channel banks is present as an anomaly in the DEM surface. Because of these restrictions, an interactive technique was developed where the user manually interpreted the location of the channel banks.

Once the approximate location of the channel banks was determined, channel width was derived by simply locating the paired location of the opposite bank and determining the distance. Channel depth for a given profile was calculated by weighting the difference in elevation between each two-meter segment and the datum represented by the bankfull elevation. Cross-section area was calculated as a product of width and depth. Each stream section has between one and three profiles whose results were averaged to produce the composite estimated morphology values.

Results and Discussion

Composite cross-section results were compared to those collected by Miller et al. (1996). It should be noted that the techniques for creating composite values for width, depth, and area were identical for these two studies. In most cases the individual profile locations were located within a tolerance of +/- 5 m. However, there were sites where errors in the IFSAR DEM made it impossible to generate a valid cross-section profile. In these cases, the profile was moved slightly up- or downstream several meters. Comparisons between the channel properties show a high degree of correlation among all three measured values (Figure 3).

As hypothesized, channel width was most highly correlated with the field observations. IFSAR channel widths have a Pearson's correlation value to the field observations of 0.87, and the coefficient of determination produced from simple linear regression is 0.74. Channel width is also highly correlated (Pearson's correlation of 0.72), but the r^2 value resulting from regression analysis is 0.52. Given that cross-section area is a product of channel width and depth, the comparative results between the IFSAR and field data were in between the channel width and are observations (Pearson's value of 0.80, r^2 of 0.63).

A two-sample t-test was used to determine if the sample populations between the IFSAR and field observations were identical. Results for channel width revealed that the samples were the same, while those of channel depth and area were not. A closer inspection of Figure 3 underscores some relevant differences in the populations. Overall, IFSAR values for channel width underpredicted the observed data. This underprediction is apparent in the regression relationship detailed in Figure 3a, where the slope of the regression is 0.82 with an offset of 9.1. In contrast, the predicted IFSAR depths fall almost entirely below the 1:1 line, indicating a clear tendency for overprediction. In this case, the slope of the regression is similar to that of width (0.79), but the offset is -0.03 (Figure 3b). In both cases the regression slopes indicate a tendency to increase their predictions relative to the observed channel morphology at high values.

While the regression relationship for width was significantly better than for depth, the absolute error of the measurements was considerably greater. The average absolute error for channel width was 10.1m with a standard deviation of 7.8. The average absolute error for

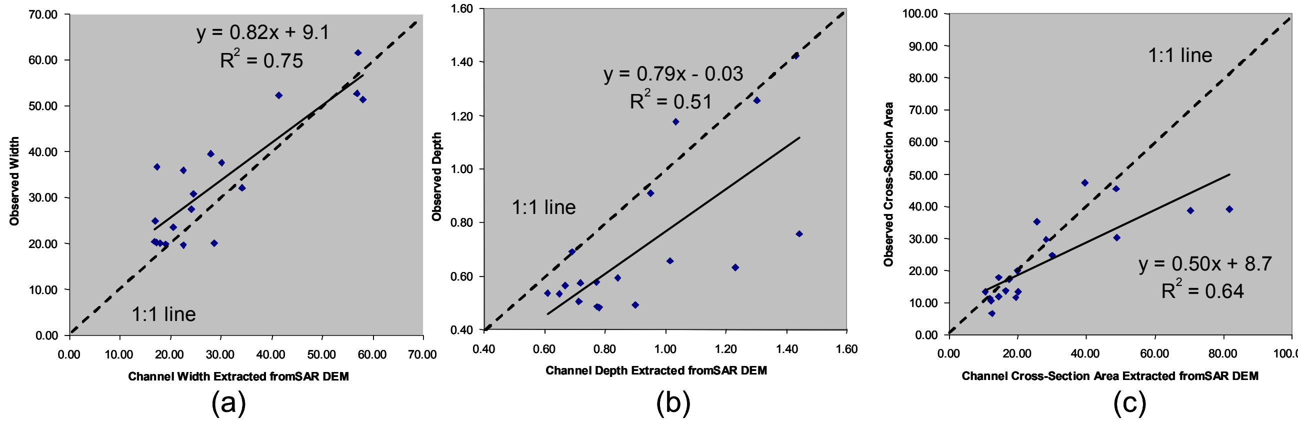

Figure 3. Comparisons of channel cross-section width (a), depth (b), and area (c) estimated from high resolution IFSAR DEM and field observations.

channel depth, on the other hand, was 0.18 with a standard deviation of 0.18. The channels of Walnut Gulch have a high width:depth ratio (53 in the case of these 20 samples) and are relatively rectangular. Thus, errors in channel width approximation do not greatly affect the estimate for channel depth. The average absolute percent errors for width and depth were relatively similar (0.29 and 0.26, respectively) with similar standard deviations (20.0 and 20.7, respectively).

Several difficulties were encountered in the extraction of cross-section data from the IFSAR DEM. The ability to discriminate small features is a function of the vertical and horizontal resolution of the terrain data, and in this project, the 2.5 m resolution of the data was an impediment to extracting fine landscape features. As noted earlier, the presence of small shrubs and dense riparian vegetation along the channel banks introduced error into the determination of the channel banks and possibly contributed to the errors in estimation. In some cases spurious elevation data were present in the DEM. These errors resolved themselves as anomalous sinks or spikes in the surface model. In such cases, the cross-section profile was slightly moved, but these anomalies are a serious impediment to the development of fully automated systems. The appropriate method for removing such spurious data is to average the raw 2.5 m data to produce a hydrologically correct 10 m DEM. This process obviously degrades the ability of the examiner to discriminate fine features in the landscape and would lead to greater errors in the estimation of channel morphology.

A time lag of approximately five years separated the field observations of Miller et al. (1996) and the IFSAR mission. Conceivably, some of the cross-sections investigated in this project could have undergone substantial change in their morphology. However, these changes are more likely to be reflected in the estimated channel depth. Miller et al. (1997) demonstrated that the effective return flow that contributes to channel forming processes on Walnut Gulch is 10 years. Thus, the likelihood of a channel-forming event having occurred on the field sites is relatively low. A review of the intervening years reveals an absence of large runoff events down the main stem of the watershed. Thus, while the time lag is unfortunate with respect to absolutely defining the differences between the two methods, it is unlikely that the basic channel morphologies observed by Miller et al. (1996) were significantly affected by runoff prior to the initiation of this investigation.

Whether in the field or using a GIS, extracting channel cross-section data is a somewhat subjective exercise, especially in ephemeral streams such as Walnut Gulch. The classic thalweg-bank-floodplain complex found on perennial streams is often absent in a sandy wash. Actively degrading channels may form no definitive bed or bank features to guide the observer in determining the appropriate bankfull depth. Field observations in such environments are relatively challenging, and the researcher must often utilize secondary information such as flood debris, soil properties, or vegetative characteristics. None of these tools is available to the researcher attempting to design a cross-section based on profiles extracted from a DEM. The user must rely on the presence of obvious landscape features; where none exist the prospect of determining an appropriate width or depth is futile. However, in the majority of cases, the channel form was clearly apparent in the graphical representation of the channel profiles. Thus, this approach shows promise for the future development of fully automated GIS-based techniques.

Conclusions

A quasi-automated approach for extracting channel morphologic properties from high resolution digital elevation models was developed. Results indicate that the extracted channel properties of width, depth, and cross-section area were highly correlated to field observations. While the absolute errors in channel width were greater than for depth, the percent errors for these measures were approximately the same. Statistical analyses showed that the populations of the field observations and IFSAR DEM-based estimates for channel width were the same.

While several obstacles remain in the development of a fully automated GIS-based routine for the estimation of channel morphology, these results are encouraging. Current research efforts are focused on developing an ArcMap tool that would represent a more streamlined approach and reduce user interaction. However, due to the high degree of subjectivity and the reliance on expert opinion in locating bankfull depth, it is expected that some degree of interaction will be required.

Field observations are generally preferable to secondary data extracted from terrain models. However, the high cost of pursuing detailed field work necessary for process-based hydrologic and geomorphic models makes a large-scale effort both difficult and time-consuming. It is anticipated that better terrain models with high vertical and horizontal resolution, such as LIDAR, will allow for a more detailed approach. The improvement in resolution and accuracy will potentially allow for the creation of a logical rule-based system for determining the channel banks based on some minimal user input. Process-based models are sensitive to the estimation of channel morphology, and the automated parameterization of channel properties would be of significant benefit to these lines of research.

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