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A watershed scale numerical model of the impact of land use change on bed material transport in suburban Maryland, USA

Mikolaj Lewicki,[1] James E. Pizzuto,[2] Glenn E. Moglen,[3] and Nicholas E. Allmendinger[4]

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[1] We predict changes in bed elevation and grain size composition caused by urbanization from 1952 to 1996 in the channel network of the Good Hope Tributary watershed. We developed methods for predicting the influence of urbanization on (1) the 1.5-year peak discharge, (2) the annual sediment supply to the network, and (3) sediment production caused by channel enlargement. The model was calibrated to reproduce bed material yield estimated from a sediment budget. Development caused channel width to increase by a factor of 1.7, and discharge, upland sediment supply, and bed material yield approximately doubled. The longitudinal profile became smoother, and the bed coarsened. After 1996, model boundary conditions were held constant and the simulation continued through 2042. The bed continued to coarsen, and the yield of bed material gradually declined. Sediment production did not approach a steady state value, suggesting that geomorphic recovery from urbanization may require more than 50 years.

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1. Introduction

[2] Decades of study have demonstrated that urban development profoundly influences river channels. Urbanization increases peak discharges [*Hollis*, 1975; *Beighley and Moglen*, 2002], causes channel widening, enlargement [*Hammer*, 1972, 1973; *Pizzuto et al.*, 2000], and incision [*Booth*, 1990], reduces pool depth and roughness [*Pizzuto et al.*, 2000], alters watershed sediment budgets [*Allmendinger et al.*, 2007; *Trimble*, 1997]. and it also causes many deleterious ecological effects [*Morley and Karr*, 2002; *Palmer et al.*, 2002].

[3] Despite the comprehensive and productive history of previous study, however, several important questions regarding the geomorphic effects of urbanization remain unanswered. For example, urban development is not spatially uniform, and different parts of a watershed will be affected by development at different times. The spatial patterning of resulting channel impacts can only be captured by a spatially explicit, watershed scale approach, but such methods remain poorly developed. Furthermore, the timescales of watershed disturbance associated with urbanization have also received little attention, how long does it take for a channel to adjust following urbanization, and what are the annual rates of change that characterize decades of channel evolution in urbanizing watersheds?

[4] In this paper, we assess how decades of watershed urbanization influence the composition and elevation of streambeds in a network of gravel-bedded river channels. In approaching this problem, we considered a wide variety of existing methods. Many studies describe ways to evaluate unsteady fluxes of bed material in rivers [*Cui and Parker*, 2005; *Lisle et al.*, 1997; *Nicholas et al.*, 1995; *Pickup et al.*, 1983, and many others], but few of these explicitly consider the branching structure of the drainage network. Network sediment routing models have been used to explain downstream trends in hydraulic geometry [*Pizzuto*, 1992] and grain size [*Gasparini et al.*, 1999; *Pizzuto*, 1995; *Sklar et al.*, 2006], but these methods assume a steady state condition that is inappropriate for evaluating the effects of land use changes. Probabilistic network routing schemes [*Benda and Dunne*, 1997; *Malmon et al.*, 2003], GIS-based reach-scale sediment budget analyses [*Wilkinson et al.*, 2006], and neural network methods [*Yitian and Gu*, 2003], though promising, do not appear to provide the detailed predictions of bed material composition that we desired. Landscape evolution models [*Coulthard et al.*, 2002, for example] could in principle provide the temporal and spatial resolution required, but specifying geomorphic and hydrologic processes across an entire urbanized landscape appeared problematic and unnecessarily complex, since our interest was primarily focused on the channels rather than on the entire watershed.

[5] On the basis of reports of preliminary success by others [i.e., *Cui et al.*, 2001], we developed an innovative, physically-based, one-dimensional sediment routing model for evaluating effects of urbanization on stream network geomorphic variables (i.e., bed elevation, bed grain size

[1]Rocky Mountain Research Station, USDA Forest Service, Boise, Idaho, USA.
[2]Department of Geology, University of Delaware, Newark, Delaware, USA.
[3]Department of Civil and Environmental Engineering, University of Maryland, College Park, Maryland, USA.
[4]Otak, Inc., Kirkland, Washington, USA.

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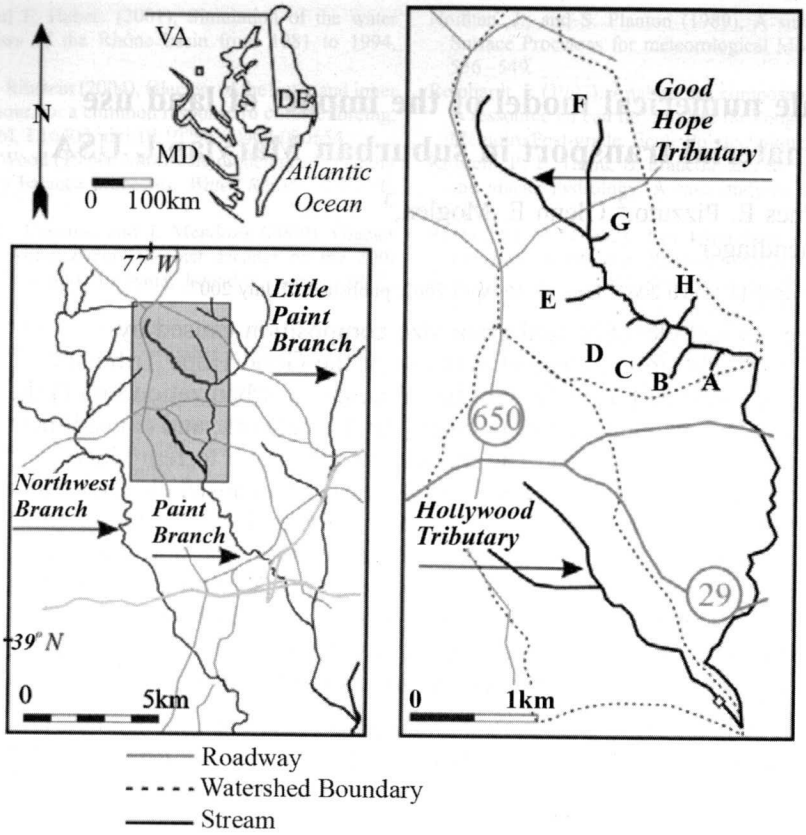

Figure 1. Location of the study area (adapted from the work of [*Allmendinger et al.*, 2007]).

distribution, and fractional bed material transport). The model is driven by annual changes in discharge and sediment supply caused by changes in land use. Sediment supply related to bank erosion is also included. Computations are performed on all tributaries, and sediment routing therefore explicitly reflects the branching structure of the channel network.

[6] After testing the model with experimental data, the model is used to evaluate the influence of urbanization between 1952 and 1996 on the channels in a small, second-order watershed in surburban Maryland, USA. Once these historical changes have been documented, the model is used to predict the evolution of the channel bed and bed material yield from the watershed through 2042. Our results emphasize (1) the remarkable stability of the longitudinal profile throughout the period of development, (2) the importance of bed coarsening as a primary response to development, and (3) the multidecadal timescale required to complete fluvial adjustments following watershed urbanization.

2. Study Area

[7] The Good Hope Tributary, a second-order stream in the Anacostia River watershed with a drainage basin area of 5.2 km^2, is located on the eastern edge of the Maryland Piedmont Geomorphic Province [*Maryland Geological Survey*, 1974] (Figure 1). The upland areas of the watershed are developed, while the hillslopes and valley bottoms are forested. The maximum relief of the watershed is about 60 m. Bedrock underlying the watershed consists of predominately Precambrian and lower Paleozoic metamorphic rocks [*Hunt*, 1973]. Field maps (J.E. Pizzuto, unpublished data, 1996) indicate that bedrock is exposed within the perimeter of the stream channel every few hundred meters, suggesting that bedrock is an important influence on alluvial processes in the watershed. The streambed has an average gradient of 1.33%, and the bed sediment consists mostly of gravel [*Lewicki*, 2005] (where "gravel" refers to particles larger than 2 mm in diameter, following the Udden Wentworth [*Boggs*, 2006] grain size scale). The banks consist predominantly of sandy mud with less than 10% gravel. The monthly mean temperature of the region ranges from −5°C in January to 32°C in July. The watershed receives an average of 106 cm of precipitation per year [*US Department of Commerce*, 1989].

[8] Several unusual sources of data made the Good Hope Tributary particularly attractive for our study. During the 1960s and early 1970s, the US Geological Survey monitored several watersheds close to the Good Hope Tributary, providing useful data on the influence of land use on sediment production in the region [*Yorke and Herb*, 1978]. In the mid-1990s, because a reproducing brown trout fishery was threatened by a proposed highway construction project, the watershed was the focus on an intensive environmental impact study, which provided cross sections, sediment data, and a professionally surveyed longitudinal profile of the entire main channel of the Good Hope Tributary. *Allmendinger* [1999, 2004] and *Allmendinger et al.* [2007] completed a sediment budget

analysis of the watershed, as well as providing additional cross sections and other data.

3. Methods

3.1. Overview

[9] A one-dimensional numerical model was developed to determine changes in bed elevation, bed grain size distribution, and fractional bed material transport rates. The model presented here is designed for gravel-bedded rivers, and bed load is the only sediment transport process considered by the model. The model is decoupled, meaning that parameters for flow (i.e., depth, velocity, shear stress, etc.) and channel bed characteristics (i.e., bed elevation, surface grain size distribution, etc.) are updated at each time step.

3.2. Bed Material Transport and Hydraulics

[10] The conservation of sediment mass is described using the Exner relations [*Exner*, 1925] for sediment mixtures. Sediment is classified separately in the following three layers: a subsurface layer, a surface layer, and a bed load layer. The grain size distribution of each layer is described by dividing the entire distribution into classes and by specifying the volumetric fraction of each grain size group. The one-dimensional Exner bed sediment continuity equation was decomposed into two components. The first equation predicts changes in bed elevation:

$$\frac{\partial \eta_b}{\partial t} + \frac{1}{1-\lambda_p}\frac{\partial q_T}{\partial x} = 0 \tag{1}$$

where η_b is the elevation of the bed, t is time, λ_p is the porosity of the bed, q_T is the volumetric sediment transport rate per unit width, and x is the downstream spatial coordinate.

[11] The second equation predicts the evolution of the grain size distribution of the surface layer [*Cui et al.*, 1996] [equations (2a) and (2b)]:

$$\frac{\partial}{\partial t}(L_a F_j) + \frac{1}{1-\lambda_p}\left(\frac{\partial}{\partial x}(q_T p_j) - f_{1j}\frac{\partial q_T}{\partial x}\right) = f_{1j}\frac{\partial L_a}{\partial t} \tag{2a}$$

$$\eta_b = \eta + L_a \tag{2b}$$

where η is the elevation of the boundary between the active layer and the substrate (referred to hereafter as the "interchange layer"), F_j is the fraction of size j in the active layer, p_j is the fraction of size j in the bed load layer, f_{1j} is the fraction of size j in the interchange layer, and L_a is the active layer thickness. Bed material transport rates in equations (1) and (2a) are computed using the surface-based bed load equation of *Wilcock and Crowe* [2003].

[12] In the case of bed degradation, grains from the substrate are directly incorporated into the interchange layer (for example, the active layer mines the substrate as the bed degrades) [*Hirano*, 1971]. This is represented in the model via equation (3), which specifies the grain size fraction of the interchange layer f_{1j} as a function of the grain size fraction of the substrate, f_{sj}:

$$f_{1j} = f_{sj} \tag{3}$$

In the case of bed aggradation, the exchange is from the active layer to the substrate. The active layer acts as a filter allowing transfer of bed load and surface material into the substrate. In this case, the substrate is slightly coarser than the bed load, while its grain size distribution is more similar to the bed load than to the surface layer. Flow resistance is characterized using equation (4) from the work of *Bray* [1979];

$$\frac{U}{u_*} = \left[1.36\left(\frac{H}{D_{50}}\right)^{0.281}\right] \tag{4}$$

where U is the mean flow velocity, u_* is the shear velocity defined as $(gHS)^{1/2}$, g is the acceleration of gravity, H is the flow depth, S is the slope of the energy grade line (approximated as the slope of the bed), and D_{50} is the median grain size. After introducing the expression for the discharge, $Q = UHW$ (where W is the channel width), and rearranging, equation (4) gives:

$$H = \left[\frac{Q}{W}\frac{D_{50}^{0.281}}{1.36\sqrt{gS}}\right]^{\frac{1}{1.781}} \tag{5}$$

3.3. Numerical Methods

[13] Equations (1) and (2a) were represented by simple forward explicit finite difference approximations. The network was discretized at a spatial interval of 20 m. A time step of 5 s was used to ensure computational stability. The finite difference equations included an external source term not represented by the continuous forms of equations (1) and (2a), these source terms represent sediment that could be added by tributaries or bank erosion to a particular cell at a particular time. The external source term provides the analytical vehicle required to explicitly include the network structure and other additional sediment sources (for example, bank erosion) into the model.

3.4. Testing the Bed Evolution Model

[14] The formulation of the model for predicting changes in grain size distribution and bed evolution was evaluated by reproducing results from a laboratory flume experiment [i.e., run 3 in the work of *Cui et al.*, 2003]. This run was part of a series of experiments designed to clarify the fate of sediment pulses in mountain rivers. The experiment was focused on the evolution of pulses with grain size distributions that differ from that of either the bed material or the bed.

[15] In order to reproduce the results of this experiment, the model was applied with constant channel width, constant water discharge and upstream sediment feed rate, and without sediment input from bank erosion.

3.5. Determining the Discharge in the Good Hope Tributary Watershed

[16] Although geomorphic changes in the watershed are actually driven by a wide spectrum of varying discharges, a constant 1.5-year return period peak discharge was selected for modeling purposes. Such an "index" discharge should adequately reflect the tendency of relatively frequent storm discharges to effectively shape the bed of the Good Hope Tributary watershed [*Hammer*, 1973]. It is important to understand, of course, that at any time, the 1.5-year discharge will increase with increasing drainage basin area,

and the 1.5-year peak discharge will also vary with time as the watershed is developed.

[17] There are no gaging stations available in the Good Hope watershed, and therefore the hydrologic modeling approach of *Beighley and Moglen* [2002] was used to estimate 1.5-year peak discharge values for the watershed for each year from 1952 to 1996. In the hydrological model, the Natural Resource Conservation Service (NRCS TR-55) graphical method was chosen [*Soil Conservation Service*, 1986]. The model requires input of elevation, land use, and hydrologic soils data along with precipitation depths for the return periods ranging from 1 month to 100 years. The hydrological model produces spatially explicit estimates of peak discharge at all channel locations within a watershed, not just at the watershed outlet [*Beighley and Moglen*, 2002]. Land use data required by the model were obtained for each year from the Property View database of the State of Maryland [*Maryland Department of Planning*, 2000]. Property View specifies the date of development for all parcels of property in the watershed, allowing us to determine the history of development of impervious surfaces through the period of our simulations. The predictions of the hydrologic model were provided at a spatial resolution of 30 m; these values were interpolated as necessary onto the computational grid of the channel network.

3.6. Determining Sediment Supply to the Upstream End of First-Order Channels

[18] The initial sediment supply to the upstream end of first-order channels was derived from *Yorke and Herb*'s [1978] measurements of sediment input from nearby watersheds in Montgomery County, Maryland. We also assumed that the initial profile before the start of the disturbance from construction was in a quasi-equilibrium state. To reflect this assumption, for the first year of the simulation (before development of the watershed), the initial sediment supply for the main channel and its tributaries was adjusted during model calibration so that the bed elevation of the first computational segment did not change (i.e., stream neither eroded nor aggraded during the first year of the simulation).

[19] After the first year of the simulation, sediment supply was increased whenever construction occurred in a subwatershed draining to any of the first-order channels. *Yorke and Herb* [1978] demonstrated that sediment yield in the region increases linearly with the fraction of construction in a watershed, so we simply increased sediment supply in proportion with the extent of construction in year (i.e., each 10% of the watershed area under construction triggers a 10% increase in the upland sediment supply above the initial value).

3.7. Sediment Supply From Channel Widening; Channel Width and Depth, 1952–1996

[20] *Allmendinger* [1999, 2004] and *Allmendinger et al.* [2007] demonstrate that sediment supply from channel enlargement provided an important component of the sediment budget from 1952 to 1996. To account for the sediment added through this process, the extent of channel enlargement was computed using a simple regression equation developed by *Allmendinger* [2004]:

$$CA = 4.800\ FI + 0.823\ DA \tag{6}$$

where CA is the channel area in units of square meters, DA is the drainage basin area, has units of square kilometers, and FI is the fraction of the watershed covered with impervious surfaces. Regression statistics and other details regarding equation (6) are provided by *Allmendinger et al.* [2007]. Because land use data are available for every year from 1952 to 1996, and because the drainage basin area is also known, equation (6) could be used to determine the channel area of each computational cell in the model for each year of the simulation. The sediment provided by channel enlargement for a given year could then be determined by the increase in channel area from the previous year multiplied by the streamwise length of each computational cell (20 m). *Allmendinger et al.* [2007] quote a range of channel enlargement ratios of 1.3 to 2.4 for the main channel with an average value of 1.7 for 1952–1996 (the enlargement ratio is defined as the channel area in 1996 divided by the channel area in 1952). According to *Allmendinger et al.* [2007], several tributaries have enlargement ratios greater than 2, while at least one tributary had no development at all (and therefore its area did not increase between 1952 and 1996).

[21] In addition to sediment supply by channel enlargement, the model also requires values of channel width and depth for each year between 1952 and 1996. *Allmendinger et al.* [2007] demonstrate that the ratio of width to depth remains approximately constant as channels enlarge during watershed development. This observation, when combined with field measurements in 1996 and equation (6), provides the basis to specify the channel width and depth for each computational cell from 1952 through 1996.

3.8. Initial Values for Predicted Variables

[22] The model requires initial values to be specified for the channel bed elevation and grain size distribution throughout the watershed at the beginning of the simulation in 1952 (methods for determining values of the boundary conditions for 1952, including the discharge, sediment supply, and channel width and depth, have been described above). Unfortunately, despite extensive field data for 1996 and ensuing years, channel surveys that could be used to determine initial values are unavailable. As a result, we estimated initial values as part of the calibration and model adjustment process described below.

3.9. Model Calibration and Approach

[23] The model is used in two separate ways (Figure 2). It is first applied to the historical period 1952–1996. During this period, changes in discharge, channel geometry, and land use are specified, but initial values for model variables of bed elevation and grain size distribution are unknown. The historical period provides an opportunity for model adjustment and calibration. The second application of the model involves a simulation of future condition through the year 2042, when model boundary conditions are held constant, but the channel bed continues to evolve.

[24] The following procedure was used to adjust the model during simulation of the historical period 1952–1996. First, the bed elevation and grain size distribution were considered "adjustable," in the sense that values in 1952 were varied until the model adequately reproduced field measurements in 1996. Second, the duration of modeling for each year was adjusted to reproduce the total volume of bed material produced by the watershed according to the sediment budget in the works of *Allmendinger* [1999, 2004] and *Allmendinger et al.* [2007].

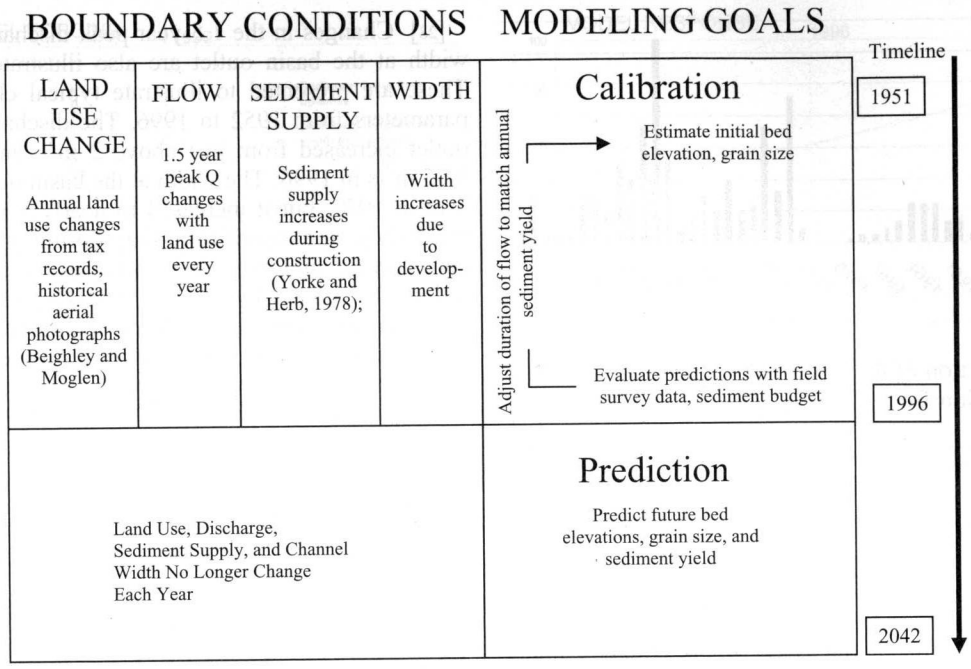

Figure 2. Illustration of model boundary conditions and modeling goals.

[25] Following the historical period 1952–1996, the watershed is treated as fully developed, and the simulation is continued until 2042 with constant discharge, sediment supply, and channel geometry. These computations were performed to better understand the timescales required for readjustment of the bed after decades of watershed surburban development.

4. Results

4.1. Evaluating Predictions of Bed Elevation and Composition

[26] The model successfully reproduces the predominantly dispersive deformation of the experimental pulse observed in the SAFL laboratory experiment used for testing predictions of bed elevation and bed composition (Figure 3). Except for the few initial minutes the maximum difference between the predicted and the measured bed elevation ranges from 0.018 to 0.008 m. The initial measured median grain size is between 4.46 and 5.17 mm. The error in the predicted bed elevation is usually less than 0.015 m. The observed values of grain size fractions are reasonably well represented in the model [*Lewicki*, 2005]. The maximum difference between the predicted and the measured median grain sizes is 0.07 mm at the beginning of simulation, 0.8 mm after 18 hours of simulation, and finally, the maximum difference in median grain sizes is 0.5 mm after 30 hours of simulation. Complete details of

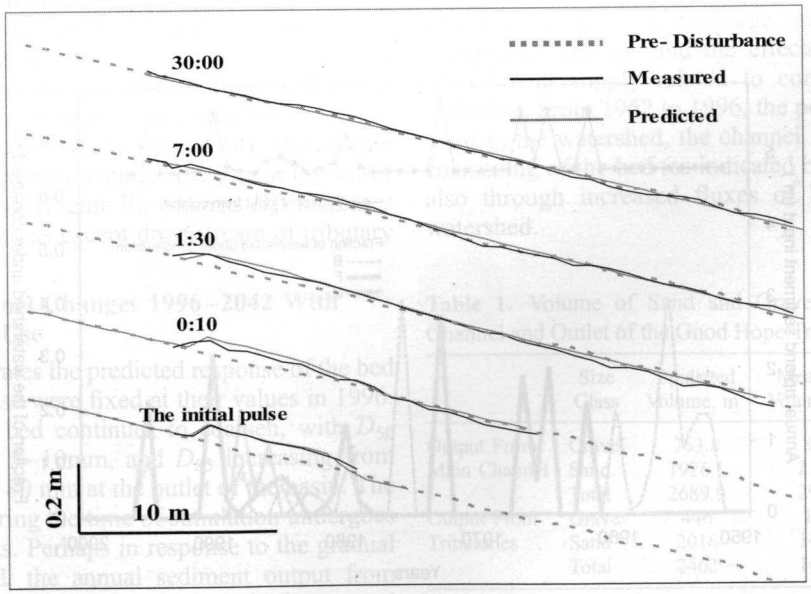

Figure 3. Longitudinal profiles of cross-sectionally averaged bed elevation for run 3 [from *Cui et al.*, 2003] and predicted bed elevation at various times. Times are in units of hours:minutes.

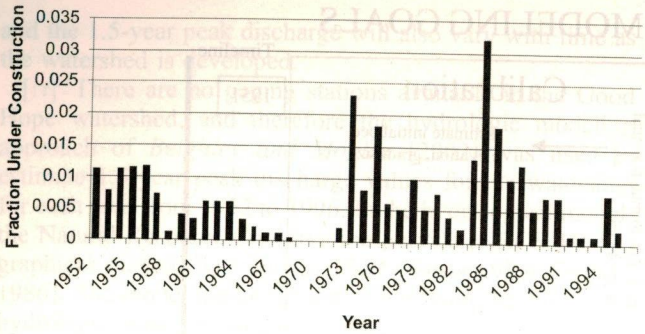

Figure 4. Fraction of the Good Hope Tributary watershed under construction from 1952 to 1996.

these model predictions are available from the work of *Lewicki* [2005].

4.2. Discharge, Upland Sediment Production, and Channel Widening, 1952–1996

[27] Annual changes in land use and model boundary conditions are illustrated in Figures 4, 5, and 6. Figure 4 illustrates the fraction of the Good Hope Tributary under construction for each year from 1952 to 1996. Figure 5 shows the history of construction activity for subwatersheds B, D, and F, and the annual sediment supply to subwatershed F. The upper panel of Figure 6 illustrates the total sediment supply from construction activity from all the tributaries. Development proceeded in a series of pulses starting in the early 1950s and continued episodically until 1996. Figures 4 and 6 suggest that there were approximately three primary pulses of development in the watershed, one spanning the 1950s and early 1960s, another in the late 1970s, and the final one in the mid to late 1980s. Each pulse of construction results in a corresponding pulse of sediment supply to the channel network (Figures 5 and 6). Because construction activity is not necessarily in phase throughout the watershed, sediment supply is spatially and temporally variable (Figure 5). The ability to explicitly capture this spatial and temporal variability is a strength of the current modeling approach.

[28] Changes in the 1.5-year peak discharge and channel width at the basin outlet are also illustrated in Figure 6. These are presented to illustrate typical changes in these parameters from 1952 to 1996. The discharge at the basin outlet increased from just above 2 m^3/s in 1952 to about 3.75 m^3/s in 1996. The width at the basin outlet was around 3 m in 1952, but it increased to nearly 5 m in 1996. It is interesting and significant that during years of intense construction and therefore increases in peak discharge, sediment supplied by channel widening in the watershed exceeded the contribution from upland soil erosion by a large margin (Figure 6a). Overall, however, the sediment produced by upland soil erosion and from channel enlargement was nearly equal from 1952 to 1996, according to *Allmendinger et al.* [2007].

4.3. Calibrating the Model to Sediment Budget Estimates

[29] Only 2 hours of peak discharge per year were required to accurately reproduce the total volume of sediment estimated by *Allmendinger et al.* [2007] for the Good Hope Tributary watershed from 1952 to 1996 (Table 1). After calibration, the predicted output of gravel and sand from the main channel were slightly underestimated by 6 and 10% respectively. The output of sand and gravel from the tributaries was overpredicted by 179 and 40%, respectively. It is important to realize that these errors are more precise than the sediment budget estimates themselves, which are subject to considerable uncertainty [*Allmendinger et al.*, 2007].

[30] According to the model, the annual sediment output increased significantly from 1952 to 1996 (Figure 6e). In 1952, watershed produced about 40 m^3 of bed material. By 1996, the annual production of bed material increased to more than 80 m^3/year.

4.4. Changes in Bed Elevation and Grain Size, 1952–1996

[31] Figure 7 indicates that predicted annual changes in bed elevation are relatively small (<0.1 m/yr). Comparison between predicted long profiles of the Good Hope Tributary

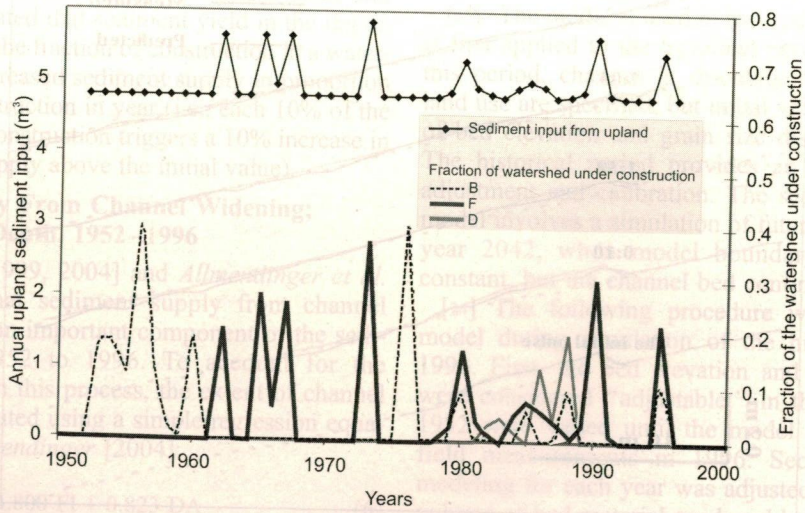

Figure 5. Fraction of subwatersheds B, D, and F under construction from 1952 to 1996. Annual upland sediment yield into subwatershed F is illustrated for reference.

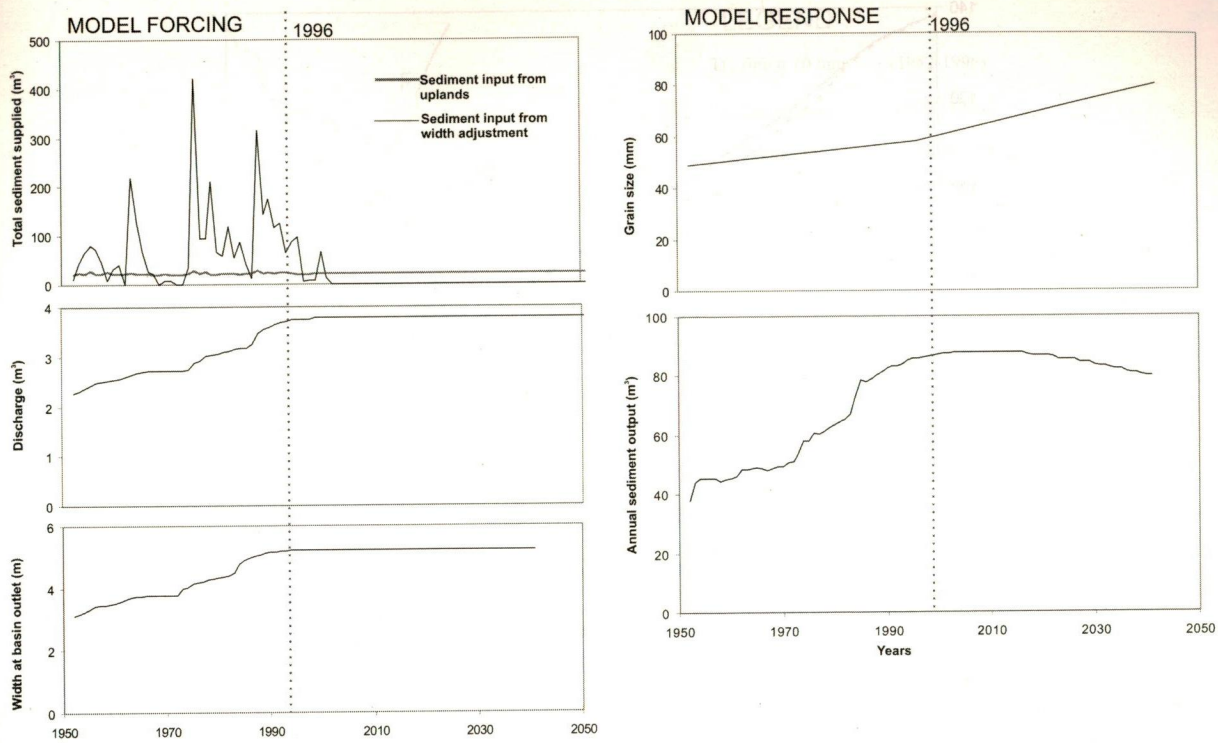

Figure 6. Variables that represent model forcing and response from 1952 through 2042. Values in 1996 are highlighted. (a) Total volume of sediment supplied from upland soil erosion and from channel widening; (b) Peak 1.5-year discharge at the outlet of the basin; (c) Channel width at the outlet of the basin; (d) 85th and 50th grain size; (e) Annual bed material output from the watershed.

and the field measurements indicates that the model tends to smooth the long profile. Topographic lows in the profile are aggraded especially in the upstream reaches (Figure 8) (located between 0 and 1800 m downstream from the beginning of the simulated long profile). Bumps in the initial profile of the bed are gradually eliminated. There is little change predicted in middle and downstream reaches, located downstream from the confluence with the tributary F, where the channel widens and decreases in gradient. In most reaches, the model predicts total changes in bed elevation of 0.3 m or less.

[32] The predicted grain size distributions indicate a general coarsening trend in the upstream and middle reaches of the Good Hope Tributary (Figures 9 and 10). The median grain size generally increases slightly (except for the lower reaches of the watershed) (Figure 9), whereas D_{85} increases significantly at all locations except downstream of tributary A (Figures 6 and 10).

4.5. Predicted Channel Changes 1996–2042 With Constant 1996 Land Use

[33] Figure 6d illustrates the predicted response of the bed after changes in land use were fixed at their values in 1996. The grain size of the bed continues to coarsen, with D_{50} increasing on average 5–10mm, and D_{85} increasing from about 55 mm to nearly 80 mm at the outlet of the basin. The longitudinal profile during the time of simulation undergoes only minor adjustments. Perhaps in response to the gradual coarsening of the bed, the annual sediment output from the watershed decreases from a peak of around 88 to around 78 m^3/year (Figure 6e). Interestingly, the annual output of sediment does not appear to be asymptotically approaching a constant value, suggesting that the bed is not close to reaching equilibrium conditions with the imposed discharge and ambient sediment supply from the watershed.

5. Discussion

5.1. Predicted Responses to Urban Development

[34] The results of our modeling study highlight the effects of increases in discharge caused by the creation of impervious surfaces and the effects of episodic increases in sediment supply related to construction and channel widening. From 1952 to 1996, the period of active development in the watershed, the channel responded primarily by coarsening of the bed (as indicated by increases in D_{85}) and also through increased fluxes of bed material from the watershed.

Table 1. Volume of Sand and Gravel Delivered to the Main Channel and Outlet of the Good Hope Tributary From 1952–1996[a]

	Size Class	Predicted Volume, m^3	Measured Volume, m^3	Error, m^3	Error, %
Output From Main Channel	Gravel	763.8	812	−48.2	−6
	Sand	1926.1	2183	−256.9	−12
	Total	2689.9	2995	−305.1	−10
Output From Tributaries	Gravel	446	160	286	179
	Sand	2016	1440	576	40
	Total	2462	1600	862	54

[a]Measured volumes are obtained from the Sediment Budget of the work of *Allmendinger* [2004]. The "error" is the difference between the volume computed by the model and the measured volume.

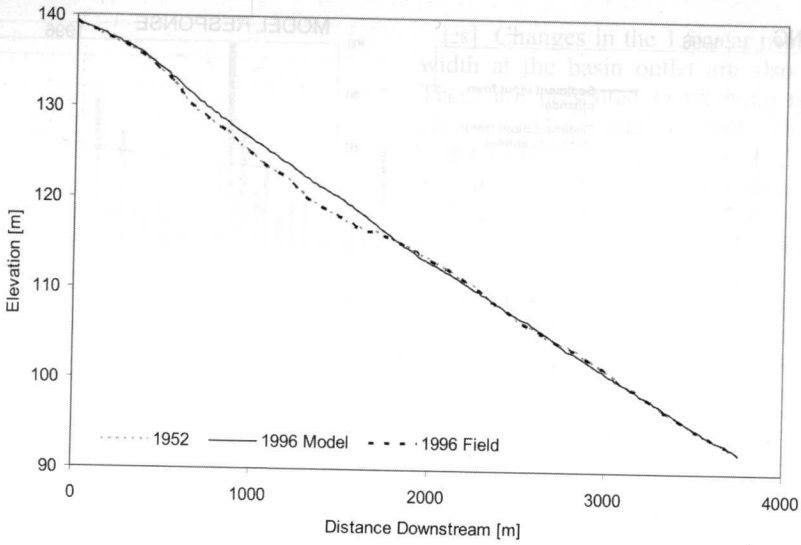

Figure 7. The longitudinal profile of the Good Hope Tributary in 1951 and 1996. Data for 1951 represent estimates required to reproduce detailed topographic surveys completed in 1996. The longitudinal profile during the time of simulation undergoes only minor adjustments.

[35] After our simulation of active development ends in 1996, we explored [following *Wolman*, 1967] a scenario where the discharge remains high, but sediment supply decreases because of the absence of construction. According to model predictions, the channel network responds by continued slow coarsening of the bed (Figure 6d). Because additional sources of sediment have been diminished, this results in a gradual reduction in sediment yield from the watershed. It is significant that this process continues for nearly 50 years without reaching a steady value of bed material yield, suggesting that the watershed response to urbanization may require more than half a century to be fully realized.

[36] Urban development is widely recognized as a profound perturbation to fluvial systems, yet the changes predicted by our model to the Good Hope Tributary are relatively modest. In other areas, extensive downcutting [*Booth*, 1990] and order-of-magnitude changes in sediment budgets [*Trimble*, 1997] have been documented in response to increases in discharge and decreases in sediment supply resulting from urban development. In the mid-Atlantic region, however, geomorphic changes imposed by urbanization, though widely recognized, are typically similar to those predicted by our numerical model and are characterized by increases in channel area [*Hammer*, 1972; *Pizzuto et al.*, 2000] and relatively modest changes in channel roughness, grain size, and planform geometry [*Allmendinger et al.*, 2007; *Pizzuto et al.*, 2000; *Nelson et al.*, 2006; *Skalak et al.*, 2007].

[37] At least two hypotheses can be offered to explain the relatively small changes in the bed characteristics and bed material transport regime of the Good Hope Tributary in response to urban development. First, it is possible that as the peak 1.5-year discharge increased, channel widening and other adjustments moderated potential increases in the shear stresses imposed on the flow, such that the increase in transport capacity relative to bed material supply could be accommodated by relatively modest coarsening of the bed, rather than by adjusting through wholesale bed degradation. Second, it is also possible that frequent bedrock exposures along the channel help to moderate the severity of fluvial responses to dramatic geomorphic changes. Bedrock exposures are common in the watershed and have been noted by others [i.e., *Costa*, 1975]. *Pizzuto et al.* [2007], in modeling bed response in a watershed adjacent to the Good Hope Tributary to land use and climate change, explicitly included bedrock as a component in the active layer of the gravel bed to allow riverbeds to absorb large imbalances in

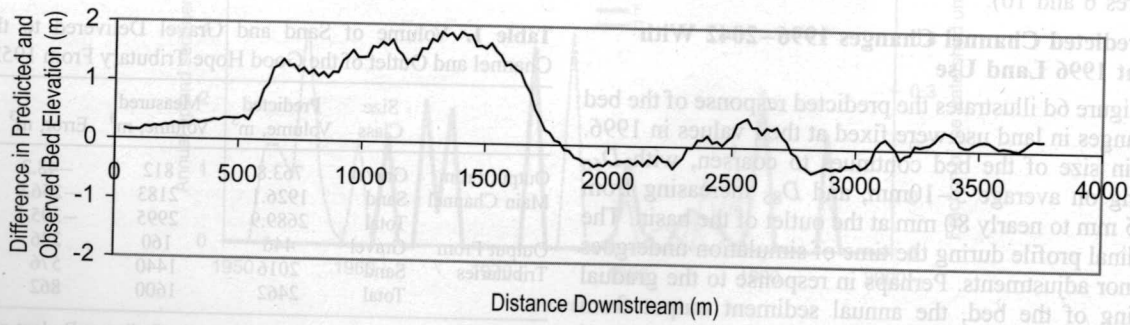

Figure 8. Difference between predicted and observed bed elevations of the main channel of the Good Hope Tributary for 1996.

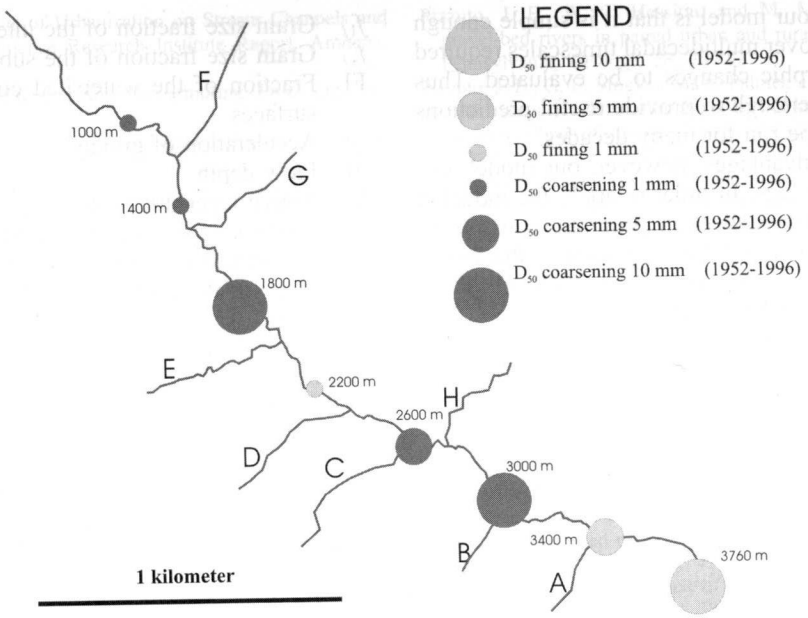

Figure 9. Summary of changes in the median grain diameter (D_{50}) between 1952 and 1996.

sediment supply and transport capacity without degradation. Thus, it is possible that in calibrating the model, we unwittingly adjusted parameters to reflect geologic control of fluvial processes in the watershed.

5.2. Strengths and Weaknesses of the Modeling Approach

[38] The model developed and tested during this study has a number of novel features. It explicitly accounts for spatial variations in watershed processes and geomorphic responses throughout an entire network of channels. This level of spatial detail has rarely been achieved with a sophisticated model of bed material transport processes. In our study area, the spatial component of geomorphic response does not appear to be particularly dramatic, but the success of this study suggests that spatially explicit modeling of a channel network should be considered where such modeling is likely to provide significant benefits.

[39] Our model also includes the most significant watershed scale geomorphic processes related to urban development, including changes in peak discharge, changes in sediment supply related to construction, and channel widening. This information has rarely been included in detailed modeling studies before and is only available to us because of intensive previous research [*Allmendinger et al.*, 2007; *Beighley and Moglen*, 2002; *Palmer et al.*, 2002; *Yorke and Herb*, 1978; *Wolman*, 1967; Pizzuto, unpublished data].

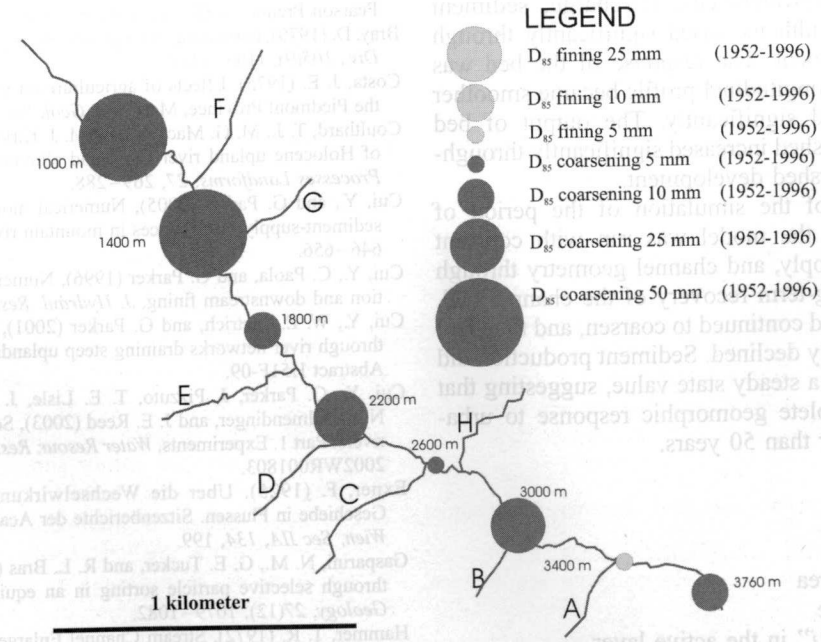

Figure 10. Summary of changes in the 85th percentile grain diameter (D_{85}) between 1952 and 1996.

Another advantage to our model is that it is simple enough to provide predictions over multidecadal timescales required for significant geomorphic changes to be evaluated. Thus the model is complex enough to provide useful predictions but simple enough to be run for many decades.

[40] Despite these advantages, however, our model also has important shortcomings. In order to apply the model, a very extensive field data collection program is essential. The long timescale of geomorphic responses in the watershed virtually guarantees, however, that some initial or boundary conditions will be undetermined by direct field measurements, leading to uncertainty in model calibration and application. Furthermore, even though the model is very comprehensive, it does neglect some significant geomorphic processes. For example, *Allmendinger et al.* [2007] conclude that floodplain storage is a significant component of the sediment budget of the Good Hope Tributary, but this process has been neglected in our study.

6. Conclusions

[41] We have presented a numerical model that predicts changes in bed elevation and grain size composition in a complete network of river channels. The bed material transport algorithm was tested using data from a flume experiment, and the model was then used to predict geomorphic response to urban development in a small watershed in suburban Maryland. The field application required developing methods for predicting sediment supply and the 1.5-year peak discharge because of urbanization, as well as sediment production caused by channel enlargement. The model was calibrated to reproduce bed material yield estimated from a sediment budget. Where necessary, initial values of model variables were adjusted to provide good agreement between model predictions and field observations made in 1996.

[42] The model provides a detailed illustration of the spatial and temporal geomorphic responses to urbanization. Development occurred in a series of pulses that vary in timing in different subwatersheds. Discharge, sediment supply, and channel width increased significantly through the period of development. The response of the bed was relatively modest; the longitudinal profile became smoother and the bed coarsened significantly. The output of bed material from the watershed increased significantly throughout the period of watershed development.

[43] After the end of the simulation of the period of development in 1996, the model was run with constant discharge, sediment supply, and channel geometry through 2042 to assess the long-term recovery of the channel bed. During this time, the bed continued to coarsen, and the yield of bed material gradually declined. Sediment production did not appear to approach a steady state value, suggesting that the timescale for complete geomorphic response to urbanization may be greater than 50 years.

Notation

CA Channel area
DA Drainage basin area
D_{50} Median grain size
F_j Fraction of size "j" in the active layer
f_{Ij} Fraction of size "j" in the interchange layer
f_{Ij} Grain size fraction of the interchange layer
f_{sj} Grain size fraction of the substrate
FI Fraction of the watershed covered with impervious surfaces
g Acceleration of gravity
H Flow depth
L_a Active layer thickness
p_j Fraction of size "j" in the bed load layer
q_T Volumetric sediment transport rate per unit width
S Slope of the energy grade line
t Time
U Mean flow velocity
u_* Shear velocity
W Channel width
x Downstream spatial coordinate.
η_b Elevation of the bed
η Elevation of the interchange layer
λ_p Porosity of the bed

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N. E. Allmendinger, Otak, Inc., 10230 NE Points Dr. Suite 400, Kirkland, WA 98033, USA. (nicholas.allmendinger@otak.com)

M. Lewicki, Rocky Mountain Research Station, USDA Forest Service, 316 E. Myrtle St., Boise, ID 83702, USA. (mlewicki@fs.fed.us)

G. E. Moglen, Department of Civil and Environmental Engineering, University of Maryland, College Park, MD 20742, USA. (moglen@umd.edu)

J. E. Pizzuto, Department of Geology, University of Delaware, Newark, DE 19716, USA. (pizzuto@udel.edu)