INTERACTION BETWEEN SEDIMENT TRANSPORT AND FLOOD FLOW: 
THE CASE OF KOMPSATOS RIVER BASIN, GREECE

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EXTENDED ABSTRACT

For the flood event of November 1996 (27-30 Nov., total rainfall depth 264.5 mm), the hydrograph and the corresponding sediment graph at the outlet of the mountainous part of Kompsatos River basin (Thrace, northeastern Greece) were computed.

The mountainous part of Kompsatos River basin has an area of about 567 km\(^2\), consisting mainly of forest and bush. For more precise calculations, the basin was divided into 18 natural sub-basins. Kompsatos River has a length of about 65 km, from which 9 km flow through the flat part of the basin, and discharges its water into Vistonis Lake.

The computation of the hydrograph was enabled by means of the following models included in the well-known hydrologic software HEC-HMS: (a) Soil Conservation Service (SCS) – Curve Number, (b) synthetic dimensionless unit hydrograph of SCS, (c) hydrograph routing model Muskingum-Cunge. The computation of the sediment graph was enabled by combination of the above composite hydrologic model with the soil erosion model of Schmidt (1992) and the stream sediment transport model of Yang and Stall (1976).

The flood hydrograph and sediment graph computed for the outlet of the mountainous part of Kompsatos River basin were routed in the flat part of the basin by means of the well-known hydraulic software HEC-RAS, for quasi-unsteady flow. The computational process is based on the Manning equation for the computation of energy slope, on the energy conservation equation for the computation of the flood depth, and on the sediment continuity equation, in combination with Yang equation, for the computation of the geomorphological bed evolution.

From the computational results of HEC-RAS application, the water surface profile, the stream bed profile and the bed variation in the cross-sections of the flat part of Kompsatos River during the flood event can be visualised.

Keywords: basin, flood, hydrograph, HEC-HMS, soil erosion, sediment transport, sediment graph, HEC-RAS, Kompsatos River.

1. INTRODUCTION

In the past, hydrologic models included in the well-known software HEC-HMS (Technical Reference Manual, 2000) were applied to basins located near the city of Xanthi (Thrace, northeastern Greece). For example, a composite hydrologic model consisting of three models (Soil Conservation Service (SCS) model for the computation of rainfall excess, kinematic wave model for the transformation of rainfall excess to direct runoff hydrograph, Muskingum-Cunge model for the routing of the hydrograph through the main stream of
the basin) was applied to Kimmeria Torrent basin, with an area of about 35 km$^2$, for a rainfall event in June 2004 (Ziogas et al., 2006). A similar composite hydrologic model consisting of three models (SCS model for the computation of rainfall excess, SCS model for the transformation of rainfall excess to direct runoff hydrograph, Muskingum-Cunge model for the routing of the hydrographs from the outlets of the sub-basins to the outlet of the whole basin) was applied to Kosynthos River basin, with an area of about 237 km$^2$, for three rainfall events in June 2006 (Charalabidis et al., 2009). The comparison result between computed and measured stream discharges was very satisfactory for both basins. The hydrologic model described in Charalabidis et al. (2009) was also applied to Kosynthos River basin in order to calculate the flood hydrograph of November 1996 at the basin outlet. In this case, a direct comparison between computed and measured flood discharges was impossible because of lack of flood discharge measurements (Hrissanthou and Theodorakopoulos, 2005).

The hydrologic model described in Charalabidis et al. (2009) was combined with the soil erosion model of Poesen (1985) and the stream sediment transport model of Yang and Stall (1976) in order to calculate the sediment graph corresponding to the flood hydrograph of November 1996, at the outlet of Kosynthos River basin (Hrissanthou and Theodorakopoulos, 2005).

In the present case of Kompatsatos River basin with an area of about 567 km$^2$, located between the cities of Xanthi and Komotini, the hydrologic model mentioned above is combined with the soil erosion model of Schmidt (1992) and the stream sediment transport model of Yang and Stall (1976) in order to calculate the hydrograph and the sediment graph, due to the flood event of November 1996, at the outlet of the mountainous part of the basin. Additionally, in contrast to the studies given above, the water surface profile and the geomorphological stream bed evolution during the flood event are computed for the flat part of Kompatsatos River by means of the well-known software HEC-RAS (Hydraulic Reference Manual, 2010).

2. HYDROLOGIC MODEL

2.1. Rainfall excess model

According to Soil Conservation Service (SCS, 1972) method, the rainfall excess is computed by:

$$h_R = \frac{(h_r - 0.2S)^2}{h_r + 0.8S}$$  \hspace{1cm} (2.1)

where $h_R$ (mm) is the rainfall excess, $h_r$ (mm) is the rainfall depth and $S$ (mm) are the maximum hydrologic losses (mm), which are computed by the equation:

$$S = \frac{25400}{CN} - 254$$  \hspace{1cm} (2.2)

where $CN$ is the curve number which can be estimated as a function of land use, hydrologic soil type and antecedent moisture conditions, by using tables published by the SCS.

2.2. Model for the transformation of rainfall excess to runoff hydrograph

The hydrograph of direct runoff is computed on the basis of the unit hydrograph theory. In the dimensionless synthetic unit hydrograph of SCS, discharges are expressed as a
portion of the peak discharge \( q_p \) and time steps as a portion of the rise time of the unit hydrograph, \( T_p \).

The values of \( q_p \) and \( T_p \) are estimated by a simplified triangular unit hydrograph, where the recession time is equal to 1.67 \( T_p \). The area which is surrounded by the curve of the unit hydrograph must be equal to the rainfall excess of 1 cm. The peak discharge \( q_p \) (m\(^3\) s\(^{-1}\)) is

\[
q_p = \frac{CA}{T_p}
\]  

(2.3)

where \( C = 2.08 \), \( A \) (km\(^2\)) is the sub-basin area and \( T_p \) (hr) is the rise time of unit hydrograph, which is given by

\[
T_p = \frac{t_R}{2} + t_p
\]  

(2.4)

where \( t_R \) (hr) is the duration of the rainfall excess and \( t_p \) (hr) is the lag time of the basin, which is approximately equal to 0.60 \( t_C \), where \( t_C \) (hr) is the concentration time.

### 2.3. Routing model of Muskingum-Cunge

The routing of the direct runoff hydrograph from the outlet of a sub-basin to the outlet of the whole basin is enabled by means of Muskingum-Cunge model. The basic equation of the model is given below:

\[
Q^ {k+1} = C_0 Q^k + C_1 Q^k + C_2 Q^ {k+1}
\]  

(2.5)

where \( Q \) (m\(^3\) s\(^{-1}\)) is the direct runoff discharge, \( i \) designates the space step \( \Delta x \) and \( k \) designates the time step \( \Delta t \). The coefficients \( C_0 \), \( C_1 \) and \( C_2 \) are defined as follows:

\[
C_0 = \frac{c\lambda - 2x}{2(1-x) + c\lambda} \quad C_1 = \frac{c\lambda + 2x}{2(1-x) + c\lambda} \quad C_2 = \frac{2(1-x) - c\lambda}{2(1-x) + c\lambda} \quad \lambda = \frac{\Delta t}{\Delta x}
\]  

(2.6)

The product \( c\lambda = c(\Delta t / \Delta x) \) is called the Courant number and is equal to the ratio of the celerity of small waves \( c \) to the grid celerity \( \Delta x / \Delta t \).

The parameter \( x \) is obtained by the relationship:

\[
x = \frac{1}{2} \left( 1 - \frac{q_o}{S_f c\Delta x} \right)
\]  

(2.7)

where \( S_f \) is the energy slope and \( q_o \) is the reference discharge per unit width (from the inlet hydrograph).

### 3. SOIL EROSION MODEL

According to Schmidt (1992), the erosive impact of droplets and overland flow is proportional to the momentum flux contained in the droplets and the flow, respectively. The momentum flux exerted by the falling droplets, \( \phi_r \) (kg m s\(^{-2}\)), is given by the relationship (Schmidt, 1992; Hrissanthou, 2006):
\[ \varphi_r = C r \rho A r \sin a \]  

(3.1)

where \( C \) is the soil cover factor, \( r \) (m s\(^{-1}\)) is the rainfall intensity, \( \rho \) (kg m\(^{-3}\)) is the water density, \( A \) (m\(^2\)) is the basin area, \( u_r \) (m s\(^{-1}\)) is the mean fall velocity of the droplets and \( a \) (\(^\circ\)) is the mean slope gradient of the sub-basin area.

The momentum flux exerted by the overland flow, \( \varphi_f \) (kg m s\(^{-2}\)), is given by

\[ \varphi_f = q \rho b u \]  

(3.2)

where \( q \) (m\(^3\) s\(^{-1}\) m\(^{-1}\)) is the runoff rate per unit width, \( b \) (m) is the width of the sub-basin area and \( u \) (m s\(^{-1}\)) is the mean flow velocity.

The sediment supply to the main stream of a sub-basin is estimated by means of a comparison between the available sediment in the corresponding sub-basin area and the sediment transport capacity by overland flow (Hrissanthou, 2006).

The sediment transport capacity by overland flow, \( q_t \) (kg s\(^{-1}\) m\(^{-1}\)), is computed by (Schmidt, 1992):

\[ q_t = c_{\text{max}} \rho_s q \]  

(3.3)

where \( c_{\text{max}} \) (m\(^3\) m\(^{-3}\)) is the concentration of suspended particles at transport capacity and \( \rho_s \) (kg m\(^{-3}\)) is the sediment density.

4. STREAM SEDIMENT TRANSPORT MODEL

The sediment yield at the outlet of the main stream of a sub-basin can be estimated by means of a comparison between the available sediment in the main stream and the sediment transport capacity by streamflow (Hrissanthou, 2006).

For the computation of the sediment transport capacity by streamflow, the following relationships are used (Yang and Stall, 1976):

\[
\log c_t = 5.435 - 0.286 \log \frac{w D_{50}}{v} - 0.457 \log \frac{u_s}{w} + (1.799 - 0.409 \log \frac{w D_{50}}{v} - 0.314 \log \frac{u_s}{w}) \log \left( \frac{u_s}{w} - \frac{u_{cr} s}{w} \right) 
\]

(4.1)

\[
\frac{u_{cr}}{w} = \frac{2.5}{\log \left( u_s D_{50} / v \right) - 0.06}, \ \text{if} \ 1.2 < u_s D_{50} / v < 70
\]

(4.2)

\[
\frac{u_{cr}}{w} = 2.05, \ \text{if} \ u_s D_{50} / v \geq 70
\]

(4.3)

where \( c_t \) (ppm) is the total sediment concentration by weight, \( w \) (m s\(^{-1}\)) is the terminal fall velocity of suspended particles, \( D_{50} \) (m) is the median particle diameter, \( v \) (m\(^2\) s\(^{-1}\)) is the kinematic viscosity of the water, \( u_s \) (m s\(^{-1}\)) is the shear velocity, \( u \) (m s\(^{-1}\)) is the mean flow velocity, \( u_{cr} \) (m s\(^{-1}\)) is the critical mean flow velocity and \( s \) is the energy slope.

5. FLOOD AND SEDIMENT ROUTING MODEL

The flood hydrograph and the corresponding sediment graph at the outlet of the mountainous part of a basin, computed by the models described above, can be routed through the flat part of the basin with the aid of the energy conservation equation and the sediment continuity equation, which is expressed as follows (HEC-RAS, Hydraulic Reference Manual, 2010):
\[(1 - \lambda_p) b \frac{\partial \eta}{\partial t} = -\frac{\partial Q_s}{\partial x} \quad (5.1)\]

where \(\lambda_p\) is the active layer porosity, \(b\) (m) is the channel width, \(\eta\) (m) is the channel bed elevation, \(Q_s\) (m\(^3\) s\(^{-1}\)) is the transported sediment load, \(x\) (m) is the distance and \(t\) (s) is the time.

For the computation of \(Q_s\), Equations (4.1), (4.2) and (4.3) are used.

6. APPLICATION TO KOMPSATOS RIVER BASIN

6.1. The case study area

The mountainous part of Kompsatos River basin has an area of about 567 km\(^2\) consisting of forest (37.3%), bush (36.1%), cultivated land (26.1%) and urban area (0.5%). The highest altitude of the basin is about 1200 m. The length of the main stream of the basin is about 65 km, from which 9 km flow through the flat part of the basin to Vistonis Lake. For more precise calculations, the mountainous part of the basin was divided into 18 natural sub-basins (area: between 13 and 50 km\(^2\)) (Figure 1; Hrissanthou et al., 2010).

![Figure 1. Kompsatos River basin – Sub-basins with main streams.](image)

6.2. Analysis of the results

The extreme rainfall in the time period from 27 November 1996 to 30 November 1996 has a total depth of 264.5 mm, registered at the meteorological station of Genisea (Koutsoyiannis, 2012). However, the daily rainfall depth from the above time period is distributed over the day considered. Figure 2 shows the flood hydrograph and the corresponding sediment graph at the outlet of the mountainous part of Kompsatos River basin, computed by means of the hydrological model described in Section 2 for the extreme rainfall of November 1996, and the soil erosion model and the stream sediment transport model described in Sections 3 and 4, respectively.
It is clear from Figure 2 that the peak of the flood hydrograph follows temporally the peak of the corresponding sediment graph, which was also observed in other hydrometric stations (Maniak, 1988).

From Figure 2, by computing the area between the sediment graph curve and the x-axis, results that the sediment transported during the flood considered amounts to about 61000 t. It seems to be a reasonable arithmetic result, if it is taken into account that the mean annual sediment yield, for the years 1966-1992, equals about 447000 t (Hrissanthou et al., 2010).

Figure 3 shows a three-dimensional graphical representation of the flat part of Kompsatos River, where the road bridge (upstream) and the railway bridge (downstream) can be seen.

The routing of the flood hydrograph and the corresponding sediment graph (Figure 2) through the flat part of Kompsatos River was enabled by applying the energy conservation equation in combination with the sediment continuity equation (5.1) for quasi-unsteady flow (HEC-RAS, Hydraulic Reference Manual, 2010).

Figure 4 illustrates the maximum water level along the flat part of Kompsatos River during the flood event, ten hours after the rainfall start, on 30 November 1996, as well as the
corresponding river bed profile. In this figure, the site of the road bridge (upstream) and the railway bridge (downstream) can be seen. Additionally, the local scour downstream of the railway bridge can be seen. The bridge piers cause a reduction of the wetted area of the river cross-section, which again implies a local velocity increase and the scouring.

According to Figure 4, the flow depth is higher in the cross-sections upstream of the road bridge, near the basin outlet, than in the downstream cross-sections near the Vistonis Lake, which is due to the fact that the downstream cross-sections are wider than the upstream cross-sections. Additionally, a rise of water surface profile upstream of the railway bridge is observed due to the damming effect of the railway bridge piers.

Figure 5 illustrates the bed variation (erosion) in the cross-section 6 (Figure 4), downstream of the railway bridge, at the beginning and the end of the simulation process. The bed erosion depth is not considerable because the cross-section considered lies near Vistonis Lake, in the flattest part of Kompsatos River, where the deposition of sediment dominates under usual rainfall conditions.

![Figure 4. Maximum water level of Kompsatos River during the flood event.](image1)

![Figure 5. Bed variation in cross-section 6, downstream of the road bridge, during the flood event.](image2)
7. SUMMARY AND CONCLUSIONS

In the case study of Kompsatos River basin (Thrace, northeastern Greece), the hydrologic software HEC-HMS was combined with the hydraulic software HEC-RAS in order to compute the flood hydrograph, due to the extreme rainfall event of November 1996 (27-30 Nov., total rainfall depth 264.5 mm), at the outlet of the mountainous part of the basin considered, and to route the flood hydrograph through the flat part of Kompsatos River.

The combination of the hydrologic model (HEC-HMS) with a soil erosion model (Schmidt) and a stream sediment transport model (Yang and Stall) enables the transition of the hydrograph, resulting from the extreme rainfall, to the corresponding sediment graph at the outlet of the mountainous part of the basin. The routing of the hydrograph and the corresponding sediment graph through the flat part of the main stream of the basin is enabled simultaneously (HEC-RAS), so that the flood depth and the geomorphological bed evolution along the main stream can be computed.

The practical merit of the hydrologic and hydraulic computations, especially for flood events, is the possibility of planning flood protection measures both in the mountainous part and the flat part of a river.

REFERENCES