ASSESSING DESIGN FLOOD IN URBAN AREA USING A DISTRIBUTED HYDROLOGICAL MODEL

G. Ravazzani[1], M. Mancini[2], P. Gianoli[3], S. Meucci[4] & M. Ghilardi[5]

(1) Dipartimento di Ingegneria Idraulica, Ambientale, Infrastrutture Viarie, Rilevamento, Politecnico di Milano, Italia, e-mail: giovanni.ravazzani@polimi.it
(2) Dipartimento di Ingegneria Idraulica, Ambientale, Infrastrutture Viarie, Rilevamento, Politecnico di Milano, Italia, e-mail: marco.mancini@polimi.it
(3) Dipartimento di Ingegneria Idraulica, Ambientale, Infrastrutture Viarie, Rilevamento, Politecnico di Milano, Italia, e-mail: paride.gianoli@mail.polimi.it
(4) Modellistica e Monitoraggio Idrologico S.r.l., Italia, e-mail: stefania.meucci@mmidro.it
(5) Dipartimento di Ingegneria Idraulica, Ambientale, Infrastrutture Viarie, Rilevamento, Politecnico di Milano, Italia, e-mail: matteo.ghilardi@mail.polimi.it

ABSTRACT

A method for indirect estimation of design flood in poorly gauged urbanized river basins is presented. It is based on the critical flood design criterion that maximizes peak flow for a given return period by transforming precipitation of depth duration frequency curve into runoff. In order to keep into account the variegated land cover of urbanized river basins, a spatially distributed hydrological model is employed. The paper shows that indirect method provides design discharges significantly greater respect to direct method when discharge measurements are strongly affected by upstream river overflows like in highly urbanized area. Indirect method, in addition to direct method, provides design hydrograph that is useful for those cases where design discharge only is not sufficient for designing or planning purposes.

1 INTRODUCTION

A number of approaches are possible for estimating design floods (*Bocchiola et al.*, 2003). In cases where long records of measured streamflow data are available, a direct statistical analysis of the data may be feasible. However, the streamflow data series are often too short to perform robust statistical inference. In many circumstances no measured streamflow data are available at the site of interest. Moreover, in urban area, when natural development of the watercourse is significantly altered by anthropic constraints such as bridges, detention ponds, and levees, design flood estimates may result significantly lower than natural discharge, with dangerous impact on downstream sections in case of further modifications of upstream river.

Under such conditions the design flood can be assessed from rainfall-runoff transformation, under the assumptions that the Depth Duration Frequency (DDF) curve characterizes the rainfall regime and assuming the critical flood design criterion. According to this, the design hydrograph is the one that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a drainage area (*Ravazzani et al.*, 2009).

The most diffused approach to hydrological modelling, mainly due to the complexity of the different phenomena involved, has been the lumped conceptual one. In lumped models the whole catchment is considered as a single entity, spatial variations are averaged and basin response is evaluated only at the outlet. Starting from the first studies by *Freeze and Harlan* (1969), research activities focused on the importance of the time-space variability either of the soil characteristics and of the rainfall field combined with the processes governing catchment response to precipitation (*Rosso*, 1994). Thus distributed hydrological models have become very common in research activities for their capability to describe spatial variability of processes, input, boundary conditions, watershed characteristics and output, but they are still not widely diffused in the engineering practice.

This paper presents the application of a distributed hydrological model for the assessment of design flood of Olona river basin, a small watershed in Italy. The significant heterogeneity of river Olona basin is enhanced by the presence of a mixture of forest, natural landscapes, and highly urbanized areas that, despite small extent of the basin, require use of a spatially distributed hydrological model.

2 THE CASE STUDY

The proposed approach has been tested on the case of river Olona, the main stream of a group of water courses in the north of Milan, Italy, most of which flow through built-up areas causing damage to the population especially during the rainy seasons. The Olona is a 71 km long river, which runs mainly through the provinces of Varese and Milan. After passing through the deep Olona Valley, cut in the porous soils of the upper Po Valley, the Olona river flows in the plain until Milan, usually contained in narrow artificial banks.

The area at the considered closing section (Lozza) is 94.5 km^2 (Figure 1). Its elevation ranges from 271 m a.s.l. at the outlet to approximately 1070 m a.s.l. at the Tre Croci crest. The average elevation is 455 m a.s.l.. Land cover is heterogeneous including broadleaf forest (38%), mixed forest (16%), agricultural (20%), and urban (26%).

Climate conditions are typically humid, characterized by higher precipitations in autumn and spring and lower in winter. The total annual precipitation is about 1600 mm.

Olona river experienced significant floods since 1584, year of the first reported event, with an increase of flood frequency in recent years (5 major floods in last twenty years).

Meteorological and hydrologic hourly data were collected by the telemetric monitoring system of Regione Lombardia. Data of four rain gauges were available from 1 January 2003 to 31 December 2010. River discharge measurements at Lozza (basin outlet) were available from 1 January 2002 to 31 December 2010. The locations of the rain gauges and Lozza hydrometric station are shown in Figure 1.

Depth duration frequency curves parameters were obtained from Regional Environmental Protection Agency of Lombardia (ARPA Lombardia). They were computed by fitting General Extreme Value (GEV) probability distribution function to annual maxima of 1- to 24-hours precipitation amounts, using scale invariance concept (*Burlando and Rosso*, 1996). GEV parameters for ungauged sites were obtained by spatial interpolation using kriging method with isotropic spherical variogram. Precipitation depth, $h_T(d)$ (mm), for a given return period, T (years), and given duration, d (hours), is thus obtained applying equation 1:

$$h_T(d) = a_1 w_T d^n \tag{1}$$

where a_1 is hourly precipitation coefficient, n is power exponent, and w_T is *Tth* GEV quantile of normalized random variable.

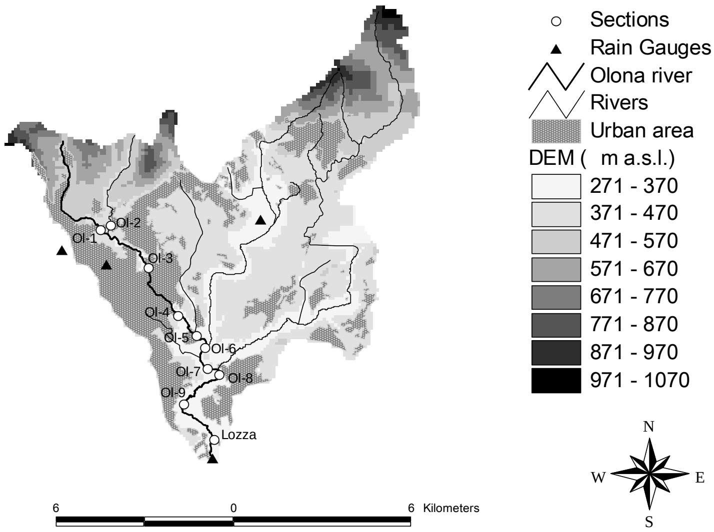

Figure 1. The Olona river basin showing locations of the rain gauges, hydrometric stations, and cross sections considered in the design flood assessment

Precipitation depth was spatially averaged over the river basins by applying Areal Reduction Factor (*ARF*) (*De Michele et al.*, 2001):

$$ARF = \left[1 + \overline{\omega}\left(\frac{A}{d}\right)^b\right]^{-\frac{b}{\nu}} \tag{2}$$

where A is basin area (km^2), ω, b and ν are parameters equal to 0.09, 0.54 and 0.484, respectively.

Ten river sections along Olona river were considered in this analysis, including Lozza basin outlet. Basin area, percentage of river basin covered by urbanized area, hourly precipitation coefficient, power exponent and GEV quantile of normalized random variable of representative depth duration frequency curves, are reported in Table 1.

Section	Area (km^2)	Urban (%)	a_1 (mm)	n (-)	w_{10}	w_{100}	w_{500}
Ol-1	5.9	26.78	34.36	0.354	1.432	2.166	2.682
Ol-2	4.8	8.96	34.29	0.352	1.432	2.167	2.685
Ol-3	17.2	33.08	34.46	0.349	1.433	2.174	2.694
Ol-4	19.6	41.12	34.69	0.347	1.434	2.180	2.704
Ol-5	27.5	36.32	34.57	0.345	1.433	2.178	2.701
Ol-6	45.5	27.54	34.31	0.342	1.431	2.170	2.690
Ol-7	50.5	30.89	34.55	0.340	1.432	2.176	2.699
Ol-8	89.5	24.69	33.96	0.339	1.427	2.156	2.670
Ol-9	91.9	25.14	34.16	0.337	1.428	2.161	2.676
Lozza	94.5	25.71	34.16	0.337	1.428	2.161	2.676

Table 1. Cross sections considered in the design flood assessment: code of cross section, extent of basin area in km^2, percentage of river basin covered by urbanized area, hourly precipitation coefficient (a_1), power exponent (n), and GEV quantile of normalized random variable for 10 years (w_{10}), 100 years (w_{100}), and 500 years (w_{500}) return period of depth duration frequency curve.

3 THE DISTRIBUTED HYDROLOGICAL MODEL FEST

In this work, for the rainfall-runoff transformation, the FEST (flash–Flood Event–based Spatially distributed rainfall–runoff Transformation, including reservoirs system) model was employed (*Montaldo et al.*, 2007; *Rabuffetti et al.*, 2008; *Corbari et al.*, 2011). FEST is a distributed hydrologic model developed at the Politecnico di Milano focusing on flash flood event simulation. As a distributed model, FEST can manage spatial distribution of meteorological forcings, and heterogeneity in hillslope and drainage network morphology (slope, roughness, etc..) and land use (*Rosso*, 1994).

The FEST model has three principal components. In the first component, the flow path network is automatically derived from the digital elevation model using a least-cost path algorithm (*Ehlschlaeger*, 1989). It assigns flow from each pixel to one of its eight neighbours, without the necessity to remove pits in the elevation data. For hillslope and channel network definition, the model uses the constant minimum support area concept. It consists of selecting a constant critical support area that defines the minimum drainage area required to initiate a channel (*Montgomery and Foufoula-Georgiou*, 1993).

In the second component, the surface runoff (or rainfall excess) is computed for each elementary cell using the SCS-CN method (*Soil Conservation Service*, 1986) in its differential form.

The third component performs the runoff routing throughout the hillslope and the river network, and the flow routing through the reservoirs. The runoff routing throughout the hillslope and the river network is performed via a diffusion wave scheme based on the Muskingum - Cunge method in its non-linear form with the time variable celerity (*Ponce and Chaganti*, 1994). Flow routing through a reservoir is described using the third-order Runge–Kutta method (*Carnahan et al*., 1969) for the classical level pool scheme.

4 INDIRECT DESIGN DISCHARGE ASSESSMENT

From a family of depth duration frequency curves, by transforming rainfall into runoff, it is possible to obtain an hydrograph for any duration at a given frequency and, finally, a series of hydrographs for each return period. According to the critical flood design criterion, the Probable Maximum Peak Design Flood (PMPDF) for a given return period, is the one related to that rainstorm duration that causes the hydrograph with the maximum peak discharge. Critical duration is the one of the precipitation event that caused the maximum peak hydrograph.

5 DIRECT DESIGN DISCHARGE ASSESSMENT

Available discharge measurements are not sufficient to perform reliable statistical inference for direct assessment of design flood. In ungauged or poorly gauged catchments, regional analysis of flood peak discharges is used for more accurate estimates of flood quantiles. This is based on the identification of homogeneous zones, where the probability distribution of annual maximum peak flows is invariant, except for a scale factor represented by an index flood, μ_Q (*Dalrymple*, 1960; *Bocchiola et al.*, 2003). The index flood method is based on the estimation of the regional growth curve of the dimensionless quantile q_T; accordingly, the T-year flood flow Q_T is estimated as (*De Michele and Rosso*, 2002)

$$Q_T = q_T \mu_Q \tag{3}$$

Direct assessment of index flood could be performed from maximum Annual Flood Series (AFS). If, at a given river site, a n-year maximum annual flood peak series of measurements is available, the index flood can be estimated as the mean of sample data $q_1, \ldots, q_n$ (eq. 4)

$$\mu_Q = \frac{1}{n}\sum_{i=1}^{n} q_i \tag{4}$$

If n'-year data are available, index flood could be estimated from the mean of the flood peaks over a threshold series, $q'_1, \ldots, q'_{n'}$, also referred to as the "partial duration series" or PDS. One computes:

$$q_{PDS} = \frac{1}{n'}\sum_{i=1}^{n'} q'_i \tag{5}$$

The index flood is associated with the mean of flood peaks of Equation (5) through the rate of occurrence, λ, of the peaks over the threshold and the parameters of the PDS growth curve. For the case of GEV distribution for the maximum annual flood peaks, the index flood is given by (*Bocchiola et al.*, 2003):

$$\mu_Q = \frac{1}{\varepsilon + \frac{\alpha}{k}\left(1 - \frac{\lambda^k}{1+k}\right)} q_{PDS} \tag{6}$$

where ε, α, and k, are the GEV parameters.

In ungauged sites a data transfer scheme can be employed. In fact, maximum annual flood peaks in homogeneous regions are characterised by statistical scale invariant properties with respect to drainage areas (*Gupta et al*., 1994; *Robinson and Sivapalan*, 1997). If A_g is the drainage area at the gauged section and A that at the ungauged one, this approach yields (*Kjeldsen and Jones*, 2007):

$$\mu_Q(A) = \mu_Q(A_g)\left(\frac{A}{A_g}\right)^m \qquad (7)$$

where m is the regional scaling exponent.

6 RESULTS AND DISCUSSION

Design hydrographs obtained with indirect method for 100-years return period for river Olona at Lozza are presented in Figure 2. Hydrograph base time and time to peak decrease significantly as return period increases. Precipitation intensity, in fact, increases with return period, causing an increase of runoff and flood celerity that, in turn, reduces flood travel time.

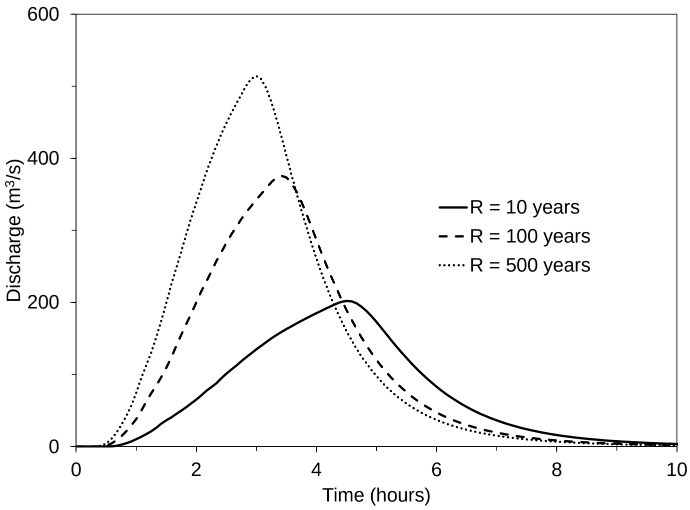

Figure 2. Design hydrographs obtained with indirect method for the river Olona at Lozza for three return periods, R: 10, 100, and 500 years

Design discharge and critical duration for 10, 100 and 500 years return period computed according to indirect method are reported for all sections in Table 2. As expected, design discharge and critical duration increase with area of the basin. Critical duration, in agreement with behaviour shown in Figure 2, decreases as return period increases for a given section.

Direct assessment of design flood can be performed in the framework of the Flood

Evaluation (VAPI) project, carried out by the National Group for Prevention from Hydrological Disasters (GNDCI) supported by the National Research Council (CNR) of Italy (*De Michele and Rosso*, 2001). This project involves studies based on the statistical analysis of the frequency of annual maxima of extreme rainfall and observed discharges, as documented by the Italian Hydrographic Services (S.I.I.). For this study the specific work performed for North-Western Italy, including Lombardia, Piemonte, Valle d'Aosta, Liguria, and Emilia Romagna regions was employed (*De Michele and Rosso*, 2002). The regionalization procedure is based on the Generalised Extreme Value distribution which proved to be accurate to explain observed peak flows. Olona river is included in the homogeneous region A, Central Alps and Prealps, for the river Po sub-basins from Chiese to Sesia.

Section	Q_{TR10}	Q_{TR100}	Q_{TR500}	D_{TR10}	D_{TR100}	D_{TR500}
Ol-1	17.02	35.52	51.15	3.33	2.25	1.92
Ol-2	14.16	27.87	38.79	2.75	1.92	1.75
Ol-3	53.46	101.85	139.87	2.50	2.17	2.00
Ol-4	63.5	119.71	162.33	2.67	1.92	1.92
Ol-5	82.59	154.98	210.21	2.58	2.00	2.00
Ol-6	114.69	215.1	293.39	3.42	2.42	2.33
Ol-7	149.77	279.09	377.49	3.33	2.58	2.25
Ol-8	191.07	356.49	488.54	4.00	3.33	3.08
Ol-9	196.08	366.91	502.14	3.92	3.33	2.83
Lozza	202.04	375.66	514.08	4.42	3.33	2.92

Table 2. Design discharge, Q (m^3/s) and critical duration, D (hours) for 10, 100 and 500 years return period computed according to indirect method.

Index flood computed using the *partial duration series* method, is 59.7 m^3/s. Design flood at Lozza for 10, 100, and 500 years return period was obtained by multiplying index flood by the quantile of normalized flood flows in the region, equal to 1.68, 2.93, and 4, respectively. Design discharge for ungauged sections can be obtained using data transfer scheme by applying equation (7) with m = 0.799 valid for region A.

In Figure 3, 100-years return period specific discharges per unit area obtained with indirect method is compared to the ones from direct method. Indirect method provides discharge significantly greater than direct method. This is in agreement with the method for index flood estimation based on annual maximum peak flow measurements that are strongly biased by upstream river overflows that reduce discharge. Specific discharges by indirect method show negative trend with basin area. An increase of specific discharge with basin area is reported for pairs of sections Ol-2 Ol-1, Ol-3 Ol-4 and Ol-6 Ol-7. This is due to significant increment of percentage of urban area, that compensates increment of basin area (Table 1).

7 CONCLUSIONS

A procedure for indirect estimation of design flood is presented. The proposed approach has been tested on the case of river Olona in the north of Milan, Italy, most of which flow through built-up areas causing damage to the population especially during the rainy seasons.

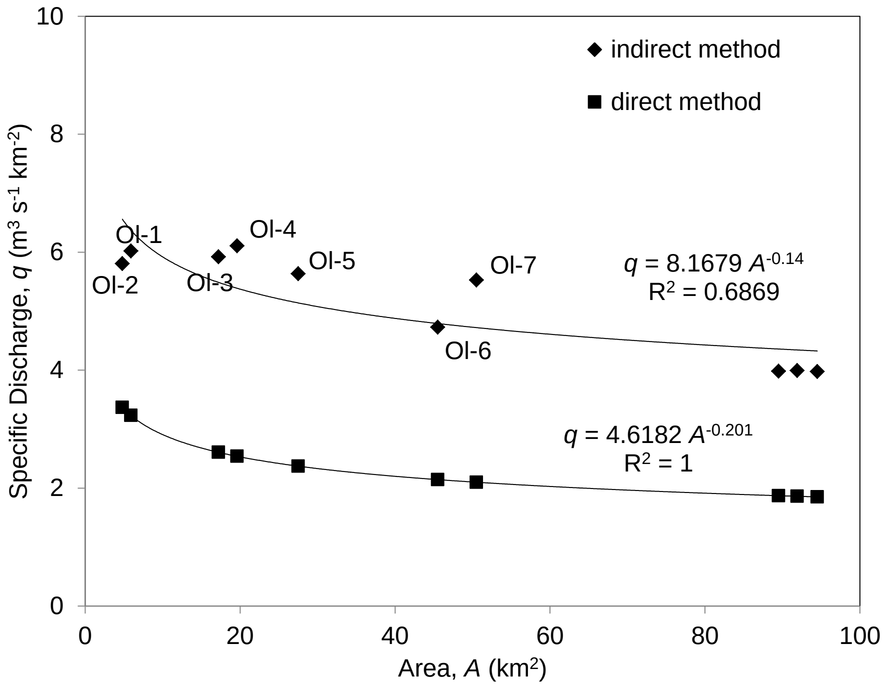

Figure 3. Specific discharge per unit area obtained with direct and indirect methods

We showed that from a family of depth duration frequency curves, by transforming rainfall into runoff, it is possible to obtain an hydrograph for any duration at a given frequency and, finally, a series of hydrographs for each return period. According to the critical flood design criterion, the design flood for a given return period, is the one related to that rainstorm duration (critical duration) that causes the hydrograph with the maximum peak discharge. For rainfall-runoff transformation a spatially distributed hydrological model was employed. This allows to take into account heterogeneity that generally characterizes river basins with an high degree of urbanization. In the river Olona case study, for example, we showed that, differences in percentage of urban area can explain an increase of specific design discharge per unit area with basin area.

The proposed approach can provide also design hydrograph. This is useful in cases when design flood only is not sufficient for planning or designing purposes such as retention pool design or flood map assessment (*Ravazzani et al*., 2009).

In highly urbanized river basins annual maximum peak flow measurements may be strongly biased by upstream river overflows, above all when rivers have been channelled into artificial drainage. In this situation, in fact, overflow of the watercourses and subsequent inundation can be frequently observed during storm events. In these cases, direct estimation of design flood can lead to significant underestimation of peak flow with negative impacts on downstream river reach when subsequent modification of water course would increase river conveyance.

Acknowledgements. This work was supported by Comune di Varese and Autorità di Bacino del Fiume Po. We thank Regional Agency for Environmental Protection (ARPA

Lombardia) for providing hydrological and meteorological data and Consorzio Fiume Olona for providing dates of historical flood events.

REFERENCES

Bocchiola, D., De Michele, C., and Rosso, R., (2003). “Review of recent advances in index flood estimation.” *Hydrol. Earth Syst. Sc.*, 7(3), 283-296.

Carnahan, B., Luther, H. A., and Wilkes, J. O. (1969). *Applied Numerical Methods*. John Wiley & Sons: New York; 604.

Corbari, C., Ravazzani, G., and Mancini, M., (2011). “A distributed thermodynamic model for energy and mass balance computation: FEST-EWB.” *Hydrol. Process*., 25(9), 1443-1452.

Dalrymple, T., (1960). “*Flood frequency analysis*.” Water Supply Paper 1543-A, US Geol. Survey, Reston, Virginia, USA.

De Michele, C., and Rosso, R., (2001). “Uncertainty assessment of regionalized flood frequency estimates.” *J. Hydrol. Eng.*, 6, 453-459.

De Michele, C., and Rosso, R., (2002). “A multi-level approach to flood frequency regionalization.” *Hydrol. Earth Syst. Sci*., 6, 185-194.

Ehlschlaeger C. R., (1989). “Using the AT search algorithm to develop hydrologic models from digital elevation data.” *Proceedings of the International Geographic Information System* (IGIS) Symposium, Baltimore, 275–281.

Freeze, R. A., Harlan, R. L., (1969). “Blueprint for a physically-based, digitally-simulated hydrologic response model.” *J. Hydrol.*, 9: 237–258.

Gupta, V.K., Mesa, O.J., and Dawdy, D.R., (1994). “Multiscaling theory of flood peaks: regional quantile analysis.” *Water Resour. Res.*, 30, 3405-3421.

Kjeldsen, T. R., and Jones, D., (2007). “Estimation of an index flood using data transfer in the UK.” *Hydrol. Sci. J.*, 52:1, 86-98, doi:10.1623/hysj.52.1.86.

Montaldo, N., Ravazzani, G., and Mancini, M. (2007). “On the prediction of the Toce alpine basin floods with distributed hydrologic models.” *Hydrol. Process.* 21, 608-621.

Montgomery, D. R., and Foufoula-Georgiou, E., (1993). “Channel network source representation using digital elevation models.” *Water Resour. Res*., 29(12), 3925–3934.

Ponce, V. M., Chaganti, P. V. (1994). “Variable – parameter Muskingum – Cunge method revisited.” *J. Hydrol.*, 162, 433 – 439.

Rabuffetti, D., Ravazzani, G., Corbari, C., and Mancini, M. (2008). “Verification of operational Quantitative Discharge Forecast (QDF) for a regional warning system – the AMPHORE case studies in the upper Po River.” *Nat. Hazard Earth Sys*. 8, 161-173.

Ravazzani, G., Mancini, M., and Meroni, C. (2009). “Design hydrograph and routing scheme for flood mapping in a dense urban area.” *Urban Water J*., 6(3), 221-231.

Robinson, J.S., and Sivapalan, M., (1997). “An investigation into the physical causes of scaling and heterogeneity of regional flood frequency.” *Water Resour. Res.*, 33, 1045-1059.

Rosso, R., (1994). “An introduction to spatially distributed modelling of basin response.” In Advances in Distributed Hydrology, R. Rosso, A. Peano, I. Becchi and G. A. Bemporad Editors, *Water Resources Publications*, 3-30.

Soil Conservation Service, (1986). “National Engineering Handbook, Hydrology, Section 4.” US Department of Agriculture, Washington, DC.