The Role of Terrain Analysis in Catchment Hydrologic Modeling

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Seminar in Honor of Professor Andrea Gavioli's Retirement
Dipartimento di Scienze Fisiche, Informatiche e Matematiche
Università degli Studi di Modena e Reggio Emilia
Wednsday, Feb 13, 2019, 9:30 am – 13:00 am, Room M1.2

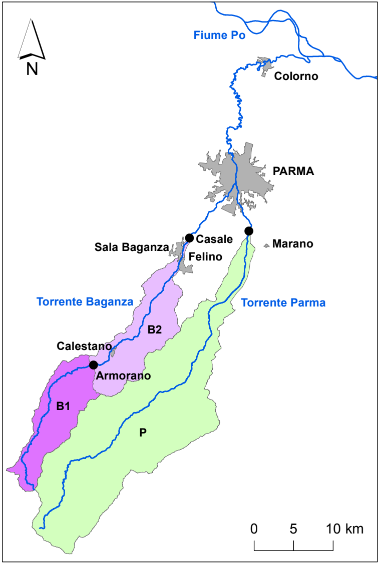
Presentation in PDF available on the web at the address
http://www.idrologia.unimore.it/orlandini/download.html

Outline

1. **Catchment Hydrologic Modeling**
   - Water Resources Engineering
   - Hydrologic modeling
   - Catchment hydrologic modeling
2. **Terrain Analysis**
   - Contour, TIN, and grid digital elevation models
   - Slope lines, curvatures, and drainage areas
   - Scaling issues
3. **Surface Flow Propagation**
   - Overland flow dispersion
   - River flows and level pool routing
   - Detailed description of surface flow propagation
4. **Final Remarks**

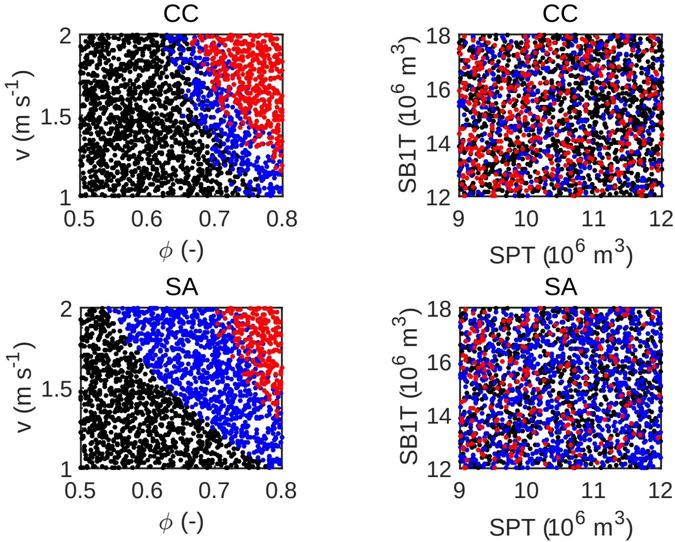
Water Resources Engineering

Case study of the Parma River fluvial system, Italy



Flood Control

2255 Monte Carlo experiments (precipitations having return period T = 200 a)



Flood Control Problem

What is the correct level of protection we need?

Panaro River, 2012

Scientific American, 2013

Sans Protective Measures, Flooding Damage Could Cost the World $1 Trillion by 2050

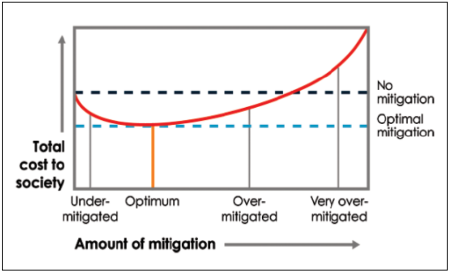
Coastal cities—rich and poor—share the risk, and face tough decisions about how to adapt to rising seas and stronger storms

By Erin Brodwin

Design return period

$$T = \frac{1}{P}$$

$$R = 1 - \left(1 - \frac{1}{T}\right)^L$$



Levee Failure Along the Secchia River, January 2014

Breach loss = 36×10^6 m^3, flooded area = 52 km^2, damage = EUR 500 million

When the flood calls
You have no home, you have no walls
Peter Gabriel – Here Comes The Flood (Peter Gabriel I, 1977)

Investigation on Causes of the Levee Failure
Wanted by the Governor of the Regione Emilia-Romagna Vasco Errani

Relazione tecnico-scientifica sulle cause del collasso dell’argine del fiume Secchia avvenuto il giorno 19 gennaio 2014 presso la frazione San Matteo

Bologna, 9 luglio 2014

Prof. Luigi D’Alpaos, Università degli Studi di Padova.
Prof. Armando Brath, Alma Mater Studiorum - Università di Bologna.
Prof. Vincenzo Fioravante, Università degli Studi di Ferrara.
Prof. Guido Gottardi, Alma Mater Studiorum - Università di Bologna.
Prof. Paolo Mignosa, Università degli Studi di Parma.
Prof. Stefano Orlandini, Università degli Studi di Modena e Reggio Emilia.

AGU PUBLICATIONS
Water Resources Research
RESEARCH ARTICLE
10.1002/2015WR017426

Key Points:
- Animal burrows are demonstrated to be a serious threat of earthen levee failure
- Internal flow and erosion around a den can cause the collapse of the levee top
- Internal flow may initiate due to direct inflow into the den or den wall failure

Evidence of an emerging levee failure mechanism causing disastrous floods in Italy

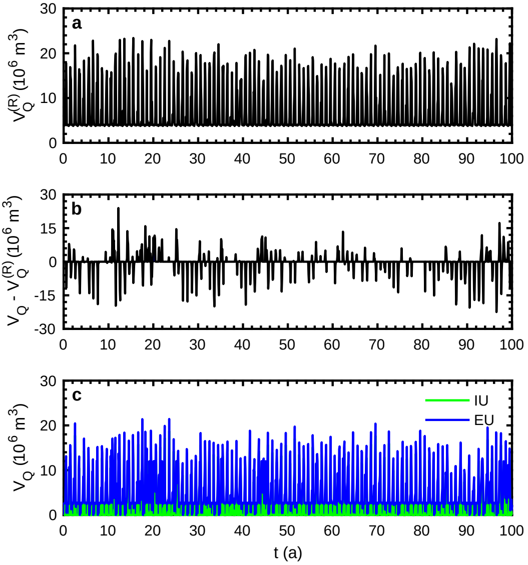
Stefano Orlandini[1], Giovanni Moretti[1], and John D. Albertson[2]

[1]Dipartimento di Ingegneria Enzo Ferrari, Università degli Studi di Modena e Reggio Emilia, Modena, Italy, [2]School of Civil and Environmental Engineering, Cornell University, Ithaca, New York, USA

Abstract A levee failure occurred along the Secchia River, Northern Italy, on 19 January 2014, resulting in flood damage in excess of $500 million. In response to this failure, immediate surveillance of other levees in the region led to the identification of a second breach developing on the neighboring Panaro River, where

Water Supply for Public, Irrigation, and Hydropower Uses

Cost-benefit analysis of the Armorano reservoir (observed precipitations)



Water Supply for Public, Irrigation, and Hydropower Uses

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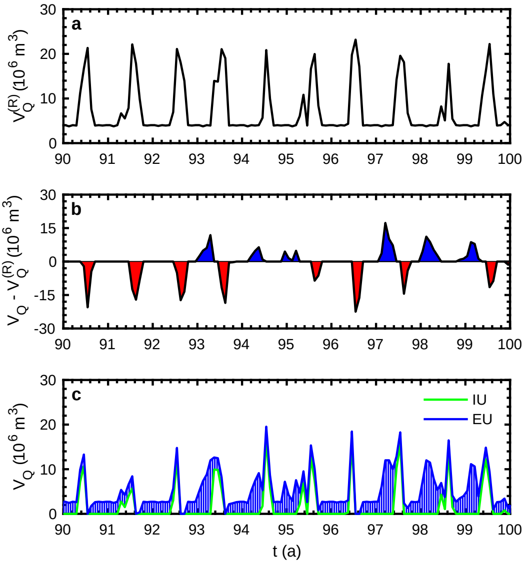
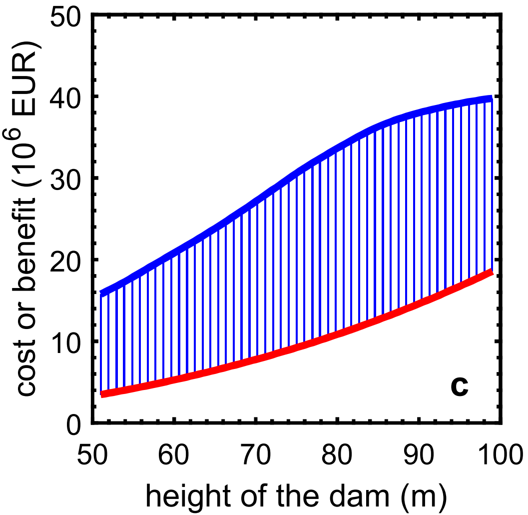


Optimal Height of the Dam

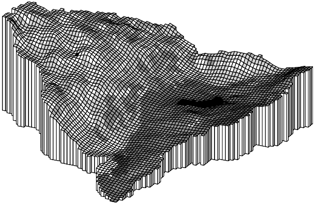
Cost-benefit analysis of the Armorano reservoir (observed precipitations)



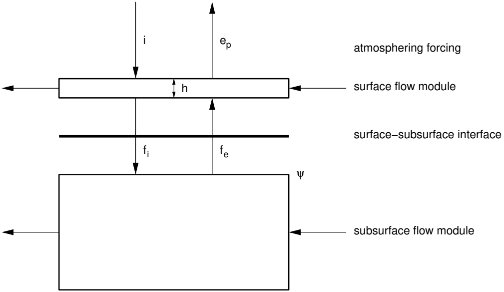
Catchment Hydrologic Modeling

The CATHY Model (Camporese, Putti, Paniconi, Orlandini, 2010, WRR)

Distributed modeling



Surface-subsurface flow interaction



3-D Richards equation-based subsurface module +
1-D rivulet/channel network diffusion wave surface module

Overland Flow Phenomenology
(Raudkivi, 1979, p. 170 and 171)

When the rate of rainfall or snowmelt exceeds the interception requirements and the rate of infiltration, water starts to accumulate on the surface. At first the excess water collects into the small depressions and hollows, until the surface detention requirements are satisfied. After that water begins to move down the slope as a thin film and tiny streams. This early stage of overland flow is greatly influenced by surface tension and friction forces. With continuing rainfall the depth of surface detention and the rate of overland flow increase, but the paths of the small streams on the surface of the catchment are still tortuous and full of obstructions. Every small obstruction causes a delay until the upstream level has risen to overflow the obstacle or to wash it away. On release a small wave speeds downstream and merges with another little rivulet. The merging of more and more of these little streams culminates in the river which drains the whole catchment in question.

Overland Flow Modeling

Resistance coefficients remain poorly understood!

- Governing equations: dynamic, diffusion, and kinematc wave equations, level pool routing equation
- Constitutive equations: Gauckler-Manning-Strickler equation

$$U = \frac{1}{n} R^{2/3} S_f^{1/2},$$

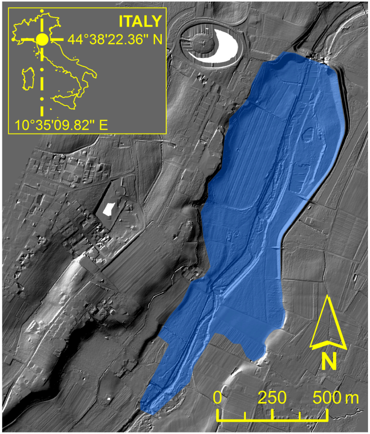
  reservoir storage and outflow equations
- Numerical methods: 0-D, 1-D, 2-D / FDM, FEM, and FVM

Terrain Analysis
Not only important to describe surface flows!

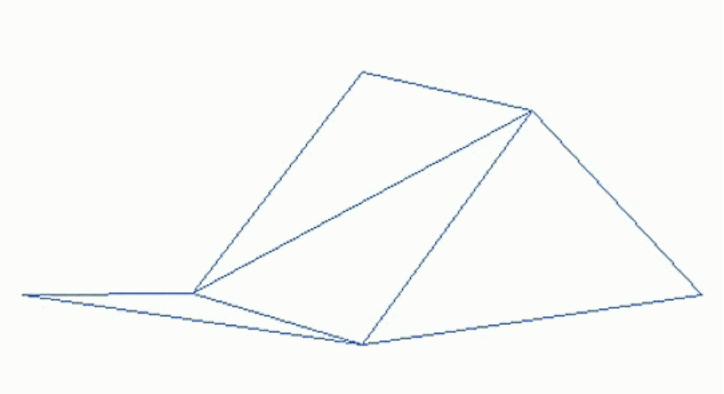
Definition

Terrain analysis is the analysis and interpretation of topographic features. Such features include elevation, slope, aspect, plan and profile curvature, drainage area, and specific drainage area. The intention is to build mathematical abstraction of surface terrain in order to delineate or stratify landscapes and create an understanding of relationships between hydrological, geomorphological, and ecological processes and physical terrain features.

Lidar survey



The Problem of Terrain Representation (http://en.wikipedia.org/wiki/Fractal)



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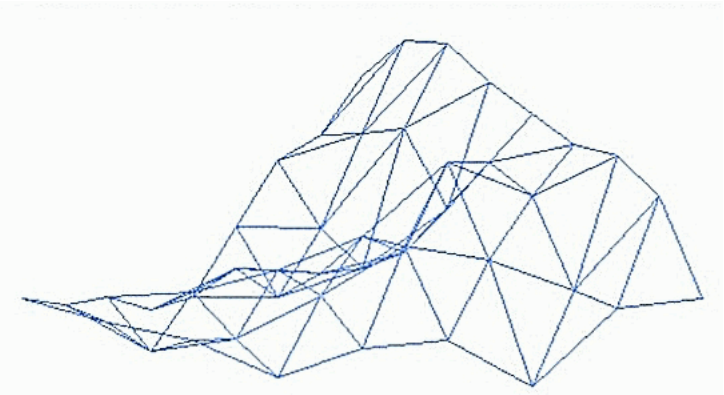

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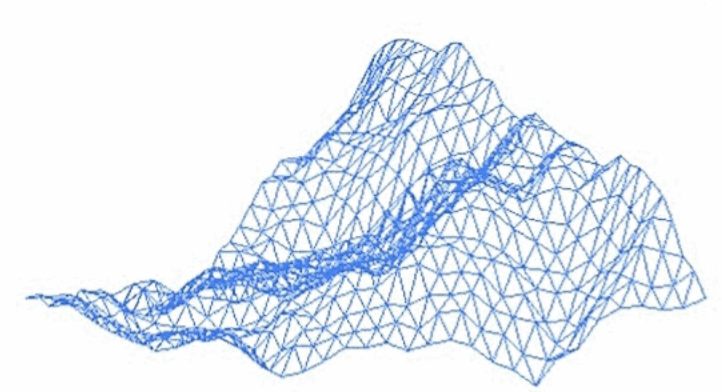

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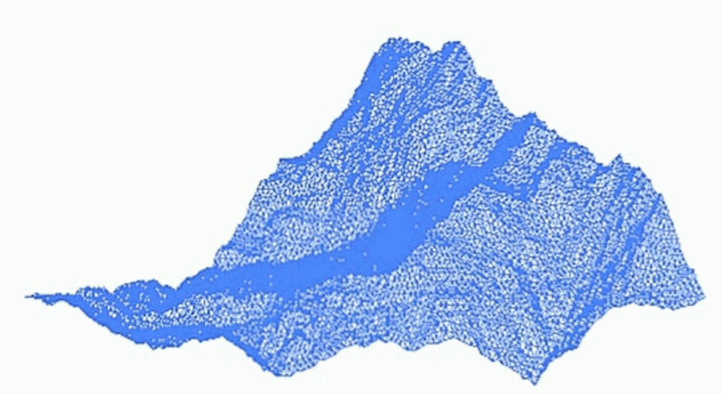


Slope Lines

(Cayley, 1859, London Edinburgh Dublin Philos. Mag. J. Sci.; Maxwell, 1870, London Edinburgh Dublin Philos. Mag. J. Sci.)

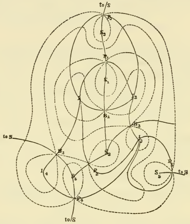
James Clerk Maxwell

On hills and dales

240 HILLS AND DALES.

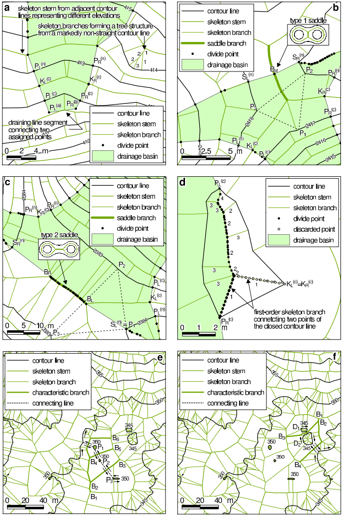
If we put L equal to the whole number of lines, and P equal to the whole number of points, we find that F, the number of natural districts named from a hill and a dale together, is equal to W, the number of watersheds or watercourses, or to the whole number of summits, bottoms, passes, and bars diminished by 2.

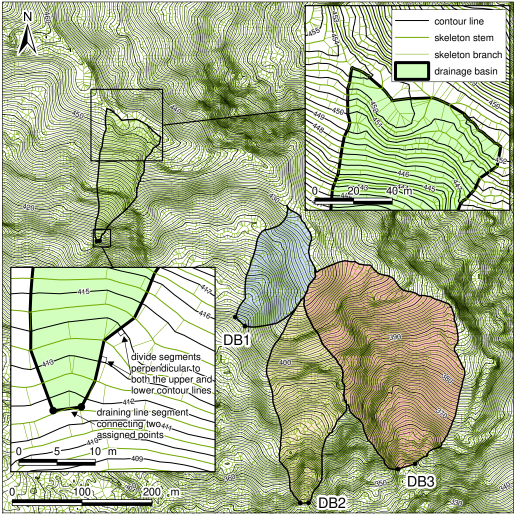
Chart of an Inland Basin.



I_1, I_2, I_3, I_4.	Lowest points, Bottoms or Immits.
S_1, S_2, S_3, S_4, S_5.	Highest points, Tops or Summits.
B_1, B_2, B_3.	Bars between regions of depression.
P_1, P_2, P_3, P_4, P_5.	Passes between regions of elevation.
$I_1\ B_1\ I_2$ &c.	Lines of Watercourse.
$S_1\ P_1\ S_3$ &c.	Lines of Watershed.
Dotted line.	Contour-lines.

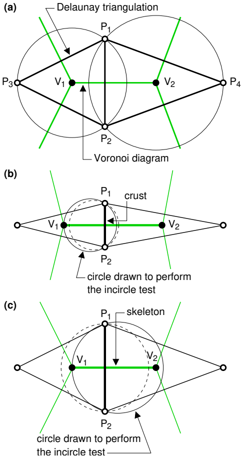
Skeleton Construction Techniques
(Gold and Snoeyink, 2001, Algorithmica; Moretti and Orlandini, 2008, WRR)



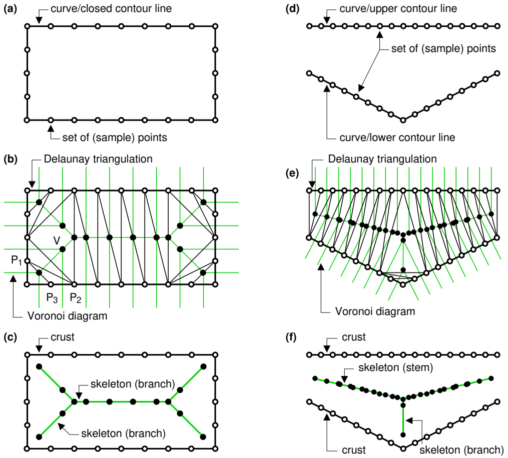


Skeleton Construction Techniques
(Moretti and Orlandini, 2008, WRR)

Skeleton



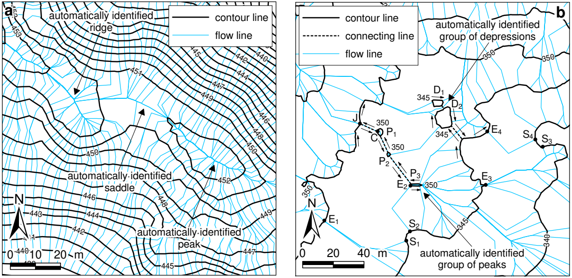
Examples



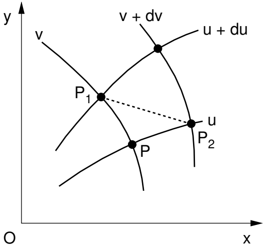
(Jonathan R. Shewchuk, Triangle, http://www.cs.berkeley.edu/~jrs)

Skeleton Construction Techniques
(Moretti and Orlandini, 2008, WRR)

Flow net



Curvilinear coordinates



A classical flow net is not suited to natural landscapes (Moore and Grayson, 1991, WRR). However, these methods may perhaps be used in the future in combination with the Gallant and Hutchinson's (2011, WRR) equations

$$\frac{dA}{dv} = a, \qquad \frac{da}{du} = 1 - ka.$$

These equations lead drainage basin hydrology into continuum mechanics.

A New Differential Equation!
(Gallant and Hutchinson, 2011, WRR)

WATER RESOURCES RESEARCH, VOL. 47, W05535, doi:10.1029/2009WR008540, 2011

A differential equation for specific catchment area

John C. Gallant[1] and Michael F. Hutchinson[2]
Received 20 August 2009; revised 21 February 2011; accepted 28 February 2011; published 25 May 2011.

[1] Analysis of the behavior of specific catchment area in a stream tube leads to a simple nonlinear differential equation describing the rate of change of specific catchment area along a flow path. The differential equation can be integrated numerically along a

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Research

Check for updates

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http://dx.doi.org/10.1098/rspa.2017.0693

On the theory of drainage area for regular and non-regular points

S. Bonetti[1,2], A. D. Bragg[1] and A. Porporato[2,3]

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[2]Department of Civil and Environmental Engineering, and
[3]Princeton Environmental Institute, Princeton, NJ 08544, USA

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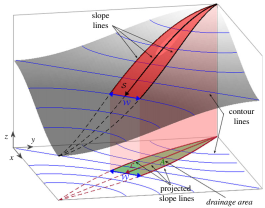
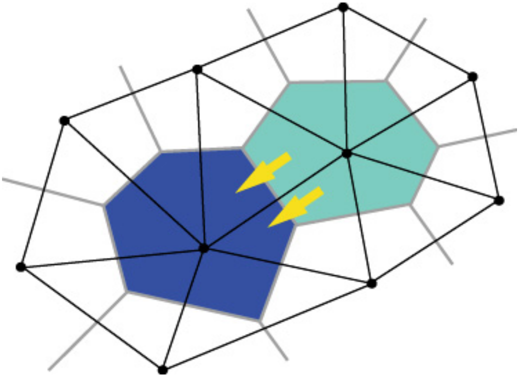


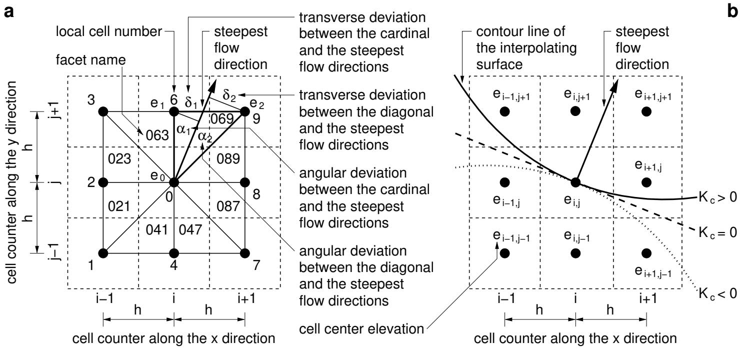
Triangulated Irregular Networks
(Ivanov, Vivoni, Bras, Entekhabi, 2004, WRR)

tRIBS model



Grid Digital Elevation Models
(O'Callaghan and Mark, 1984; Zevenbergen and Thorne, 1987; Quinn et al., 1991; Tarboton, 1997; Orlandini et al., 2003; Seibert and McGlynn, 2007)

D8, MD8, D∞, D8-LTD, and MD∞ methods



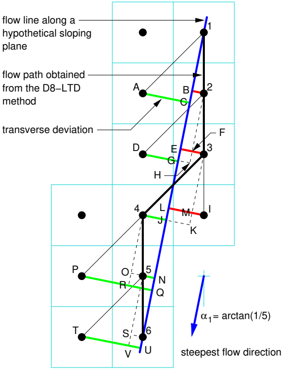
(Orlandini and Moretti, 2009, WRR)

D4 propagation across adjacent cells is not robust enough.

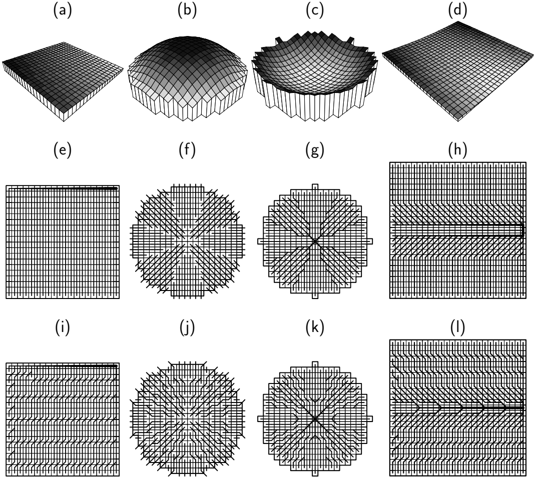
Slope lines in grid digital elevation models

D8-LTD method (Orlandini, Moretti, Franchini, Aldighieri, Testa, 2003, WRR)

D8-LTD method



D8 vs D8-LTD methods



Analytical Basis for the D8-LTD Method
(Orlandini, Moretti, Gavioli, 2013, WRR)

WATER RESOURCES RESEARCH, VOL. 50, 526–539, doi:10.1002/2013WR014606, 2014

Analytical basis for determining slope lines in grid digital elevation models

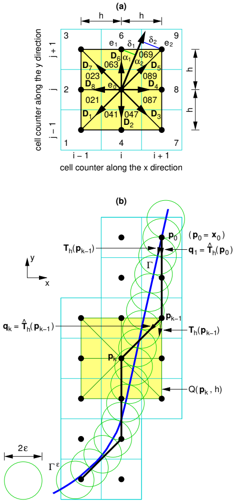
Stefano Orlandini,[1] Giovanni Moretti,[1] and Andrea Gavioli[2]

Received 19 August 2013; revised 2 December 2013; accepted 12 December 2013; published 22 January 2014.

[1] An analytical basis for the determination of slope lines in grid digital elevation models is provided by using the D8-LTD method (eight slope directions, least transverse deviation).

Proof
(Orlandini, Moretti, Gavioli, 2013, WRR)

D8-LTD method



Theorem

Let $z : \mathbb{R}^2 \to \mathbb{R}$ be a C^2-function whose gradient ∇z never vanishes. Let $\mathbf{p}_0 \in \mathbb{R}^2$ be given, and $\mathbf{x}(t)$ be the solution of

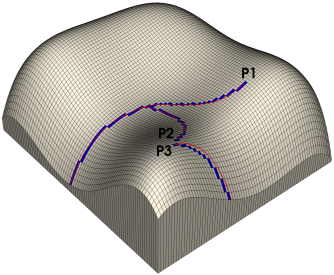
$$\mathbf{x}'(t) = -\nabla z(\mathbf{x}(t))$$

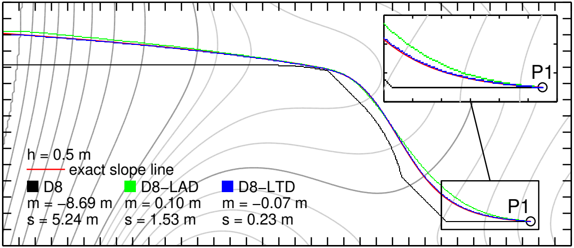
$$\mathbf{x}(t_0) = \mathbf{x}_0$$

with $\mathbf{x}_0 = \mathbf{p}_0$. Then, for any $\varepsilon > 0$, there exists $n_\varepsilon \in \mathbb{Z}^+$ such that

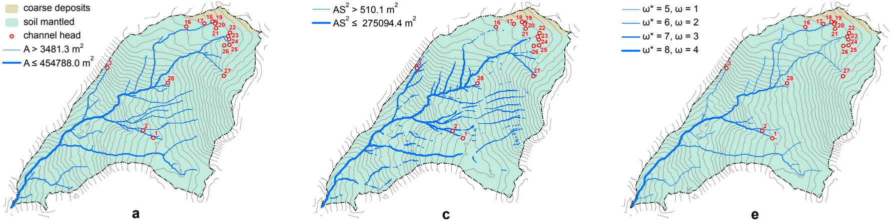
$$\Gamma_n \subseteq \Gamma^\varepsilon, \quad n \geq n_\varepsilon .$$

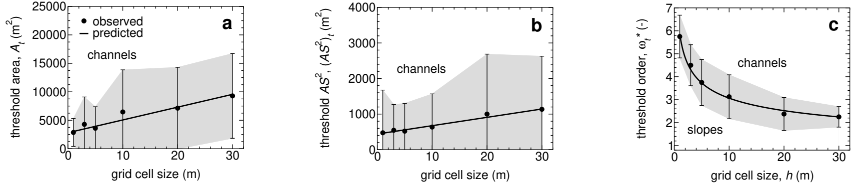
Numerical Evidence
(Orlandini, Moretti, Gavioli, 2013, WRR)





Channel Initiation
(Orlandini, Tarolli, Moretti, Dalla Fontana, 2011, WRR)

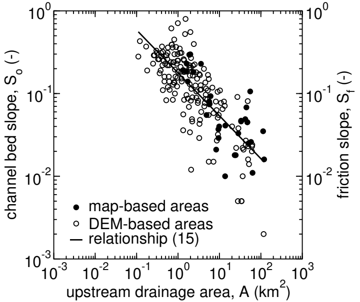




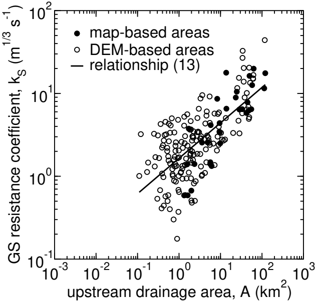
(Sensitivity and specificity issues)

Resistance to Flow Along Channel Networks
(Orlandini, 2002, WRR)

Matching S_f and S_0



Scaling $k_S = 1/n$



Profile and Planar Overland Flow Dispersion Along Hillslopes

Surface flow hydraulics

$$\frac{\partial Q}{\partial t} + c_k \frac{\partial Q}{\partial s} = D_h \frac{\partial^2 Q}{\partial s^2} + c_k\, q$$

$$c_k = \frac{dQ}{d\Omega}$$

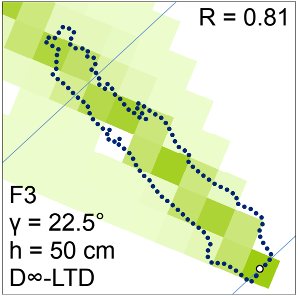
$$D_h = \frac{Q}{2\,W\,S_0}\left(1 - \mathrm{Ve}^2\right)$$

$$\mathrm{Ve} = \frac{c_k - U}{c_d} \qquad \left(\mathrm{Fr} = \frac{U}{c_d}\right)$$

$$U = \frac{1}{n} R^{2/3} S_0^{1/2}$$

$$c_d = \sqrt{g\,Y_m}$$

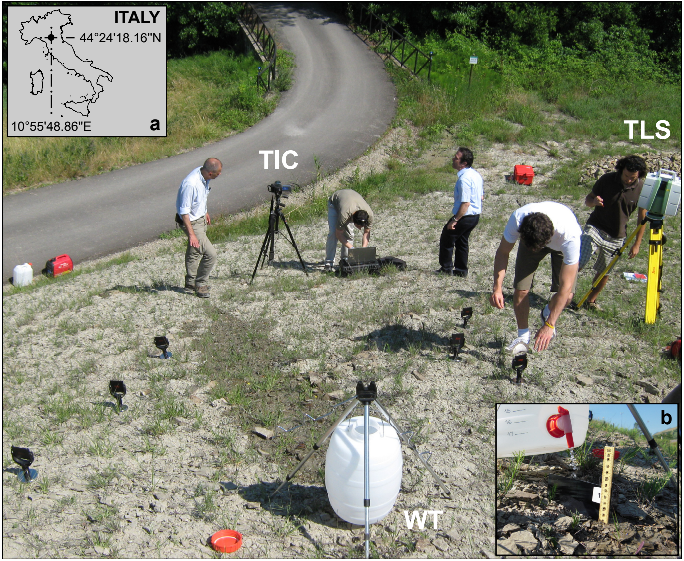
Planar dispersion



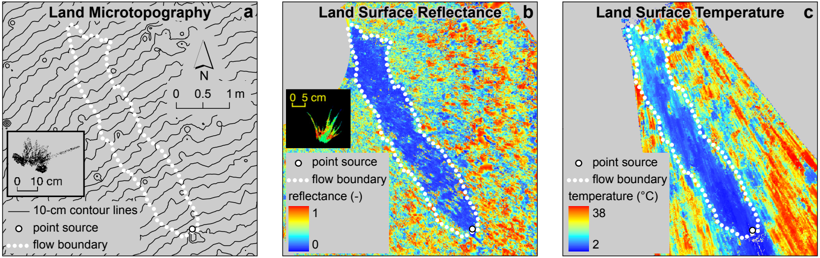
Cell shades indicate the fraction of released water passing through the cell.

Green is the colour of her kind
quickness of the eye deceives the mind
(Pink Floyd, Green is the Colour, More, 1969)

How does water move over the land surface?
(Orlandini, Moretti, Corticelli, Santangelo, Capra, Rivola, Albertson, 2012, WRR)

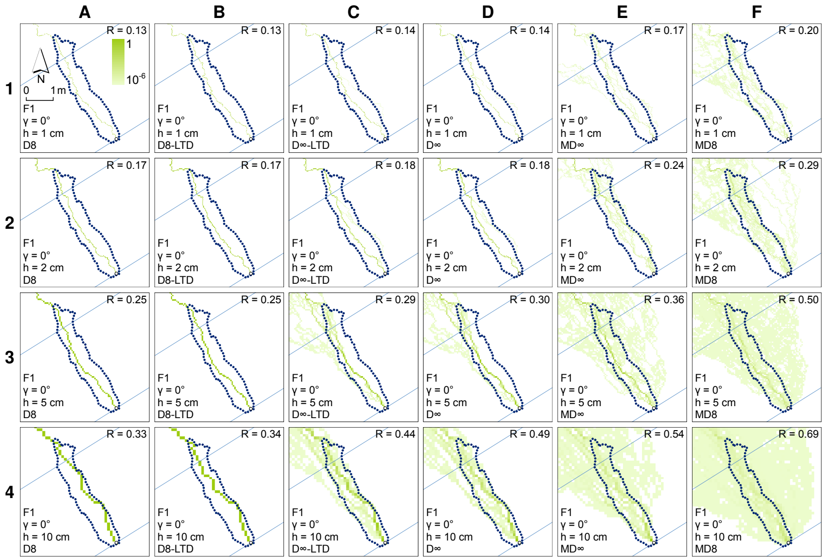


Observed overland flow patterns

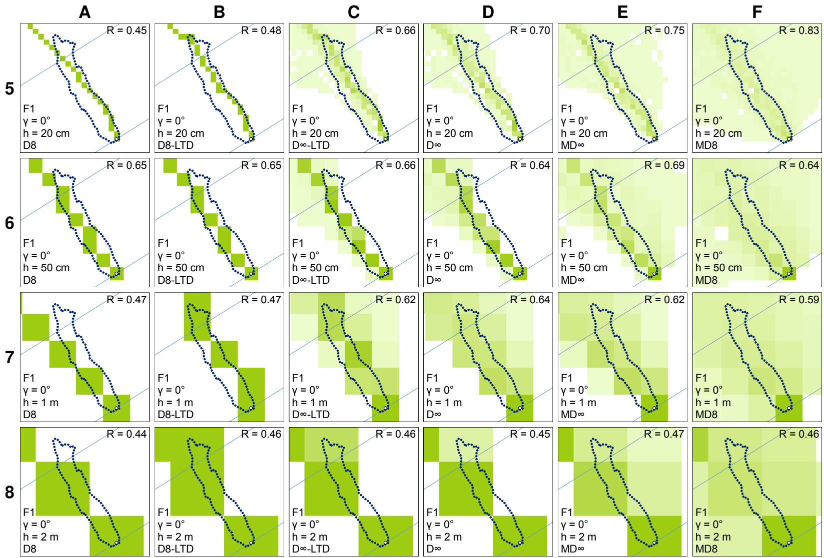


I'm coming up on infra-red, there is no running that can hide you,
'Cause I can see in the dark.
I'm coming up on infra-red, forget your running, I will find you.
(Placebo, Infra-red, Meds, 2006)

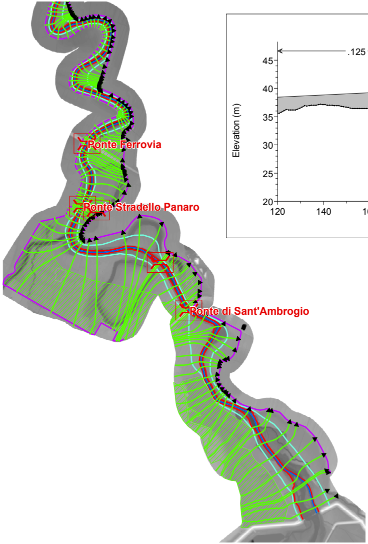
Predicted Propagation Patterns

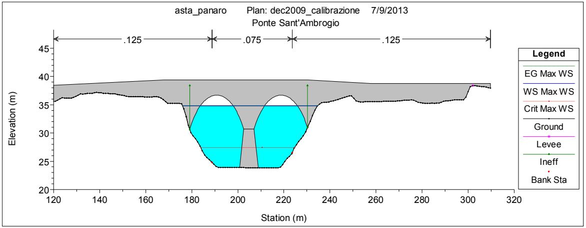


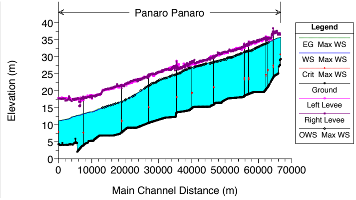
Predicted Propagation Patterns



River Channel Geometry

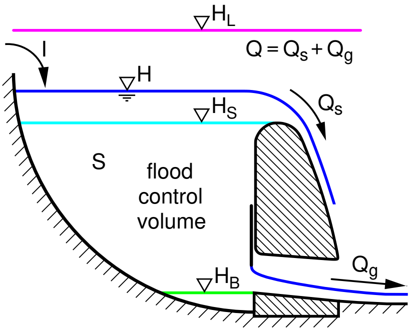




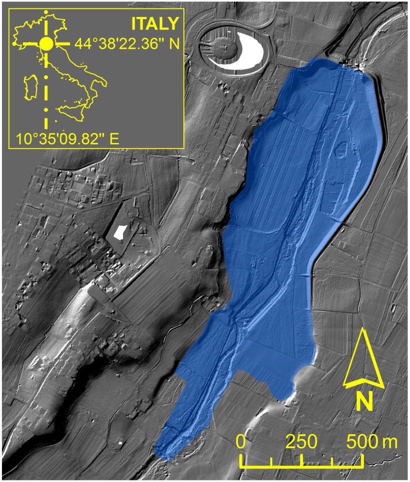


Reservoir Geometry
(Fiorentini and Orlandini, 2013, AWR)

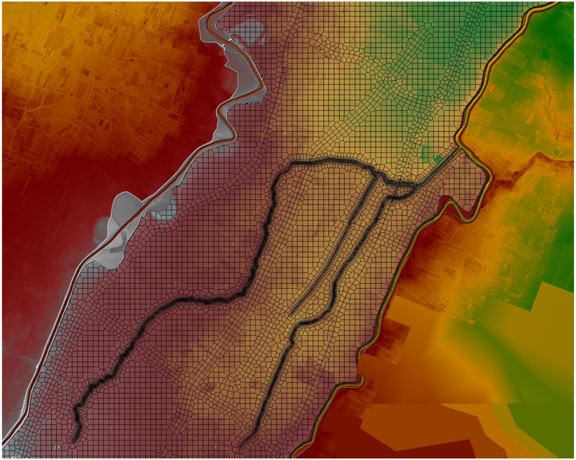
Flood control reservoir



Lidar survey



Hydrology-oriented Terrain Analysis
Unstructured Meshes



Detailed Surface Flow Propagation

Detail is used only where needed...

test

Final Remarks

New data and methods are now available!

- High-resolution (1 m or less) digital elevation models generated from lidar surveys are increasingly available for hillslope to continental scale hydrologic modeling.
- Grid-based digital elevation models are relatively easy to use numerically.
- TIN-based digital elevation models are efficient to reduce the computational burden of hydrologic models.
- Contour-based digital elevation models are suitable to mathematical abstraction of land surface topography.
- There is room for future research in hydrology-oriented description of terrain analysis.
- Terrain analysis and surface flow propagation can be further investigated at UNIMORE.