From Precipitation to Streamflow: Simulating the Movement of Water Within Landscapes

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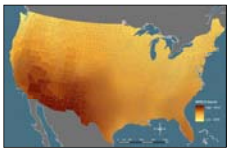
Inspiration

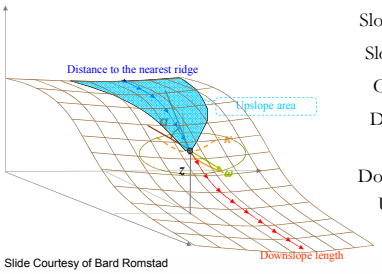
- Moore et al. 1991
- ANUDEM / ANUSPLIN
- Soil-Land Inference Model (SoLIM)
- Precision Farming



Roadmap

- Topographic attributes
- Flow routing algorithms
- Flow routing algorithm assessments
- Some enduring challenges
- What we need to do next

Topographic attributes



Slide Courtesy of Bard Romstad

Elevation (**z**)
Slope gradient (**α**)
Slope aspect (**ω**)
Curvatures (**κ**)
Distance to the nearest ridge
Downslope length
Upslope area

Terrain shape

- 3 x 3 moving window
- Water flow, soil erosion, non-point source pollution, etc.
- Calculation is specific to scale, data, and algorithm

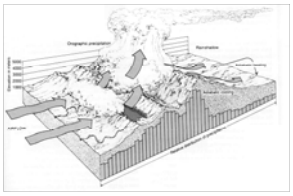
Distribution of point elevation errors	2	2	2	8	8	8	0	2	4	0	8	16
	2	2	2	8	8	8	2	0	4	8	0	16
	2	2	2	8	8	8	4	0	2	16	0	8
Mean local error	2			8			2			8		
Local RMSE	2			8			√(20/3)			√(320/3)		
Currently adopted error description	low			high			low			high		
Distortion of terrain shape	none			none			low			high		
Local standard deviation of errors	0			0			2/√3			8/√3		

Topographic position

- Usually defined with reference to process (upslope contributing area) or feature (distance to ridgeline)
- Point-to-point connections
- Influenced by data scale and landscape properties

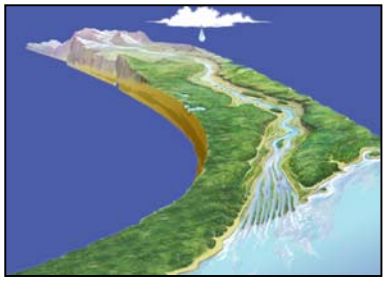
Topographic contexts

- Expanding windows / linkages across scales
- Defines new topographic attributes
- Explicit consideration of scale
- Multi-resolution valley bottom index
- Peakness index



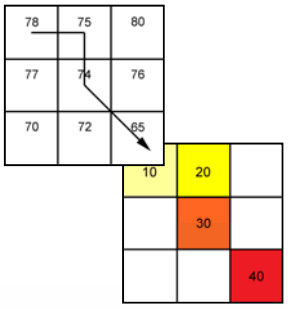
The vision

Goal is to follow a drop of water from where it falls on the land, to the stream, and all the way to the ocean



Implementation

- Remove depressions from DEM
- Select one or more rules to determine drainage direction
- Define connectivity and contribution of individual elements to each other

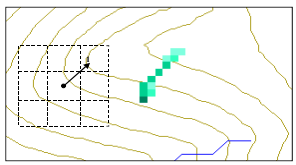


Flow routing algorithms

- D8 (O'Callaghan and Mark 1984)
- Rho8 (Fairfield and Leymarie 1991)
- FD8 (Quinn et al. 1991)
- 2D-Lea (Lea 1992)
- DEMON (Costa-Cabral and Burges 1994)
- ANSWERS (Beasley and Huggins 1978)
- Flux decomposition (Desmet and Govers 1996)
- D∞ (Tarboton 1997)
- MFD-md (Qin et al. 2007)

SFD algorithms

Numerical representations of flow direction field in which each cell takes on one of eight values depending on which of its eight neighboring cells is in direction of steepest descent



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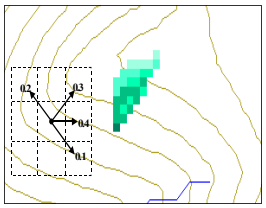
MFD algorithms

Numerical representations of flow direction field in which flow is partitioned between one or more of the eight neighboring cells such that proportions add up to one



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Assessments

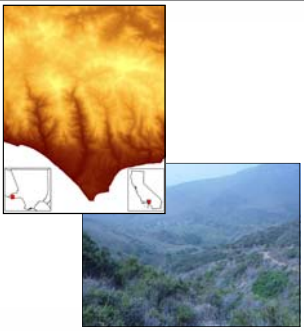
- Desmet and Govers (1996)
  - ANSWERS, flux decomposition algorithms
- Wilson et al. (2000)
  - DEMON, FD8 algorithms
- Zhou and Liu (2002)
  - DEMON
- Endreny and Wood (2003)
  - D∞, 2d_Jensen, 2D-Lea, D8-buf, MF(3)
- Wilson et al. (2006)

Wilson et al. – null hypotheses

- Performance of five popular flow routing algorithms in computing specific catchment area does not change as flow descends from higher to lower elevations (#1)
- Performance does not vary across different fuzzy *k*-means landscape classes (#2)

Study area metrics

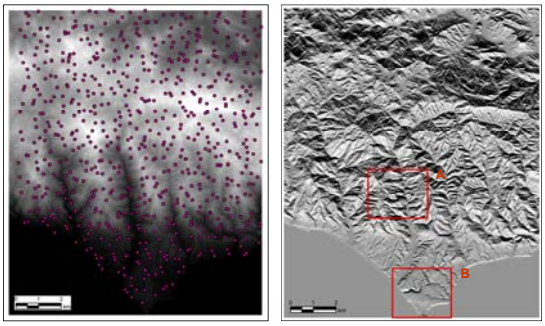
- Point Dume, CA 1:24K USGS map quadrangle
- 1.3 million grid points with 10 m spacing
- Elevations range from 0 m (sea level) to 859.7 m
- Much of region is parkland or some other type of protected open space



Fuzzy Classification

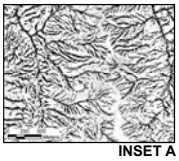
- Used PCRaster to calculate 8 topographic attributes
  - Elevation
  - Slope
  - Profile Curvature
  - Plan Curvature
  - Distance to Ridgelines
  - Solar Insolation
  - Topographic Wetness Index
  - Sediment Transport Capacity Index
- Used FUZNLM fuzzy *k*-means classifier to identify 6 landform classes
  - Assigns membership values to grid cells
  - Assigns classes based on largest membership values

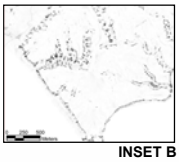
Fuzzy Classification



Hilltops / ridgelines

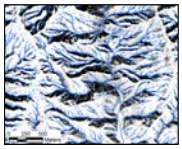
- High elevations
- Ridgelines are nearby
- Low topographic wetness index
- High solar radiation


INSET A

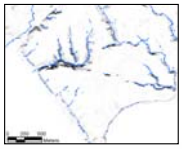

INSET B

North-facing slopes

- High elevations
- Very steep slopes
- Low solar insolation



INSET A

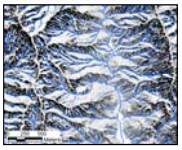


INSET B

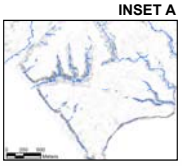
Wilson, Lam, Deng, and Aggett
TADTM 2006

South-facing slopes

- High elevations
- Very steep slopes
- High solar insolation



INSET A

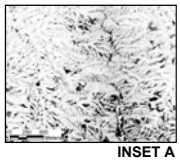


INSET B

Wilson, Lam, Deng, and Aggett
TADTM 2006

Footslopes / lower valley slopes

- Low elevations
- Moderately steep slopes
- Ridgelines are far away
- High topographic wetness index



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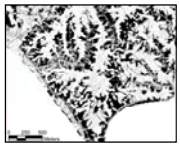

INSET B

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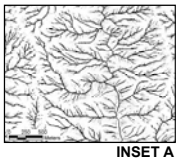
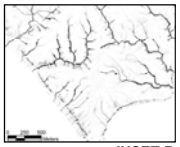
Stream channels

- Long distances to ridgelines
- High topographic wetness index
- High sediment transport capacity index



INSET A



INSET B

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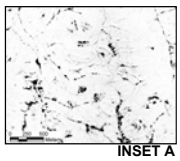
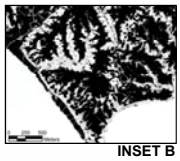
Coastal plain / gentle slopes

- Low elevations
- Gentle slopes
- High topographic wetness index



INSET A



INSET B

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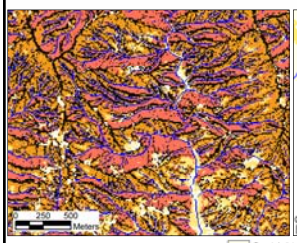
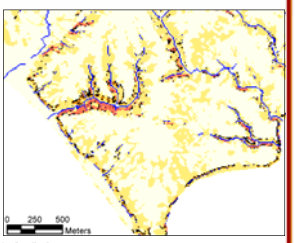
Crisp landscape classes





INSET A

INSET B

Coastal plains / gentle slopes
Moderately steep lower valley slopes
Stream channels
Steep north-facing slopes
Steep south-facing slopes
Hilltops / ridgelines

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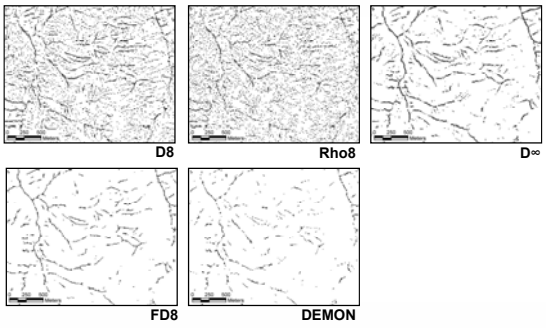
Hypothesis #1

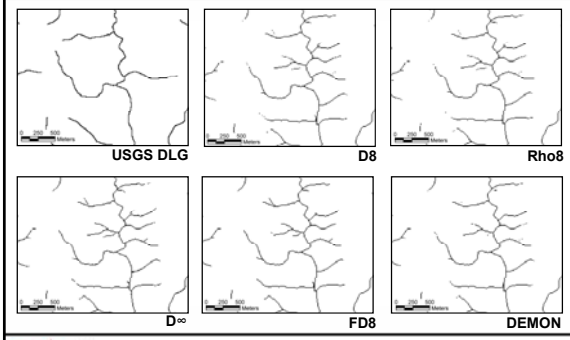
	Number of cells	Minimum	Maximum	Mean SCA (m^2m^{-1})	Standard Deviation (m^2m^{-1})
D8	1,263,296	7.07	2237670.25	3715.27	60584.28
Rho8	1,263,296	7.07	2236030.25	3714.18	60469.64
D∞	1,263,296	10.00	2236762.00	3934.18	61469.07
FD8	1,263,296	2.56	2341777.00	**4355.83**	69911.69
DEMON	1,263,296	7.07	2214353.00	**3428.91**	55657.18

	SCA (m^2m^{-1})						
	≤ 10.0	10.1 – 20	20.1 - 40	40.1 - 70	70.1 - 100	100.1 – 1000	> 1000
D8	12.8	18.5	26.9	16.3	7.2	13.3	5.1
Rho8	**13.4**	**21.6**	25.0	14.3	6.7	14.0	5.1
D∞	7.6	12.9	29.9	20.1	7.9	16.0	**5.7**
FD8	4.5	12.1	24.5	20.7	**10.0**	**23.2**	5.2
DEMON	2.7	12.2	**29.3**	**23.6**	9.6	17.6	5.0

Low flow cells (SCA ≤ 10 m^2 m^{-1})



High flow cells (SCA ≥ 5,300 m^2m^{-1})



Hypothesis #2

- Chose every 1000th cell and calculated differences between pairs of cell values
- Used matched paired t-test to test whether differences were significantly different than 0
- Compared t-test results by landscape class and flow routing algorithm

Matched pairs t-test

Used critical t-test values of ±1.96 (5%) and ±2.58 (1% level of significance)

Class 6 – Ridgelines

	D8	Rho8	D∞	FD8	DEMON
D8	--				
Rho8	-3.55	--			
D∞	-10.97	1.38	--		
FD8	-5.94	-3.67	-3.44	--	
DEMON	-10.93	-5.22	-6.81	1.16	--

Class 4 - North-facing slopes

	D8	Rho8	D∞	FD8	DEMON
D8	--	--	--	--	--
Rho8	-1.04	--	--	--	--
D∞	-2.20	-1.42	--	--	--
FD8	4.00	-3.33	-1.98	--	--
DEMON	-3.78	-1.09	0.76	3.08	--

Matched pairs t-test

Class 5 – South-facing slopes

	D8	Rho8	D∞	FD8	DEMON
D8	--	--	--	--	--
Rho8	-0.94	--	--	--	--
D∞	-2.24	0.40	--	--	--
FD8	-5.12	-0.45	-2.37	--	--
DEMON	-3.46	0.50	0.71	3.91	--

High elevation summary

	D8	Rho8	D∞	FD8	DEMON
D8	-				
Rho8	1	-			
D∞	3	0	-		
FD8	3	2	3	-	
DEMON	3	1	1	2	-

Matched pairs t-test

Class 2 – Moderately steep lower valley slopes

	D8	Rho8	D∞	FD8	DEMON
D8	--	--	--	--	--
Rho8	1.78	--	--	--	--
D∞	0.85	-1.96	--	--	--
FD8	-0.38	-2.26	-1.16	--	--
DEMON	-0.55	-2.16	-1.19	0.16	--

Class 3 - Stream channels

	D8	Rho8	D∞	FD8	DEMON
D8	--				
Rho8	1.02	--			
D∞	-0.94	-1.15	--		
FD8	-1.82	-1.44	0.82	--	
DEMON	2.40	0.08	1.17	2.71	--

Matched pairs t-test

Class 1 - Coastal plain / gentle slopes

	D8	Rho8	D∞	FD8	DEMON
D8	--	--	--	--	--
Rho8	-1.61	--	--	--	--
D∞	0.98	0.99	--	--	--
FD8	-1.13	-1.05	-1.00	--	--
DEMON	-0.19	1.01	-0.98	1.01	--

Low elevation summary

	D8	Rho8	D∞	FD8	DEMON
D8	-				
Rho8	0	-			
D∞	0	0	-		
FD8	0	1	0	-	
DEMON	1	1	0	1	-

T-test summary

- Number of landscape classes for which null hypotheses was rejected

	D8	Rho8	D∞	FD8	DEMON
D8	-				
Rho8	1	-			
D∞	3	0	-		
FD8	3	3	3	-	
DEMON	4	2	1	3	-

Distribution of low flow cells

Landscape Class	Number of Cells	Number of Cells with SCA ≤ 10 m^2m^{-1}				
		D8	Rho8	D∞	FD8	DEMON
Hilltops / ridgelines	256,012	114,186	79,789	64,966	39,215	23,583
Steep south-facing slopes	323,989	1,686	25,568	481	107	91
Steep north-facing slopes	231,180	5,630	18,584	331	72	86
Moderately steep lower valley slopes	169,173	37	8,245	175	15	9
Coastal plains / gentle slopes	177,787	39,893	36,526	28,995	16,709	9,960
Stream channels	103,888	35	459	94	62	27
Total Area	1,262,029	161,467	169,171	95,042	56,180	33,756

Distribution of high flow cells

Landscape Class	Number of Cells	Number of Cells with SCA ≥ 5,300 m^2m^{-1}				
		D8	Rho8	D∞	FD8	DEMON
Hilltops / ridgelines	256,012	0	13	15	0	1
Steep south-facing slopes	323,989	8	158	133	11	5
Steep north-facing slopes	231,180	5	137	159	6	6
Moderately steep lower valley slopes	169,173	949	1,439	1,669	1,013	810
Coastal plains / gentle slopes	177,787	801	1,221	1,494	884	793
Stream channels	103,888	26,866	25,744	27,853	27,896	25,678
Total Area	1,262,029	28,685	28,766	31,340	29,885	27,316

Wilson et al. – Summary

- Flow routing results vary systematically from top to bottom of catchments
- Previous studies have demonstrated that different groups of algorithms perform in similar ways
  - D8 and Rho8
  - D∞ and DEMON
  - FD8
- This outcome is partially repudiated by our results – Rho8 and D∞ are most similar and FD8 is most unique
- D8 and Rho8 have many undesirable properties and should be avoided as often as possible

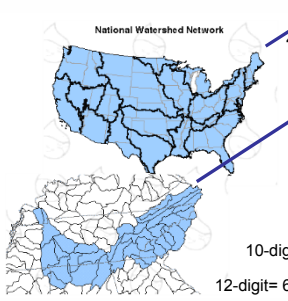
Enduring challenges

- Role of scale and landscape hierarchies
  - Characterizing local conditions with some consideration of topographic contexts
- Complex process feedbacks
  - Sensitivity of RHESSys model performance to model design decisions and SoLIM inputs
- Dynamic character of key processes
  - Quasi-dynamic topographic wetness index
  - Inclusion of cloud cover in solar radiation models
- Role of measurement, calibration, validation, and uncertainty
  - Difficulty of handling scale mismatches and possibility that process regimes change with time

Final Remarks

- Nine flow routing algorithms – numerous studies assessing variations in their performance
- Only one assessment looked at their ability to predict distribution of soil water content and hydrologic response of catchments
- Need greater investment in fieldwork and data modeling than is evident in papers published in past 20 years … to connect the precipitation falling on land surface with hydrologic response of catchment

Hydrologic Units



2-digit= 1st level = 22 regions

4-digit= 2nd level = 222 subregions

6-digit= 3rd level = 789 accounting

8-digit= 4th level = 2223 cataloging

new!

10-digit= 5th level = ~22,000 watersheds

12-digit= 6th level = ~160,000 subwatersheds

Slide Courtesy of Bob Pierce