MATHEMATICAL MORPHOLOGY IN GEOSCIENCES AND GISci

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FOUNDING FATHERS OF MATHEMATICAL MORPHOLOGY Georges Matheron Jean Serra



My Connection Degree





Two-degree separation with Georges Matheron (through SVLN Rao and Jean Serra)



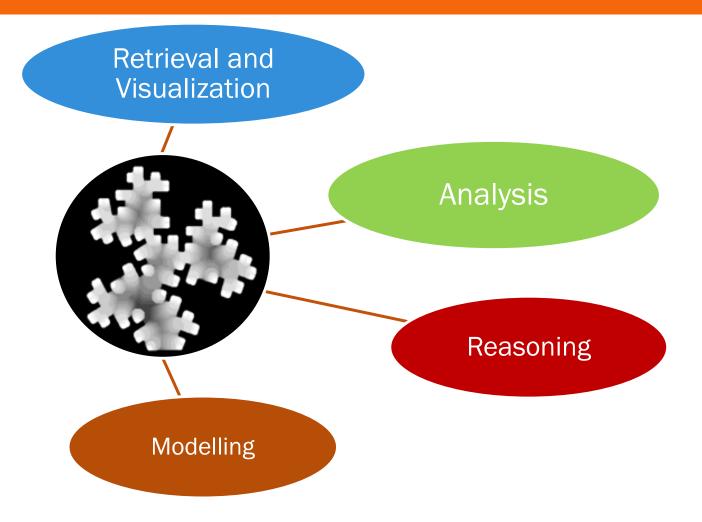
SVLN Rao (v. 31, no. 2, *Mathematical* Geosciences; Associate Editor for MG 1975-77).

Motivation

To understand the dynamical behavior of a phenomenon or a process, development of a good **spatiotemporal model** is essential. To develop a good spatiotemporal model, well-**analyzed** and well-**reasoned information** that could be **extracted** / **retrieved** from spatial and/or temporal data are important ingredients.

Mathematical Morphology is one of the better choices to deal with all these key aspects mentioned.

Mathematical Morphology in Spatial Informatics





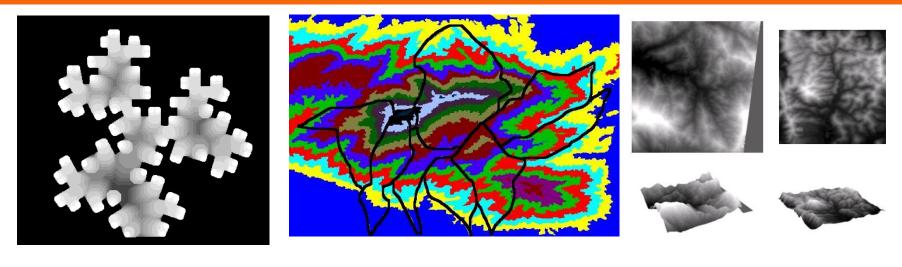
Basic description of Multivalued Functions (e.g.: Terrestrial Data)

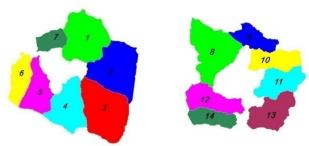
Mathematical Morphology in Image Analysis and Spatial Informatics

Retrieval of unique phenomena (e.g. Networks), Analysis and quantitative characterization of unique phenomena and processes via various metrics

Spatial interpolation, Spatio-temporal modeling, spatial reasoning, spatial information visualization

Digital Elevation Models





I. Mathematical Morphology

Binary Mathematical Morphology

Grayscale Morphology

Mathematical Morphology: Recent Advances



Adaptive Mathematical Morphology

Concepts, Techniques & Tools

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- Morphological Skeletonization
- Multiscale operations, Hierarchical segmentation
- Recursive Morphological Pruning
- Hit-or-Miss Transformation
- Morphological Thinning
- Morphological Reconstruction
- Watersheds
- Morphological shape decomposition
- Granulometries
- Hausdorff dilation (erosion) distance
- Morphological interpolation
- Directional Distances
- SKIZ and WSKIZ

Mathematical Morphological Operations

The mathematical morphological transformations useful to develop elegant

algorithms to address the challenges in relation to Image Analysis and Spatial Informatics include:

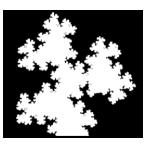
- Morphological Erosion
- Morphological Dilation
- Morphological Opening
- Morphological Closing
- Multiscale Morphological Operations
- Hit-or-Miss Transformation
- Morphological Thinning , Thickening, Pruning
- Geodesic Morphological Operations
- Morphological Skeletonization
- Skeletonization by Zones of Influence
- Weighted Skeletonization by Zones of Influence
- Granulometries and Anti-Granulometries
- Morphological Distances
- Hausdorff Dilation Distances
- Hausdorff Erosion Distances
- Morphological Interpolations and Extrapolations
- The implementations of the aforementioned transformations binary, grayscale, graph and geodesic domains

Spatial Data : Various Representations

Functions (DEMs, Satellite Images, Microscopic Images etc)



Sets (Thresholded Elevation regions, Binary images decomposed from images)



Skeletons (Unique topological networks)



Basic Transformations

Mathematical Morphology Dilation Erosion Opening Closing

Binary MM

Binary erosion transformation of X by structuring element, B

• the set of points s such that the translated B_x is contained in the original set X, and is equivalent to intersection of all the translates.

$$X \ominus B = \{x: B_x \subseteq X\} = \bigcap_{b \in B} X_{-b}$$

- Binary dilation transformation of X by B
 - the set of all those points s such that the translated B_x intersects X, and is equivalent to the union of all translates.

$$X \oplus \mathsf{B} = \{ x : B_x \cap X \quad \mathcal{A} \} = \bigcup_{b \in B} X_b$$

- ⁵⁰ The dilation with an elementary structuring template expands the set with a uniform layer of elements, while the erosion operator eliminates a layer from the set.
- Multiscale erosions and dilations are

 $-(X \ominus B) \ominus B \ominus \dots \ominus B = (X \ominus nB),$

 $-(X\oplus B)\oplus B\oplus \ldots\oplus B=(X\oplus nB),$

where $nB = B \oplus B \oplus ... \oplus B$ and *n* is the number of transformation cycles.

Binary MM (cont)

- By employing erosion and dilation of X by B, opening and closing transformations are further represented as:
 - $X \circ B = ((X \ominus B) \oplus B))$
 - $\circ \quad X \bullet B = ((X \oplus B) \ominus B))$
- After eroding X by B, the resultant eroded version is dilated to achieve the opened version of X by B.
- Similarly, closed version of X by B is obtained by first performing dilation on X by B and followed by erosion on the resultant dilated version.
- Multiscale opening and closing transformations are implemented by performing erosions and dilations recursively as shown below.

 $-(X \circ nB) = [(X \ominus nB) \oplus nB)],$

 $-(X \bullet nB) = [(X \oplus nB) \ominus nB)],$

where *n* is the number of transformations cycles.

Greyscale MM

- Greyscale dilation and erosion operations expansion and contractions respectively
- Let f(x,y) be a function on Z^2 , and B be a fixed structuring element of size one. The erosion of f(x) by B replaces the value of f at a pixel (x, y) by the minima values of the image in the window defined by the structuring template B

$$(f \bigoplus^{\circ} B)(x, y) = \min_{(i, j) \in B} \{f(x+i, y+j)\}$$

The dilation of f(x) by B replaces the value of f at a pixel (x, y) by the maxima values of the image in the window defined by the structuring template B

$$(f \oplus B)(x, y) = \max_{(i,j)\in B} \{f(x-i, y-j)\}$$

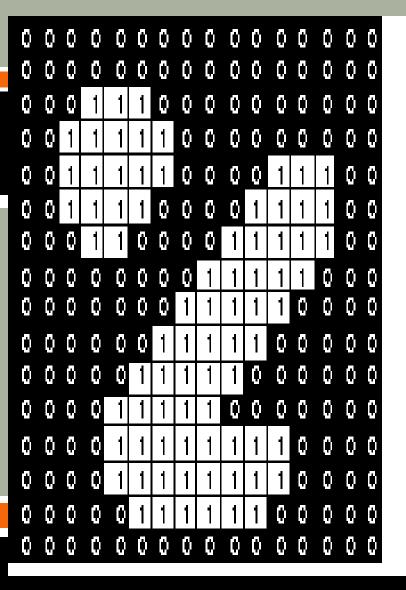
- In other words, $(f \ominus B)$ and $(f \oplus B)$ can be obtained by computing *minima* and *maxima* over a moving template *B*, respectively.
- **Erosion is the dual of dilation :**
 - Eroding foreground pixels is equivalent to dilating the background pixels.

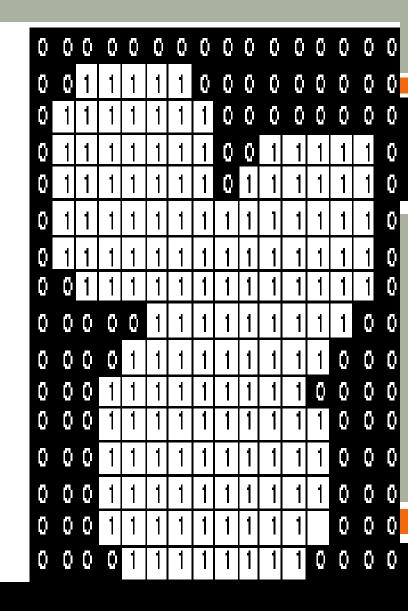
Grey-scale MM (cont)

- Opening and closing are both based on the dilation and erosion transformations.
- Opening of f by B is achieved by eroding f and followed by dilating with respect to B, $(f \circ B) = [(f \ominus B) \oplus B]$,
- Closing of *f* by *B* is defined as the dilation of *f* by *B* followed by erosion with respect to B, $(f \bullet B) = [(f \oplus B) \ominus B],$
- Opening eliminates specific image details smaller than B, removes noise and smoothens the boundaries from the inside, whereas closing fills holes in objects, connects close objects or small breaks and smoothens the boundaries from the outside.
- Multiscale opening and closing can be performed by increasing the size (scale) of the structuring template nB, where n = 0, 1, 2, ..., N. These multiscale opening and closing of f by B are mathematically represented as: $(f \circ nB) = \{[(f \ominus B) \ominus B \ominus ... \ominus B] \oplus B \oplus B \oplus ... \oplus B\} = [(f \ominus nB) \oplus nB], (f \circ nB) = \{[(f \oplus B) \oplus B \oplus ... \oplus B] \ominus B \ominus B \ominus ... \ominus B\} = [(f \oplus nB) \ominus nB], at scale <math>n = 0, 1, 2, ..., N$.
- Performing opening and closing iteratively by increasing the size of B transforms the function f(x,y) into lower resolutions correspondingly.

- Multiscale opening and closing of f by nB effect spatially distributed greyscale regions in the form of smoothing of contours to various degrees. The shape and size of B control the shape of smoothing and the scale respectively.
- Important problems like feature detection and characterisation often require analysing greyscale functions at multiple spatial resolutions. Recently, non-linear filters have been used to obtain images at multi-resolution due to their robustness in preserving the fine details.
- Advantages of mathematical morphology transformations
 - popular in object recognition and representation studies.
 - The non-linearity property in preserving the fine details.

Effect of Dilation using 3X3 structuring element

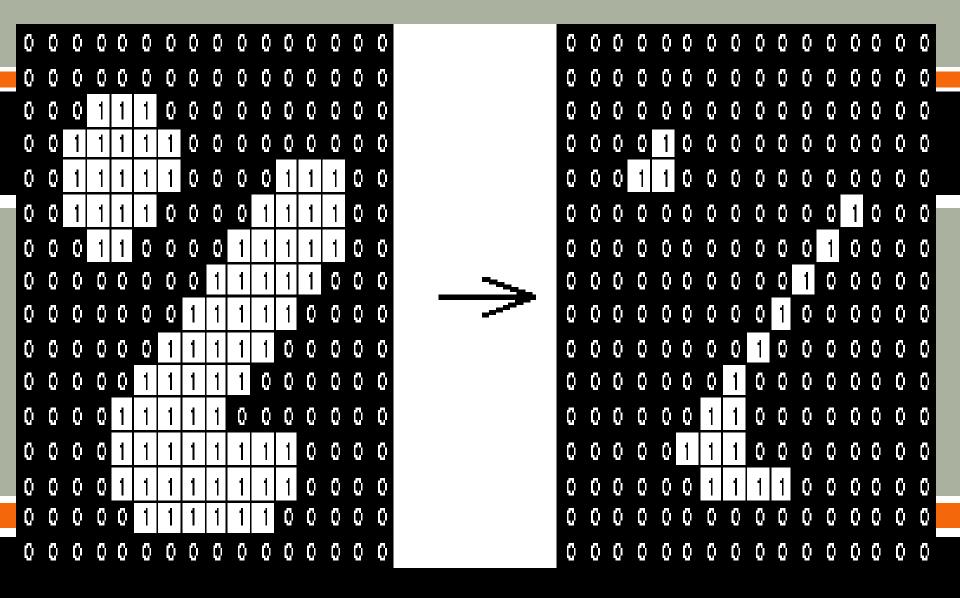




Steps in Dilation of X by B

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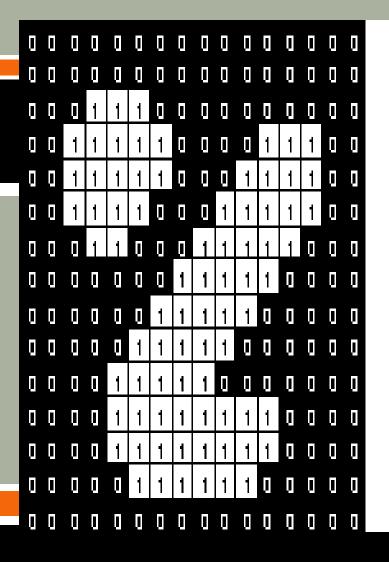
Effect of Erosion using 3X3 structuring element

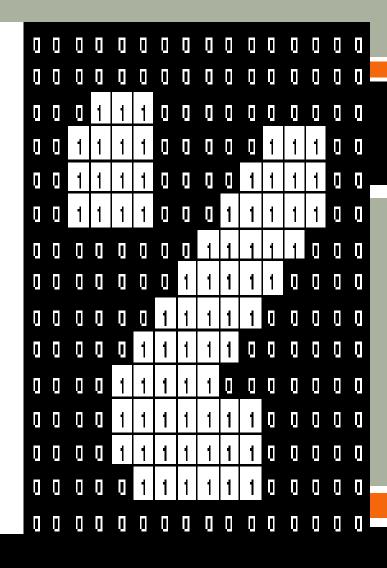


Steps in Erosion of X by B

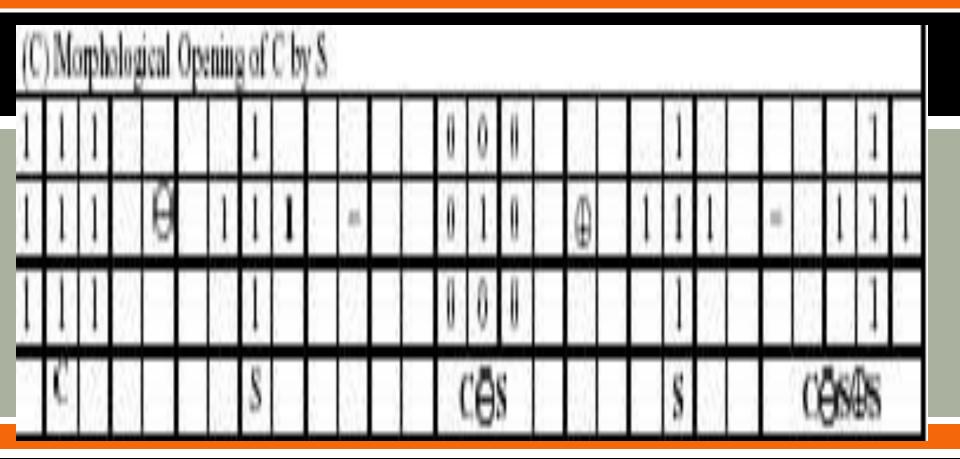
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Effect of Opening using 3X3 structuring element

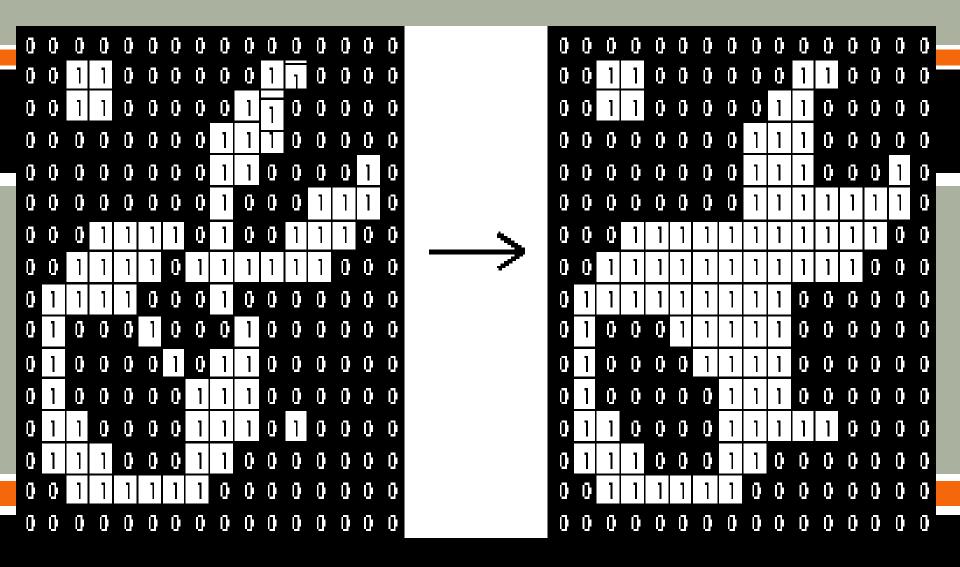




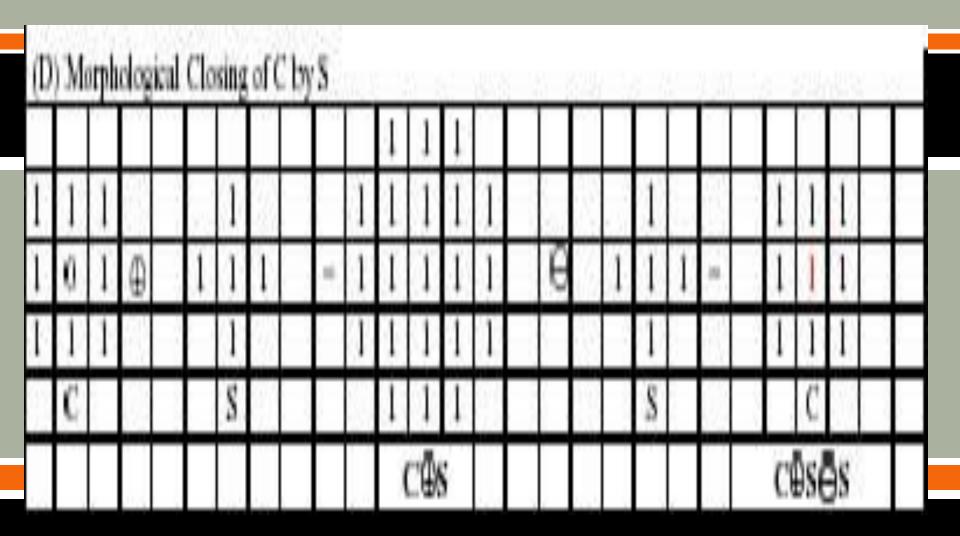
Steps in Opening of X by B

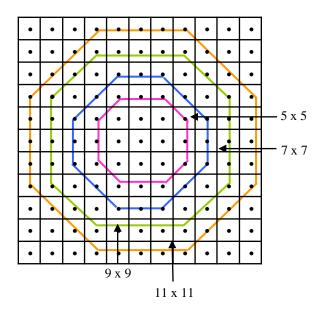


Effect of Closing using 3X3 structuring element



Steps in Closing of X by B





Octagonal symmetric structuring elements of various primitive sizes ranging from 5×5 to 11×11 . These primitive sizes can be considered as B.

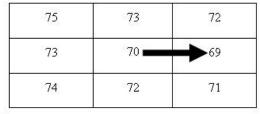
Important phases of Research related to Image Analysis

- I. Information Retrieval
 II. Information Analysis
 III. Information Reasoning
 IV. Information Modelling and Simulation
 V. Information Visualization
 Is there a single mathematical field that can address Research related to Digital Images?
- **Deal Images with Mathematical Morphology!**

II.I NETWORKS EXTRACTION & THEIR PROPERTIES

Networks extraction and their properties : Sub-basins delineation

- Geomorphologic basin is an area outlined by a topographic boundary that diverts water flow to stream networks flowing into a single outlet.
- DEM is an useful source for watershed and network extraction.
- Hydrologic flow is modelled using eight-direction pour point model (Puecker et. al., 1975).

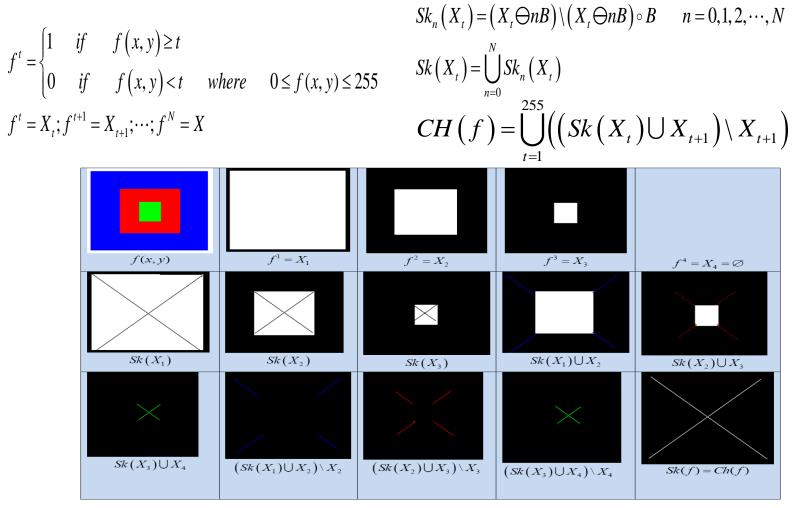


- The two topologically significant networks, include Channel & Ridge networks.
- 50 The paths of these extracted networks are the crenulations in the elevation contours.
- Crenulations can be isolated from DEMs by using nonlinear morphological transformations.

Network Extraction: <u>Binary Morphology-Based</u>



Equations for Network Extraction



Networks extraction: Grayscale Morphology-Based

The DEM, *f* is first eroded by B_n with n=1, 2,...,N, and the eroded DEM is opened by *B* of the smallest size. The opened version of each eroded image is subtracted from the corresponding eroded image to produce the *n*th level subsets of the ridge network. Union of these subsets of level n = 0 to *N* gives the ridge network for the DEM.

$$\operatorname{RID}_{n}^{i}(f) = [(f \ominus B_{n}^{i}) \setminus \{ [(f \ominus B_{n}^{i}) \ominus B_{n}^{i}] \oplus B_{n}^{i} \}]$$
$$\operatorname{RID}(f) = \bigcup_{n=0}^{4} [\operatorname{RID}_{n}^{i}(f)]$$

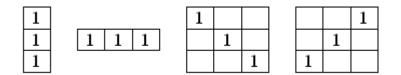
i=1

Networks extraction and their properties

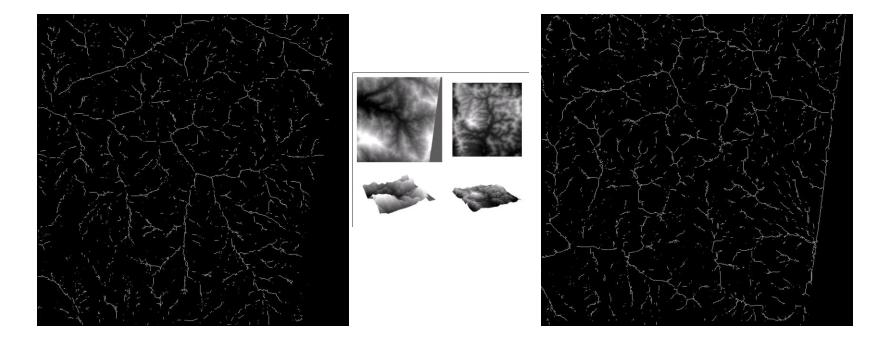
DEM, *f* is first dilated by B_n and the dilated *f* is closed by *B* of the smallest size. The closed version of each dilated image is subtracted from the corresponding dilated image to produce the *n*th level subsets of the channel network. Union of these subsets of level *n* = 0 to *N* gives the channel network for the DEM.

$$CH_{n}^{i}(f) = [(f \oplus B_{n}^{i}) \setminus \{[(f \oplus B_{n}^{i}) \oplus B_{1}^{i}] \ominus B_{1}^{i}\}]$$
$$CH(f) = \bigcup_{\substack{n=0\\i=1}}^{4} [CH_{n}^{i}(f)]$$

1-D structuring elements of primitive size

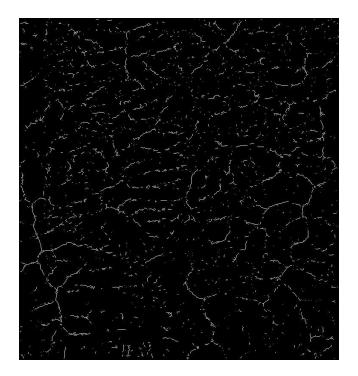


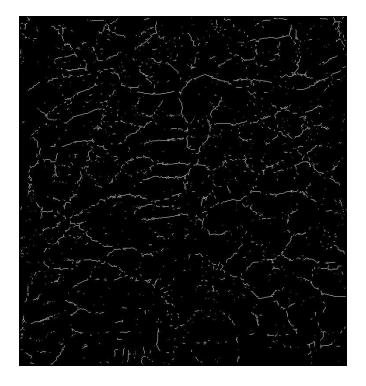
Networks extraction and their properties



(a) Ridge networks, and (b) channel networks extracted from Cameron Highlands DEM.

Networks extraction and their properties





(a) Ridge networks, and (b) channel networks extracted from Petaling DEM.

Algorithm

- Step-1: Algorithm is to extract singular networks such as channel and ridge connectivity networks from step-2 DEMs.
- Sub watershed boundary in DEM is automatically generated by considering channel and so Step-3: ridge connectivity networks.
- Mathematical morphology ∞ Step-4 transformations such as dilation, erosion, opening and closing are used in this algorithm.

$$\begin{aligned} & \operatorname{CH}_{\epsilon}(M) = \epsilon_{s}^{\ell}(M) / \gamma_{s}^{1} \{ \epsilon_{s}^{\ell}(M) \} \\ & e = 0, 1, 2, \dots, N \end{aligned}$$

CH (M) =
$$\bigcup_{e=0}^{N} CH_{e}(M)$$

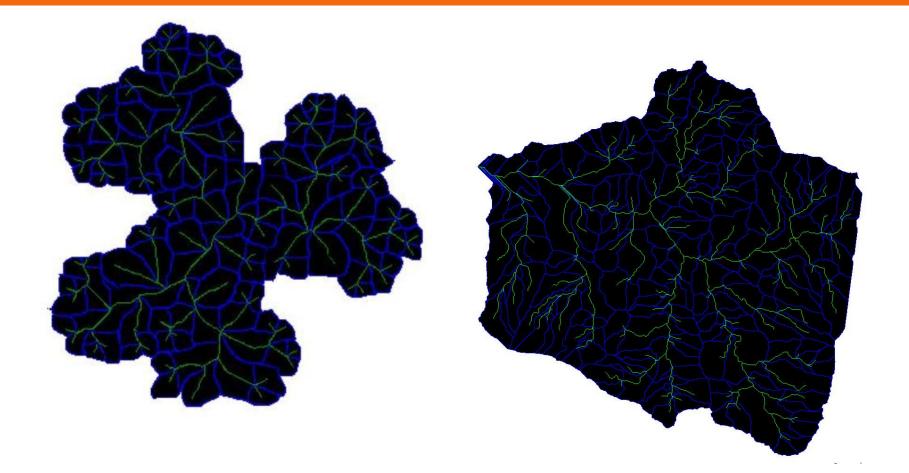
e = 0,1,2,...,n

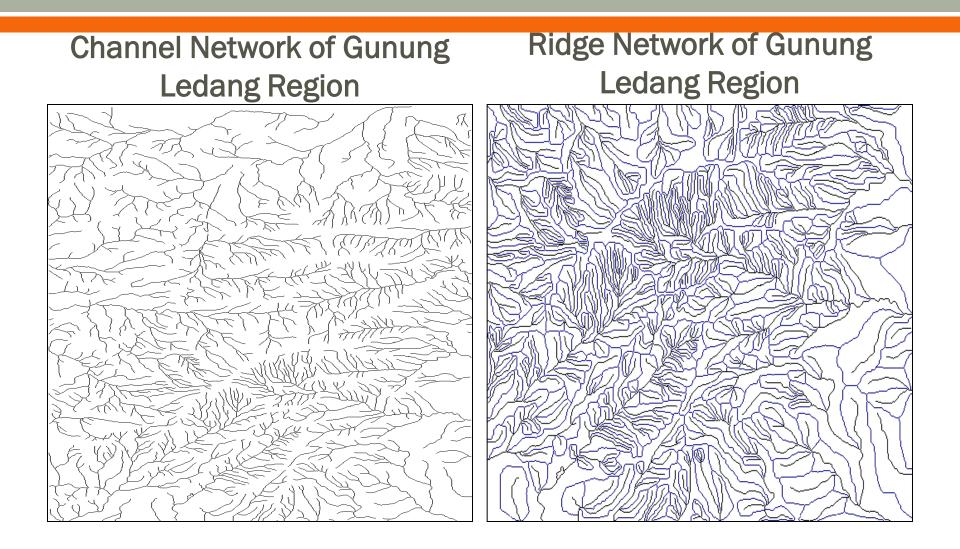
$$\operatorname{RID}_{e}(M) = e_{s}^{e} \{ (\operatorname{CH}(M))^{c} \} / (\gamma_{s}^{1} \{ e_{s}^{e} \{ (\operatorname{CH}(M))^{c} \} \}$$

$$RID(\mathbf{M}) = \bigcup_{e=1}^{N} RID_{e}(\mathbf{M})$$
$$e = 0, 1, 2, \dots, n$$

∞ Step-5

Decomposed basins and networks





Networks : Binary Vs Grayscale

Binary Morphology

Binary morphology-based network extraction is:

- more stable,
- more accurate, and
- computationally expensive

Gray-scale Morphology

Grayscale-based network extraction—

- may not be accurate like binary-morphology based—
 - generates network that yields disconnections some times, but
- computationally not expensive.

II.II. Terrestrial Analysis

Scale invariance and Power-laws in networks

Shape-dependant power-laws

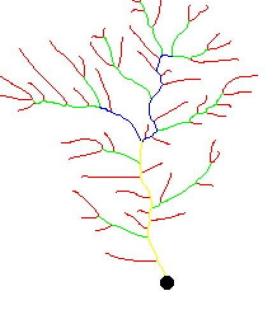
Granulometric analysis

II.II.I. Scale Invariant Power-laws: Morphometry and Allometry of Networks

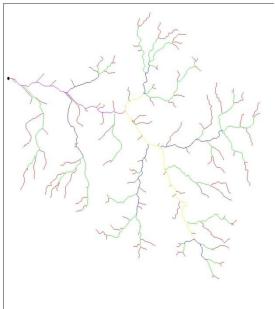
First step in drainage basin analyses is the classification of stream orders by Hortonordering Strahler's system (Horton, 1945; Strahler, 1957). The order of the whole tree is defined to be the order of the root. This ordering system has been found to correlate well with important basin properties wide in a range of environments.

This figure shows a sample network classified based on Horton-Strahler's ordering system.

13 April 2015



First order
Second order
Third order
Forth order
Outlet
Model network.



First order
 Second order
 Third order
 Forth order
 Outlet

Cameron Highland channel network.

Scale Invariant Power-laws: Two Topological Quantities

Two topological quantities bifurcation ratio $(R_{\rm b})$ and length ratio $(R_{\rm l})$ େ

$$R_{b} = \frac{N_{i}}{N_{i+1}}$$
 $R_{1} = \frac{L_{i}}{L_{i-1}}$

Networks extraction and their properties : <u>Morphometry</u>

Besides these two ratios, the universal similarity of stream network can େ be shown through Hack's law and Hurst's law as follows:

^{so} Hack's Law:
$$L_{\rm mc} \propto A^h$$

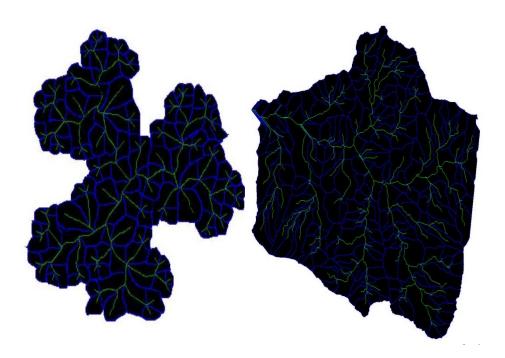
where A is the area of basin with main channel length L_{mc} .

 $T^+ \propto T_{H}^+$ <u>Hurst's law</u>: େ where L_{11} is the longitudinal length and L transverse length respectively.

Allometric power-laws

- Allometric power-laws are derived between the basic measures such as basin area, basin perimeter, channel length, longitudinal length and transverse length
- Observed that these powerlaws are of universal type as they exhibit similar scaling relationships at all scales.

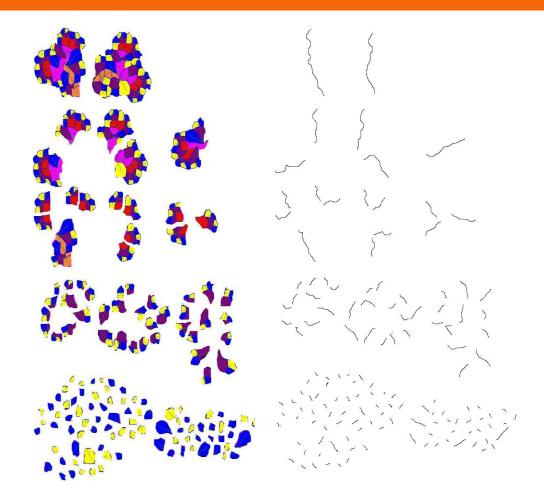
Existing allometric power-laws: Decomposed basins & networks



Existing allometric power-laws : Decomposed basins and networks

The number of decomposed sub-basins of respective orders from the simulated 6th order F-DEM include:

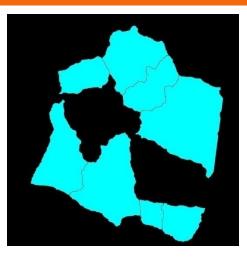
- two 5th
- five 4th
- ten 3rd
- thirty six 2nd, and
- eighty six 1st order basins.

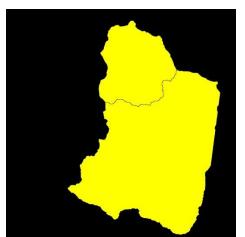


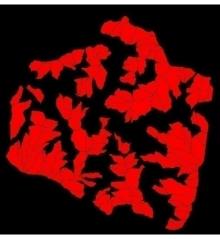
Existing allometric power-laws : <u>Decomposed basins and networks</u>











Decomposed sub-basins

are

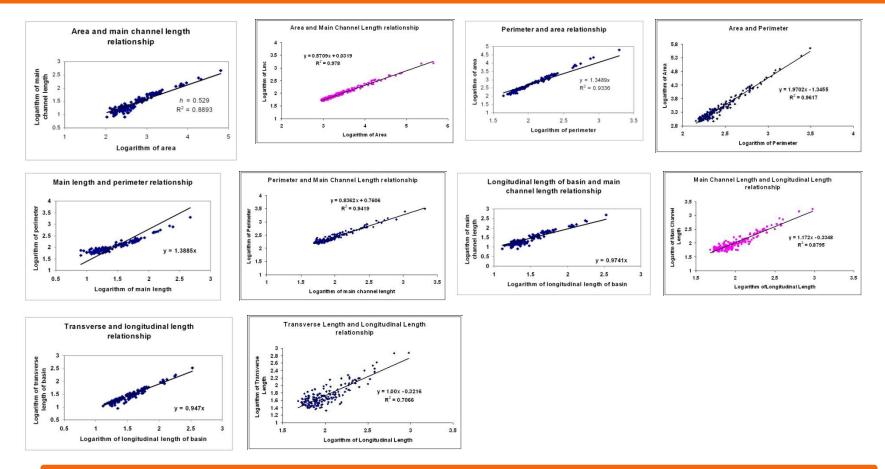
- two 4th
- eight 3rd
- twenty-eight 2nd, and
- one hundred twenty-four 1st order basins.

Existing allometric power-laws : Basic Measures



Basic measures for a basin, (a) basin area, (b) total channel length, (c) main channel length, (d) basin perimeter, (e) longitudinal length and (f) transverse length.

Scale Invariant allometric power-laws



Allometric relationships among various areal and length parameters for all sub-basins of F-DEM and TOPSAR DEM.

Scale Invariant allometric power-laws F-DEM TOPSAR DEMs

Relations	Notatio							
	ns	all orders	1	2	3	4	5	6
A and L_{mc}	h	0.53	0.502	0.56	0.56	0.55	0.55	0.56
A and P	α	1.35	1.31	1.36	1.41	1.44	1.48	1.46
P and L_{mc}	β	1.39	1.51	1.32	1.28	1.26	1.23	1.23
\boldsymbol{L}_{mc} and \boldsymbol{L}_{ll}	-	0.97	0.92	1.01	1.04	1.03	0.94	0.95
L_{\perp} and L_{\parallel}	Н	0.95	0.94	0.94	0.96	0.98	0.94	0.98
2h	D _{Lmc}	1.06	1.00	1.11	1.11	1.10	1.10	1.12
2/α	D _p	1.48	1.53	1.47	1.42	1.39	1.35	1.37
$1 + \frac{D_{Lmc}}{1 + H}$	-	1.55	1.52	1.57	1.59	1.56	1.57	1.57

Relations	Notatio	For all orders	Basin's order					
	ns		1	2	3	4	5	
A and L_{mc}	h	0.57	0.60	0.57	0.50	0.58	0.56	
A and P	α	1.97	1.62	1.78	1.78	1.69	1.62	
P and L_{mc}	β	0.84	0.78	0.92	0.88	1.09	1.05	
$\rm L_{mc}$ and $\rm L_{ll}$	-	1.17	0.75	1.00	0.92	1.02	1.08	
L_{\perp} and L_{\parallel}	Н	1.00	0.39	0.53	0.68	1.00	0.97	
2h	$\mathrm{D}_{\mathrm{Lmc}}$	1.14	1.20	1.14	1.00	1.16	1.12	
2/ a	D_p	1.02	1.23	1.12	1.12	1.18	1.23	
$1 + \frac{D_{Lmc}}{1 + H}$	-	1.57	1.86	1.74	1.60	1.58	1.57	

Existing allometric power-laws : Scaling laws

Our results shown for basins derived from F-DEM and TOPSAR DEM are in good accord with power-laws derived from Optimal Channel Networks (Maritan et. al., 2002) and Random Self-Similar Networks (Veitzer and Gupta 2000) and certain natural river basins.

Novel scaling relationships between travel-time channel networks, convex hulls and convexity measures

Network topology and watershed geometry are important features in terrain characterization.

Travel-time networks are sequence of networks generated by removing the extremities of the network iteratively. Hit-or-Miss transformation and Thinning transformations is used in generating travel-time network. Half-plane closing-based algorithm (Soille, 2005) is employed to generate convex hulls for these travel-time networks.

Length of the travel-time network and area of the corresponding convex hull are used to derive new scaling exponents.

Travel-time networks

- The process of deleting the end points from the networks is named as pruning.
- To decompose the stream network subsets from n = 1 to N, structuring template of B_1 and B_2 are decomposed into various subsets, B_n^i where i = 1, 2, ..., 8 and n = 1, 2
- Both structuring templates are disjointed into eight directions. The intersecting portion of eroded S and eroded Sc by disjointed templates $\{B_1^k\}$ and $\{B_2^k,\}$ k = 1,2,...,8respectively are computed to derive pruned version of S.
- The X's in the structuring templates signifies the 'don't care' condition – it doesn't matter whether the pixel in that location has a value of 0 or 1.

$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccc} 0 & 0 & 1 \\ B_1^2 = 0 & 1 & 0 \\ 0 & 0 & 0 \end{array}$	$\begin{array}{cccc} 0 & 0 & 0 \\ B_1^3 = 0 & 1 & 0 \\ 0 & 0 & 1 \end{array}$	$\begin{array}{cccc} 0 & 0 & 0 \\ B_1^4 = 0 & 1 & 0 \\ 1 & 0 & 0 \end{array}$
$\begin{array}{cccc} & \times & 1 & \times \\ B_1^5 = 0 & 1 & 0 \\ 0 & 0 & 0 \end{array}$	$\begin{array}{cccc} 0 & 0 & X \\ B_1^6 = 0 & 1 & 1 \\ 0 & 0 & X \end{array}$	$\begin{array}{cccc} 0 & 0 & 0 \\ B_1^7 = 0 & 1 & 0 \\ \times & 1 & \times \end{array}$	$ \begin{array}{cccc} X & 0 & 0 \\ B_1^8 = 1 & 1 & 0 \\ X & 0 & 0 \end{array} $
$\begin{array}{cccc} 0 & 1 & 1 \\ B_2^1 = 1 & 0 & 1 \\ 1 & 1 & 1 \end{array}$	$ \begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	$\begin{array}{ccccc} 1 & 1 & 1 \\ B_2^3 = 1 & 0 & 1 \\ 1 & 1 & 0 \end{array}$	$\begin{array}{ccccccc} 1 & 1 & 1 \\ B_2^4 = 1 & 0 & 1 \\ 0 & 1 & 1 \end{array}$
$\begin{array}{ccc} X & 0 & X \\ B_2^5 = 1 & 0 & 1 \\ 1 & 1 & 1 \end{array}$	$\begin{array}{cccc} 1 & 1 & X \\ B_2^6 = 1 & 0 & 0 \\ & 1 & 1 & X \end{array}$	$B_2^7 = 1 0 1 \\ X 0 X$	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$

Proposed scaling relationships : Travel-time networks

So Mathematically,

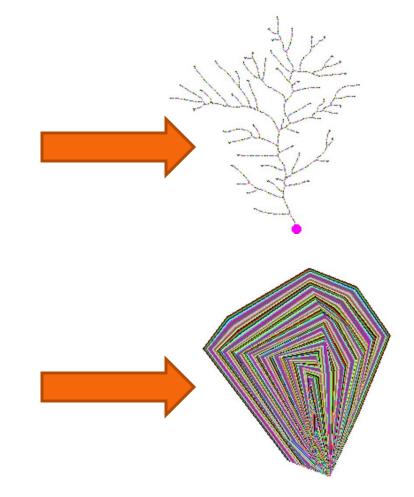
 $S * B = (S \ominus B_1^k) \cap (S^c \ominus B_2^k)$, where $B = B_1^k \cup B_2^k$

- By subtracting (S * B) from S, a pruned version of S is obtained and expressed as
- So $S_1 = S \otimes \{B\}$ where, $S \otimes \{B\} = S (S * B))$ So $\{B\}$ is the sequence of $\{(B_1^1, B_1^2, \dots, B_1^8), (B_2^1, B_2^2, \dots, B_2^8)\}$
- After pruning of S in first pass with B_1 , the process continue with pruning with B_2 and so on until S is pruned in the last pass with B_8 . $S \otimes \{B\} = ((\cdots ((S \otimes B^1) \otimes B^2) \cdots) \otimes B^8)$
- ⁵⁰ The whole process removes the first-encountered open pixels of S and produces S_1 .
- Repeating the same process on S_1 will produce S_2 . The process is repeated until no further changes occur, where the closed outlet is reached.

Proposed scaling relationships : Convex hull

Convex hull is the smallest convex set that contains all the points of the network.

Since convex hull represents the basin of network, convex hulls of the travel-time networks are generated.



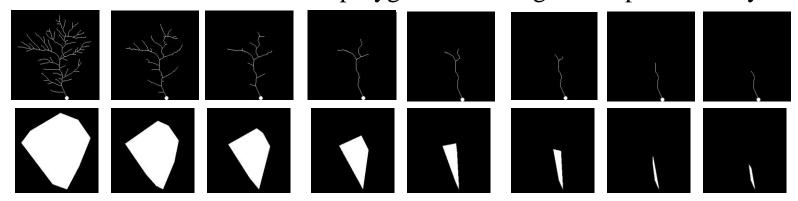
Proposed scaling relationships : Pruned network and convex hull

Properties of the pruned network:

1.
$$S = \bigcup_{n=0}^{N-1} (S_n - S_{n+1})$$

$$2. \quad S_N \subset S_{N-1} \subset \cdots \subset S_2 \subset S_1 \subset S$$

3. S, S_1, S_2, \dots, S_N obtained by iterative **pruning**. The final convex polygon containing all the points of S yields C(S).



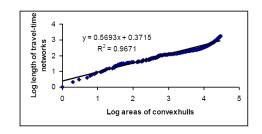
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- Network pruning network length = S_n
- Convex hull computed 80 convex hull area = $C(S_n)$
- ∞ Convexity measures, CM = ratio between the areas of S_n and $C(S_n)$.

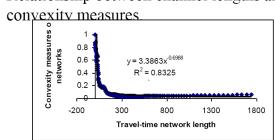
$$L(S_n) \sim A[C(S_n)]^{\alpha}$$
$$CM(S_n) \sim \frac{1}{L(S_n)^{\beta}}$$

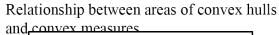
$$CM(S_n) \sim \frac{1}{A[C(S_n)]^{\lambda}}$$

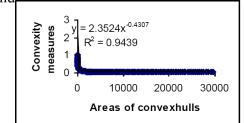
Graph of lengths of the sequential pruned networks versus the corresponding areas of convex hulls.



Relationship between channel lengths and



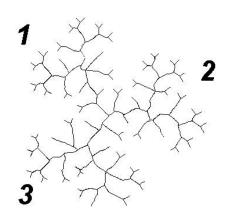


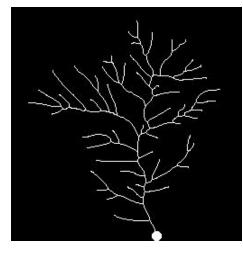


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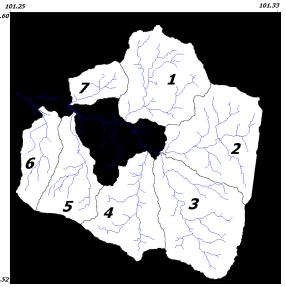
B. S. Daya Sagar

Sample basin
Simulated F-DEM basins
Cameron basins
Petaling basins









Network	α, (R ²)	σ, R ²	λ, R ²	R _b	R ₁	h	Н
Sample	0.5693, (0.9671)	0.6988, (0.8325)	0.4307, (0.9439)	3.84	1.66	-	-
Basin 1 (Cameron)	0.5777, (0.9883)	0.7109, (0.9358)	0.4223, (0.9783)	3.60	2.21	0.5414	0.9714
Basin 2 (Cameron)	0.5774, (0.9925)	0.7189, (0.9586)	0.4226, (0.9861)	4.35	2.25	0.5561	1
Basin 3 (Cameron)	0.5799, (0.9934)	0.7131, (0.963)	0.4201, (0.9875)	3.31	2.39	0.5612	0.9256
Basin 4 (Cameron)	0.5521, (0.9835)	0.7814, (0.92)	0.4479, (0.9752)	4.47	3.18	0.5671	0.9506
Basin 5 (Cameron)	0.5798, (0.9905)	0.7083, (0.9469)	0.4202, (0.982)	3.31	2.16	0.5766	0.9162
Basin 6 (Cameron)	0.5819, (0.9865)	0.6955, (0.925)	0.4181, (0.9743)	4.00	2.64	0.5746	0.8597
Basin 7 (Cameron)	0.5885, (0.9887)	0.68, (0.9348)	0.4115, (0.9772)	2.82	2.39	0.5548	0.895
Basin 1 (Petaling)	0.5462, (0.969)	0.7741, (0.8561)	0.4538, (0.9557)	5.00	2.57	0.5568	0.9319
Basin 2 (Petaling)	0.5393, (0.9899)	0.8357, (0.9532)	0.4607, (0.9863)	4.00	3.51	0.5828	0.8623
Basin 3 (Petaling)	0.5198, (0.9852)	0.8953, (0.9367)	0.4802, (0.9827)	4.24	3.30	0.597	0.9019
Basin 4 (Petaling)	0.5592, (0.9938)	0.7771, (0.9684)	0.4408, (0.99)	4.24	2.96	0.5807	0.8902
Basin 5 (Petaling)	0.5729, (0.9906)	0.729, (0.9492)	0.4271, (0.9832)	4.79	3.96	0.5844	0.8704
Basin 6 (Petaling)	0.5547, (0.9872)	0.7798, (0.937)	0.4453, (0.9804)	4.89	3.42	0.5713	0.9116
Basin 7 (Petaling)	0.6059, (0.9929)	0.6387, (0.9551)	0.3941, (0.9834)	3.60	3.39	0.5865	0.8312

Allometric power-laws between travel-time channel networks, convex hulls, and convexity measures for model network, networks of Hortonian fractal DEM, and networks of fourteen basins of Cameron Highlands and Petaling region.

These proposed scaling exponents are shown for basins derived from simulated F-DEM and TOPSAR DEMs.

These exponents are scale-independent.

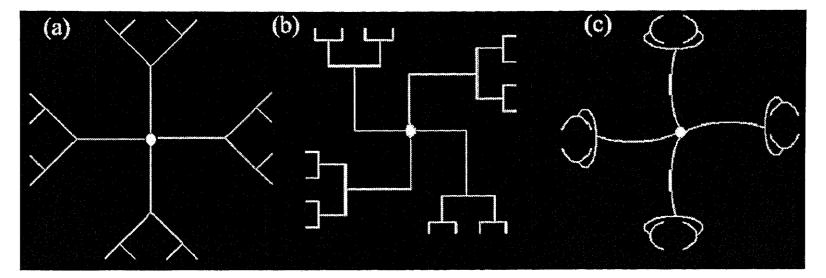
At macroscopic level, these exponents complement with other existing scaling coefficients can be used to identify commonly sharing generic mechanisms in different river basins.

II.II.II. Scale Invariant But Shape Dependent Power-laws



To propose morphology based method via fragmentation rules to compute scale invariant but shape-dependent measures of non-network space of a basin.

To make comparisons between morphometry based parameters / dimensions and dimensions derived for non-network space.



Topologically Invariant networks with variant geometric organization

Proposed Technique

Step1: Channel network is traced from topographic map.

Step2: Channel network is dilated and eroded iteratively until the entire basin is filled up with white space. This step is to generate catchment boundary automatically. Dilation followed by erosion is called structural closing, which will smoothen the image.

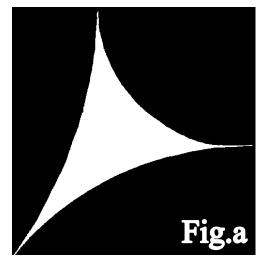
Step3: Generate the basin with channel network and non-network space with boundary by subtracting the channel network from the catchment boundary achieved in Step2.

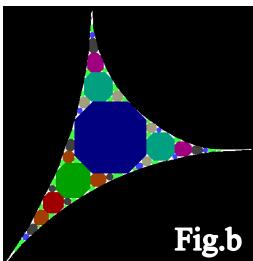
Step4: Structural opening (erosion followed by dilation) is performed recursively in basin achieved in Step3 to fill the entire basin of non-network space with varying size of octagons.

Step5: Assign unique color for each size of octagons.

Step6: Compute morphometry for the basin.

Step7: Compute shape dependent dimension.





Power law relationship

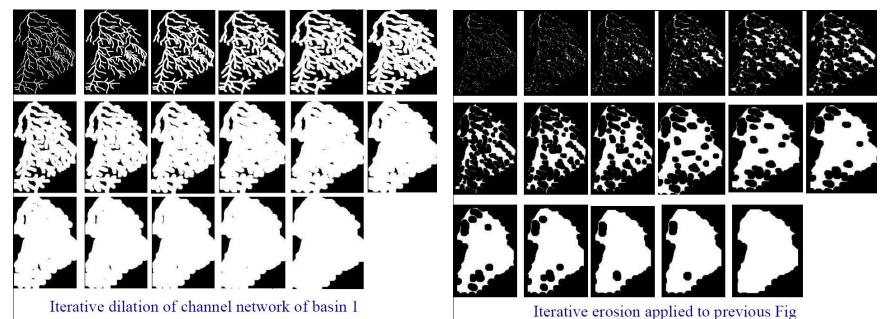
- As per the previous fig. the slopes of the best-fit lines (α_N and α_A) for number-radius and area-radius relationships yield 2.37 and 1.34.
- These slope values of the best-fit lines provide shape dependent dimensions as $D_N = \alpha_N - 1$ and $D_A = \alpha_A$.
- As in previous Fig., D_N and D_A for non-network space yield 1.37 and 1.34.
- A Power-law relationship is shown in earlier Fig. with an exponent value 1.79 between the area and number of NODs observed with increasing radius of structuring template.

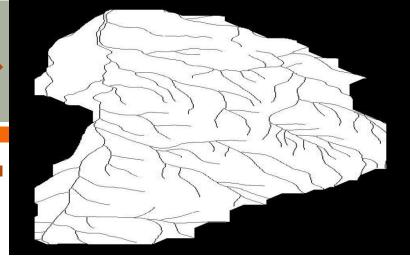
(a) Appollonian Space, and (b) after decomposition by means of octagon.

Algorithm Implementation:

Step 1: Channel network of sub basin 1

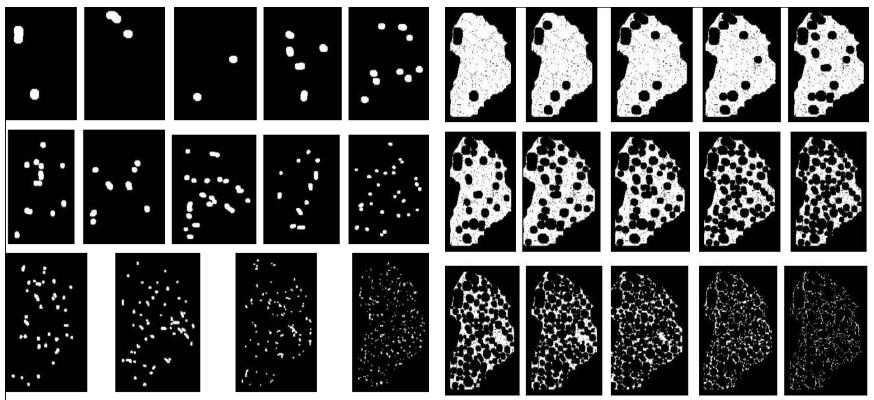
Step 2: Close-Hull Generation





Step 3: Non-network space of basin 1

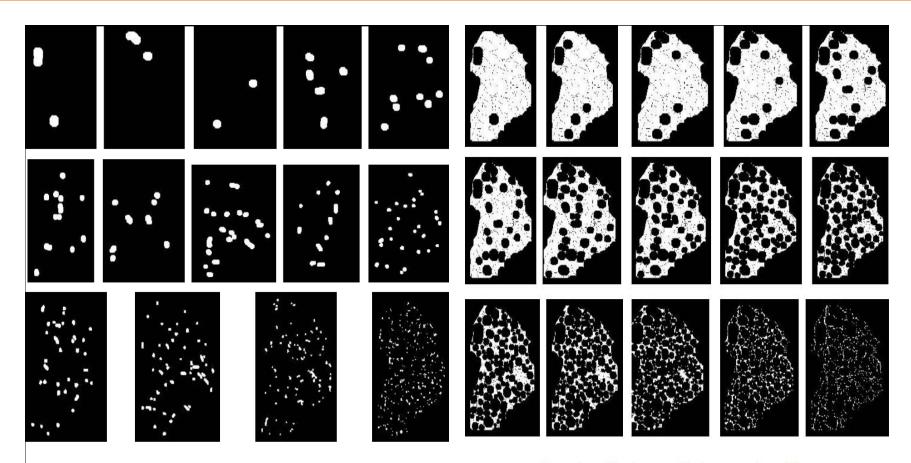
Iterative erosion applied to step-3 Fig.



Iterative erosion applied to previous Fig.

Iterative dilation applied to previous Fig.

Step 4: Non-Network Space Decomposition

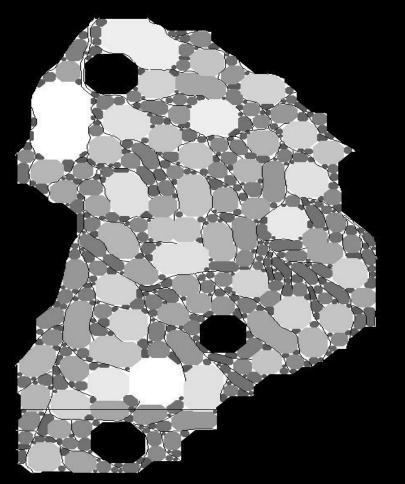


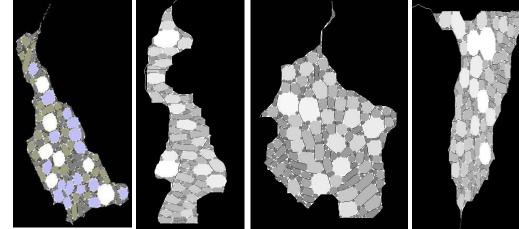
Iterative erosion applied to previous Fig.

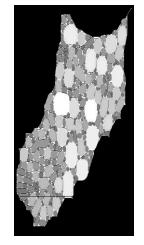
Iterative dilation applied to previous Fig.

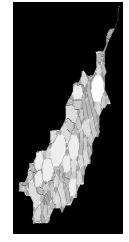
Decomposition of Non-network space in to non-overlapping disks of octagon shape of several sizes for basin 1

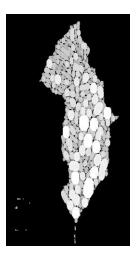
Non-Network Spaces Packed with Non-Overlapping Disks of basins 2 to 8







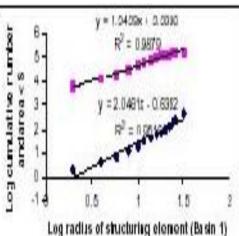


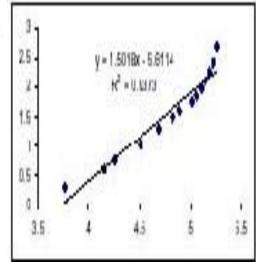


Dimensions derived from morphometry of network and non network space

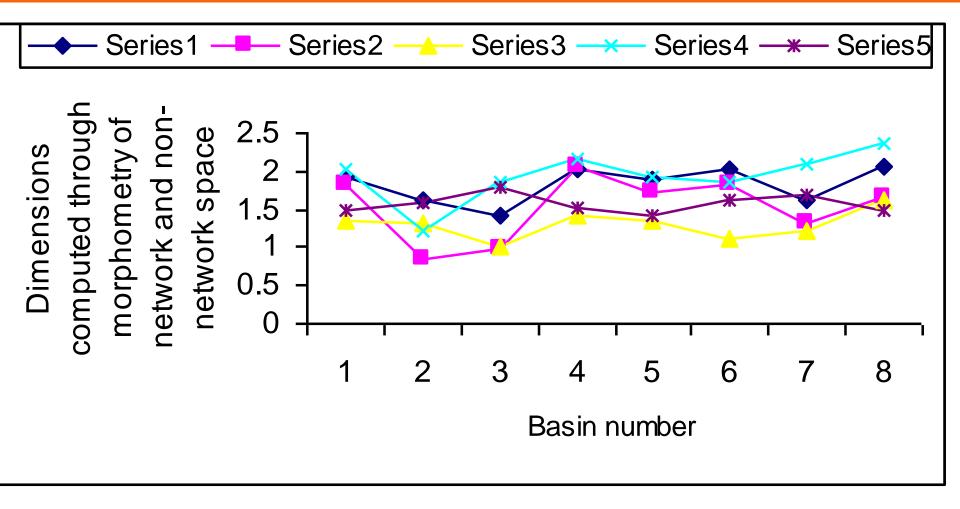
Morphometric parameter computations achieved through decomposition of non-network space

Basi n #	Network FD	Log Rs/ Log RN	R vs A	R vs N	A vs N
1	1.83	1.93	1.34	2.06	1.50
2	0.86	1.63	1.33	1.23	1.59
3	0.98	1.41	1.02	1.87	1.80
4	2.07	2.01	1.43	2.17	1.52
5	1.73	1.90	1.34	1.94	1.43
6	1.84	2.04	1.13	1.87	1.63
7	1.33	1.61	1.23	2.08	1.70
8	1.65	2.06	1.61	2.38	1.49





Basin number versus varied dimensions derived from morphometry of networks and non-network spaces



II.II.III. Granulometric analysis of digital topography

Granulometric analysis

Morphological multiscaling transformations are shown to be a potential tool in deriving meaningful terrain roughness indexes.

Consider two different basins of two different physiographic setups (fluvial and tidal) that possess similar topological quantities, i.e., their networks may be topologically similar to each other. But the processes involved therein may be highly contrasting due to their different physiographic origins. Under such circumstances, the results that exhibit similarities in terms of topological quantities and scaling exponents would be insufficient to make an appropriate relationship with involved processes.

Therefore, granulometric approach is proposed to derive shape-size complexity measures of basins. This approach is based on probability distribution functions computed for both protrusions and intrusions (in other words supremums and infimums) of various degrees of sub-basins.

This granulometry-based technique is tested on sub-basins with various sizes and shapes decomposed from DEMs of two distinct geomorphic regions.

Granulometric Analysis

- Multi-scale opening till completely black
- Multi-scale closing till completely white
- Subtraction ∞
- Probability function
- 🔊 Average size

So Average roughness

$$PS_{f}(-n,B) = A[(f \bullet B_{n}) - (f \bullet B_{n-1})], 1 \le n \le K$$

$$PS_{f}(+n,B) = A[(f \circ B_{n}) - (f \circ B_{n+1})], 0 \le n \le N$$

$$ps(n,f) = \frac{A(f \circ B_{n}) - A(f \circ B_{n+1})}{A(f \circ B_{0})}, n = 0, 1, 2, ..., N$$

$$ps(-n,f) = \frac{A(f \bullet B_{n}) - A(f \bullet B_{n-1})}{A(f \bullet B_{K}) - A(f \bullet B_{0})}, n = 1, 2, ..., K$$

$$AS(f / B) = \sum_{k=1}^{N} nps(n, f)$$

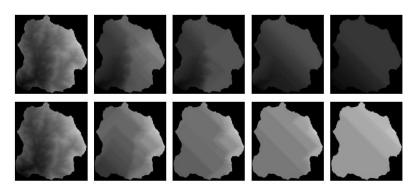
n=0

$$H(f/B) = -\sum_{k=0}^{n} ps(n, f) \log ps(n, f)$$

Anti(Granulometric) Analysis

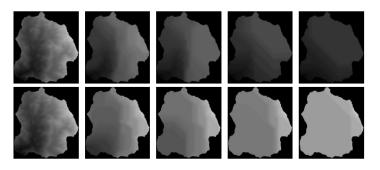
Multiscale opening/closing by rhombus

• Scale 1, 40, 80, 120, 160



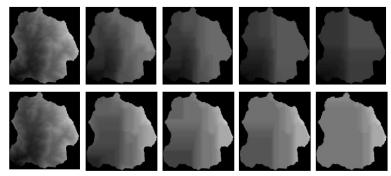
Multiscale opening/closing by octagon

• Scale 1, 30, 60, 90, 120



Multiscale opening/closing by square

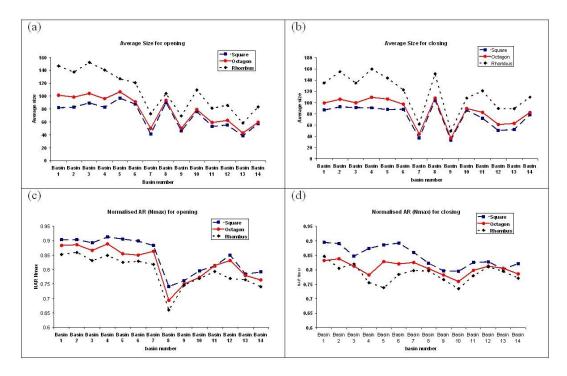
• Scale 1, 20, 40, 60, 80



Granulometric analysis : Basin wise analysis

∞ Average size – 14 sub-basins

∞ Average roughness – 14 sub-basins



Granulometric Analysis : Basin wise analysis

The number of iterations required to make each sub-basin either become darker or brighter depends on the size, shape, origin, orientation of considered primitive template used to perform multiscale openings or closings, and also on the size of the basin and its physiographic composition. More opening/closing cycles are needed when structuring element rhombus is used, and it is followed by octagon and square.

Mean roughness indicates the shape-content of the basins. If the shape of SE is geometrically similar to basin regions, the average roughness result possesses lower analytical values. If the topography of basin is very different from the shape of SE, high roughness value is produced, which indicates that the basin is rough relative to that SE. In general, all basins are rougher relative to square shape as highest roughness indices are derived when square is used as SE.

A clear distinction is obvious between the Cameron and Petaling basins. Generally, roughness values of Cameron basins are significantly higher than that of Petaling basins.

The terrain complexity measures derived granulometrically are scale-independent, but strictly shape-dependent. The shape dependent complexity measures are sensitive to record the variations in basin shape, topology, and geometric organisation of hillslopes.

Granulometric analysis of basin-wise DEMs is a helpful tool for defining roughness parameters and other morphological/topological quantities.

III. Mathematical Morphology in GISci

Spatial Interpolations

Spatial Reasoning

- Strategic set identification
- Directional Spatial Relationship
- Spatial-Interactions
- Point-to-Polygon Conversion

III.I. Spatial Interpolations

VISUALIZATION OF SPATIO-TEMPORAL BEHAVIOUR OF DISCRETE MAPS VIA GENERATION OF RECURSIVE MEDIAN ELEMENTS

<u>Outline</u>

Mathematical Morphological Transformations employed include:

Hausdorff Dilation, Hausdorff Erosion, Morphological Median Element Computation, and Morphological Interpolation.

Objectives

To show relationships between the layers depicting noise-free phenomenon at two time periods.

To relate connected components of layers of two time periods via FOUR possible categories of spatial relationships of THREE groups.

To propose a framework to generate recursive interpolations via median set computations.

To demonstrate the validity of the framework on epidemic spread.

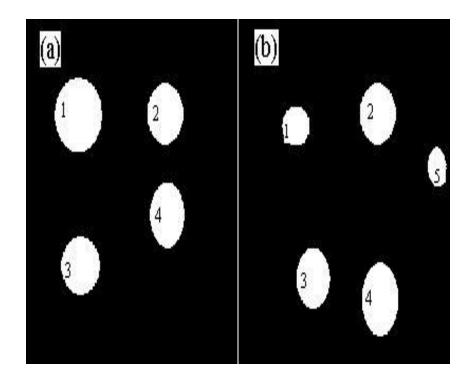
THREE Groups and FOUR Categories?

Three groups are conceived by checking the intersection properties between the corresponding connected components.

Four categories under the above three groups are visualized via logical relationships and Hausdorff erosion and Hausdorff dilation distances.

What are these Hausdorff distances?

What basics do we require to know to compute these distances?



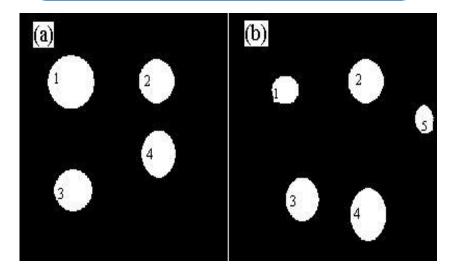
Spatial Relationships Between Sets and Their Categorization

so Ordered sets.

semi-ordered sets, if subsets of X^t (resp. X^{t+1}) are only partially contained in the other set X^{t+1} (resp. X^t).

Whereas, (X^t) and (X^{t+1}) are considered as *disordered sets* if there exists an empty set while taking the intersection of (X^t) and (X^{t+1}) (or) of their corresponding subsets.

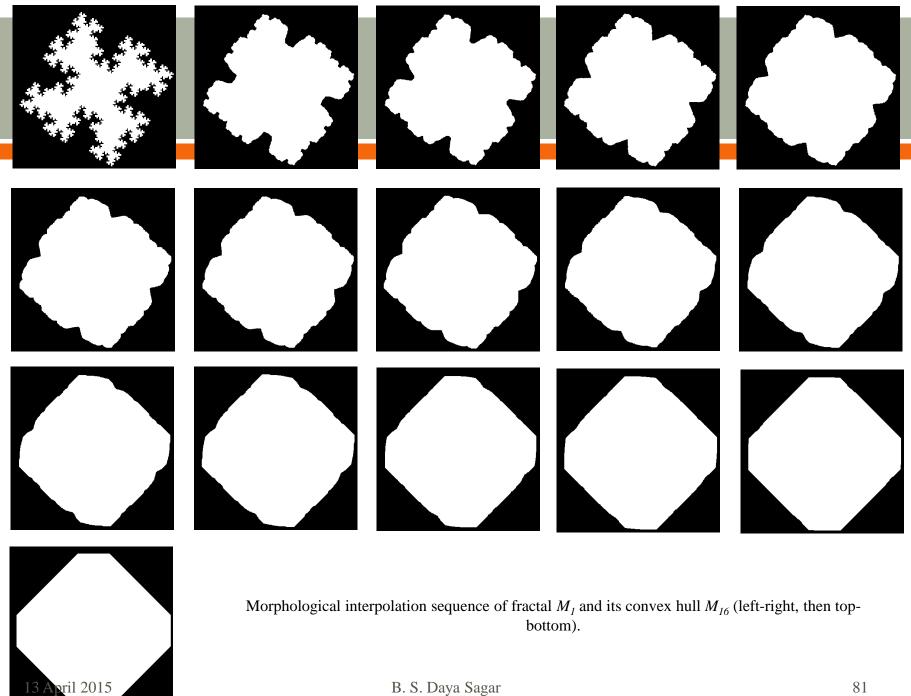
Description of categories via logical relations



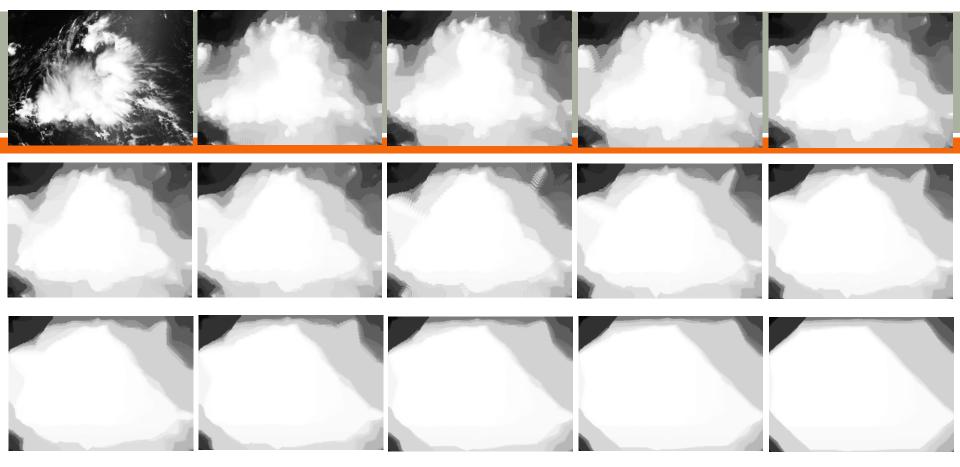
Categories via Hausdorff Erosion and Dilation Distances

TABLE 1. CATEGORY-WISE HAUSDORFF DISTANCES

Group	Category	$\sigma\left(\boldsymbol{X}_{i}^{t},\boldsymbol{X}_{i}^{t+1}\right)$	$\rho\left(X_{i}^{t}, X_{i}^{t+1}\right)$
I	1	0	0
I	2	≥ 1	≥ 1
II	3	Does not exist	≥ 1
	4	Does not exist	Does not exist



B. S. Daya Sagar





Morphological interpolation sequence of cloud field f_I and its convex hull f_{I6} (left-right, then topbottom).

Interpolated Sequence of Lakes' Data of Two Seasons

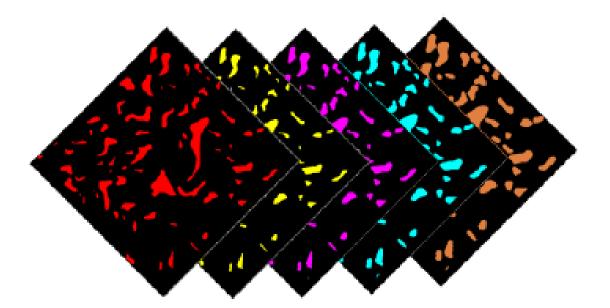
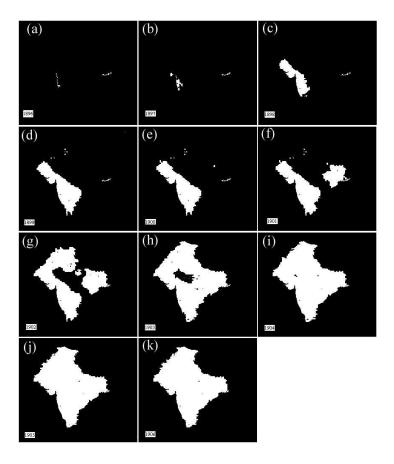
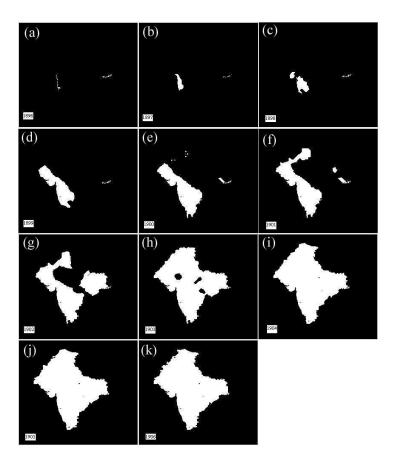


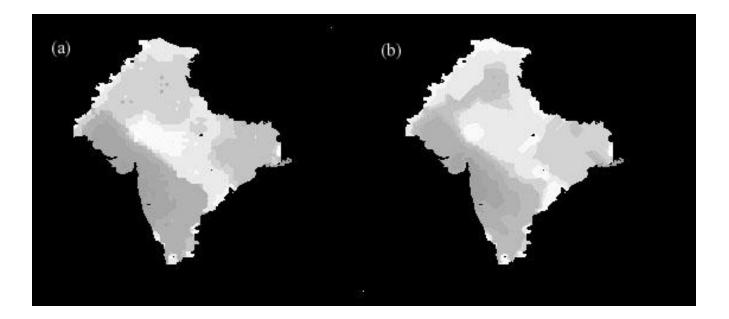
Fig. 4. A sequence of interpolated sets (slices) in between the two input slices shown in Figs. 3a, b. Equations 8(a) and 14 are used to recursively generate the interpolated slices. The layer depicting water bodies with magenta color is the median set shown in Fig. 3c.

Observed and Interpolated Epidemic Spread Maps http://www.isibang.ac.in/~bsdsagar/AnimationOfEpidemicSpread.avi



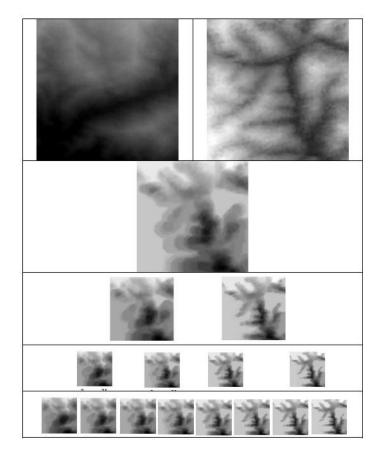


Observed and Interpolated Sequences



Earth Surface Transformation

Hierarchical Morphological Interpolation between landscape functions, say, f_1 and f_{256} .



III.II. Spatial Reasoning Strategically important set(s) **Directional spatial relationship**

Point-polygon conversion

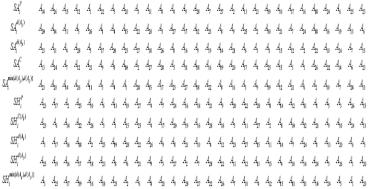
III.II.I. Strategically significant state(s)

$$\begin{split} H/P(A_{ij}) &= -\sum_{\substack{\forall j \\ i \neq j}} \Pr\left[P(A_{ij})\log\Pr\left[P(A_{ij})\right]\right] \\ H/C(A_{ij}) &= -\sum_{\substack{\forall j \\ i \neq j}} \Pr\left[C(A_{ij})\log\Pr\left[C(A_{ij})\right]\right] \\ H/d(A_{ij}) &= -\sum_{\substack{\forall j \\ i \neq j}} \Pr\left[d(A_{ij})\log\Pr\left[d(A_{ij})\right]\right] \\ H/d(A_{ij}) &= -\sum_{\substack{\forall i \\ i \neq j}} \Pr\left[d(A_{ij})\log\Pr\left[d(A_{ij})\right]\right] \\ H/d(A_{ij}) &= -\sum_{\substack{\forall i \\ i \neq j}} \Pr\left[d(A_{ij})\log\Pr\left[d(A_{ij})\right]\right] \\ H/d(A_{ij}) &= -\sum_{\substack{\forall i \\ i \neq j}} \Pr\left[d(A_{ij})\log\Pr\left[d(A_{ij})\right]\right] \\ H/d(A_{ij}) &= -\sum_{\substack{\forall i \\ i \neq j}} \Pr\left[d(A_{ij})\log\Pr\left[d(A_{ij})\right]\right] \\ H/d(A_{ij}) &= -\sum_{\substack{\forall i \\ i \neq j}} \Pr\left[d(A_{ij})\log\Pr\left[d(A_{ij})\right]\right] \\ H/d(A_{ij}) &= -\sum_{\substack{\forall i \\ i \neq j}} \Pr\left[d(A_{ij})\log\Pr\left[d(A_{ij})\right]\right] \\ H/d(A_{ij}) &= -\sum_{\substack{\forall i \\ \forall i \neq j}} \left\{H/P(A_{ij})\right\} \left(SA_{i}^{P}\right) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} NP(A_{ij})\right\} \right) \\ (SH_{i}^{P}) &= \min_{\substack{\forall i \\ \forall i \neq j}} \left\{H/C(A_{ij})\right\} \\ (SH_{i}^{P}) &= \min_{\substack{\forall i \\ \forall i \neq j}} \left\{\min\left[\sum_{i \in I} Nd(A_{ij}), \sum_{j \in I} Nd(A_{ji})\right]\right\} \\ (SA_{i}^{P}) &= \min_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \\ \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \atop \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \atop \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \atop \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \atop \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \atop \forall i \neq j}} \left\{\sum_{i \in I} C(A_{ij})\right\} \\ (SA_{i}^{P}) &= \max_{\substack{\forall i \atop \forall i \neq j}}$$

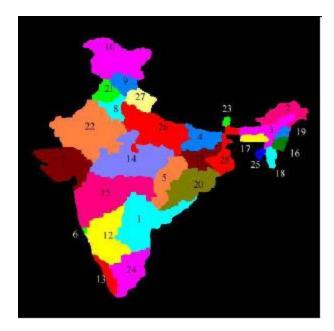
Matrices and Parameters

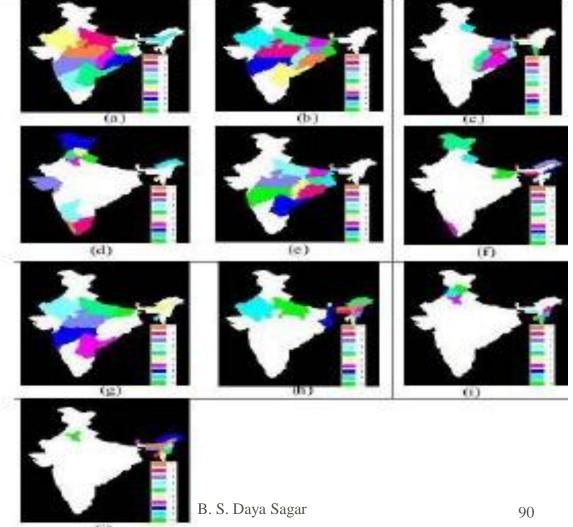
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| | A1 | A. / | A2 / | _ | _ | | | _ | _ | | _ | _ | _ | _
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 | - | | _
 | | |
 | A. |
| | A,
A, | 0 | 0 | | 0 2 | | | | 0 0 | 0 | 130 | 0 | | 75
 | | 0 0 |
 | 91 0 | | | 61 0
 | | 0 | 0
 | | | Α,
 | 0 |
| | A, | 0 | 0
112 | | 0 | | | | 0 0 | | 0
0 | | 0
0 | 0
0
 | 0 (
17 8: | 0 0
2 16 |
 | 0 0
0 0 | - | | 0 0
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19
 | | | Α,
 | 178 |
| | A | 0 | 0 | | 0 1 | | | | 0 0 | | 0 | | 0 | 0
 | | 0 0 | 43
 | 0 0 | | | 0 0
 | | | 20
 | | | A,
A,
 | 158 |
| | A, | 26 | 8 | | | 0 0 | | | 0 0 | | 0 | | | 52
 | | 0 0 |
 | 26 0 | | | 0 0
 | | | 0
 | | | A,
 | 110 |
| | A. | 8 | 8 | | | 0 0 | | | 0 0 | | 16 | | 8 | 7
 | | 0 0 | 0
 | 0 0 | | | 0 0
 | | | 0
 | | | A.
 | 65
50 |
| | A, | 0 | 0 | | | 0 0 | | | 0 0 | | | | | 55
 | 0 1 | |
 | | 74 | | 0 0
 | | | 0
 | | | Α,
 | 132 |
| | Α. | 8 | 8 | 0 | 0 1 | 0 0 | 0 | 0 1 | 0 0 | 8 | 0 | 8 | 8 | 8
 | 0 1 | 0 0 | 0
 | 8 54 | 77 | 0 | 0 0
 | 55 | 15 | 0
 | | | Α.
 | 158 |
| | Α, | 0 | 8 | | 0 1 | | | 11 | 8 74 | 8 | 0 | 8 | 8 | 8
 | 0 1 | 0 0 | 0
 | 8 48 | 8 | 0 | 0 0
 | 0 | 39 | 0
 | | | Α,
 | 195 |
| | Au | 0 | 0 | | 0 1 | | | 0 7 | | | 0 | | 0 | 0
 | | 0 0 | 0
 | 0 14 | | | 0 0
 | 0 | | 0
 | | | Α.
 | |
| | A | 0 | 0 | | 9 3 | | | | 0 0 | | 0 | | 0 | 0
 | | 0 0 |
 | 54 0 | | | 0 0
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 | | | A
 | |
| | An | 128 | 8 | | 0 1 | | | | 0 0 | | | | | 100
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 | | | A 12
 | |
| | An | 0 | 0 | | 0 1 | | | | 0 0 | | | 0 | 0 | 0
 | | 0 0 | 0
 | 0 0 | | | 0 0
 | | | 0
 | | | An
 | |
| | As | 0 | 0 | | 0 7 | | 20
56 | | 0 0 | | | | | 140
 | | 0 0 | 0
 | | 163 | |
 | 202 | | 0
 | | | A
 | 102 |
| | Au | 75 | | | 0 5
0 1 | | 8 | | 0 0 | | 101
0 | | 139
8 | 8
 | | 0 0
0 16 |
 | 0 0 | | | 0 0
 | | | 0
 | | | A ss
A ss
 | |
| | Au | 0 | | | 0 1 | | | | 0 0 | | | 0 | 0 | 0
 | | 0 0 | 0
 | 0 0 | | | 0 0
 | | | 0
 | | | Au
 | |
| | An | 8 | 8 | | 0 1 | - | | | 0 0 | | 0 | | 8 |
 | | 0 0 | 0
 | 8 0 | - | | 0 15
 | | | 0
 | | | Au
 | |
| | An | 8 | | | 0 1 | | | | 0 0 | | | | 0 |
 | | 0 0 |
 | 0 0 | | | 0 0
 | | | 0
 | | | An
 | 149 |
| | Aze | 90 | 0 | | 0 12 | | | | 0 0 | | 0 | | 0 | 0
 | | 0 0 |
 | 0 0 | | | 0 0
 | | | 0
 | | | Aze
 | 45 |
| | A 21 | 0 | 0 | | 0 1 | | | | 1 12 | | 0 | 0 | 0 | 0
 | | 0 0 | 0
 | 0 0 | 12 | 0 | 0 0
 | 0 | 0 | 21
 | | | An
 | |
| | An | 0 | 8 | 0 | 0 | 0 0 | 75 | 80 | 0 0 | 8 | 0 | 8 | 166 | 8
 | 0 1 | 0 0 | 0
 | 8 12 | 8 | 0 | 0 0
 | 26 | 0 | 0
 | | | A 22
 | |
| | An | 8 | 8 | | 8 | | | | 0 0 | | | | 8 | 8
 | | 0 0 |
 | 0 0 | | | 0 0
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 | | | A 23
 | |
| | A 24 | 40 | 0 | | | 0 0 | | | 0 0 | | | | 0 | 8
 | | 0 0 | 0
 | 0 0 | | | 0 0
 | - | | 0
 | | | A 24
 | |
| | An | 8 | 8 | | 0 1 | | | | 0 0 | | 0 | 0 | 8 | 8
 | | 0 16 | 0
 | 8 0 | | | 0 0
 | | | 0
 | | | A 25
 | |
| | Azz | 8 | 8 | | | 8 0 | | | 0 0 | | 0 | | 204 | 0
 | | 0 0 |
 | 0 0 | | | 0 0
 | | | 8
 | | | Azz
 | 152 |
| | Aze | 0 | 0 | | | | | 15 3 | 9 0
0 0 | | 0
0 | | 0 | 0
 | 0 | 0 0 |
 | 0 0
21 0 | | | 0 0
 | | | 0
 | | | A22
A28
 | |
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 | |
| A, / | A. A. | A. | A ₅ | A. | A, | A. | Α, | Au | An | An | A., | A., | A .s. 4 | An
 | A A | A | n A 21
 | A 24 | An | An / | 824 A
 | a A | a A | - An
 | I | |
 | |
| A, 0 | A, A, | | | A.
0.29 | A,
0.81 | A.
0.75 | A,
0.79 | | A
0.69 | | | | |
 | | | n A21
 | | | |
 | | | 75 0.79
 | | S.4° | A
 | A. |
| A, 0
A: 0.79 | 0.79 0.7 | 19 0.68
56 0.85 | 8 0.94
9 0.87 | 0.29 | 0.81
0.96 | 0.75 | 0.79
0.85 | 0.91
0.94 | 0.69
0.88 | 0.43
0.94 | 0.55
0.88 | 0.88
0.82 | 0.93
0.83 | 0.59
0.7
 | 0.57 0
0.48 0 | 1.54 0.
1.88 0. | 58 0.63
49 0.9
 | 0.76 | 0.98
0.85 | 0.63
0.42 | 0.75 C
 | .49 0
0.7 (| .95 0
).81 0 | .75 0.79
.85 0.76
 | | SA ^P | A _{li} ,
 | A ₂₆ . |
| A. 0
A. 0.79
A. 0.79 | 0.79 0.7
0 0.5
0.56 | 79 0.68
56 0.85
0 0.85 | 8 0.94
9 0.87
3 0.83 | 0.29
0.77
0.76 | 0.81
0.96
0.97 | 0.75
0.85
0.84 | 0.79
0.85
0.84 | 0.91
0.94
0.92 | 0.69
0.88
0.83 | 0.43
0.94
0.94 | 0.55
0.88
0.88 | 0.88
0.82
0.8 | 0.93
0.83
0.83 | 0.59
0.7
0.3
 | 0.57 0
0.48 0
0.22 0 | 1.54 0.
1.88 0.
1.57 0. | 58 0.63
49 0.9
22 0.92
 | 0.76
0.85
0.84 | 0.98
0.85
0.85 | 0.63
0.42
0.25 | 0.75 C
0.95
0.98
 | 0.7 0
0.31 0 | 1.95 0
0.81 0
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85 0.76
82 0.67
 | | SA_i^p | A _l
 | A ₂₆ . |
| A. 0
A. 0.79
A. 0.79
A. 0.68 | 0.79 0.7
0 0.5
0.56 0.8
0.89 0.8 | 79 0.66
56 0.85
0 0.83 | 8 0.94
9 0.87
3 0.83
0 0.59 | 0.29
0.77
0.76
0.72 | 0.81
0.96
0.97
0.88 | 0.75
0.85
0.84
0.84 | 0.79
0.85
0.84
0.82 | 0.91
0.94
0.92
0.79 | 0.69
0.88
0.83
0.79 | 0.43
0.34
0.34
0.88 | 0.55
0.88
0.88
0.91 | 0.88
0.82
0.8
0.55 | 0.93
0.83
0.83
0.63 | 0.59
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0.3
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 | 0.57 0
0.48 0
0.22 0
0.79 0 | 1.54 0.
1.88 0.
1.57 0.
1.62 0. | 58 0.63
49 0.9
22 0.92
69 0.74
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0.85
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0.85 | 0.98
0.85
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0.7 | 0.63
0.42
0.25
0.34 | 0.75 0
0.95
0.98 0
0.85 0
 | 0.7 0
0.7 0
0.31 0
0.54 0 | 195 0
0.81 0
1.87 0
1.54 0 | 75 0.79
85 0.76
82 0.67
79 0.87
 | | SA_i^p
$SA_i^{d(A_g)}$ | A ₁₁ .
A ₂₀ .
 | A ₂₆ .
A ₁₄ . |
| A. 0
A. 0.79
A. 0.79
A. 0.68
A. 0.94 | 0.79 0.7
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0.89 0.8 | '9 0.61 6 0.81 0 0.83 13 0.55 | 8 0.94
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0.91 | 0.69
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0.79
0.86 | 0.43
0.94
0.94
0.88
0.98 | 0.55
0.88
0.88
0.91
0.86 | 0.88
0.82
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0.51 | 0.93
0.83
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0.63
0.43 | 0.59
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0.84
 | 0.57 0
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0.79 0
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0.85 0
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 | 0.7 0
0.7 0
0.31 0
0.54 0
0.73 0 | 195 0
181 0
187 0
154 0
196 0 | 75 0.79
85 0.76
82 0.67
79 0.87
67 0.91
 | | SA_i^p
$SA_i^{d(A_i)}$ | Д ₁ ,
Д ₂₀ ,
 | A ₂₆ .
A ₁₄ . |
| A, 0 A, 0.79 A, 0.68 A, 0.84 A, 0.94 | 0.79 0.7
0 0.5
0.56 0.8
0.89 0.8
0.87 0.8 | 9 0.65 9 0.65 0 0.85 13 0.55 16 0.75 | 8 0.94
9 0.87
3 0.83
0 0.59
9 0
2 0.69 | 0.29
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0.76
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0.69 | 0.81
0.96
0.97
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0.55 | 0.75
0.85
0.84
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0.7
0.84 | 0.79
0.85
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0.62
0.87 | 0.91
0.94
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0.98 | 0.55
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0.86
0.43 | 0.88
0.82
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 | 0.57 0
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0.98 0
0.85 0
0.93 0
0.28 0
 | 0.49 0
0.7 0
0.31 0
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0.73 0
0.98 0 | 1.95 0
0.81 0
1.87 0
1.54 0
1.96 0
1.63 0 | 75 0.79
85 0.76
82 0.67
79 0.87
67 0.91
87 0.82
 | | SA_t^p
$SA_t^{d(A_t)}$
$SA_t^{d(A_p)}$ | A ₁₁ - A ₂₀ | A ₂₆ .
A ₁₄ .
A ₁₁ .
 |
| A1 0 A2 0.79 A1 0.79 A4 0.68 A3 0.94 A4 0.29 | 0.79 0.7
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0.77 0.7
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3 0.83
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0.83 | 0.91
0.94
0.92
0.79
0.91
0.81
0.98 | 0.69
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0.86
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0.94
0.94
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0.98
0.12
0.87 | 0.55
0.88
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0.7 0
0.31 0
0.54 0
0.73 0
0.98 0
0.78 | 1.95 0
1.81 0
1.87 0
1.54 0
1.96 0
1.63 0
0.9 0 | 75 0.79
85 0.76
82 0.67
79 0.87
67 0.91
 | | SA_{i}^{P}
$SA_{i}^{d(A_{i})}$
$SA_{i}^{d(A_{i})}$ | A ₁₁ .
A ₂₀ .
A ₂₃ .
 | A ₂₆ -
A ₁₄ -
A ₁₁ - |
| A1 0 A2 0.79 A3 0.79 A4 0.68 A5 0.94 A5 0.29 A7 0.81 A5 0.75 A5 0.79 | 0.79 0.7
0 0.5
0.56 0.8
0.89 0.8
0.87 0.8
0.77 0.7
0.96 0.8
0.85 0.8 | 9 0.61 9 0.61 9 0.81 | 8 0.94
9 0.87
3 0.83
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9 00
2 0.69
8 0.81
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0.8 | 0.55
0.88
0.91
0.86
0.43
0.96
0.91
0.93 | 0.88
0.82
0.55
0.55
0.55
0.7
0.58
0.72 | 0.93
0.83
0.63
0.43
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0.73
0.73 | 0.59
0.7
0.3
0.7
0.84
0.84
0.81
0.93
0.93
 | 0.57 0
0.48 0
0.22 0
0.79 0
0.86 0
0.9 0
0.9 0
0.84 0
1
0.52 0 | 1.54 0. 1.88 0. 1.57 0. 1.62 0. 1.78 0. 1.79 0. 0.9 0. | 58 0.63
49 0.3
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92 0.96
94 0.97
 | | SA_i^p
$SA_i^{d(h_i)}$
$SA_i^{d(h_i)}$
SA_i^C | A ₁₁ A ₂₀ | A ₂₆ - A
A ₁₄ - A
A ₁₁ - A
A ₂₄ - A
 |
| A1 0 A2 0.79 A3 0.79 A4 0.88 A5 0.94 A4 0.29 A5 0.34 A6 0.29 A7 0.81 A6 0.75 A7 0.79 | 0.79 0.7
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 | | SA_i^p
$SA_i^{d(A_i)}$
$SA_i^{d(A_i)}$
SA_i^C
$= \min\{d(A_i)d(A_i)\}$ | A ₁₄ A ₂₉ A ₂₉ A ₂₅ A ₁₃ A
 | A ₂₆ A
A ₁₄ A
A ₁₁ A
A ₂₄ A |
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 | | $\begin{array}{c} SA_{i}^{P}\\ SA_{i}^{d(A_{i})}\\ SA_{i}^{d(A_{i})}\\ SA_{i}^{d(A_{i})}\\ SA_{i}^{C}\\ SA_{i}^{min(d(A_{i})M(A_{i}))}\end{array}$ | A_{14} , A_{20} , A_{23} ,
 | 4 ₂₆ 4
4 ₁₀ 4
4 ₁₁ 4
4 ₂₁ 4 |
| A. 0 A. 0.79 A. 0.88 A. 0.88 A. 0.94 A. 0.29 A. 0.86 A. 0.29 A. 0.76 A. 0.77 A. 0.78 A. 0.79 A. 0.78 A. 0.91 A. 0.93 A. 0.43 | 0.79 0.7
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 | | SA_i^p
$SA_i^{d(A_i)}$
$SA_i^{d(A_i)}$
SA_i^{C}
$SA_i^{mid(A_i),bd(A_i)}$ | A ₁₄ A ₂₉ | 4 ₂₆ 4
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4 ₁ 4
4 ₁ 4
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| A. 0 A. 0.79 A. 0.79 A. 0.88 A. 0.34 A. 0.29 A. 0.81 A. 0.79 A. 0.81 A. 0.79 A. 0.79 A. 0.81 A. 0.79 A. 0.91 A 0.83 A 0.83 A 0.83 A 0.85 | 0.79 0.7
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 | | SA_i^{p}
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$SA_i^{d(A_i)}$
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$SA_i^{min(d(A_i)d(A_i)B}$
SH_i^{P} | A ₁₁ A ₂₀ | A ₂₆ .
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| A. 0 A. 0.79 A. 0.88 A. 0.88 A. 0.29 A. 0.28 A. 0.29 A. 0.29 A. 0.75 A. 0.79 A. 0.79 A. 0.79 A. 0.81 A. 0.75 A. 0.81 A. 0.81 A. 0.81 A. 0.81 A. 0.81 A. 0.82 A. 0.83 | 0.79 0.7
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 | | $\begin{array}{c} St_{i}^{p^{\prime}}\\ St_{i}^{p^{\prime}(d_{i})}\\ St_{i}^{p^{\prime}(d_{i})}\\ St_{i}^{p^{\prime}(d_{i})/(d_{i})}\\ St_{i}^{p^{\prime}(d_{i})/(d_{i})}\\ St_{i}^{p^{\prime}}\end{array}$ | A ₁₁ , A ₂₀ | 4 ₂₆ 4
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 | | $\begin{array}{c} S4^{l}\\ S4^{l(k_{j})}\\ S4^{l(k_{j})}\\ S4^{l(k_{j})}\\ S4^{l(k_{j})}\\ S4^{l(k_{j})}\\ SH^{l(k_{j})}_{i}\\ SH^{l(k_{j})}_{i}\\$ | A ₁ A ₂ A ₃ | 426 - 426 - 426 - 426 - 426 - 426 - 427
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	A.	A,	Α,	Α.	As	A.	Α,	Α.	Α,	Au	A	A 12	A 13	A 14	Ass	Au	A	Au	An	Aze	A 21	A 22	A 23	A 24	Azs	Azs	Azr	Az
Α,	0	225	200	161	69	172	163	210	246	274	129	104	126	116	63	247	202	240	255	72	238	146	204	87	225	145	225	14
A,	178	0	20	135	189	351	342	289	269	255	137	283	302	213	242	54	62	73	39	139	301	282	125	253	74	175	240	10
Α,	158	36	8	115	168	329	320	269	248	229	115	261	280	191	220	50	41	53	54	119	280	260	104	232	54	165	219	8
Α,	110	120	95	0	55	215	207	154	134	125	39	159	209	78	106	147	57	135	150	69	164	147	70	197	120	51	107	4
A,	65	165	140	94	0	159	152	140	214	284	63	103	160	48	53	187	147	180	195	28	168	85	134	149	165	85	155	8
Α,	50	270	250	155	110	0	72	179	217	244	155	8	43	87	12	297	257	290	305	122	207	116	224	57	275	130	194	19
Α,	132	355	330	234	188	130	0	107	143	169	233	105	173	90	65	381	331	367	383	201	135	45	302	162	352	140	148	27
Α,	158	245	225	130	98	213	82	0	37	64	129	175	255	54	123	277	227	265	280	125	28	27	200	243	249	35	45	17
Α,	195	228	208	110	133	250	119	36	0	29	124	213	293	93	160	259	205	247	261	153	29	50	180	280	230	42	30	15
A	248	270	249	158	185	303	173	89	53	0	175	266	346	145	215	301	251	288	304	206	67	99	220	336	273	95	80	19
A 11	89	120	95	31	54	215	199	154	129	146	0	156	188	75	104	147	57	135	150	39	164	145	74	168	119	50	105	4
A 12	45	265	245	180	105	68	121	228	265	294	149	0	79	134	61	177	247	285	300	117	261	164	222	69	269	174	244	19
An	69	265	245	230	138	99	166	279	315	342	199	49	0	185	111	279	246	273	289	138	306	214	272	19	258	223	293	19
A 14	102	260	239	142	95	157	129	93	129	157	142	119	200	0	70	290	240	277	294	109	119	69	210	188	262	65	108	18
A 15	68	290	265	168	124	108	0.000	168	284	231	168	51	130	75	0	315	265	298	318	135	190	104	237	119	289	119	183	21
An	145	38	15	103	157	317	309	258	236	216	104	199	269	179	209	0	29	20	19	108	273	254	91	219	34	155	209	7
A 17	115	30	9	72	127	287	278	228	106	186	74	218	238	150	179	50	0	39	53	78	233	219	62	188	25	124	179	4
A	129	64	30	84	148	299	289	239	219	200	85	232	249	160	190	27	42	8	44	89	249	230	74	284	20	135	190	5
An	149	19	12	104	160	322	313	262	240	220	108	254	273	183	213	14	34	33	0	112	272	253	95	223	39	158	208	7
Aze	45	154	129	93	50	209	199	150	178	205	61	142	166	69	100	174	130	168	183	0	164	140	134	128	157	86	154	7
A	180	255	235	140	120	235	105	25	30	34	140	200	279	79	148	285	235	275	289	140	0	32	209	268	264	45	55	18
A 22	149	330	305	209	164	204	75	79	94	127	208	167	248	67	115	354	305	343	359	174	91	0	308	234	338	114	123	24
An	129	52	26	24	69	225	217	165	145	125	39	169	219	88	120	78	29	65	80	79	174	157	0	208	52	60	117	1
An	65	265	236	231	139	100	172	280		343	199	51	50	184	113	259	244	248	263	139	307	211	273	0	233	226	294	19
A 25	110	52	17	65	120	282	273	222	200	180	68	215	233	144	173	26	29	15	34	73	232	213	55	184	0	225	168	4
An	152	215	190	94	89	207	100	184	91	118	93		249	49	119	240	_	229		109	113	93		238	214	0	69	13
A 27	168	205	180	85	104	222		49	32	52	98	184	264	64	134	226	182	220	235	124	58	46	149	253	204	20	0	12
Aze	116	80	59	39	79	240		179	159		27	183	213	-	132	105	_	93	109	67	190	-	78	194	78	78	132	



Strategically significant state(s) w.r.t 10 parameters





13 April 2015

(i)

III.II.II Directional Spatial Relationship

<u> http://www.isibang.ac.in/~bsdsagar/AnimationOfDirectionalSpatialRelationship.wmv</u>

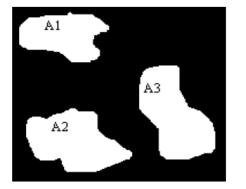


Fig. 1. (A_1, A_2, A_3) three disjoint objects possessing different directional spatial relationship.

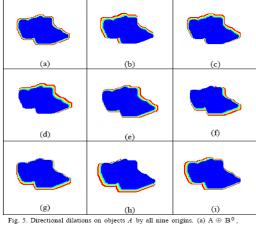


Fig. 5. Directional dilations on objects A by all nine origins. (a) $A \oplus B^0$, (b) $A \oplus B^1$, (c) $A \oplus B^2$, (d) $A \oplus B^3$, (e) $A \oplus B^4$, (f) $A \oplus B^5$, (g) $A \oplus B^6$, (h) $A \oplus B^7$, (i) $A \oplus B^8$.

1	1	1	(1)	1	1	1	(1)	1
1	(1)	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
	(B^0)			(B^1)			(B^2)	
1	1	(1)	1	1	1	1	1	1
1	1	1	1	1	(1)	1	1	1
1	1	1	1	1	1	1	1	(1)
	(B^3)			(B^4)			(B^5)	
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	(1)	1	1
1	(1)	1	(1)	1	1	1	1	1
	(B^6)			(B^7)			(B^8)	

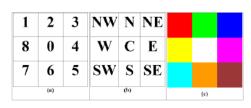


Fig. 4 Shows (a) origins of structuring element, and their corresponding directions in (b) and color codes in (c).

Fig. 3. Structuring element is shown with different possible origins. Except the first structuring element for which the origin is shown at the center, all other eight structuring elements are with other eight possible positions as origins. Those eight other structuring elements are asymmetric structuring elements as their transposes are not equivalents of their non-transposed versions.

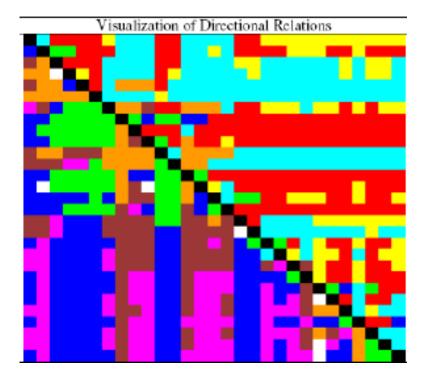
 $A_i \oplus nB^i$ $\Delta(A_i$ $i \min\{n : A_j \subseteq$

TABLE 1. DISTANCES, UNIQUE ORIGINS AND DIRECTIONS

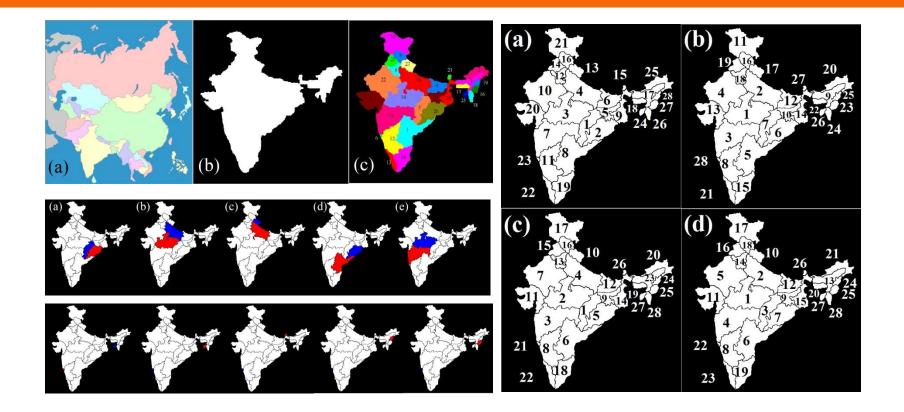
M	inimur Dist	n Dilat ances	ion	τ	inique	Origi	15	Di	irection	al Rela	tio n s	Visualization of Directional Relations				
	A_1	A_1	A_3		A_1	A_{2}	A_{j}		A_1	A_1	A_5		A_1	A_2	A_{i}	
A	0	53	50	A_1	0	2	1	$A_{\rm I}$	С	Ν	NW	Ą				
A_2	46	0	36	A_{2}	6	0	7	A_2	s	С	SW	A_2				
A_{j}	52	49	0	A_3	5	3	0	A3	SE	NE	С	А,				

III.II.I Directional Spatial Relationship





III.III Spatial Interactions: Gravity Models



III.II.V Spatiotemporal Visualization

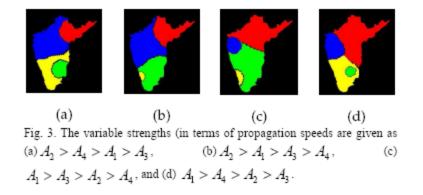
To visualize point-data into polygonal data

Weighted Skeletonization by Influence Zones (WSKIZ)

Point-to-Polygon Conversion



(a) (b) Fig. 2. (a) region considered is south India, and (b) gauge-station locations (A₁, A₂, A₃, A₄).



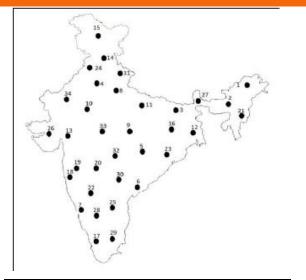
 $Z(A_i) = \bigcup_{n} \left(\delta^{\frac{n}{2}}(A_i) \cap A \right) \setminus \bigcup_{i \neq j} \left(\delta^{\frac{n}{2}}(A_j) \cap A \right)$ $Z(A) = \left(\bigcup_{i} (Z(A_i))\right)^{2}$ (a) (1) (d) (h) (8) O (10) (111) an

Fig. S1. (a) original map with three points (shown with 1s) for (A_1) , (A_2) , and (A_3) , (b) f^{h} point $(\mathcal{A}) = (\mathcal{A})$, (c) mion of f^{h} points, $\bigcup \mathcal{A}_j = (\mathcal{A}_j) \bigcup (\mathcal{A}_j)$, (d) first cycle of dilation of i^{h} point by B (Square in shape) with the propagation speed of

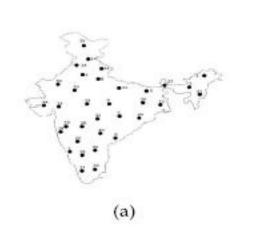
 $\lambda-1,$ denoted by $\delta^{-1}(A_1)$, (c) first cycle of dilation cf_1^{0} point (A_2) by with the propagation speed of $\lambda-2, \delta^{-1}(A_1), (G)$ first cycle of dilation of δ^{0} point (A_2) by B with the propagation speed of $\lambda-2, \delta^{-1}(A_1)$ of $\delta^{-1}(A_1)$ of $\delta^{-1}(A$

Point-to-Polygon Conversion

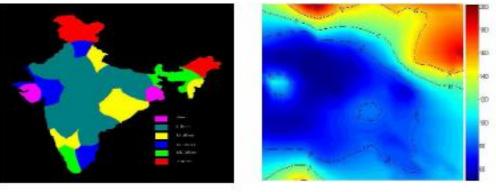
http://www.isibang.ac.in/~bsdsagar/AnimationOfPointPolygonConversion.wmv







(b)

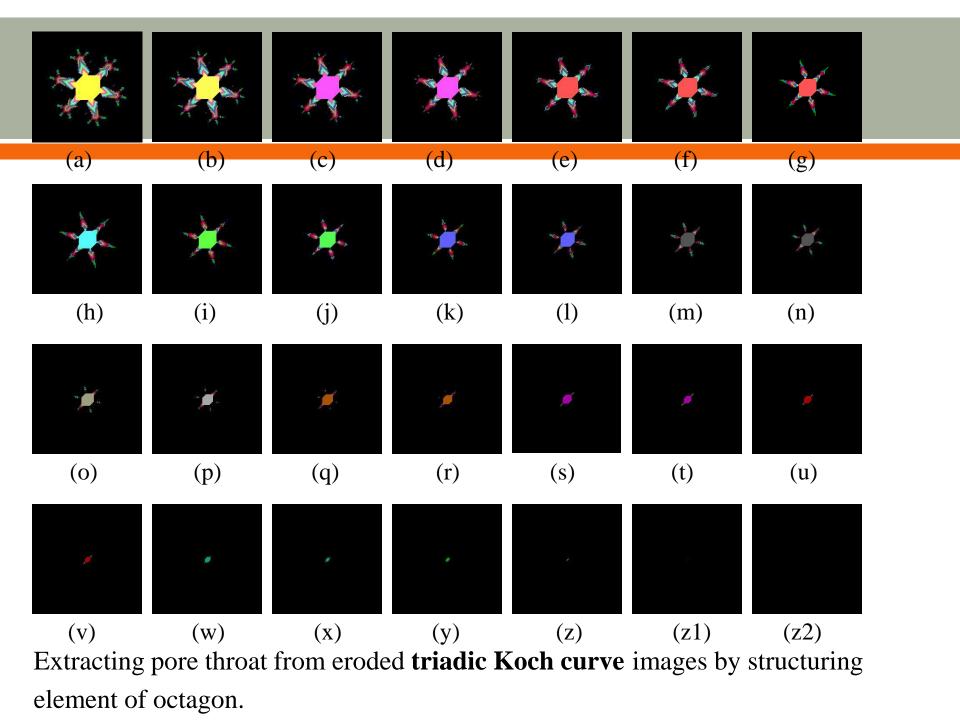


8.00

(c)

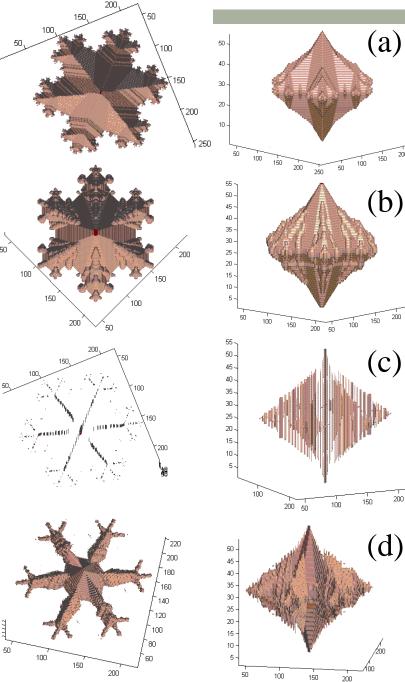
(d)

Fig. 4. (a) 34 points (locations) of rain-gauge stations spread over India indexed $(A_1 - A_{34})$, (b) Rainfall zonal map generated by having various possible propagation speeds, and the variable strengths in terms of propagation speeds are given according to ranks shown in Table 1, (c) broader zones obtained after merging the zones (Fig. 4b) obtained with similar propagation speeds, and (d) kriged map generated for 34 gauge station data.



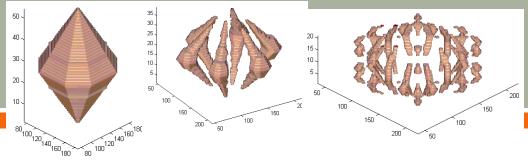


- Top and side views of 3D model at
- (a) binary pore,
- (b) pore-bodies,
- (c) pore-channel, and
- (d) pore-throat
- of triadic Koch curve

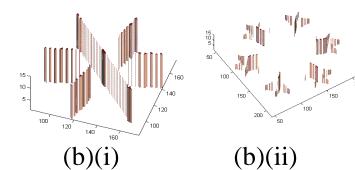


200

200

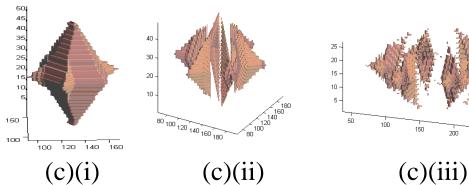


(a)(ii) (a)(iii)



(a)(i)

(b)(iii)



The diagram shows the order-wise isolated 3D pore quantities at (i) inner, (ii) middle and (iii) outer layers of

(a) pore bodies,

(b) pore channels, and

(c) pore throats.

200 150

100

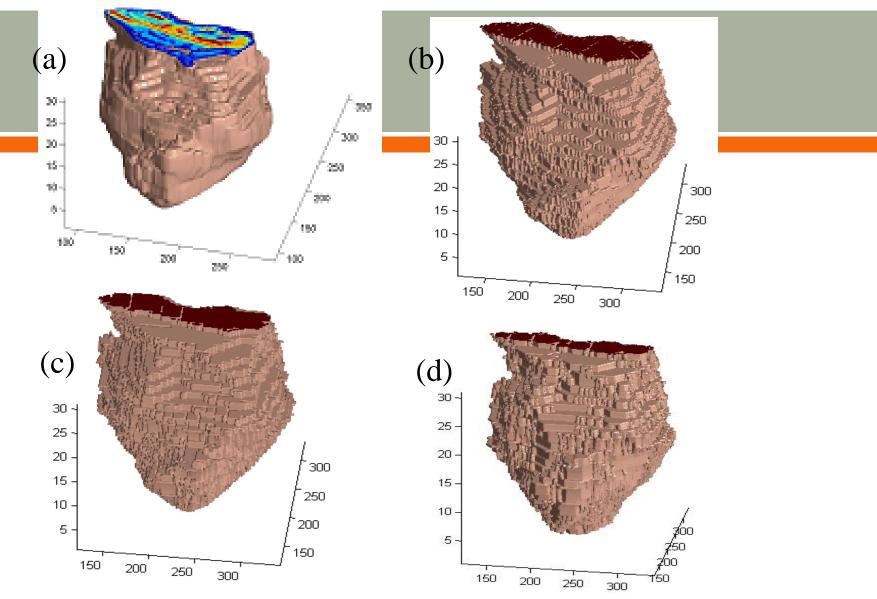
200 50



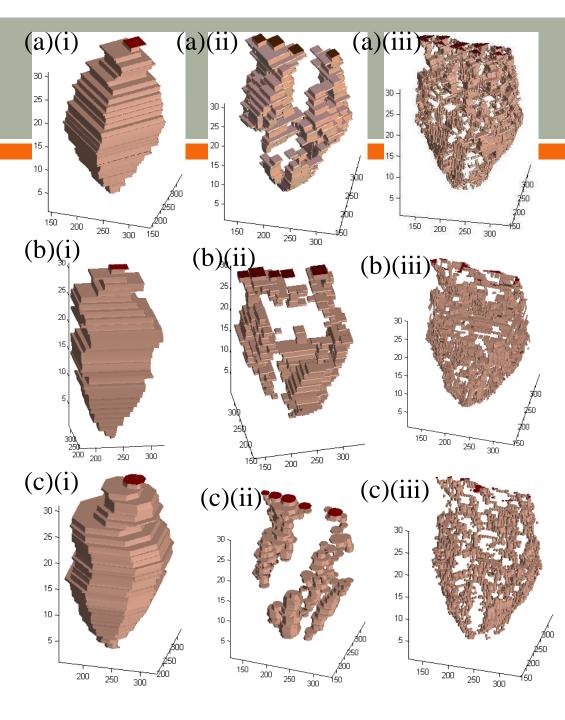
(a)

(b)

(a) The photograph of schist rock sample; (b) the CT scans applied at schist rock sample



The 3D reconstruction of (a) binary schist image; non-overlapping decomposition technique by structuring elements of (b) rhombus, (c) square and (d) octagon



Order-wise isolated 3D rock quantities at (i) inner, (ii) middle and (iii) outer layers rock by structuring elements

(a) rhombus

(b) square, and

(c) octagon.



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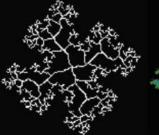
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A Book on Mathematical Morphology in Geomorphology and GISci (CRC Press, Boca Raton, FL, 2013)

Mathematical Morphology in Geomorphology and GISci





B. S. Daya Sagar



GIS

Mathematical Morphology in Geomorphology and GISci

"... great care is taken in introducing the morphological notions in a pedagogical way... the numerous examples will allow engineers and researchers in structural geology to exercise their creative faculties and to find new formulations of their own problems."

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Mathematical Morphology in Geomorphology and GISci presents a multitude of mathematical morphological approaches for processing and analyzing digital images in quantitative geomorphology and geographic information science (GISci). Covering many interdisciplinary applications, the book explains how to use mathematical morphology not only to perform quantitative morphologic and scaling analyses of terrestrial phenomena and processes, but also to deal with challenges encountered in quantitative spatial reasoning studies.

For understanding the spatiotemporal characteristics of terrestrial phenomena and processes, the author provides morphological approaches and algorithms to:

- Retrieve unique geomorphologic networks and certain terrestrial features
- Analyze various geomorphological phenomena and processes via a host of scaling laws and the scale-invariant but shape-dependent indices
- Simulate the fractal-skeletal-based channel network model and the behavioral phases of geomorphologic systems based on the interplay between numeric and graphic analyses
- Detect strategically significant sets and directional relationships via quantitative spatial reasoning
- Visualize spatiotemporal behavior and generate contiguous maps via spatial interpolation

Incorporating peer-reviewed content, this book offers simple explanations that enable readers – even those with no background in mathematical morphology – to understand the material. It also includes easy-to-follow equations and many helpful illustrations that encourage readers to implement the ideas.





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