GIS in Hydrology and Water Management

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GIS Analysis Functions and Operations

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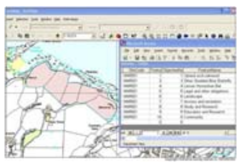
Advantageous of GIS for Water Resources Engineering

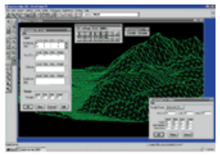
- In respect to other information systems – GIS holds spatial automatic analysis functionalities.
- In water resources engineering – emphasis on map-oriented analysis: land map representation -> planning and design of facilities to accommodate terrain relief (gravity flow conditions in pipelines design).
- Modeling (‘visualizing’) the world in a physically realistic manner to enable analysis (slope, direction, vegetative cover, etc.): 3D + 4D (prediction, simulations, forecast).
- Integration of conventional water resources analysis procedures into GIS working environment extended the realm of GIS, including: advanced surface modeling, simulation, optimization functions, decision-support planning.
- Communication aspect – much of the work in water resources engineering concern the public resources and interest groups.

GIS Analysis Functions

11 general categories of analysis (Johnson, 2010):

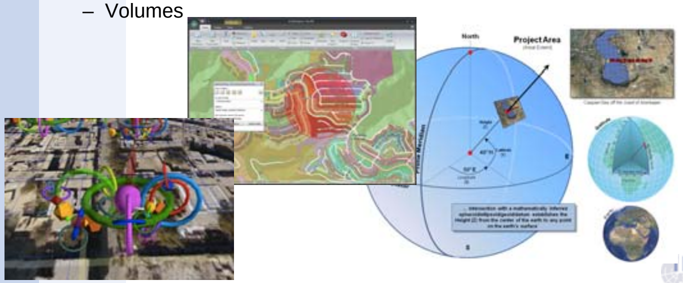
- 1. Spatial data capture and maintenance – incorporate a wide variety of spatial analysis techniques fundamental to achieve accurate and efficient GIS functions!
  - Digitizing
  - Scanning
  - Remote sensing and image processing
  - Surveying, GPS
  - Geometric transformations, projection conversions
  - …





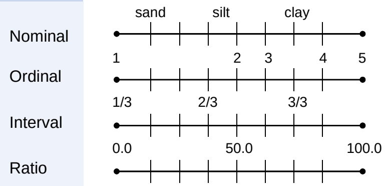
GIS Analysis Functions

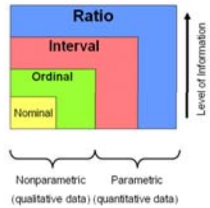
- 2. Geometrics and measurements – derived from spatially and geospatially oriented data (‘layers scheme’)
  - Intersections
  - Distances, weighted distances
  - Perimeters, areas
  - Volumes



5

2. Geometries and measurements

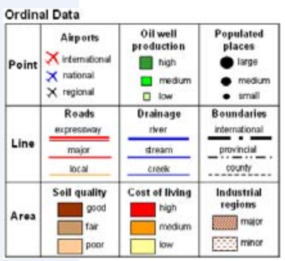


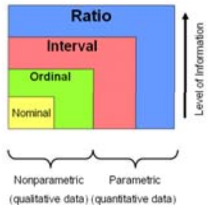


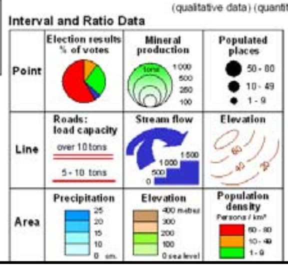
- Understanding the influence of different scaling:
  - Nominal – an identifier of equivalence (soil type)
  - Ordinal – portioning and ranking of data (ranking used for equality and order)
  - Interval – placing values on a meaningful scale for performing computations (absolute zero should be taken into account)
  - Ratio – true base value (0.0) and mathematical operations involving the ratio of two numbers (flood runoff scale)

6

2. Geometries and measurements



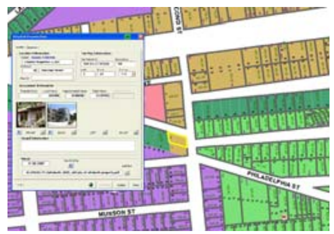




7

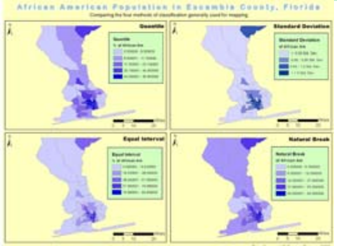
GIS Analysis Functions

- 3. Spatial and non-spatial queries (classifications) – perhaps one of the primary justifications for the development of GIS (relations, layers)
  - Selection
  - Relations, joins
  - Classification and generalization
  - …



8

3. Spatial and Non-spatial Queries

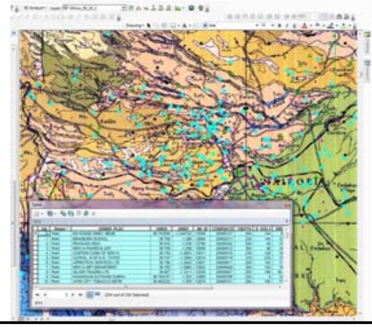


- Classification (Generalizing) procedures are a primary means for resolving spatial data into patterns to understand data:
  - Exogenous – threshold levels considered relevant or standard
  - Arbitrary – similar to exogenous, allowing nonstandard classification
  - Idiographic – 'natural breaks' exist in data
  - Serial class intervals – statistical analysis of data (equal frequency, mathematical normalization, and such)

3. Spatial and Non-spatial Queries

- Selection of attributed data without making changes in database
- SQL (Structured Query Language)

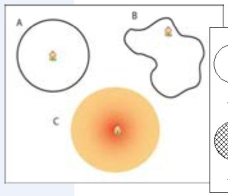
```
SELECT * FROM Boreholes WHERE Depth >= 1000
```

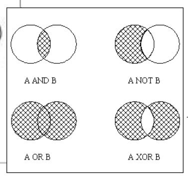


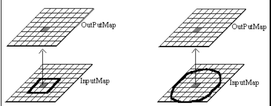
10

GIS Analysis Functions

- 4. Neighborhood operations (spatial) – 'search' functions, neighborhood can change its shape
  - Search
  - Proximity
  - Buffer
  - Filters
  - Slope, aspect, convexity
  - Finite differences and elements

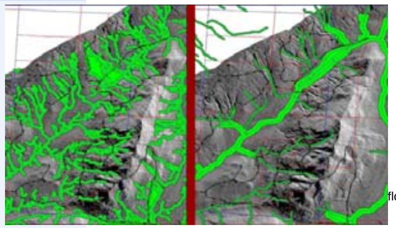


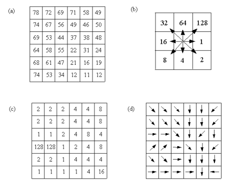




11

4. Neighborhood Operations





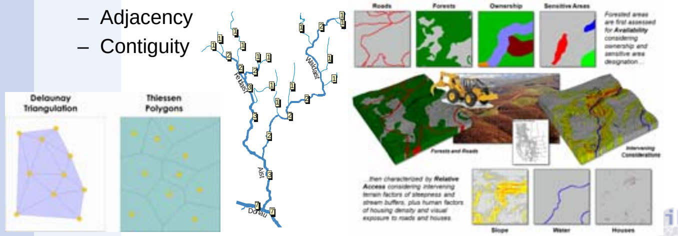
Flow directions with D8 model: (a) elevations, (b) flow direction codes, (c) flow direction grid values, (d) symbolic representation of flow directions.

- Mathematical procedures applied to spatial-phenomena data. Mathematical expressions quantify fundamental physical principles: surface and groundwater hydraulics.
  - Finite-element methods applied for a region characterized as a collection of sub-regions (finite elements), which also leads to a set of algebraic relations between adjacent sub-regions.
  - Finite-differences methods the solution region is envisaged as an ensemble of grid point – algebraic structure.

12

GIS Analysis Functions

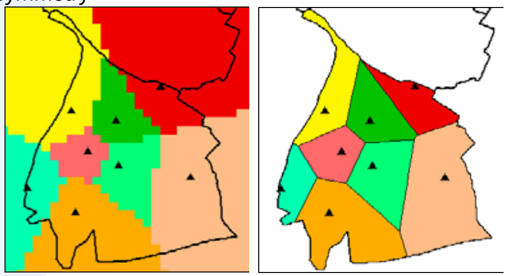
- 5. Spatial arrangement and connectivity functions - topology = logical connectedness of vector data
  - Proximity (based on measures of: distance, time, cost, etc. - buffer zones, Thiessen polygons, flow times)
  - Spread (floods, pollutants)
  - Path (optimal, short, decision rules, …)
  - Network functions (utilities, drainage,..)
  - Adjacency
  - Contiguity



13

5. Spatial Arrangement and Connectivity Functions

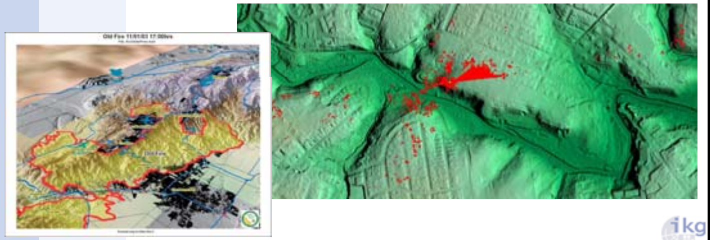
- Proximity - Thiessen-Polygons
- Raster based → assign proximity, vector based → line of symmetry



14

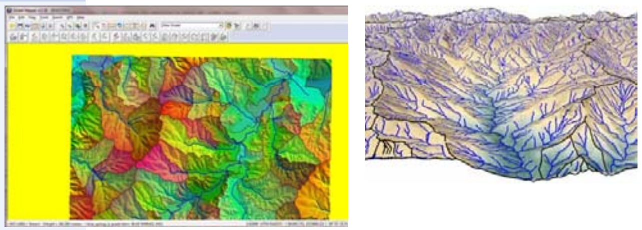
GIS Analysis Functions

- 6. Surface operations
  - Regular and irregular tessellations
  - Volume (cut and fill)
  - Visibility
  - Perspective view
  - Watershed and terrain modeling



15

6. Surface Operations

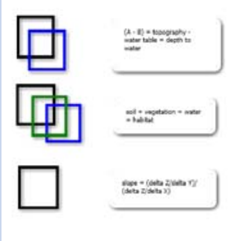


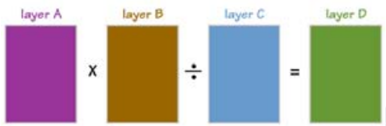
- Most commonly, surfaces are representations of terrain using DEMs (raster or TIN), but procedures are often applied to ‘surfaces’ created for other variables.
  - Automated extraction of watersheds or surface drainage, channel networks, drainage divides, etc. from DEMs is a standard surface processing in modern GIS.

16

GIS Analysis Functions

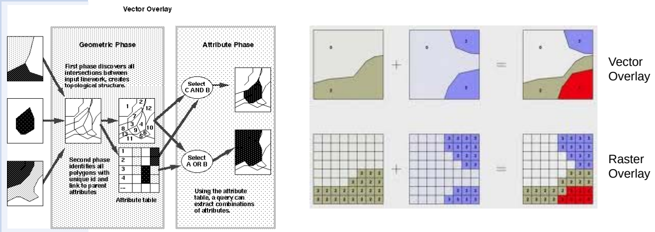
- 7. Overlays and map algebra – sets GIS apart from any other data-management and analysis software.
  - Overlays (raster and vector)
  - Map algebra (raster)
  - Cartographic modeling
  - Suitability assessment





17

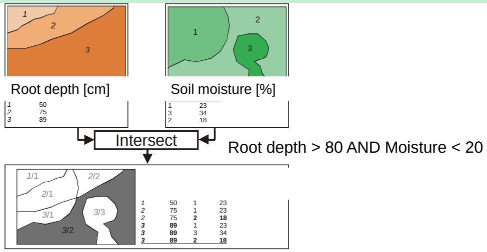
7. Overlays and Map Algebra



- Overlay operations may be logical or mathematical and are applicable to both raster and vector coverage data.
  - Logical overlays involve application of Boolean logic to the values of a map to derive another map containing those areas that meet the specified condition(s).
  - Mathematical overlays use algebraic manipulation to generate a new coverage where every 'new' value is some function of the original map(s) value(s).

18

7. Overlays and Map Algebra

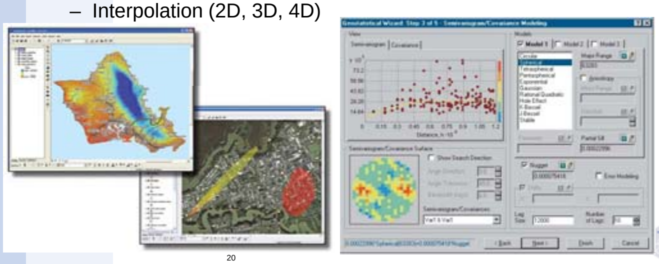


- M:N relationship between entities in two layers/maps each having different geometrical basis
- After intersection - analysis is carried out in a single layer
- Operations:
  - Arithmetic/mathematical (addition, multiplication, ...)
  - Logical expressions (AND, OR, XOR)
  - Application of conditions (rules)

19

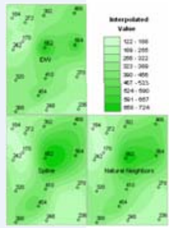
GIS Analysis Functions

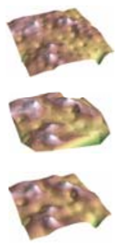
- 8. Spatial statistics – need to interpolate/extract from point values to unstapled locations (geostatistics).
  - Descriptive statistics (histograms)
  - Patterns and units
  - Thiessen polygons (nearest neighbor, Voronoi tessellations)
  - Trend surfaces
  - Interpolation (2D, 3D, 4D)

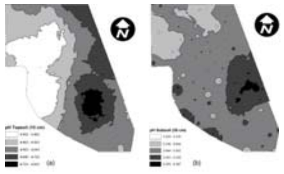


20

8. Spatial Statistics







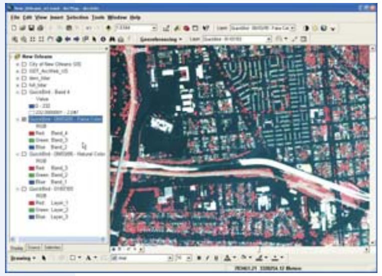
Interpolated soil maps (a) kriging, and (b) IDW

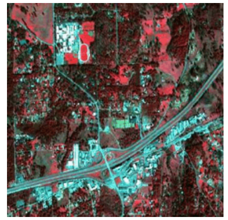
- Analyzing spatial distributions, patterns, processes, and relationships - geostatistics.
- Spatial statistics are unique in that (some) were developed specifically for use with geographic data since they incorporate space (proximity, area, connectivity, and/or other spatial relationships) directly into their mathematics.

21

GIS Analysis Functions

- 9. Image processing
  - Image enhancement
  - Image classification
  - …

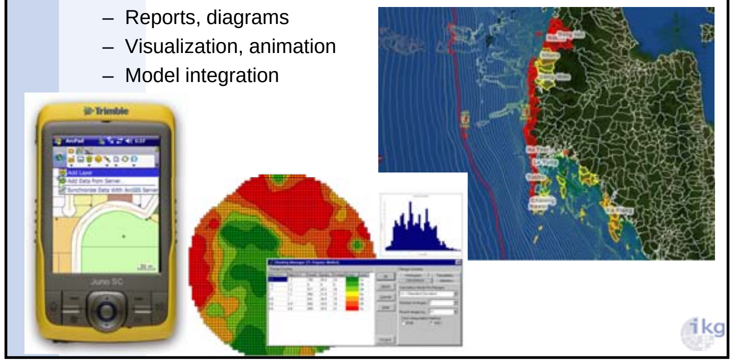




22

GIS Analysis Functions

- 10. Display, interfaces, integration
  - Map design
  - Symbology, color representation
  - Reports, diagrams
  - Visualization, animation
  - Model integration



10. Display, Interfaces, Integration

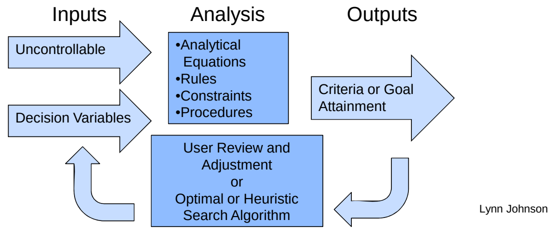
- GIS color-graphics display vast capabilities and varied visualizations formats; perhaps one of the main reasons for the popularity of modern spatial data management systems.
- The visual portrayal of spatial data and analysis results helps communicate the character of the natural and built environment.
- GIS provides a flexible means to access and view spatial data, plan and design.
- GIS software is advancing to 3D display and animation capabilities that support visualizations of complex environmental phenomena over time.
- GIS is used as an integrated model-development environment – modeling sequences for having seamless integrated modeling.

24

GIS Analysis Functions

- 11. Management models/ing
  - Simulations
  - Multiple criteria
  - Optimization
  - Decision-support systems

11. Management Models/ing



- Management modeling refers to the use of mathematical models to solve management problems: engineering planning, management, and design.
  - Simulation (descriptive models) – conducting experiments with a model of a system that is being studied or designed. *What if? Creating alternatives.*
  - Optimization (prescriptive models) – expanded capability to systematically select optimal solutions under agreed-upon objectives and constraints. *What is the 'best' solution?*

GIS in Hydrology and Water Management

Introduction to DEMs

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Data Models (Entities) – Intr.

- Vector models
  - 'simple' points, lines and polygons
  - complex points, lines, polygons and objects
    - Used to capture the internal structure of an entity; functional or descriptive. ('city' contains streets, houses and parks, each having different functionality and may respond differently to queries or operations).
    - Object-oriented systems support a hierarchical construction of objects from simple building blocks and a framework for description of properties as well as behaviour.
  - TINs (triangulation)
- Raster models
  - Mainly integer grids with lookup table of categories (e.g., Heights)
  - Loss of spatial resolution - location is only expressed by multiples of pixel size

Data Models (Entities) – Intr.

- There exist strong correspondence between the data model used and the data types stored and analyzed
  - If location and shape of an entity are time-invariant and known with very high complexity → **Vector model**
  - If attributes are fixed, entity might change shape but not its position (water surface of lake) → **Raster model**
  - If attributes can vary, object changes position, but not shape → behavior can be represented by **object-oriented models**
- Water bodies
  - Changing water levels in lakes, reservoirs or rivers can change their size, shape and position
  - During flood events, rivers can change their path (breakthrough of meanders, new reaches) → change of geometry and topology!
- Continuous fields in hydrological models
  - Continuous fields in GIS only spatially described (TIN, raster)

29

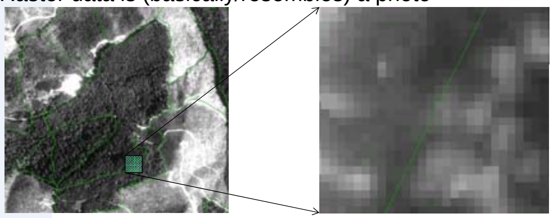
Data Models (Entities) – Intr.

- Decision depends on classes of represented objects:
  - Linear phenomena are better handled in vector models
  - Raster model has advantages with areal data
  - If high positional accuracy is important, rasters will normally need much higher data storage
- Applications define the criteria
  - Coordinate transformation is easy in vector models
  - Coordinate transformation is more difficult for raster models, because input pixel generally do not have only a single output pixel → (usually) irreversible process
  - Raster structure might not be preserved (global and local distortions)

30

Raster Data Structure

- Raster data is (basically/resembles) a photo

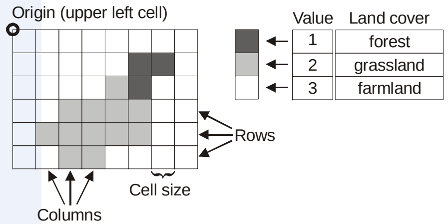


- There exist three ways to interpret a pixel:
  - Classification: a range of values is allocated to certain objects (gray pixels are roads, blue pixels are water surfaces,...).
  - Measure the value: intensity of a color, concentration, etc.
  - Relative height over reference height.

31

Raster Data Structure

- Position is represented by discrete cells

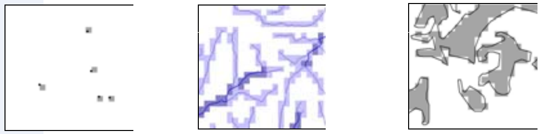


- Types of raster maps
  - Nominal data, such as land use (forest, grassland, farmland, ...).
  - Continuous values, concentration, light intensity.
  - Relative measures, such as elevation.

32

Raster Data Structure

- Entities represented both as vector model – and as a raster



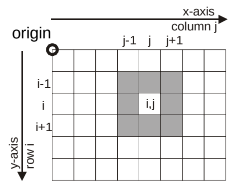
  – Points Lines Polygons

- Cell/pixel size determines resolution: aspiration is that the cell size area will be/cover maximum 50% of smallest recognized object (photographed, scanned,…).

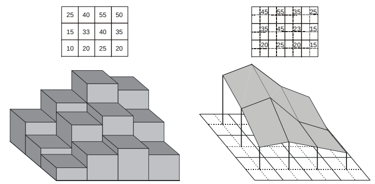
33

Raster Data Structure

- Topology is described implicitly by raster models – neighbors, pixel size, inner structure,...



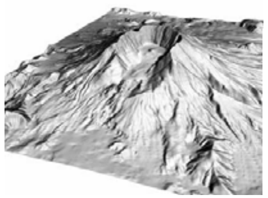
- Cell raster (categorial, discrete) vs. point raster (lattice, continous)



34

DEM = Digital Elevation Model

- Definition: a DEM is a set/array/matrix of numbers that describe the spatial distribution of terrain elevations above a reference plane.
- DTM (Digital Terrain Model) is often used synonymously, but usually oriented to the bare earth representation.
- DEM are used not only for earth surface, but also for other surfaces, such as groundwater, geological layers, artificial structures (buildings), vegetation, etc.



DEM

- Miller and Laflamme (1958):

  …"The digital terrain model (DTM) is simply a statistical representation of the continuous surface of the ground by a large number of selected points with known X, Y, Z coordinates in an arbitrary coordinate field"…
- Model stands for (Goodchild et al. 1993):

  …"A model is a computer program that takes a digital representation of one or more aspects of the real world and transforms them to create a new representation."…
- The purpose of a model can be narrowed down to a single application or geoprocessing task, and as suggested by Saaty and Alexander (1981):

  "… to function as a tool for understanding the real world and discovering natural laws…".

36

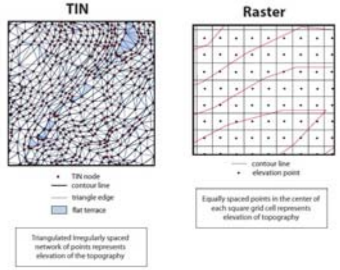
DEM

- DEM is a mathematical model that has to satisfy several criteria (Meyer, 1985), amongst them:
  - **Accuracy** - the model representation is - as far as possible - a correct and reliable one (or very nearly so)
  - **Descriptive Realism** - the model was put together based on correct hypotheses and observations
  - **Precise** - the model prediction is definite, whether in numbers, functions, or geometric figures
  - **Robustness** - the model is somewhat immune to errors in the input data
- DEMs are a somewhat 'reduced' 3D representation of the continuous reality of the terrain since it is merely a discrete data structure storing "number".
- Still, this 'reduced' spatial representation has to maintain certain aspects and features to continue and be reliable and 'true' to the phenomenon it models.

37

DEM – Data Structures

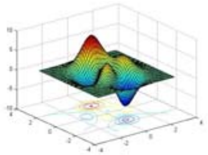
- Three main structures are commonly used today to represent terrain surfaces in digital form (choice depends mostly on application and computer resources):
  - Contour lines - vector
  - Raster-based (known also as grid and elevation matrix)
  - TINs (Delauny triangulation / Voroni diagram) - vector

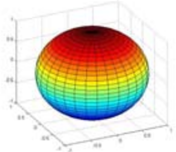


38

DEM – Data Structures

- All three structures conform to functional surfaces - continuous field of values that may vary over an infinite number of (sample) points - terrain representation = elevation value.
- All sample-positions on the modeled-surface have only one elevation, e.g., a single z-value exists apiece {x,y} coordinate (sometimes referred to as 2.5D).
- (In contrast to a functional surface, which preserves surface continuity, solid model surfaces can model and store true 3D entity, e.g., multiple z-values apiece {x,y} coordinate.)

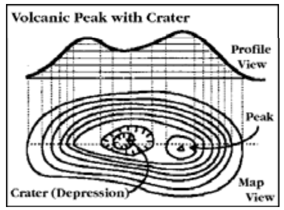




39

DEM – Contours

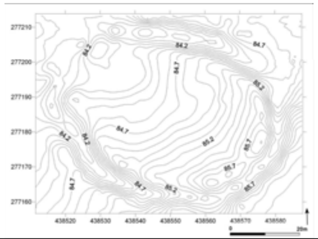
- A contour (iso-line) is a line following the same exact potential of a specific attribute or phenomena. Such that contour lines connect sample points, or positions, that store equal value – in this case elevation (also: temperature, precipitation, etc.).
- Usually, contours will be produced in an equally-spaced height interval (spacing) that differs between all contours exist in the model.
- Consequently, contours cannot intersect one another as it is not physically possible.



40

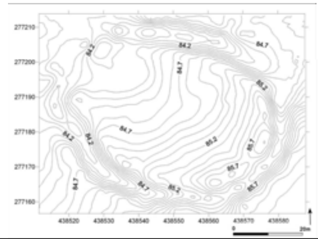
DEM – Contours

- Advantages:
  - popular for display of maps, intuitive, cognitive (dense, sparse)
  - Overlay
  - Computation of terrain parameters (e.g. crenulations ratio)
  - Stream lines: orthogonal to contours, and used for runoff modeling
  - Trend surfaces are presented with high reliability



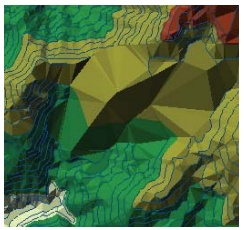
DEM – Contours

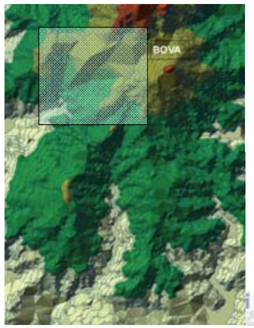
- Disadvantages:
  - data storage is (usually) not very compact
  - Data-acquisition mostly relies on existing analog data
  - Geo-processing analysis is not reliable and adequate
  - Inflexible to conform to terrain complexities
  - Specific features and characteristics might not be apparent – sensitive to predefined interval value (interpolation will not help)



DEM – TIN

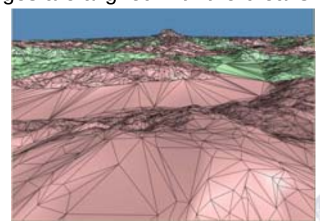
- Triangulated Irregular Network (TIN) is an efficient and accurate digital data-structure to model continuous surfaces.
- An array of irregularly distributed vertices (sample points) that store three-dimensional coordinates arranged as a network of non-overlapping triangles.





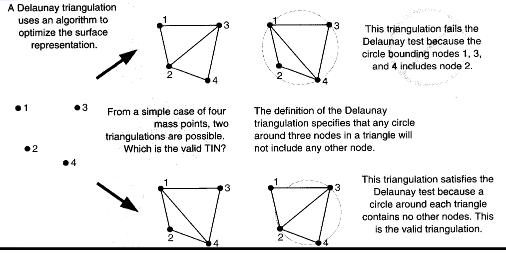
DEM – TIN

- The main advantage of the TIN structure is perhaps its efficiency to be flexible to point density: on any area of the surface the density can change and be proportional to the variation of the terrain (as opposed to raster-based structure).
- Sample points are to be located to capture significant changes in the topography, such as non-continuous features, pits, peaks, etc. Triangles fit best in areas with sharp breaks in slope, where the TIN edges are aligned with the breaks completely.



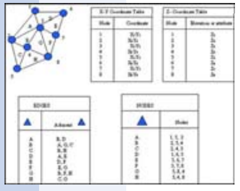
DEM – TIN

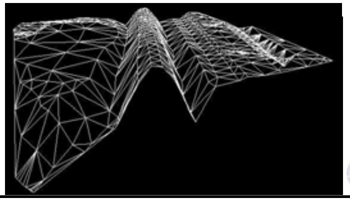
- Usually constructed based on the Delaunay triangulation that employs certain geometric restrictions to form the mesh of contiguous and non-overlapping triangles.
- Fundamentally, the aim is that each triangle that is created in the TIN network is to be as close to equilateral as possible, while the interior of the circumscribing circle contains no network points (adjacent triangles are mosaiced).



DEM – TIN

- TIN representation holds specific structure-elements: vertices, edges, triangles, and topology.
- Vertices are the kernel element composing the triangles. The vertices themselves are connected by edges that form the triangles, which are formed by the Delaunay restrictions.
- The topology defines the neighboring (adjacent) triangles to each triangle (mostly three neighboring triangles exist except on the TIN mesh periphery where one or two neighbors could also exist), and also stores the vertices list that builds the

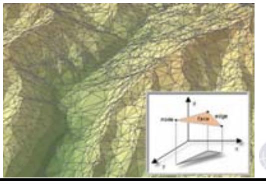




46

DEM – TIN

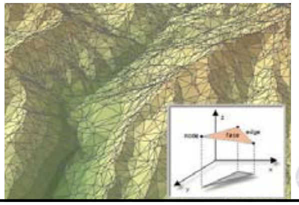
- Advantages:
  - Different 'levels of resolution' (changing density) required to model the terrains changing complexities
  - Trend surfaces are presented with high reliability
  - The vector data-structure supports the integration of point-, line-, and polygon- based features (original sample data is stored)
  - Primitive geometrical surfaces exist in the model, no interpolation is required
  - Set of triangles derive additional surface information, such as volume, profile, line-of-sight, and more



47

DEM – TIN

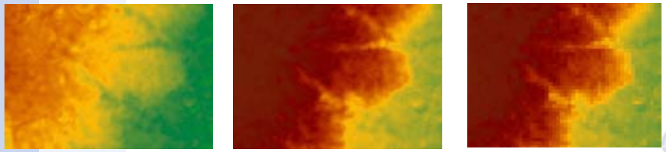
- Disadvantages:
  - Data handling and algorithms might be more difficult to implement, less native and more complex data arrangement
  - Might requires post-processing of acquired data to achieve optimal structure
  - Maintenance issues regarding this structure are (usually) less efficient
  - TIN models are less widely available than raster surface models and tend to be more expensive to build and process



48

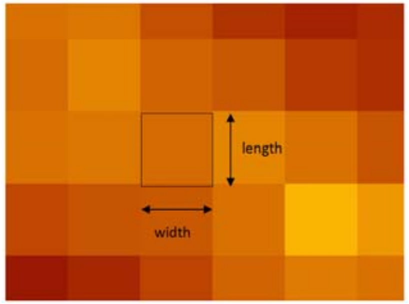
DEM – Raster

- A raster-based structure (grid) consists of a matrix of cells (or pixels) organized into rows and columns where each cell contains a value representing specific data - height.
- Sample point elevations are stored and are spaced spatially at regular intervals.
- The intervals are analogous to the structure spatial resolution, and usually have to preserve consistency.
- The grid's spatial resolution derives the reliability of the model, and also its capacity in representing different terrain elements.



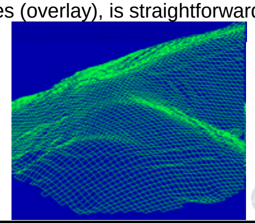
DEM – Raster

- Each data-cell, or pixel, dimension 'covers' a specific area, such that the spatial resolution can be divided into two dimensions, which are regarded to as length (vertical cell resolution) and width (horizontal cell resolution).



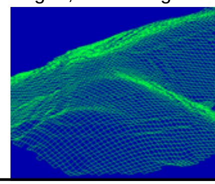
DEM – Raster

- Advantages:
  - Conceptual model that is simple with (usually) compact data storage (mainly binary format), but dependent on the resolution
  - Trend surfaces are presented with high reliability
  - Appearance of terrain features is continuous and natural
  - Established geo-processing and statistical analysis algorithms
  - Maintenance issues regarding this structure are (usually) more efficient and inexpensive. Integration with other raster-based databases, such as imagery ones (overlay), is straightforward



DEM – Raster

- Disadvantages:
  - Grid structure is relatively too rigid to conform to the terrain variability and to model all surface anomalies and features (discontinuities might not be modeled)
  - Extreme points, such as highest and lowest points, are unlikely to be represented (improbable that they are sampled in the grid)
  - Different terrain complexities are not represented
  - Qualitative representation of linear features is not always feasible in all geoprocessing applications
  - When interpolating to regularly spaced grid, not all original data is preserved



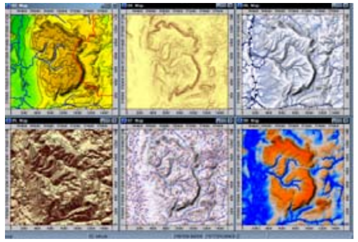
DEM – Topographic Descriptors

- The investigation of the terms of a measurable, i.e., geomorphometric, surface form, as well as the processes that give rise to the geomorphometric and terrain characteristics, i.e., phenomena, are important when discussing topographic-derived modeling issues.
- **Quantitative descriptors**, i.e., numeric descriptors, referring to some extent of quantity - that is not categorized - with a range of numerical values. Quantitative data can be grouped into categories and thus becoming qualitative data - geomorphological processes and analysis.
- **Qualitative descriptors** are more general and refer to a particular distinct category. It should be noted that data that was originally obtained as qualitative information about specific features can contribute to quantitative data where they are statistically valued in terms of calculation and mathematical processes - land cover and land formation.

53

DEM – Topographic Descriptors

- Geomorphometry analysis, which uses systematic parameterization of altimetric and planimetric variations, is unified under the use of the first and second derivatives of the altitude values across the plane.
- Several known local terrain variations of terrain characteristics, such as slope, aspect, profile convexity and plan convexity = “landform signatures“ / “relief units”.



54

DEM – Topographic Descriptors

- **First-order derivatives** - measure the steepness of an area exists in the surface:
  - ***Slope***, the rate of change in elevation over a change in planar position. Slope is usually measured in degrees, but sometimes also in percentage. Slope can be facilitated in finding the direction and magnitude of the steepest gradient, and is also a key descriptor for hydrographic analysis and the establishment of flow networks.
  - ***Aspect***, the direction to which an extent of the surface is oriented at. The direction itself is usually categorized to several quantitative groups within the compass rose. Aspect also defines the direction of surface flow.
- **Second-order derivatives** - describe the slope rate of change of the terrain (e.g., first derivative of slope), also referred to as plan and profile curvatures. This descriptor describes the physical characteristics of a drainage basin, important in understanding erosion and runoff processes.

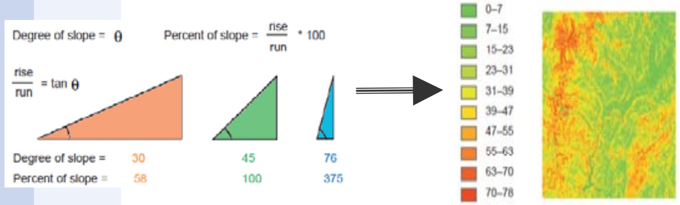
DEM – Application in Hydrology

- DEM and derived products have a large potential for hydrological modeling.
- Applications: runoff models, soil erosion, snow melt, evapotranspiration, groundwater studies, ...
- Properties that can be defined for each DEM pixel/triangle:
  - Terrain elevation
  - Aspect (Exposition)
  - Slope
  - Upslope area, mean height and slope of upslope area
  - Maximum and mean length of flow path
  - Profile and contour curvature
- Area properties:
  - Mean slope
  - Area
  - Basin length

56

DEM – Application in Hydrology

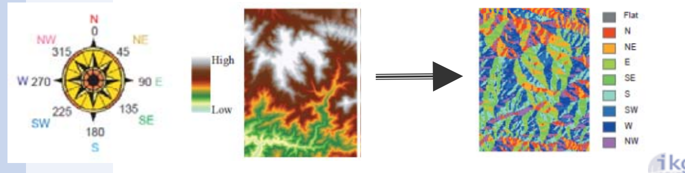
- Slope finds the magnitude of the steepest gradient for each kernel area – cell or triangle.
- It produces a new raster map with all slopes.
- Slope is calculated as angle (0-90) or percentage (0-100).
- Slope = $(dx^2 + dy^2)^{1/2}$



57

DEM – Application in Hydrology

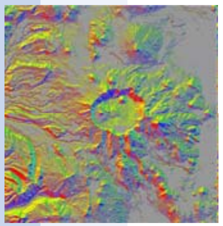
- Aspect finds the direction in which the slope is facing, i.e., the direction of the magnitude of the steepest gradient for each kernel area – cell or triangle.
- It produces a new raster map with all aspects.
- Aspect is calculated in categories, 0 = north, 180 = south, …
- Flat areas have the value of -1.
- Aspect = arctan (gy/gx)



58

DEM – Application in Hydrology

- Slope and aspect can be used for:
  - Direct use for hillshading
  - Solar radiation
  - Effective sunshine



59

DEM – Application in Hydrology

- Curvature calculates the slope of the slope (the second derivative of the surface) of a surface; whether a given part of a surface is convex or concave.
- Convex parts of surfaces, like ridges, are generally exposed and drain to other areas.
- Concave parts of surfaces, like channels, are generally more sheltered and accept drainage from other areas.
- These are used primarily to interpret the effect of terrain on water flow and erosion.
- Profile curvature is in the direction of the maximum slope and affects the acceleration and deceleration of flow, which influence erosion and deposition.
- Plan curvature is perpendicular to the direction of the maximum slope and influences convergence and divergence of flow.

60

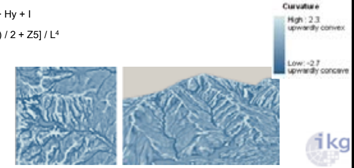
DEM – Application in Hydrology

- Plane fitted through each cell and eight surrounding neighbors.
- A positive curvature indicates the surface is upwardly convex at that cell. A negative curvature indicates the surface is upwardly concave at that cell. A value of 0 indicates the surface is flat.
- Units of the curvature output raster are one hundredth (1/100) of a z-unit. The reasonably expected values of all three output rasters for a hilly area (moderate relief) can vary from -0.5 to 0.5; while for steep, rugged mountains (extreme relief), the values can vary between -4 and 4.

$$Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I$$

$$A = [(Z1 + Z3 + Z7 + Z9) / 4 - (Z2 + Z4 + Z6 + Z8) / 2 + Z5] / L^4$$
$$B = [(Z1 + Z3 - Z7 - Z9) /4 - (Z2 - Z8) /2] / L^3$$
$$C = [(-Z1 + Z3 - Z7 + Z9) /4 + (Z4 - Z6)] /2] / L^3$$
$$D = [(Z4 + Z6) /2 - Z5] / L^2$$
$$E = [(Z2 + Z8) /2 - Z5] / L^2$$
$$F = (-Z1 + Z3 + Z7 - Z9) / 4L^2$$
$$G = (-Z4 + Z6) / 2L$$
$$H = (Z2 - Z8) / 2L$$
$$I = Z5$$

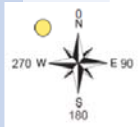
Curvature = -2(D + E) * 100



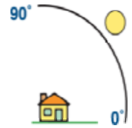
61

DEM – Application in Hydrology

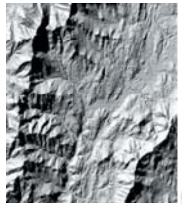
- Hillshade is a function the describes the (theoretical) illuminated areas on the surface.
- This is carried out by knowing the slope for all areas and the position of the sun.
- Light and shadow receive values between 0 and 255.



Azimuth



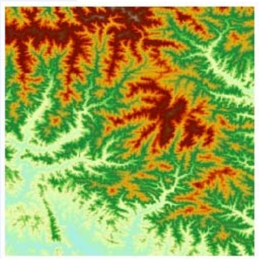
Inclination



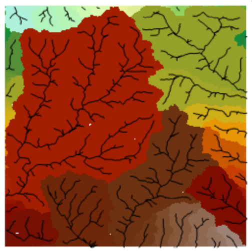
62

DEM – Application in Hydrology

- Basin and watershed boundaries



DEM



Basins and stream network

63