ΤΜΗΜΑ ΠΟΛΙΤΙΚΩΝ ΜΗΧΑΝΙΚΩΝ
ΜΠΣ “ΔΙΑΧΕΙΡΙΣΗ ΥΔΡΟΜΕΤΕΩΡΟΛΟΓΙΚΩΝ ΚΑΤΑΣΤΡΟΦΩΝ”

ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ

Υδροπληροφορική και Συστήματα Υποστήριξης Αποφάσεων (DSS) για τον κίνδυνο πλημμύρας σε αστικές περιοχές

Γεωγραφικά Συστήματα Πληροφοριών, Συστήματα Υποστήριξης Ομαδικών Αποφάσεων, Συστήματα διαχείρισης βάσεων δεδομένων και μοντέλων. Χωρική πολυκριτηριακή ανάλυση δεδομένων με χρήση Γεωγραφικών Συστημάτων Πληροφοριών

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Τμήμα Πολιτικών Μηχανικών, ΔΠΘ

Διδάσκων: Επίκ. Καθηγητής Γεώργιος Παπαϊωάννου

Τμήμα Δασολογίας και Διαχείρισης Περιβάλλοντος και Φυσικών Πόρων, ΔΠΘ

- Geographic Information System
- Geodatabase and modelling systems
- Decision Support Systems
- Spatial multicriteria analysis using Geographic Information System

- **Geographic Information System**
- Geodatabase and modelling systems
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Water Resources Overview

- 2 broad categories of water
  - Surface water
  - Groundwater
- 2 broad categories of water modeling
  - Quantity
  - Quality

- Today’s focus ***surface water quantity***

Surface Water Quantity

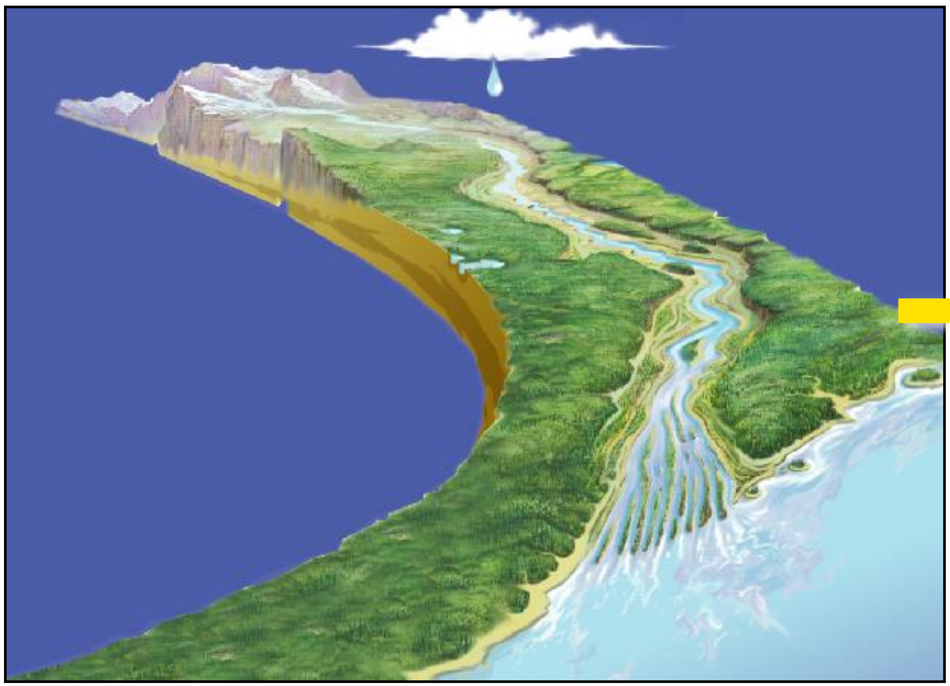
- How much water is there?
  - Rainfall runoff modeling, a type of hydrologic modeling, determines for a given storm on a landscape, how much water will become runoff.
- Where will it go?
  - Hydraulic modeling takes the quantity of water and the shape of the landscape and stream channel and determines how deep the water will be and what area it will cover in the event of a flood.

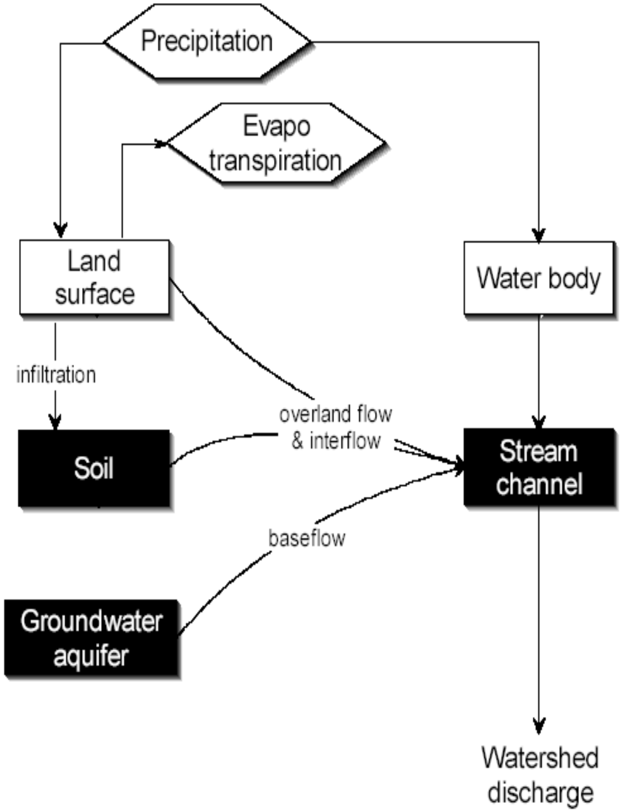
Hydrologic Modeling

- **Goal**: Find stream discharge, **Q**, at a location for a given precipitation.
- GIS is used to summarize terrain and hydrologic characteristics of the watershed for input to a model.
- Many ways to calculate Q.
  - Statistical methods
    - USGS regression equations (NFF, StreamStats)
  - “Physical” modeling (rainfall-runoff models)
    - HEC-HMS (successor to HEC-1), TR-20, etc.

Hydrologic Modeling

- Map natural processes onto software tasks
- Aggregate landscape characteristics to simplify
  - “Lumped parameter model”





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Hydraulic Modeling

- **Goal:** to predict water surface elevations for the creation of flood inundation maps.
  - Also velocity, sedimentation, quality
- **Input:** channel and floodplain geometry with hydraulic characteristics, plus discharge and initial water surface level.
- **Output:** water surface elevation at each cross section and other characteristics.

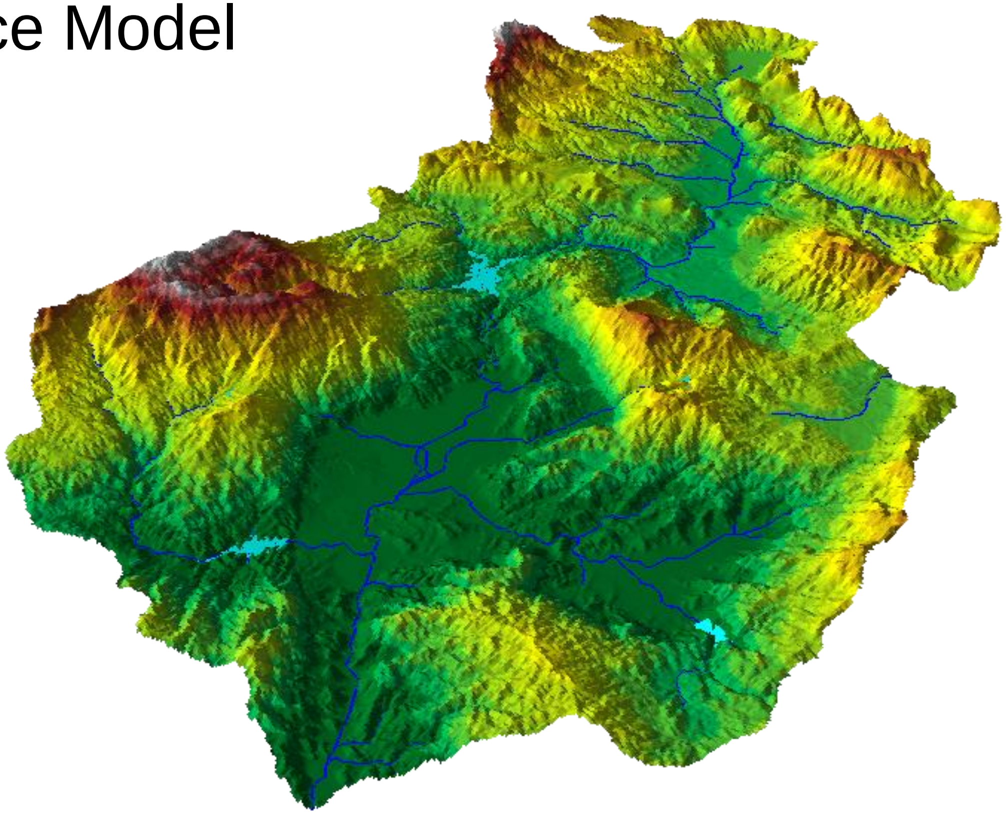
GIS Data for Hydrologic and Hydraulic Modeling

- Digital Elevation Model
  - http://seamless.usgs.gov/
  - http://edna.usgs.gov/
- Watershed boundaries
  - http://www.ncgc.nrcs.usda.gov/products/datasets/watershed/
- Hydrography
  - http://nhd.usgs.gov/
- Soils
  - http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/
  - http://soildatamart.nrcs.usda.gov/
- Landcover
  - http://seamless.usgs.gov/
- Current and historic water records
  - http://waterdata.usgs.gov/nwis
  - http://www.epa.gov/STORET/index.html
- Climate, weather, rainfall
  - http://www.ncdc.noaa.gov/oa/ncdc.html
  - http://www.nws.noaa.gov/ndfd/
- Channel geometry (cross sections)

Elevation Data

- Types
  - DEM : Digital Elevation Model
  - DSM : Digital Surface Model

- Data Structure
  - Raster
  - TIN



Where do you get DEM data?

- Sources
  - USGS DEM, NED, DTED, ETOPO30, SRTM
  - Interpolated from points and lines
  - Generated photogrammetrically
  - LiDAR
- Created with interpolation tools
  - especially TOPOGRID, TopoToRaster
- What cellsize and accuracy?
  - Horizontal and Vertical resolution must be appropriate for the landscape and scale being modeled.

DEM Construction

- DEM construction issues
  - Resolution and extent
  - Projection (for hydrology - equal area)
  - Source elevation data
  - Interpolation techniques (IDW, spline, via TIN)
    - Problems with contour input
  - Specialized DEM construction software/components (ANUDEM, TOPOGRID, TopoToRaster)

DEM Construction continued

- Hydrologically correct DEM
  - Sinks
    - Do not fill in the Great Salt Lake
  - Streams in the correct place?
    - To burn or not to burn
  - Watershed boundaries in the correct place?
    - To fence or not to fence

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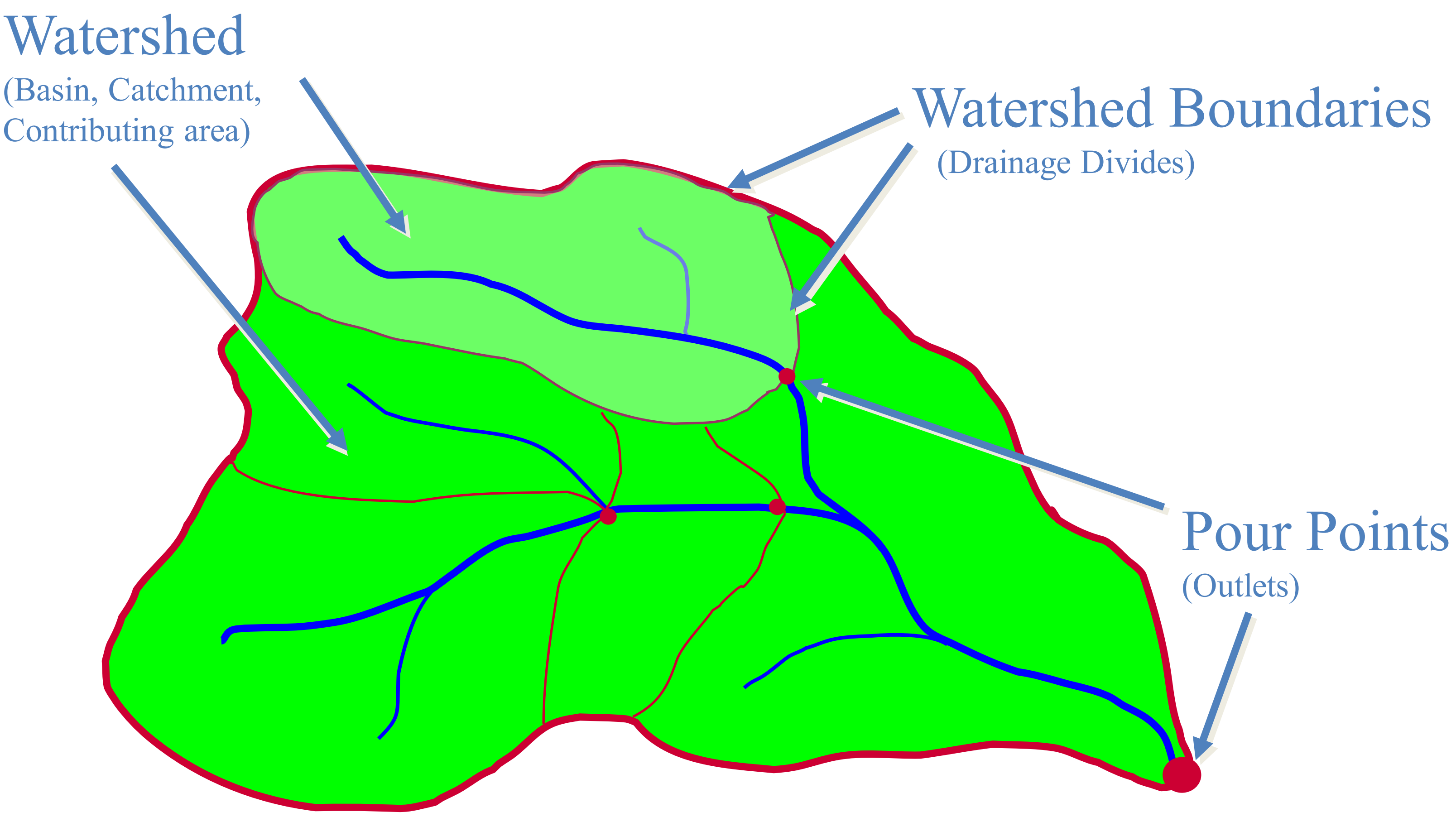
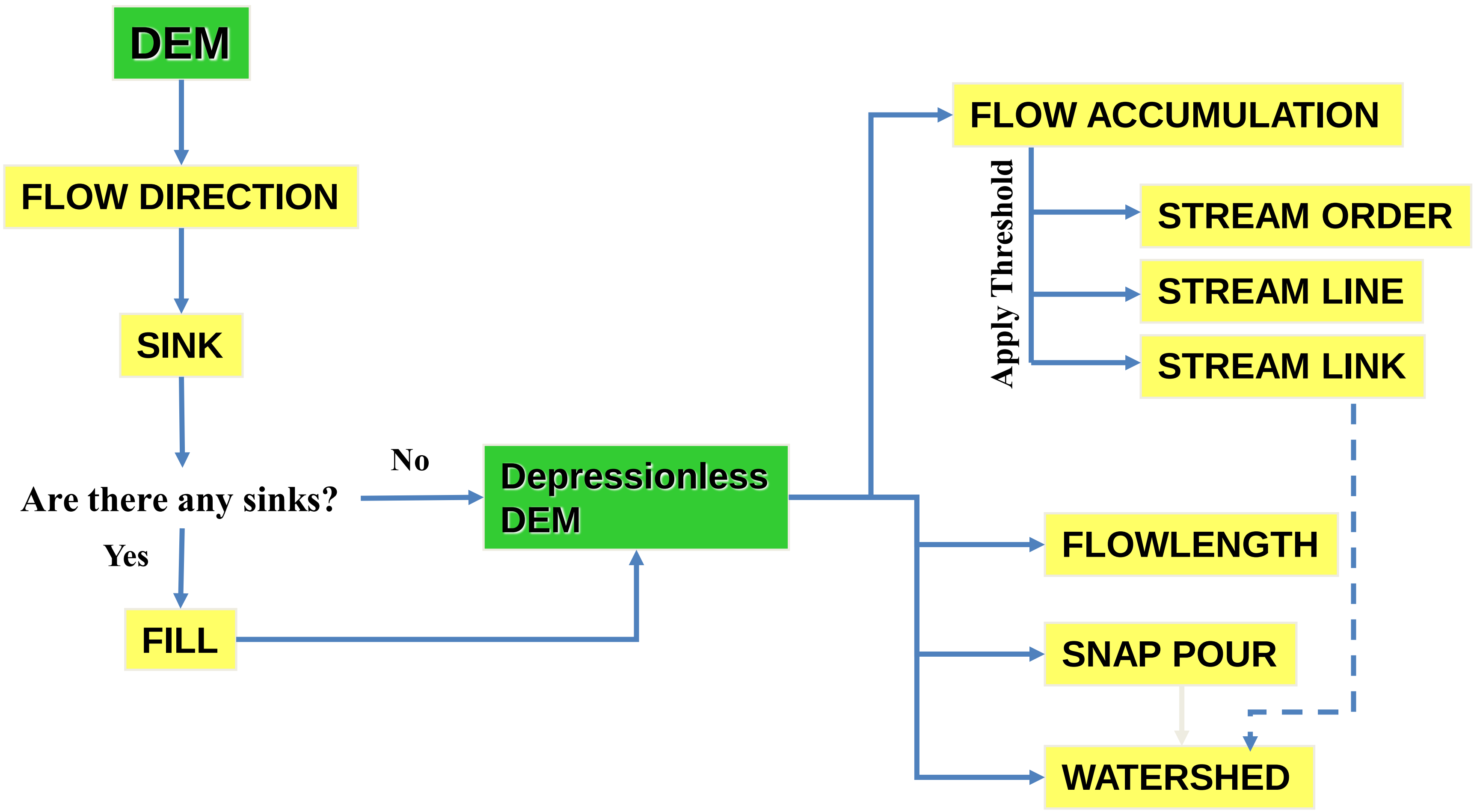
Drainage System



GIS Tools for Describing Surface Water Movement



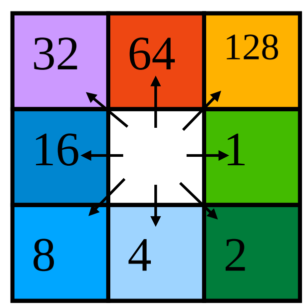
Flow Direction

78	72	69	71	58	49
74	67	56	49	46	50
69	53	44	37	38	48
64	58	55	22	31	24
68	61	47	21	16	19
74	53	34	12	11	12

Elevation

2	2	2	4	4	8
2	2	2	4	4	8
1	1	2	4	8	4
128	128	1	2	4	8
2	2	1	4	4	4
1	1	1	1	4	16

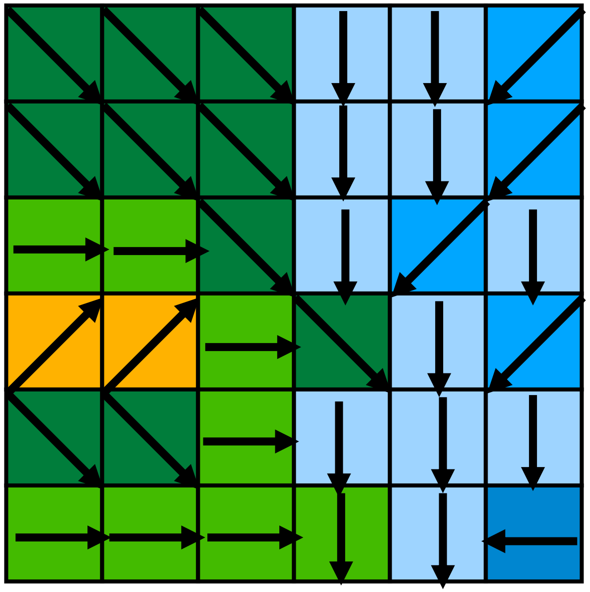
Flow Direction



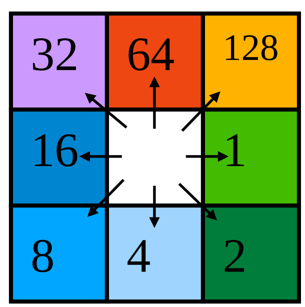
Direction Coding

ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ

Flow Accumulation



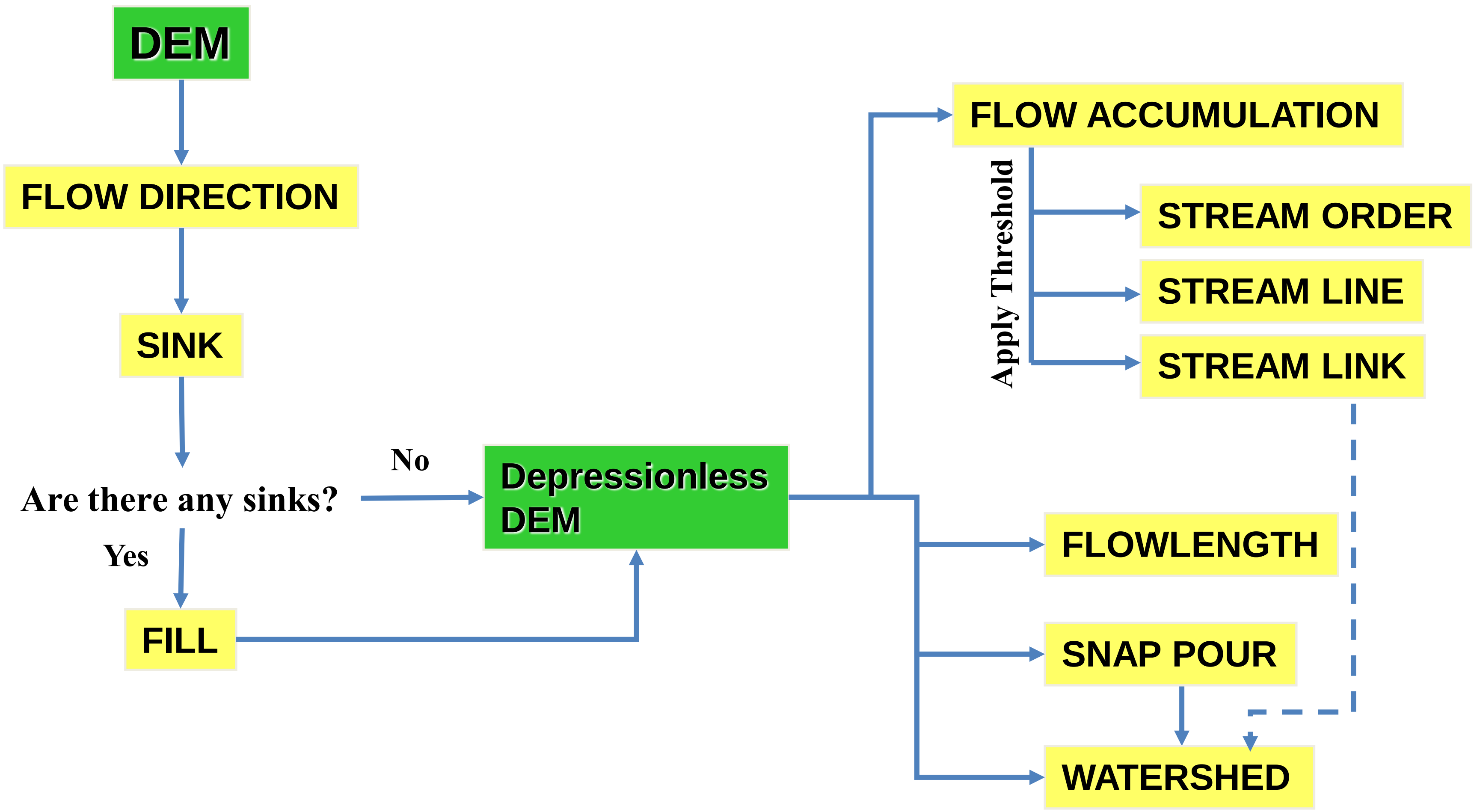
0	0	0	0	0	0
0	1	1	2	2	0
0	3	7	5	4	0
0	0	0	20	0	1
0	0	0	1	24	0
0	2	4	7	35	2



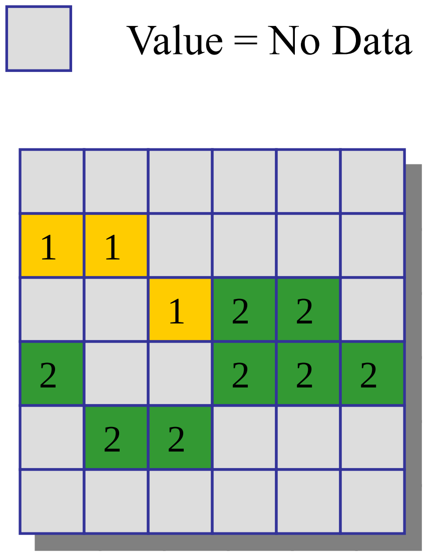
Direction Coding

ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ

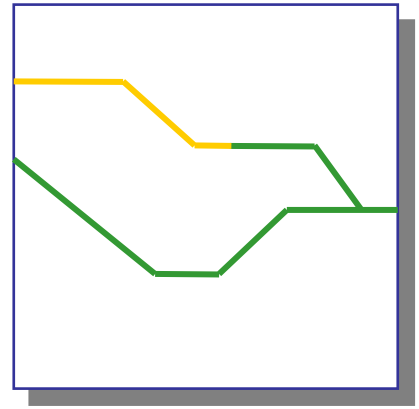
GIS Tools for Describing Surface Water Movement



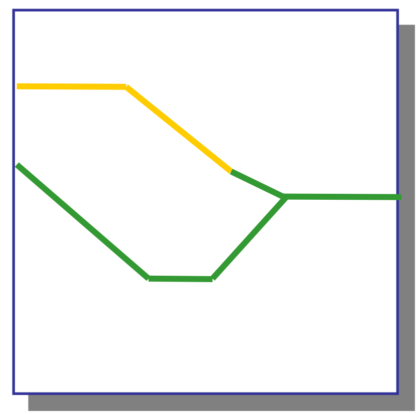
Creating Vector Streams



NET_GRID



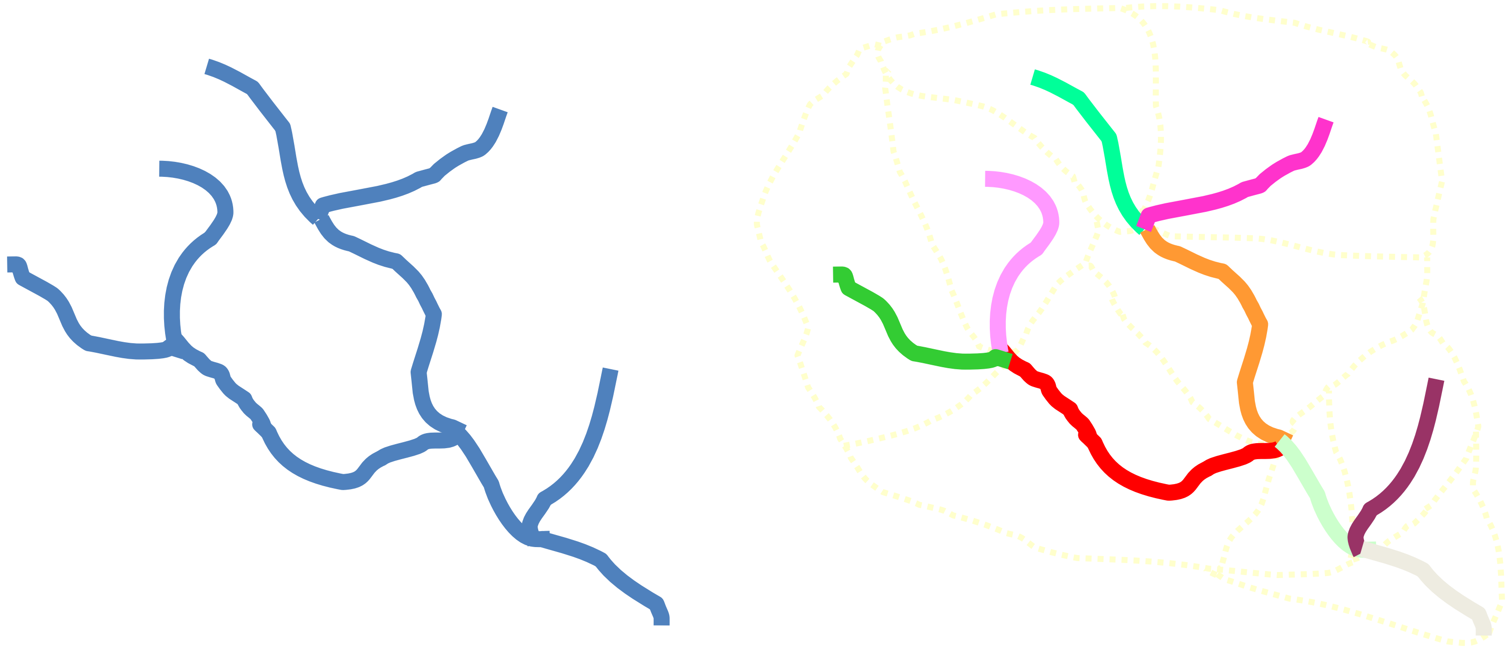
StreamToFeature



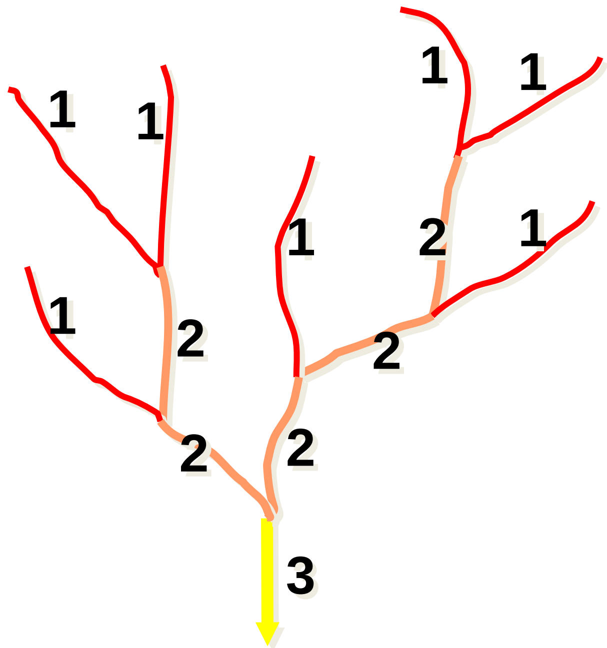
RasterToFeature

Stream Link

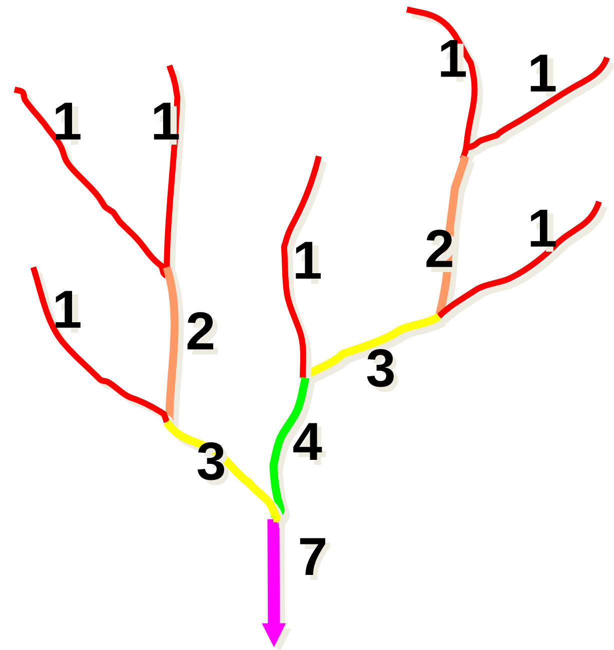
- Assign a unique value to each stream segment.
  - Can be used as input to Watershed



Stream Ordering



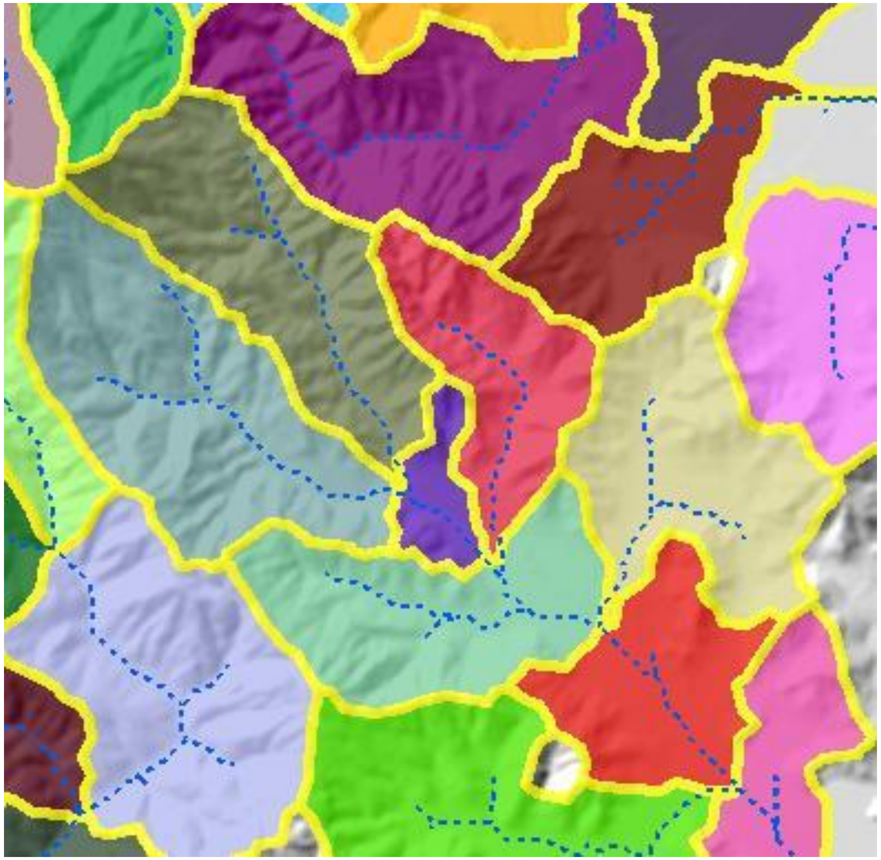
Strahler



Shreve

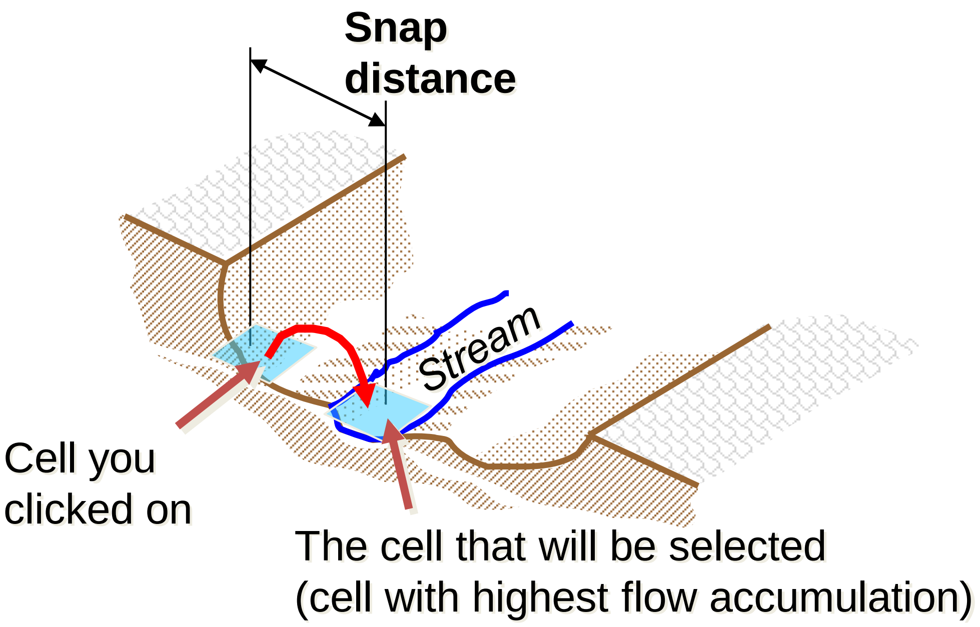
Watershed

- Delineate the contributing area to a cell or group of cells.



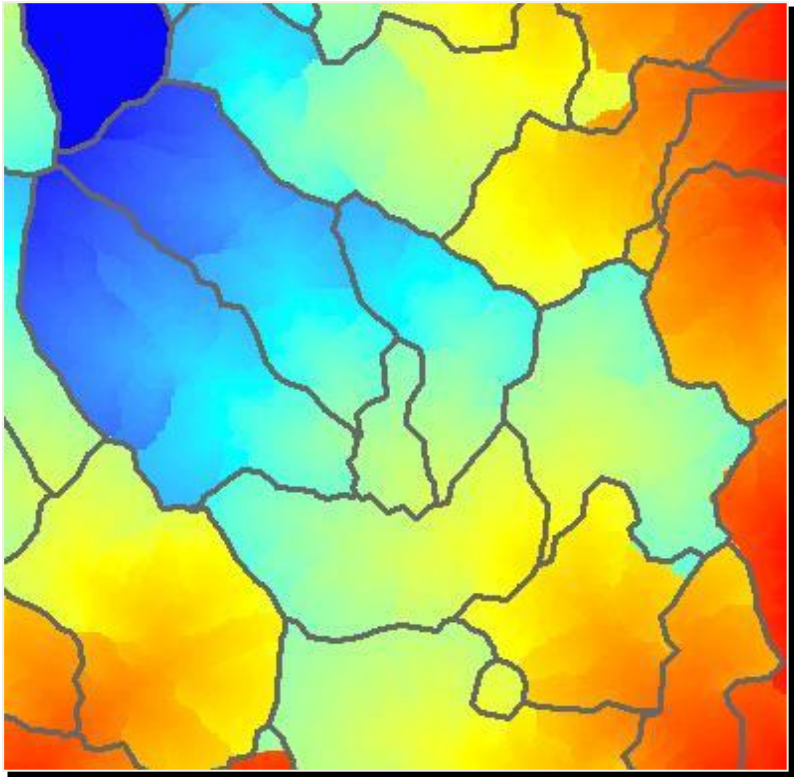
SnapPour

- Snap the "pour point" of a watershed to the cell of highest flow accumulation within a neighborhood.
  - Prevents accidental creation of tiny watersheds on channel side slopes.



Flow Length

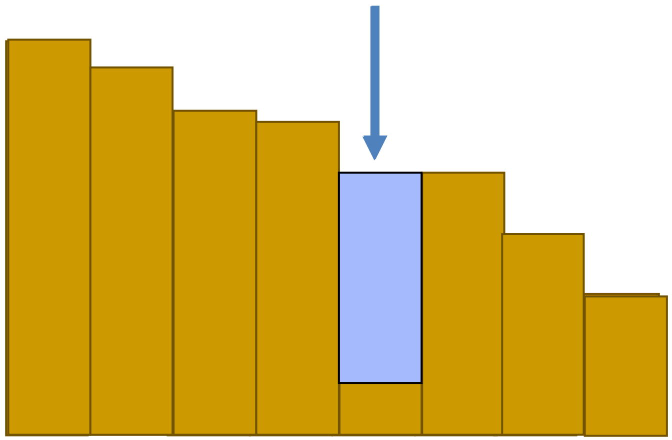
- Calculate the length of the upstream or downstream flow path from each cell.



DEM Errors – Sinks and Spikes

- Sinks: when sinks are (or are not) sinks – lakes, depressions, …
  - Global fill
  - Dealing with internal basins
  - Selective fill
    - Depth
    - Area

Filled sink



Summarizing Watershed Characteristics- (Zonal Statistics)

- A ***zone*** is all the areas/cells with the same value.
- Calculate a statistic within the zones for each cell in a raster.
- Input zones can be feature or raster.
- Output as a raster, summary table, or chart.
  - Max flow length per watershed
  - Average slope per watershed
  - Average curve number per watershed

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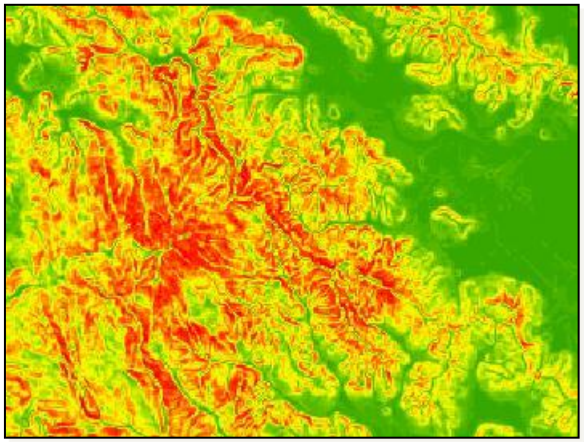
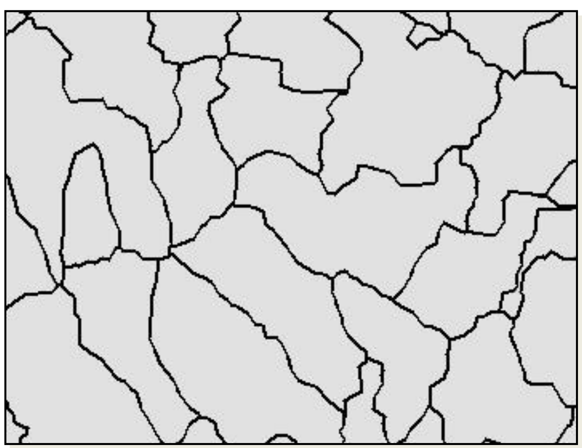
Zonal Overlay (cont.)

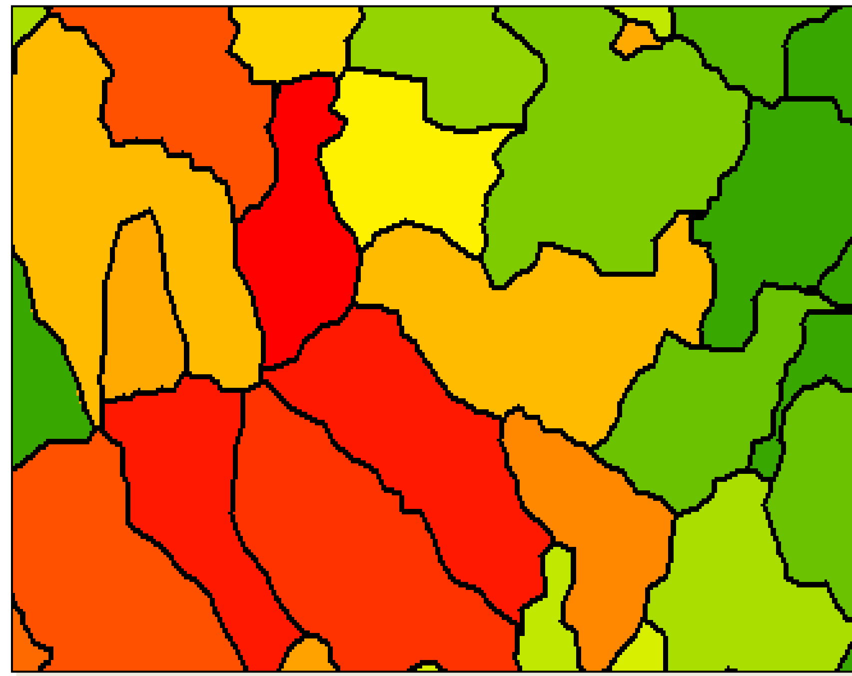
Slope



Watersheds

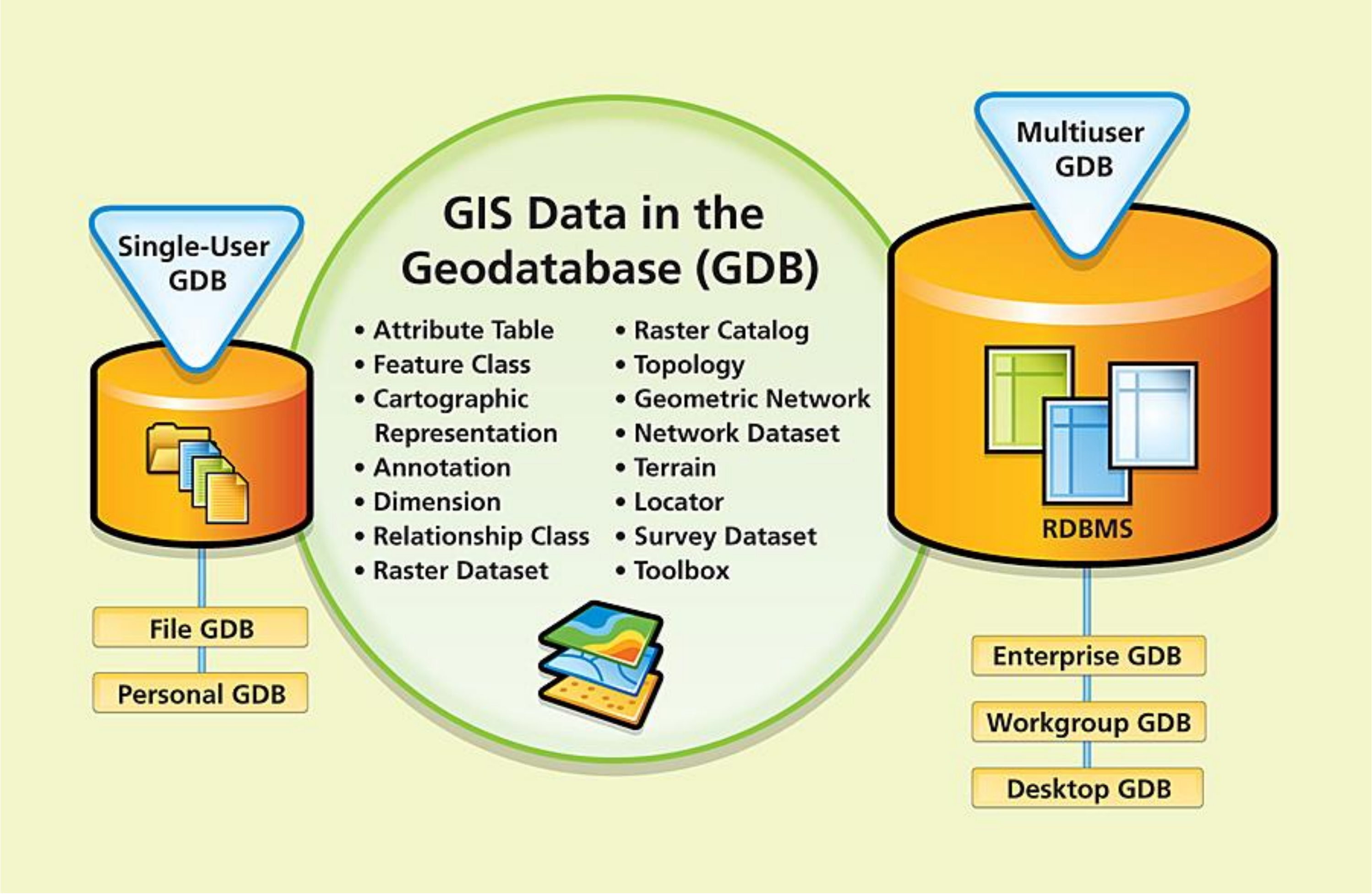


Mean Slope per Watershed

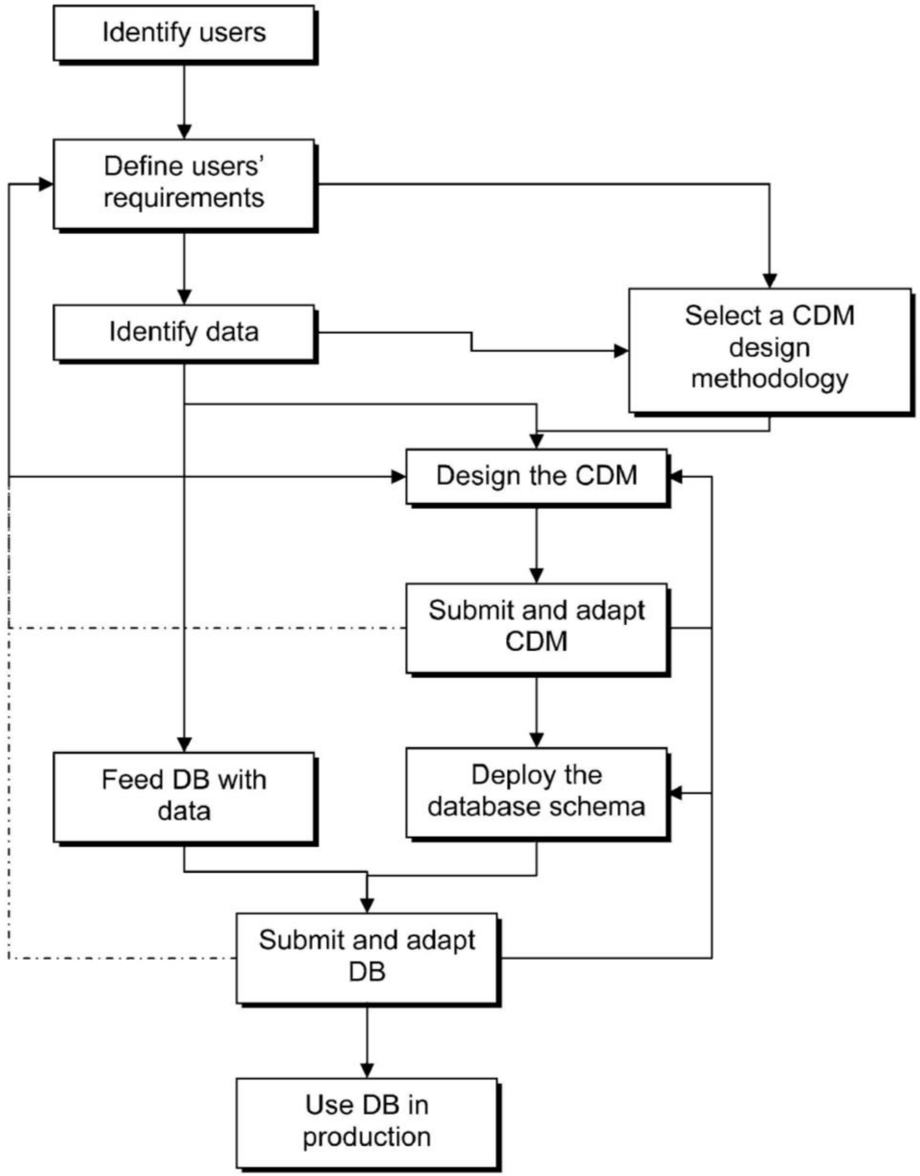


- Geographic Information System
- **Geodatabase and modelling systems**
- Decision Support Systems
- Spatial multicriteria analysis using Geographic Information System

Geodatabase



Geodatabase



Database development steps

Soutter et al., 2009

Geodatabase

Some successive steps for the structure of a GIS-based integrated management tool:

1. **Stakeholder analysis.** The scope of this first and very important step is to **identify the stakeholders involved in water management** at the global (river basin and country wide) and local levels.
2. **Assessment of needs** This second step should as much as possible include all identified stakeholders. The assessment is targeted onto the various **stakeholders needs**, in terms of **data** and **functionalities**, **according to their assignments**. It includes the definition of the **objectives pursued** and the **methods used**, the list of **available data and lacking data** that would be needed to improve the fulfillment of the assignments, data acquisition priorities, and a **list of needed and/or expected functionalities**.

Soutter et al., 2009

Geodatabase

Some successive steps for the structure of a GIS-based integrated management tool:

3. **Physical database and data acquisition.** The conceptual data model can be engineered into a physical database (a set of interlinked data tables in a database management software). These tables then need to be filled with data, acquired by the various usual means.
4. **Development of specific GIS functionalities.** Depending on the used **GIS software**, a large part of the needed **functionalities** will be present as part of the set of fundamental spatial analysis tools included in the software (visualization, edition, spatial selection, network functions, etc.). The various, more domain specific functionalities identified during the assessment of the needs stage, then needs to be developed and included in the selected GIS platform.

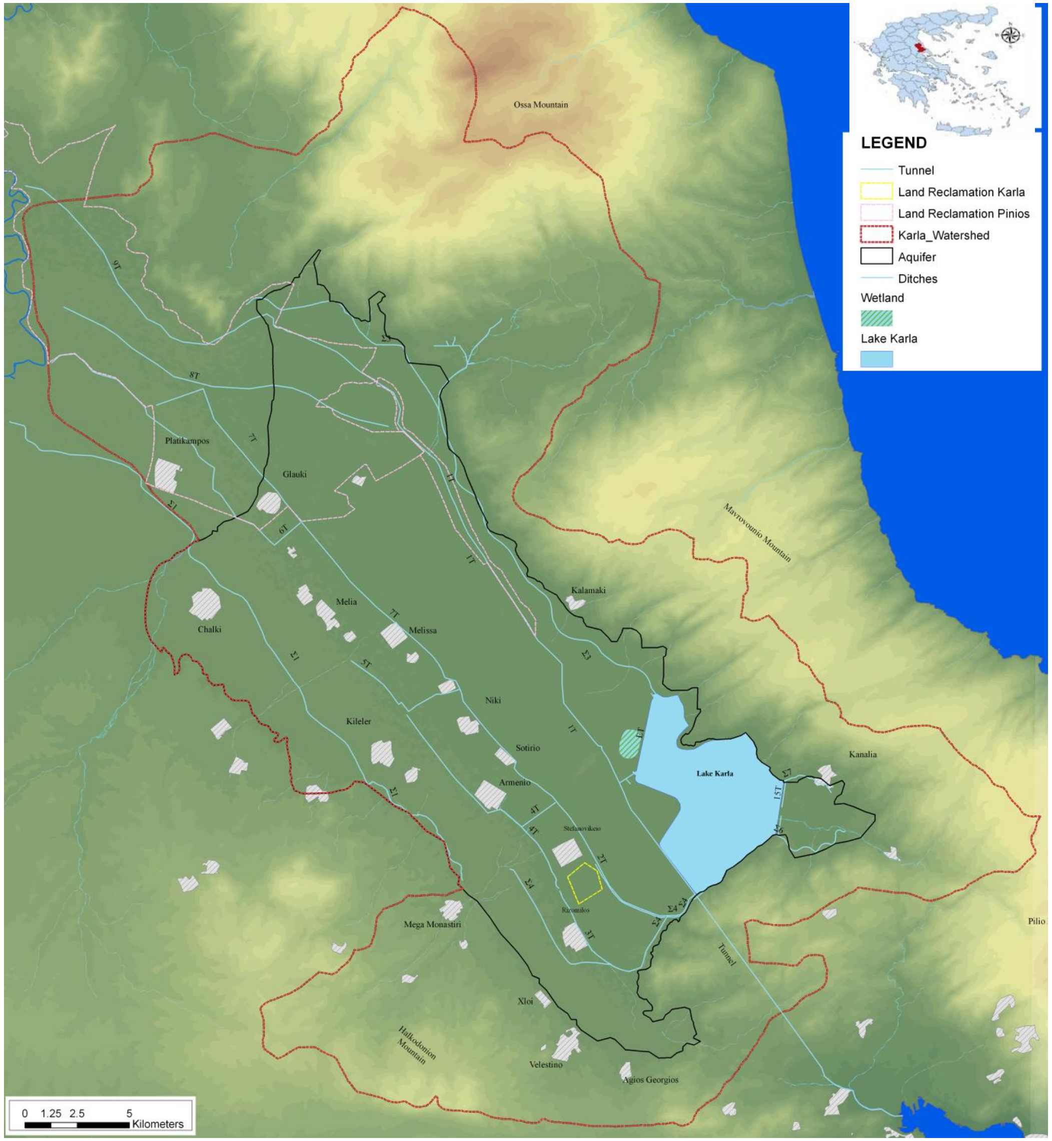
Soutter et al., 2009

Watershed Information System

STUDY AREA

Lake Karla Basin

	Area (km^2)
Lake Karla Watershed	1161
Lake Karla Aquifer	500
Lake Karla	38
Local Authoritiy of Land Reclamation of Pinios	275
Local Authority of Land Reclamation of Karla	12



Sirrimed, 2013

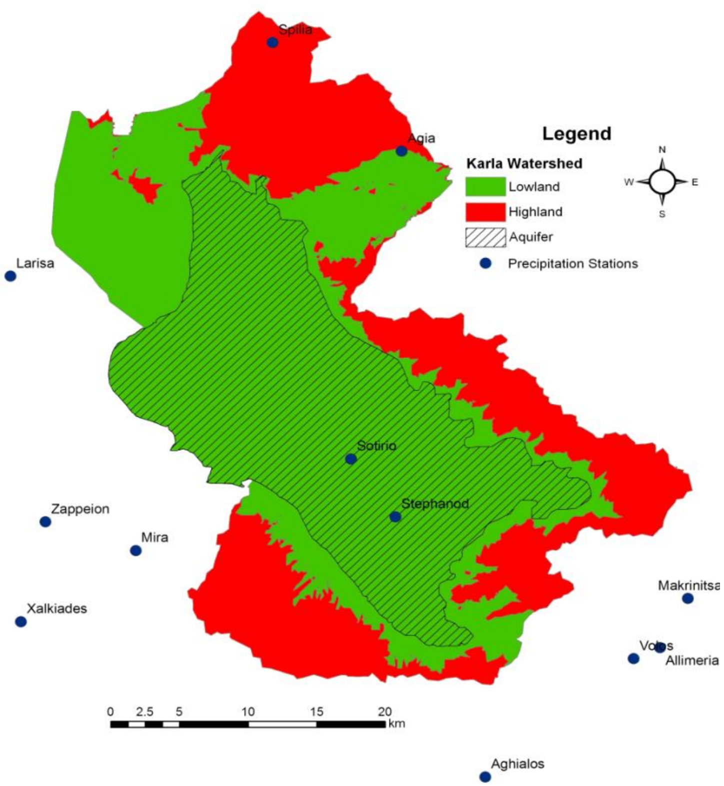
Watershed Information System

- Collection of the necessary field data (topography, land uses, meteorology, hydrology, geology-hydrogeology, water consumption)
- Application of the mathematical models (UTHBAL, UTHRL, LAK3, MODFLOW) for water resources estimation in Lake Karla watershed
- The linking platform of the models is based on the OpenMI standard

Sirrimed, 2013

Watershed Information System

- UTHBAL Application



Geomorphological characteristics and hydrological budget of lowland and highland for historical period 1960-2002

Attribute	Lowland	Highland
Area (km^2)	411.68	808.2
Mean Elevation (m)	81.5	521.0
Mean Annual Temperature (°C)	15	12.9
Mean Annual Precipitation (mm)	483.3	737.1
Mean Annual Potential Evapotranspiration (mm)	832.3	735.8
Mean Annual Actual Evapotranspiration (mm)	413.4	423.0
Mean Annual Recharge (mm)	64	239.1
Mean Annual Runoff (mm)	59.6	75.0

Sirrimed, 2013

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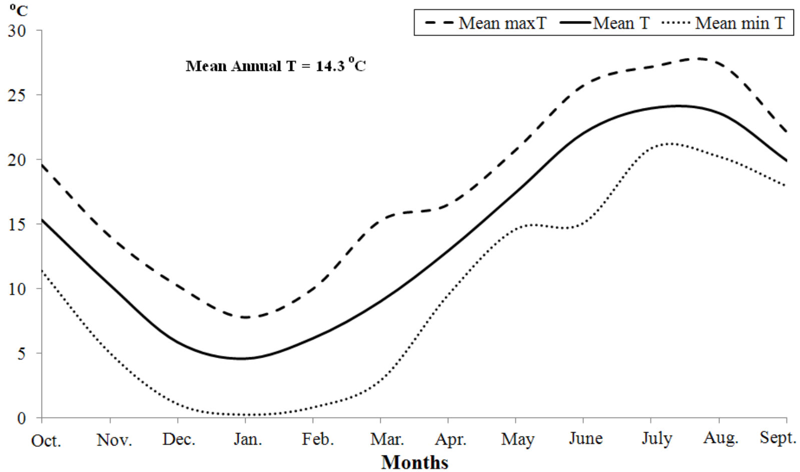
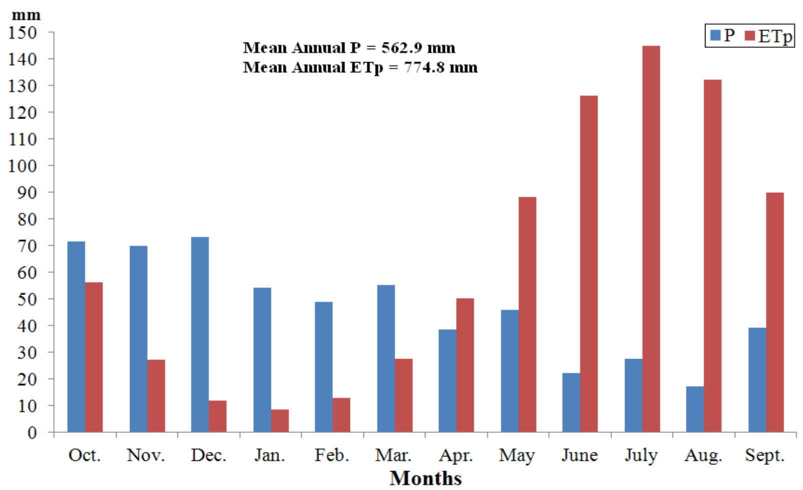
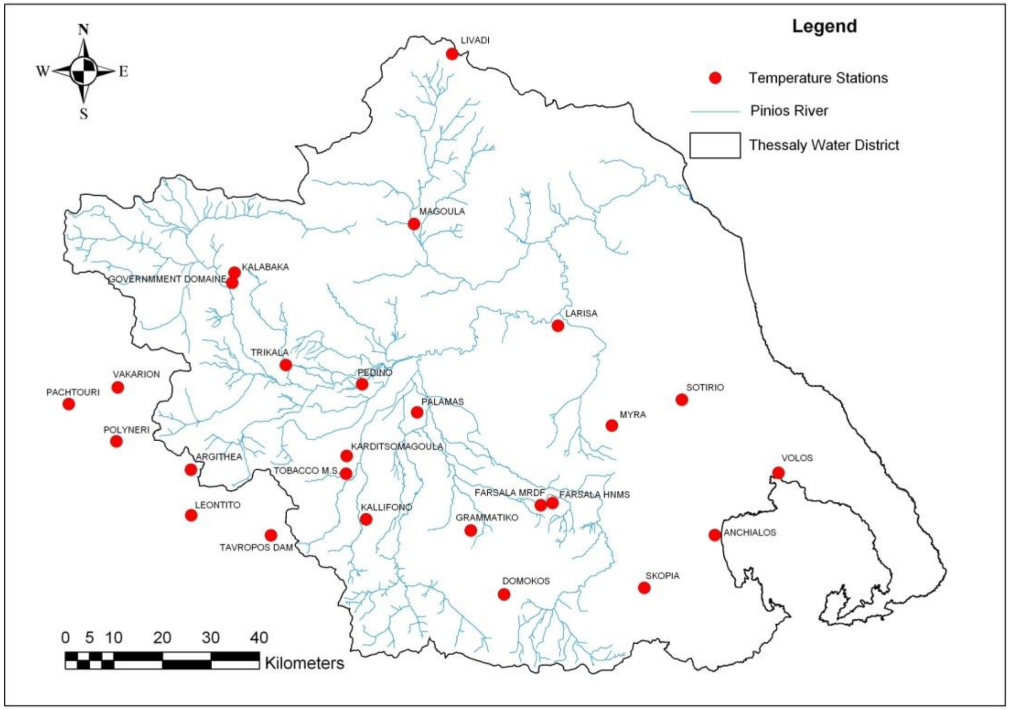
Watershed Information System







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Watershed Information System

UTHRL

- The natural surface runoff has been simulated as presented by the hydrological model
- The water transfer from Pinios river has been simulated according to operation schedule of the pumping station and the conveyance of the water transfer system.
- The net water losses of the reservoir were calculated as the subtraction of precipitation from evaporation from the reservoir water surface and the percolation losses.
- The reservoir operation model calculates the spillway overflows and reservoir water storage. The calculated water stages of the reservoir were used for the calibration of the lake-aquifer interaction LAK3 model.
- Calibration of the reservoir operation model (i.e. UTHRL) has not been performed due to the recent completion of the reservoir works and the lack of reservoir stage measurements.

Sirrimed, 2013

Watershed Information System

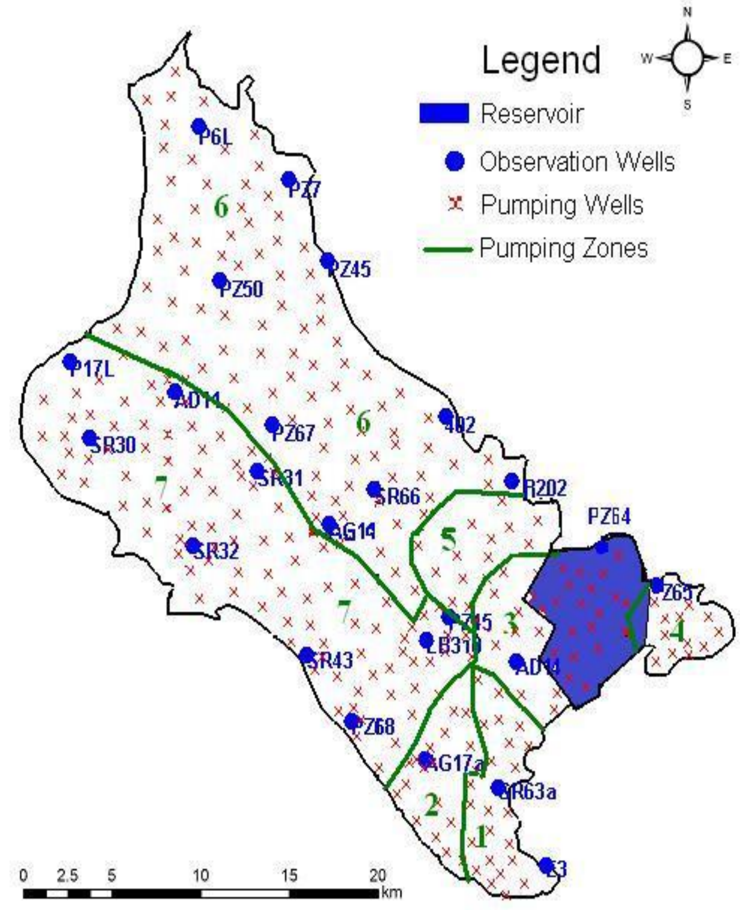
- **Lake-Aquifer Interaction Model (LAK3)**

- The lake-aquifer interaction was simulated in transient flow conditions
- Updating at the end of each time step a water budget for the lake that is independent of the groundwater budget represented by the solution for heads in the aquifer.
- Implicit in the calculations of a lake water budget is the recomputation of current values of lake volume and stage.
- The lake stage is crucial in estimating ground-water seepage to and from the lake and it estimated from the results of UTHRL model.
- The results estimated the leakage from reservoir to aquifer at 18 hm^3/year

Sirrimed, 2013

Watershed Information System

- The **Groundwater Model** :
  - In MODFLOW, one layer, a grid of 12500 cells, with its spacing of 200 m x 200 m
  - Simulation period 01/1987 – 01/1997
  - 25 observations wells for starting heads (01/1987) and for model calibration (01/1997)
  - West Boundary → Hydraulic contact with a adjacent aquifer
  - East Boundary → Impermeable because of schist presence
  - Groundwater recharge → UTHBAL
  - 7 pumping zones
  - Specific storage = 0.02, specific yield = 0.1
  - Hydraulic conductivity: Varying spatially → Simple Kriging



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Watershed Information System

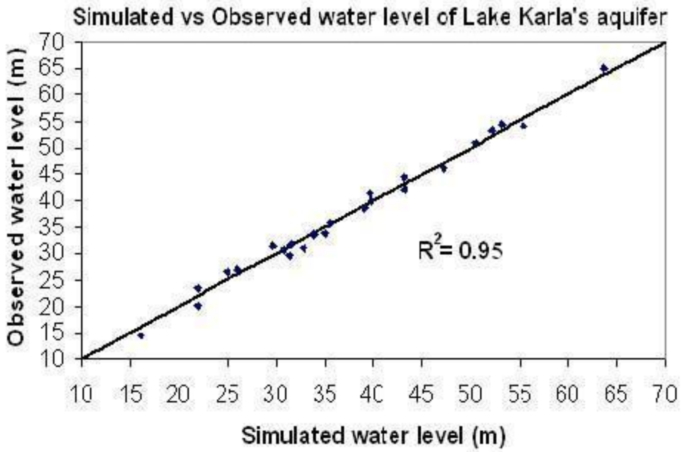
Results of **Groundwater Model**

- Historical Period without → 1987-1997

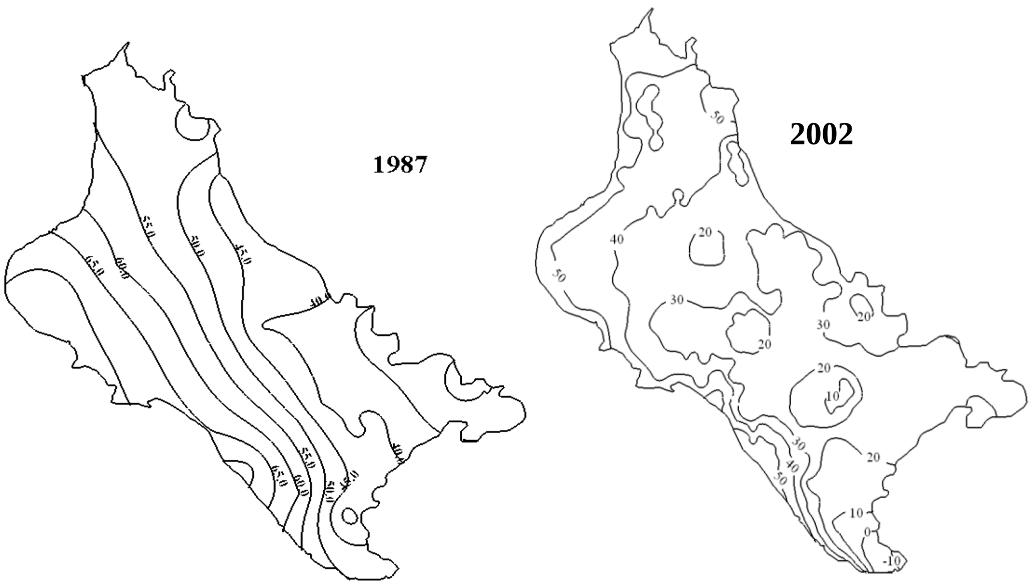
Renewable aquifer water → 372.9 hm^3 or mean annual 37.29 hm^3

<u>Extracted water from aquifer → 565.3 hm^3</u>

Non-Renewable water → 938.2 hm^3 or mean annual 93.82 hm^3



Hydraulic head contours



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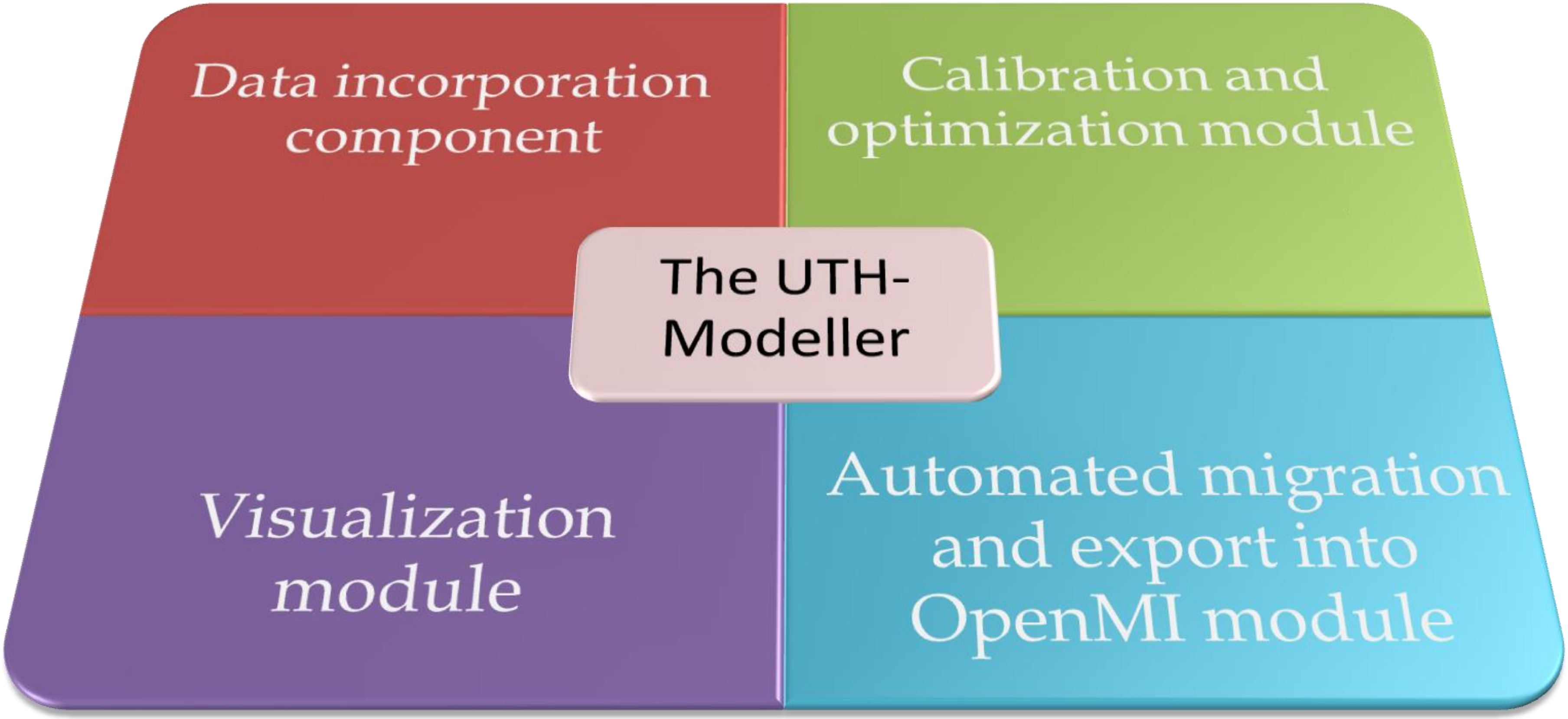
The Construction of the Framework



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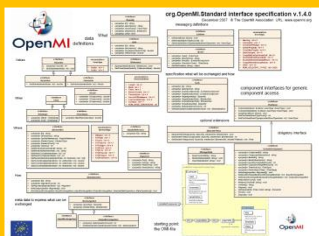
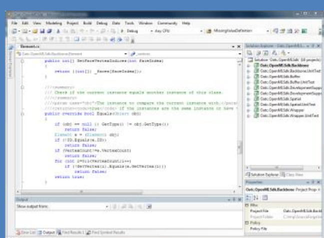
How to migrate models: *SDK: Balancing stability and flexibility*



The OpenMI **Standard**

- The OpenMI.Standard interfaces
- The OpenMI standard definition
- XSD’s

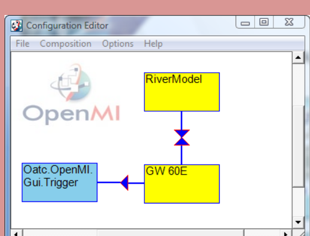
- Provided by OA
- Rigid release procedure
- Non frequent releases
- Makes components linkable



The OpenMI **SDK**

- Source code C# (and Java)
- Default implementaion
- Wrapper
- Targeting developers

- Provided by OATC
- Flexible release procedures
- Frequent releases
- Makes OpenMI easier
- OATC.SDK targeting models
- Not required
- Components compliant to same version of the standard can be linked regardless of which SDK is used.



The OpenMI **Configuration Editor**

- Create linked systems
- Run linked systems
- Targeting users (e.g. modellers)

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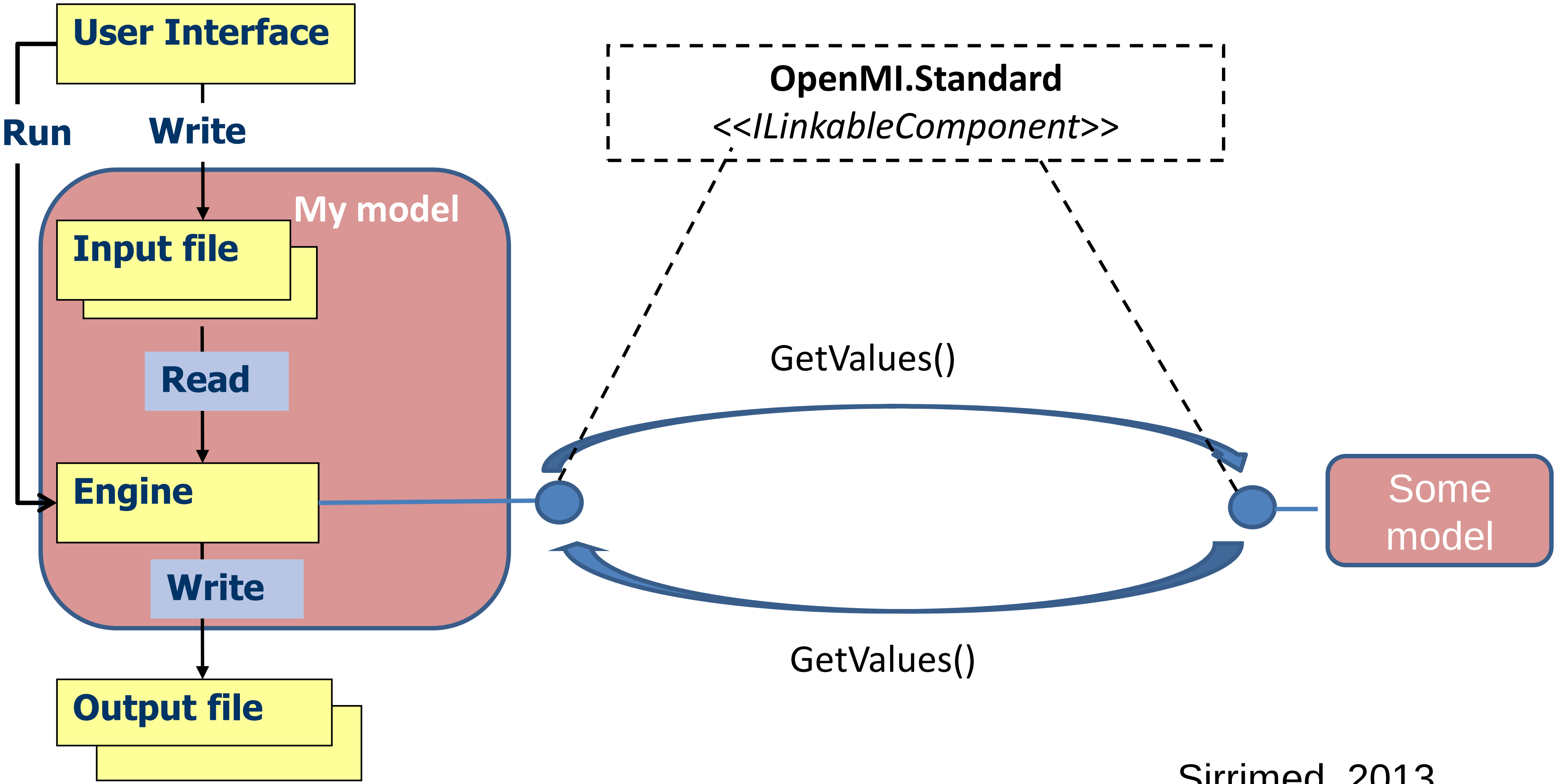
ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ

Watershed Information System

Data Interchange



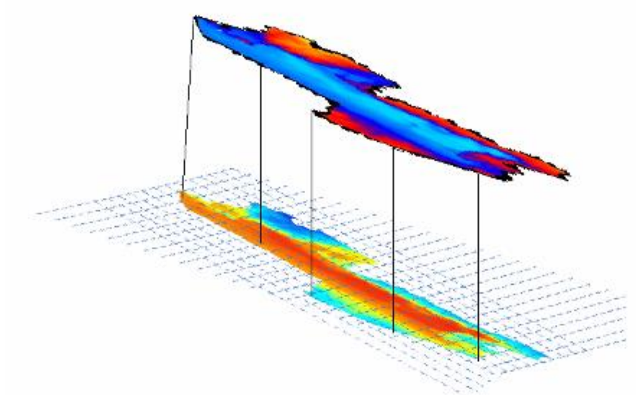
Sirrimed, 2013

Watershed Information System

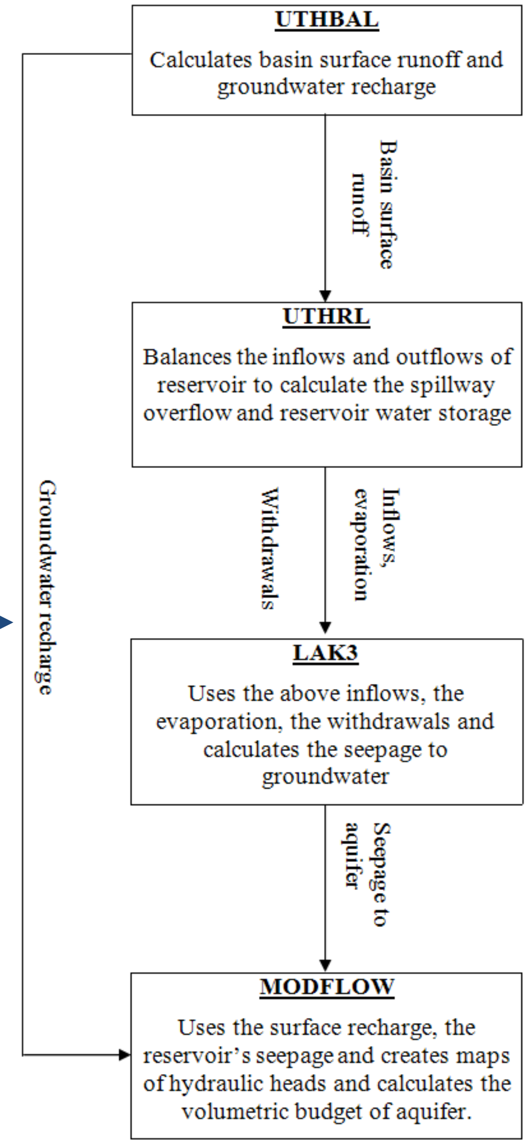
➢ Model Linking

- The models are linked sequentially to each other in the OpenMI

Semi – Distributed application of UTHBAL



Flow chart and collaboration of the WIS models



Sirrimed, 2013

Watershed Information System

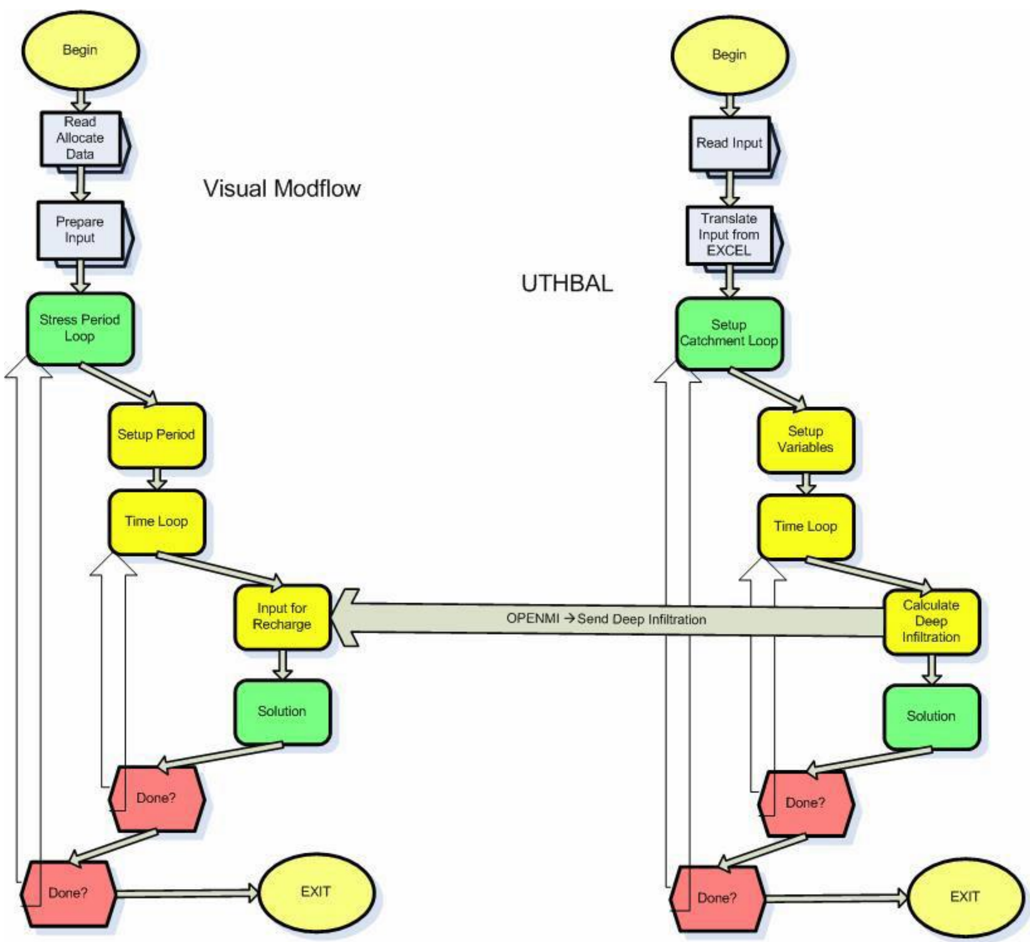
Basic components of framework architecture:

- Database Management Component
- Data Migration and XML-Conversion Component
- Visualization Component
- Model Linking and Interoperability Component
- WIS- Decision System Component

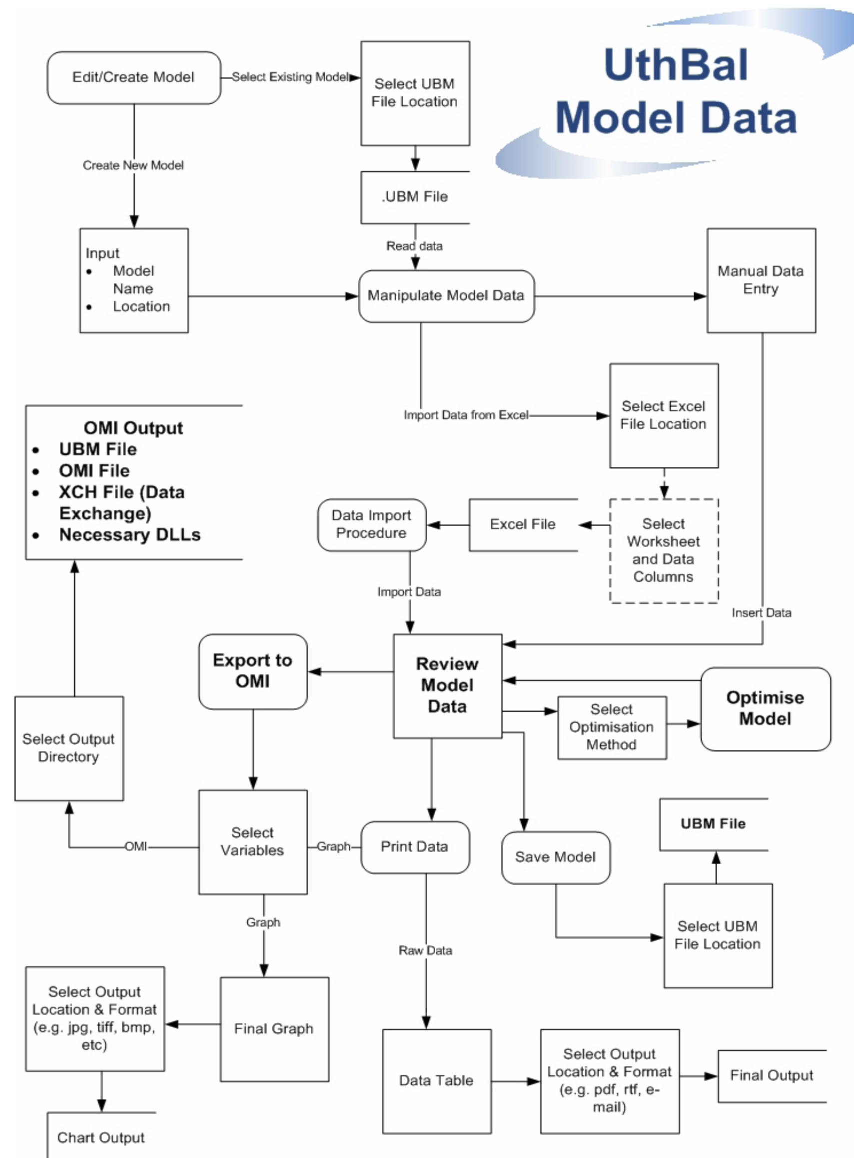
Sirrimed, 2013

Watershed Information System

The coupling procedure and the architecture of UTHBAL



Sirrimed, 2013



SIGNIFICANT FINDINGS OF WP5

- Almost 90% of Lake Karla water resources are used to cover the irrigation needs.
- The water balance of Lake Karla Watershed is deficit since mid '80s
- The aquifer of Lake Karla is in an over-exploitation status since this period with the hydraulic drawdowns exceeding 60 m at the south side of Karla Watershed and the water deficit reaching the 90 hm^3 per year.
- Although the reservoir has not started to operate its contribution to aquifer's water balance through leakage is important reaching about 12 hm^3 per year.

Sirrimed, 2013

- Geographic Information System
- Geodatabase and modelling systems
- **Decision Support Systems**
- Spatial multicriteria analysis using Geographic Information System

Decision Support Systems

- What is a DSS? The classic definition of a DSS provided by Sprague and Carlson (1982) is “an interactive computer-based support system that helps decision makers utilize data and models to solve unstructured problems.”
- A Decision Support System (DSS) is an integrated, interactive computer system, consisting of analytical tools and information management capabilities, designed to aid decision makers in solving relatively large, unstructured water resource management problems.
- Three main subsystems must be integrated in an interactive manner in a DSS (Orlob, 1992; Close et al., 2003): (1) a user-interface for dialog generation and managing the interface between the user and the system; (2) a model management subsystem; and (3) an information management subsystem.

SEPIC, 2004

Decision Support Systems

Considering this in more detail, DSS architecture consists of the following components

- **Data measurement** – the tasks involved in data gathering;
- **Data processing** – the tasks involved in registration of measurements into databases and their subsequent processing, retrieval, and storage;
- **Analysis** – the models used to infer the state of the system so that reasonable decision alternatives can be formulated;
- **Decision support** – the gathering and merging of conclusions from knowledge-based and numerical techniques and the interaction of users with the computer system through an interactive and graphical user interface.
- **Decision implementation** – the formulation of actions to be implemented in solving a specific problem.

SEPIC, 2004

Decision Support Systems

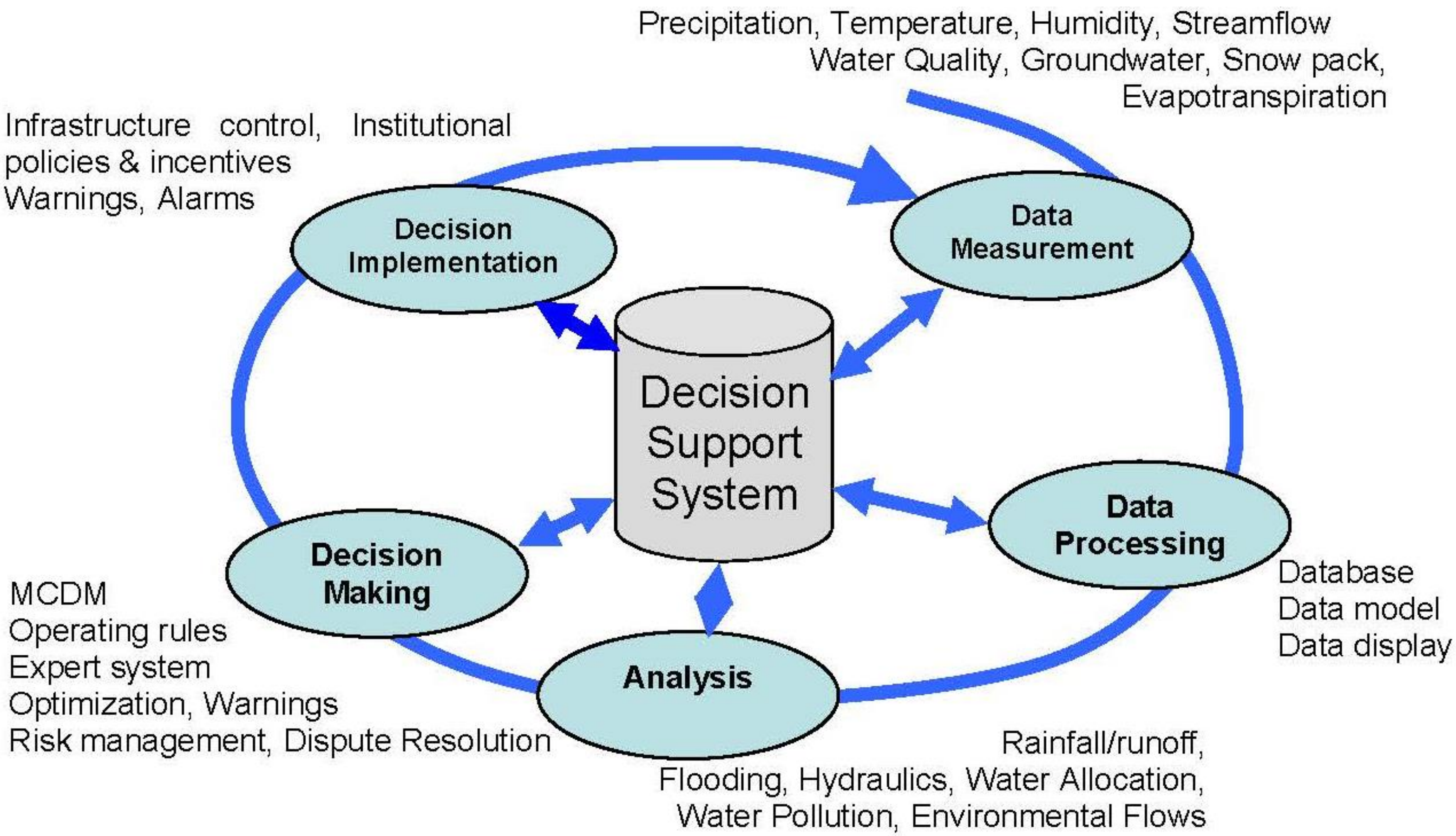


Figure 1. Diagram of a general framework for a water resources decision support system.

SEPIC, 2004

Decision Support Systems

Main fields of Integrated Water and Environmental management

Field	**Main features - effects**	**Role of measures and BMPs**	**Indicative literature**
Disasters	Floods, droughts, pollution	Forecast, protection, warning, prevention, evaluation, restoration	[10,11]
System Analysis	Management in watershed/ River Basin level	Optimising system’s efficiency and performance under specific criteria	[12]
Transboundary waters and water rights	Different demands and precures	Balancing interests through fair agreements	[13]
Resources Allocation	Covering competitive demands with available resources	Combination and management of surface and groundwater use, water conservation (maximum profits, minimum costs)	[14]
Water storage works	Dams, reservoirs (design, operation, hydropower, pollution control)	Different strategies for the optimum performance and efficiency	[15]
Water distribution	Pipelines (open, closed), pumping stations, networks, diversions	Optimum design, operation, pollution control, damage and leakage control	[16]
Water quality	Wastewater treatment, desalination, tracking pollutants, control river-Delta, lakes and wetlands quality, nature-based solutions	Optimum design, performance, protection, warning, prevention, restoration, control of point and non-point pollution sources	[17]

Alamanos et al., 2021

ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ

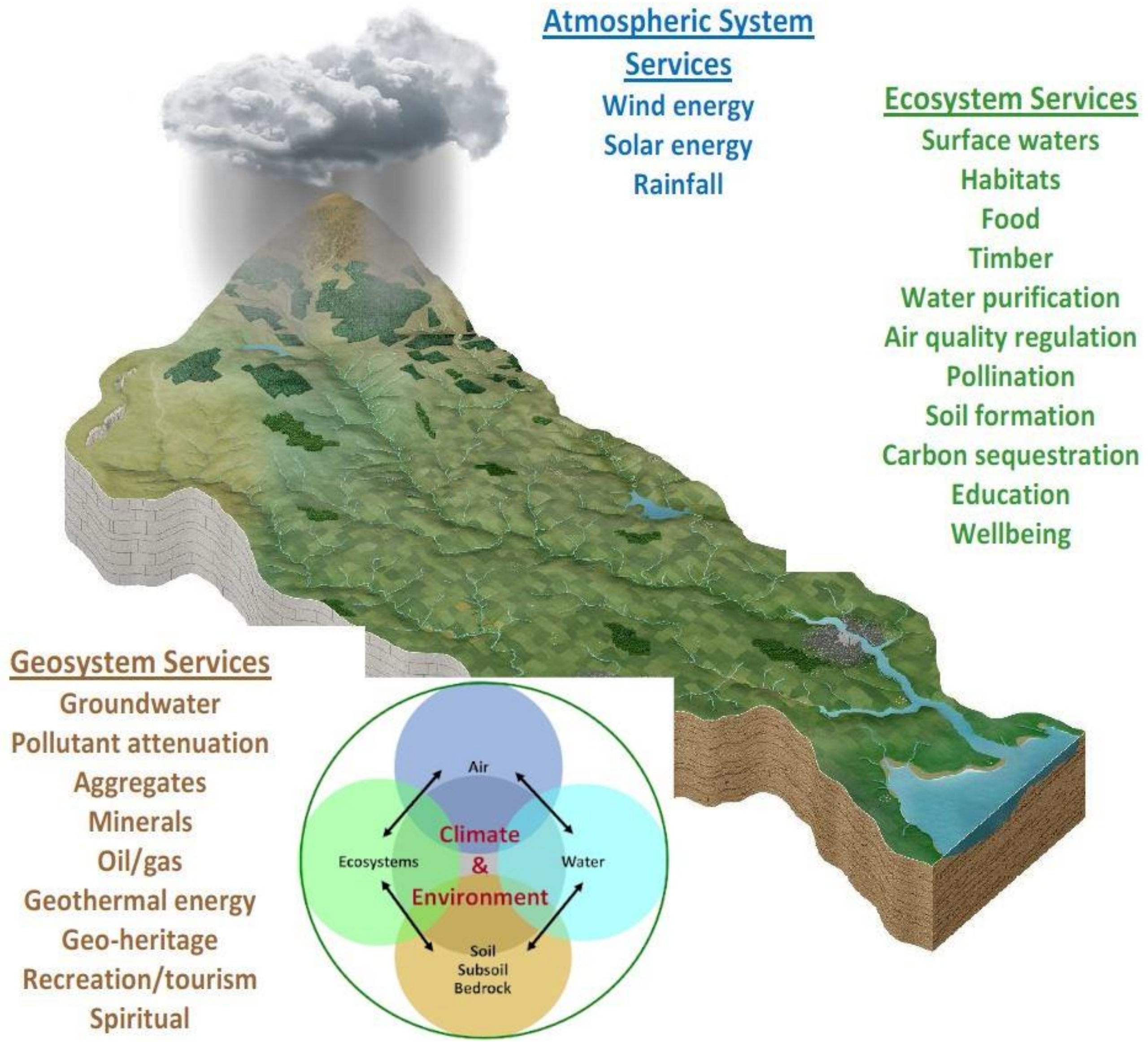
Decision Support Systems

Main fields of Integrated Water and Environmental management

Field	Main features - effects	Role of measures and BMPs	Indicative literature
Soil – Land	Land use and land cover changes, deforestation, erosion, deposition, desertation	Protection, prevention, evaluation, restoration (reforestation), Surface Roughening,	[18]
Air – atmosphere	Air pollution, Climate change, extreme weather conditions	Monitoring, forecast, protection, warning, prevention, evaluation, restoration	[19]
Biology – Ecology	Stream ecology, ecohydrology, ecological flow, habitat (fishes, macroinvertables, diatoms), riparian areas, ecosystems	Monitoring, modelling, fish passages, Retain riparian vegetation, control of point and non-point pollution sources	[20–22]
Socio-economic aspects	Costing, payments, project investments, Environmental Evaluation, pricing, rights and shares, distribution	Different policies, alternative ways methods and applications	[23]
Policy and Governance	Combining the above into strategies, informing, education, Public Participation, Collaborative Modeling	Evaluating alternatives, globally optimum solutions, planning, legislations, game theory approaches	[24]
Other cross-disciplinary fields as Ecohydrology, Socio-hydrology, climate change impacts, Water- Energy-Food Nexus etc. combining the above BMPs and decisions			[25]

Alamanos et al., 2021

Decision Support Systems



All environmental components, linkages and the respective services provided in catchments (adapted from: the Water Forum [26])

Alamanos et al., 2021

Decision Support Systems

Stages and methods of the Framework for Integrated Land and Landscape Management (FILLM). Differently coloured blocks refer to stages of the same (broader) expertise fields.

Stages	Description/Methods–Recommendations	
Public engagement - Awareness raising. - Sharing knowledge. *Collaboration with local communities* - Identify key stakeholders. - Identify their issues and concerns. - Build partnerships. - Conduct public outreach.	Raising awareness and sharing knowledge on the major problems of the catchment related to the FILLM's components. Local communities and *key representatives* must be involved in *social and environmental learning* and decision-making by using participatory processes. Meetings with groups can identify the optimum paths to achieving both "improvement" and "protection" objectives. Stakeholders need to see *commitment* and receive *training* in each of the FILLM's components to understand their businesses' interactions and effects. Going from a "single-profit" to a "*team growth*" *mindset*.	*Desk study*, including relevant papers (short reviews). Scientific support for the meetings: >*Techno-economic background* for catchment and management issues. >*Social background* for legislation issues, stakeholder mapping, grouping and training. >Support from a respective *software* to monitor and assess the groups, opinions and progress (see next section).
Developing a shared vision - Integrated catchment science and management. - Growth of communities and environment. - Sustainability. - Cooperation.	The previous stage is a continuous process, so each of the following ones must be communicated to the public, accordingly. This stage is a component of the public engagement.The existing *legislation* must also be communicated to clarify under which framework we can act, or what we would need to modify.	

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Decision Support Systems

Stages	Description/Methods–Recommendations	
Characterisation at catchment scale - Integrated monitoring and modelling, including all the FILLM's components. - Significant pressures and their impacts. *Characterisation at local scale* - "Downscale" further to sub-catchments. - In line with WFD and river basin management plans (RBMPs).	This is a multi-disciplinary process and *collaboration with relevant public bodies* is mandatory. *Data gathering, developing databases and organising them* to create an integrated catchment inventory is the first and most important step. *Monitoring* processes will need to be initiated and continued. Data analysis. *Integrated modelling is essential* to understand the system's functions, interactions, uncertainties, pressures and drivers. This must include the natural (environmental) components, but also the socio-economic modelling aspect. With the knowledge of the system's causes–effects, local-scale *measures will naturally come up and be evaluated.*	This needs specific tools and the cooperation of different scientists to *combine the FILLM's components into models* (see next section). >*Engineering*, meteorology, hydrology, bio-physical sciences (hydrogeology, soil science, bio-ecology, hydrochemistry, etc.). >*Socio-economics*, environmental economics, multi-agent modelling, etc. >*Case-specific expertise* (e.g., drainage systems, agronomic science, coastal science, etc.).
Programmes of measures - Existing measures. - New measures (BMPs). - Tests under various conditions. - Optimisation considering spatially targeted measures. - DSS.	The *integrated modelling of the previous step is the basis.* 1. *Simulate the existing measures* and management actions, in order to quantify their effects and *evaluate* them based on predefined criteria. 2. *Examine* the mandatory and suggested measures included in the *RBMPs*. 3. *Develop new* possible management options. BMPs can include nature-based solutions, environmentally friendly techniques, cost-effective practices and protection–mitigation options. 4. Test these further using *uncertainty* analysis and *future conditions* (e.g., climate change). 5. Undertake *assessments*, as required by the Habitats and Strategic Environmental Assessment Directives, as appropriate. 6. *Optimise* the measures based on multi-objective objective functions, using all the necessary constraints, considering the spatial distribution. 7. Develop a *DSS to rank the measures* based on the predefined integrated criteria—multicriteria analysis (MCA).	Strong *modelling skills, holistic understanding and judgment* are required. >Steps 1, 2 and 4 are a repetition of the previous stage, under different conditions (*measures = modelling scenarios*). >Steps 3 and 5 can be desk-based interactive processes with the other steps. >The last two steps are the most challenging because they require the setting the of the optimisation's objective function and of the constraints, the manipulation of the data accordingly and the selection of the best optimisation method. The criteria of the MCA must include all the inputs from the previous steps (stakeholder input, environmental and economic modelling) and the most appropriate method must be selected.

Alamanos et al., 2021

Decision Support Systems

Stages	Description/Methods–Recommendations	
Policy, Regulations and Incentives - Move from theory to practical implementation. - Cooperative approach. - Continued investment needed.	Identify possible policy/regulatory gaps. Develop *solid suggestions for modifications, using the results of the previous stage's models*. Their combination with the *input from the public engagement and vision stages and the proof that the suggestions are socially acceptable measures and enhance the local economy and environment* must be the basis for any change. *Top-down or bottom-up* approaches can be used or combined. Principles such as *"public money for public goods"* and *using "results-based payments"* can be considered as means of achieving the desired outcomes.	The scientific support of the proposed measures from the *techno-economic background* can be a basis for the *social-political science* to provide/modify/approve and *support the actions* through *incentives* and policy regulations. This stage is subject to each case's policy, and there are numerous paths for the application (e.g., from *start-ups* relevant to implementing the measures to horizontal measures approaches).

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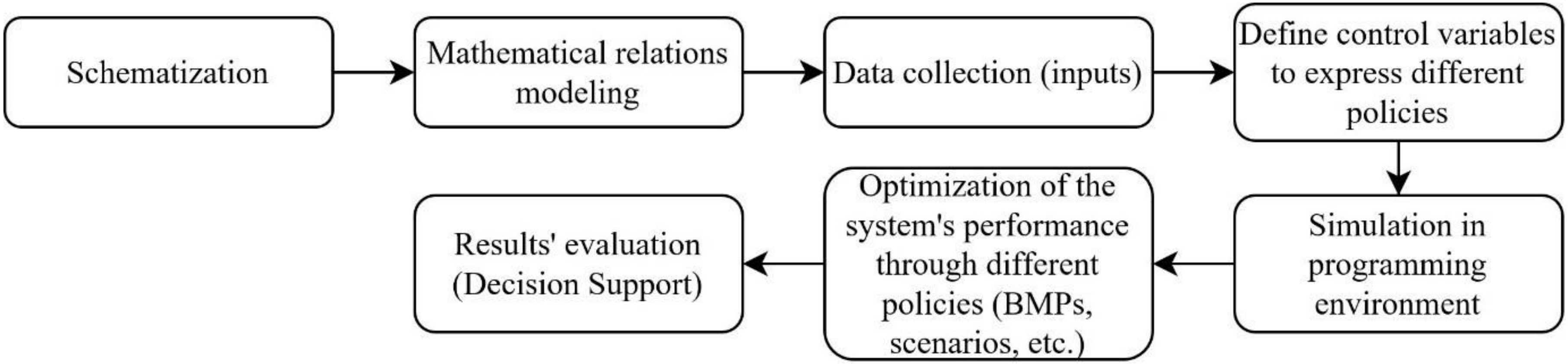
Decision Support Systems

Stages	Description/Methods–Recommendations	
Tracking the progress - Inspections. - Continuous monitoring and modelling. - Meetings with stakeholders. - Flexible and adaptive management.	*Inspections* are an extension of the FILLM's actions, based on and considering *the characterisation results.* The same can be said with regard to *continuous monitoring and modelling.* The observations regarding each action must be *communicated to the stakeholders, thus continuing the regular meetings.* Flexible management: adjustments and "plan Bs", if necessary. For this reason, the whole process may need to be repeated, but if the meeting routine and the models exist, there will not be any delays. *Having already set the tools of the previous stages will make the management flexible and will make it possible to move very quickly to alternative options, with "known" (simulated) results.*	>*Specialised and trained inspectors* combine the backgrounds mentioned in the previous stages. *Communication among scientists* is essential to ensure the "same language" and scope. >Use metrics (based on models) to *track and evaluate progress* and analyse trends and outcomes. >*Update the previous stages* based on the observed changes (e.g., models, stakeholders, etc.) and make the necessary application adjustments (flexibility).

Alamanos et al., 2021

Decision Support Systems

Structure of a decision support system (DSS) process. For a more detailed interaction of sub-systems, see Meire et al. and Loucks and Beek [1,46]



Alamanos et al., 2021

- Geographic Information System
- Geodatabase and modelling systems
- Decision Support Systems
- **Spatial multicriteria analysis using Geographic Information System**

Multicriteria analysis

Multicriteria analysis (MCA) represents a structured approach used to analyze overall possible alternatives and preferences and evaluate them under different criteria at the same time.

Some common MCA approaches are:

1. **MAUT** (Multi-Attribute Utility Theory)
2. **AHP** (Analytic Hierarchic Process)
3. **FAHP** (Fuzzy Analytic Hierarchic Process)
4. **ELECTRE I** (ELimination Et Choix Traduisant la REalité – ELimination and Choice Expressing REality)
5. **TOPSIS** (Technique for Order of Preference by Similarity to Ideal Solution)

Multicriteria analysis

1. **MAUT** (Multi-Attribute Utility Theory)

MAUT is based on Utility Theory, a fundamental of the theoretical development and practical implementation of MCA. MAUT became the most indicative example of using utility functions.

2. **AHP (Analytical Hierarchic Process)**

AHP which classifies the alternative solutions in a way that ranks them by assigning and distributing weights of significance of the defined criteria. The decision makers can characterize a specific comparison as 'equal', 'marginally strong', 'very strong', and 'extremely strong'. The degree of randomness of the answers is expressed by the Consistency Ratio (C.R), which has to be smaller than 10%.

Alamanos et al., 2018

Multicriteria analysis

AHP		
Linguistic scale for importance	**Intensity of imprortance**	**Values for reciprocal scale**
Equally important	1	1
Intermediate 1	2	1/2
Moderately important	3	1/3
Intermediate2	4	1/4
Important	5	1/5
Intermediate 3	6	1/6
Very important	7	1/7
Intermediate 4	8	1/8
Absolutely important	9	1/9

3. FAHP (Fuzzy Analytical Hierarchic Process)

Fuzzy AHP is based on the AHP method but the intensity of importance is fuzzified using several fuzzy memberships, e.g.:

1. Triangular membership (most common one)
2. Trapezoidal membership

Alamanos et al., 2018

Multicriteria analysis

4. **ELECTRE I** (ELimination Et Choix Traduisant la REalité – ELimination and Choice Expressing REality)

The methodology of ELECTRE uses a series of comparisons between the alternatives. The superiority (outranking) relation is a mathematical expression that represents the decision maker’s preferences.

5. **TOPSIS** (Technique for Order of Preference by Similarity to Ideal Solution)

TOPSIS method is a simpler and easier-to-use alternative method to ELECTRE.

Alamanos et al., 2018

Multicriteria analysis

Characteristics and description of each method

MCA Method	Theory	Weightings	Description
MAUT	Utility Theory	The alternatives are evaluated under each sub-criterion.	The alternatives are ranked according to the sum product of the performances of the alternatives to the respective weights
AHP	Hierarchical Theory	Comparing every pair of criteria, and then every pair of alternatives, under each criterion.	Linear algebra is used to extract the overall score for each alternative. The alternatives are ranked in descending order of the resulting priority values, i.e., in order of suitability.
ELECTRE I	Outranking Theory	Scores of importance for each criterion	Outranking relations are formed to represent the preferences of the respondents, through pairwise comparisons of the alternatives.
TOPSIS	Classification Theory	Scores of importance for each criterion	The alternatives are ordered between the best and the worst solution, based on the distances of their respective performances. A closeness index expresses each alternative's similarity to the optimal solution.

Alamanos et al., 2018

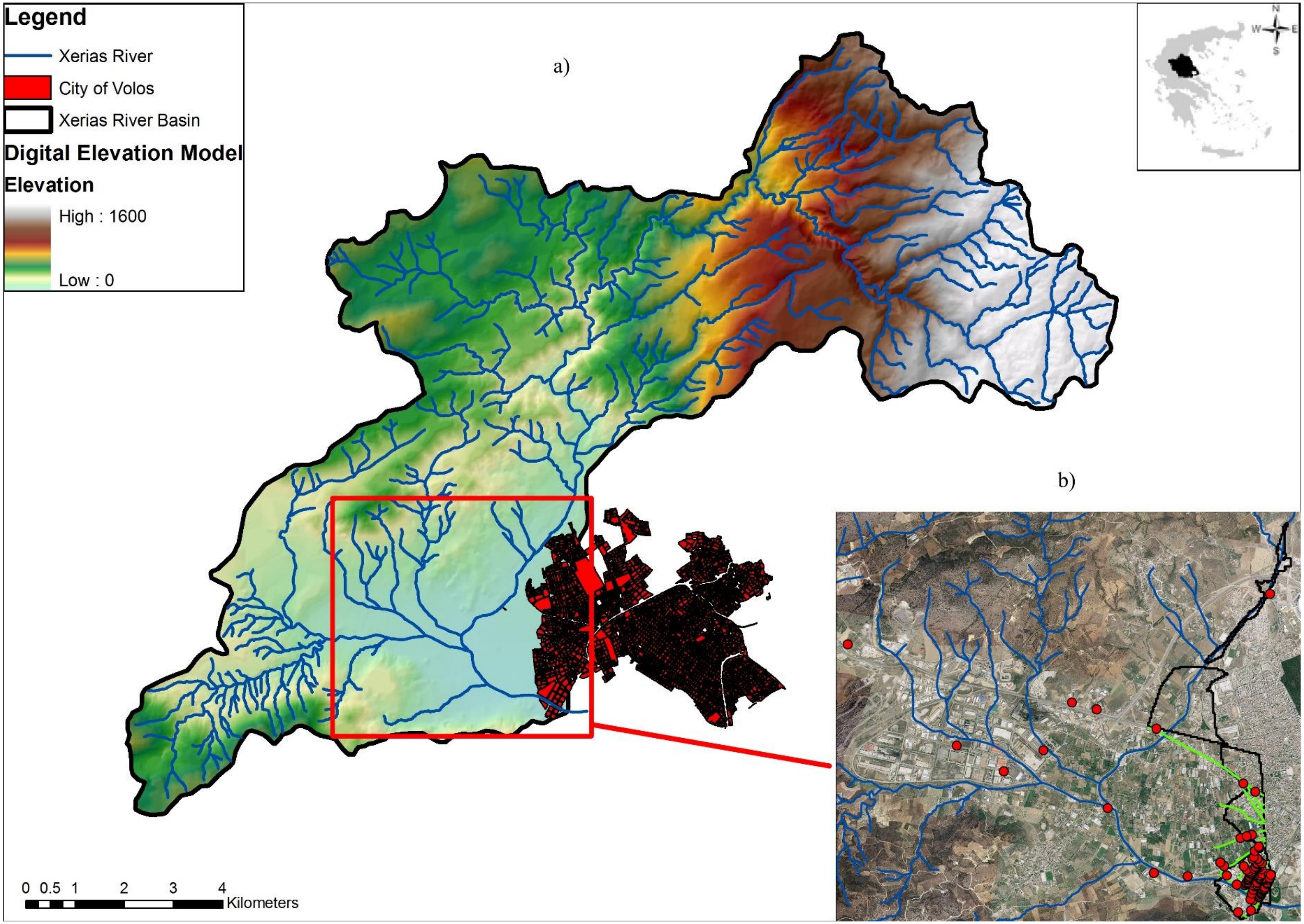
Multi-criteria analysis framework for potential flood prone areas

- to evaluate the ability of using multi-criteria analysis and GIS to identify potential flood prone areas
- to use geomorphological, topographical and land use indices for potential flood inundation areas identification and mapping
- to develop an objective GIS-based spatial multi-criteria evaluation framework for identification of potential flood prone areas.
- to demonstrate the methodology for Xerias watershed, Greece

Papaioannou, et al, 2015

Study Area

Papaioannou, et al, 2015



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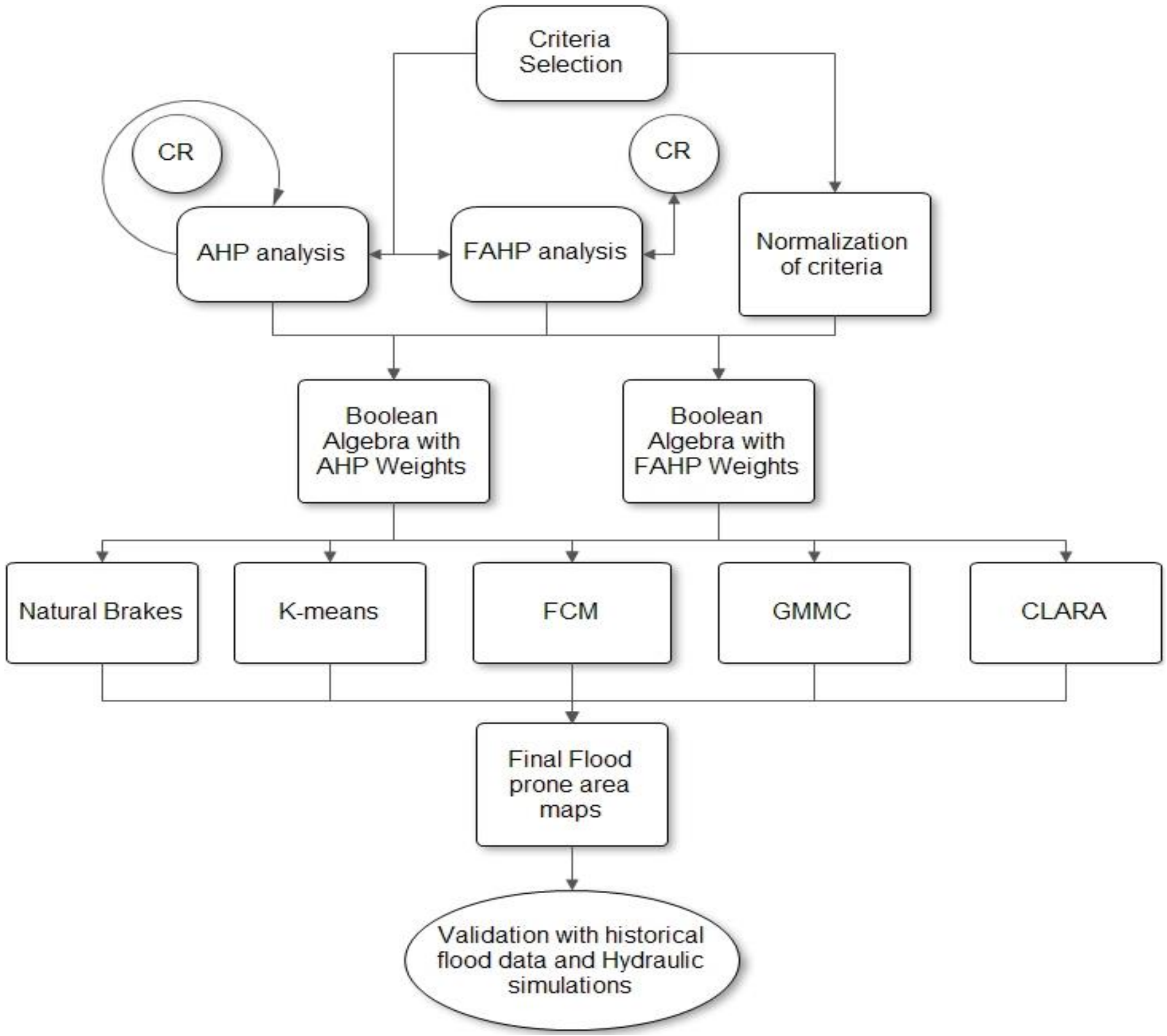
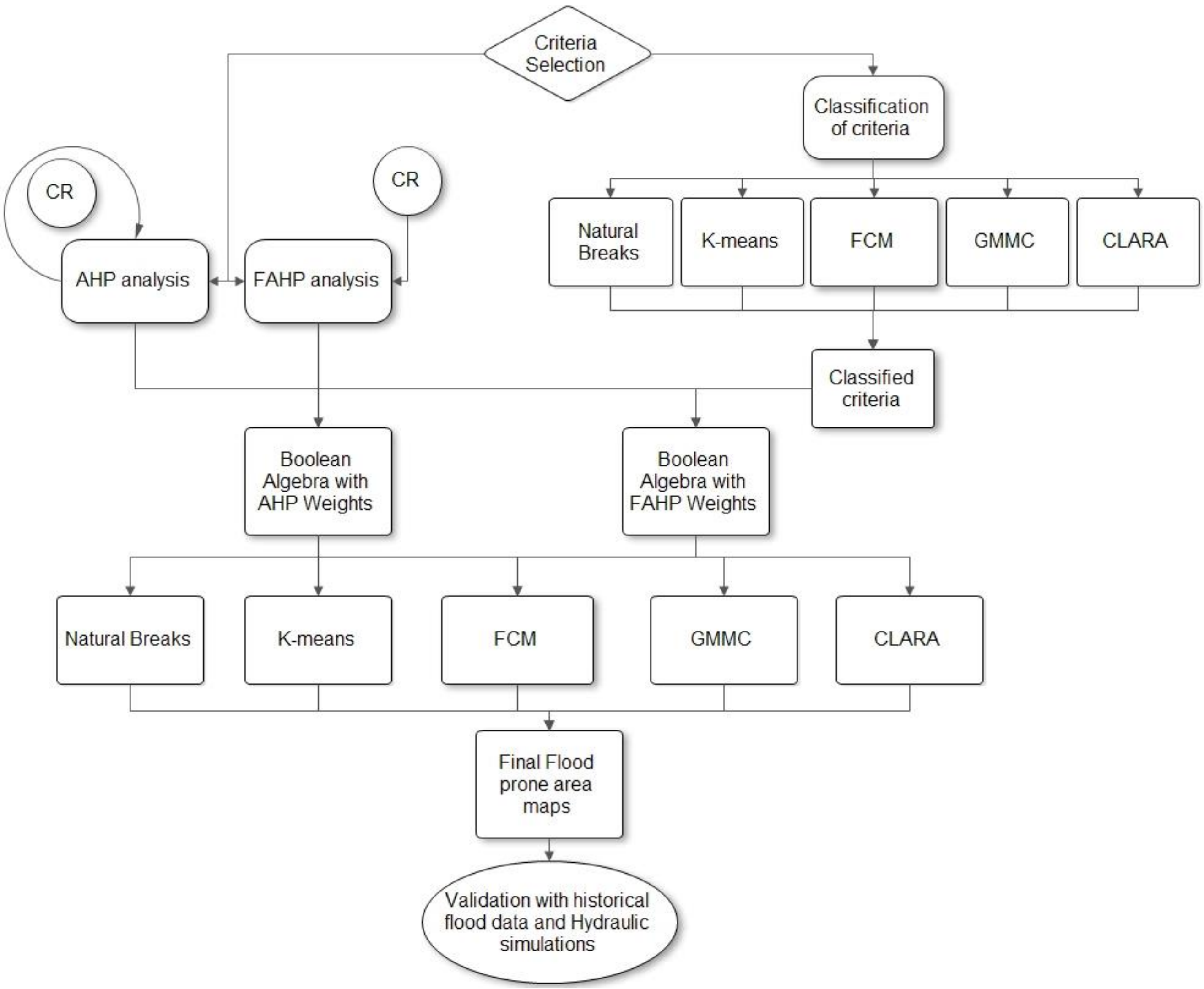


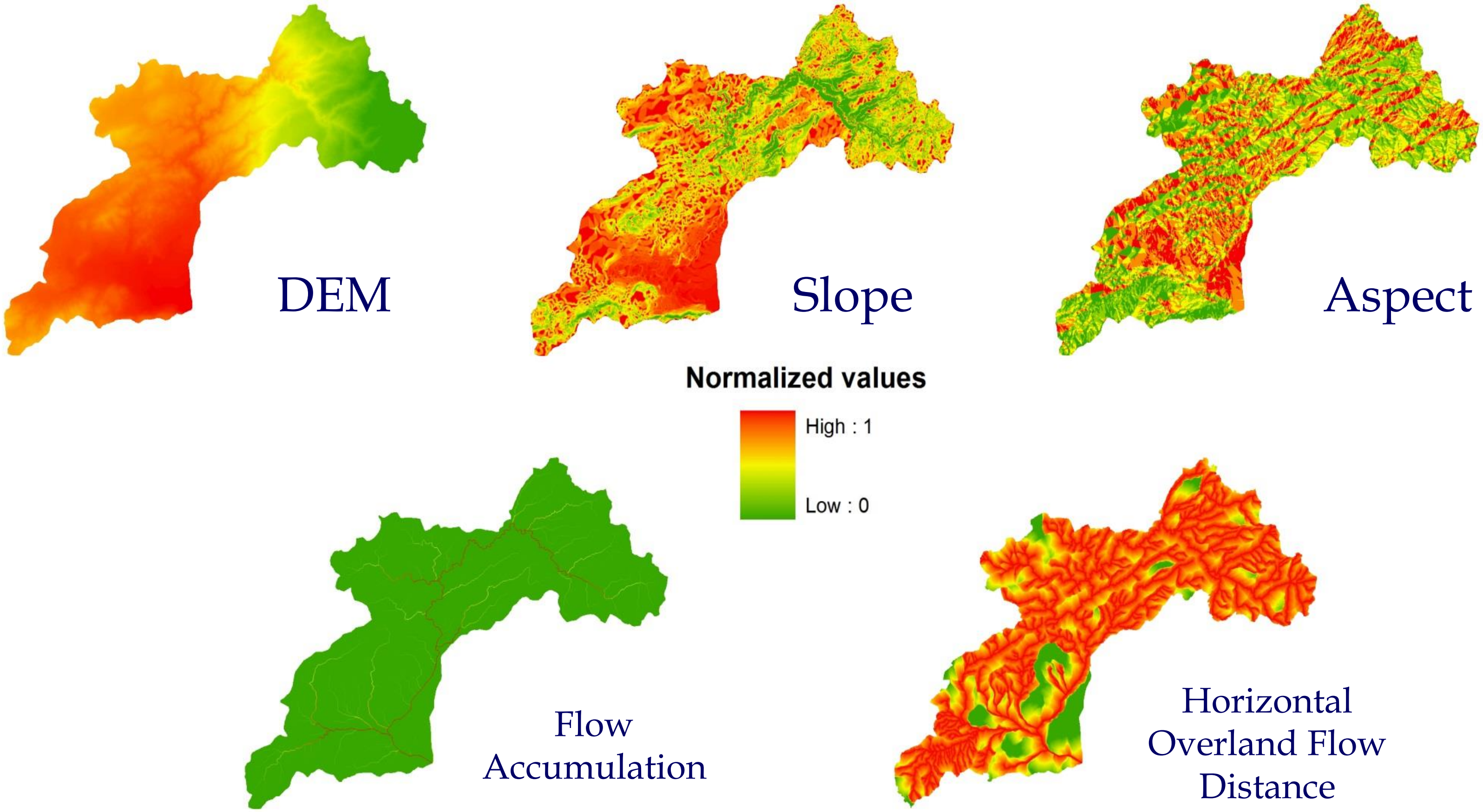
Papaioannou, et al, 2015



Papaioannou, et al, 2015

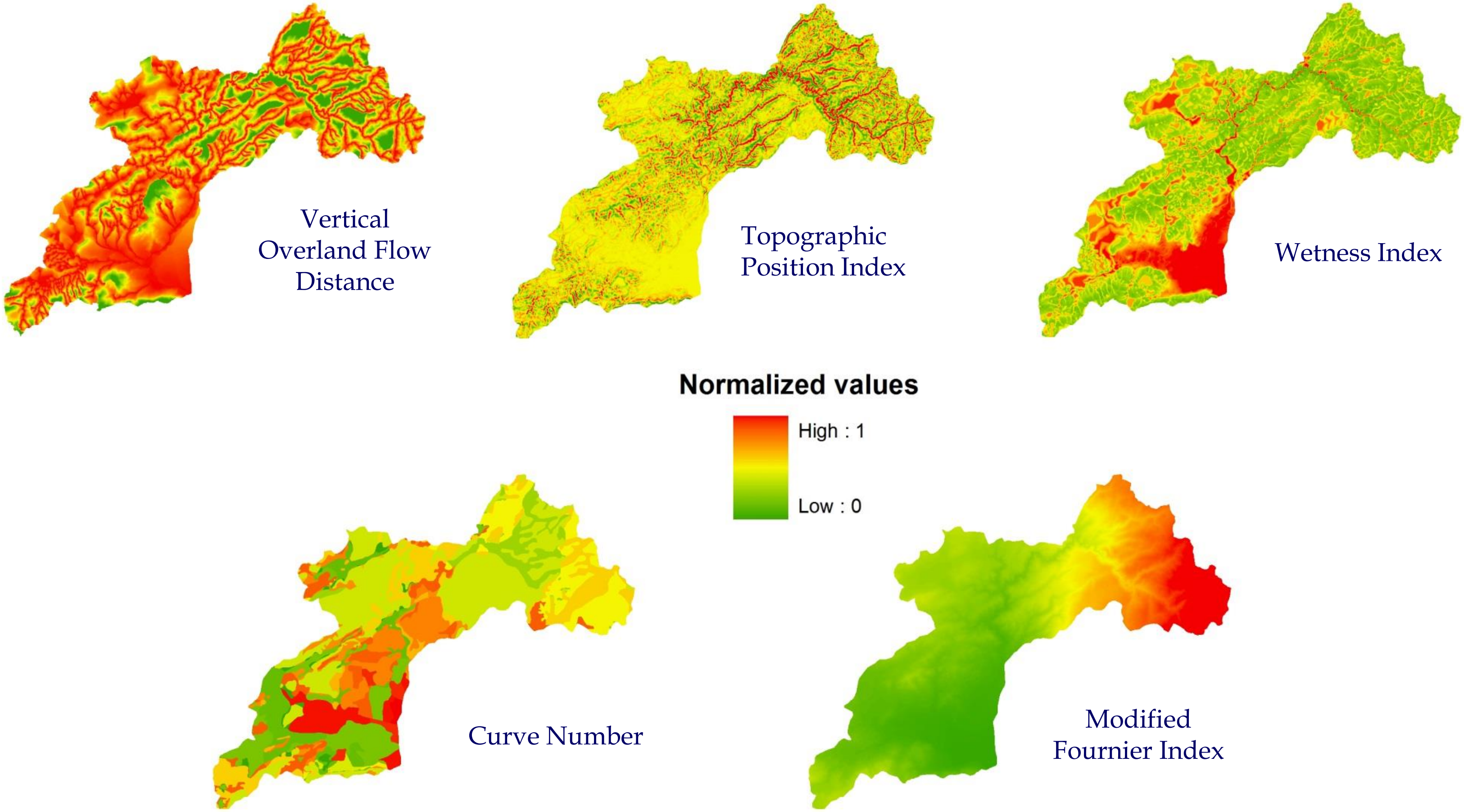
Based on preliminary independency analysis through correlation matrix analysis. Ten (10) criteria out of 32 were selected.

The selected criteria are:



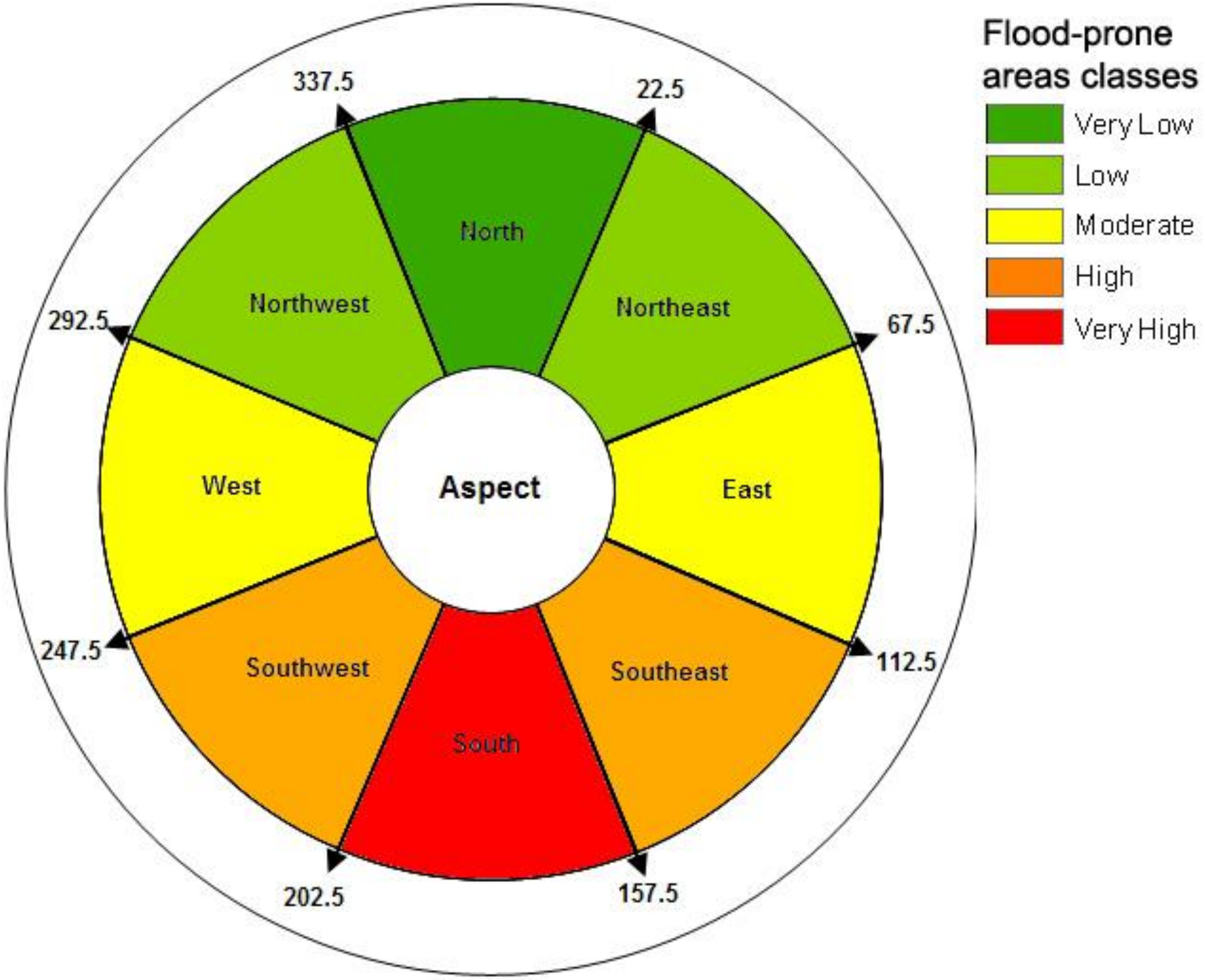
Papaioannou, et al, 2015

Criteria Identification



Papaioannou, et al, 2015

Criteria – Aspect (Xerias Watershed)



Papaioannou, et al, 2015

Results

Pairwise Comparison Table (Multi-Criteria Analysis)

- The pairwise comparison table were completed by 9 experts in the field of hydrology.
- Their results normalized and examined with the Consistency Ratio (CR). In this study, 10 criteria were used and the consistency ratio should be less than 10%.
- In AHP method the experts modified their pairwise comparison tables until their CR decrease less than 10% which is the approved ratio. Consistency Ratio of FAHP was also less than 10% for the final selected tables.

The final selected weights stem from one pairwise comparison table of an expert and referred as "Expert Knowledge" and the median of all the pairwise comparison matrices referred as "Group of Experts".

Papaioannou, et al, 2015

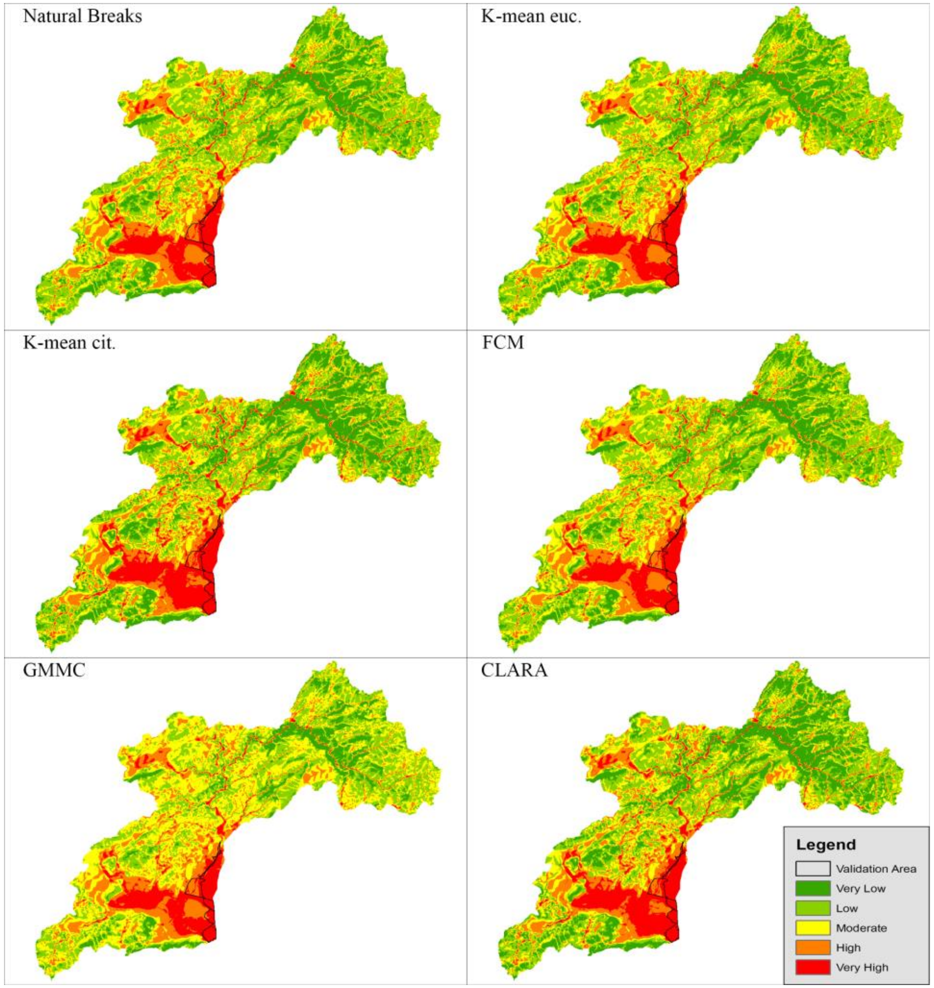
Multi-Criteria Analysis (AHP and FAHP relative weights of the criteria)

	DEM	**Slope**	**Aspect**	**Flow Acc.**	**HOFD**	**VOFD**	**TPI**	**WI**	**CN**	**MFI**	**CR**
AHP Expert Knowledge	0.03	0.09	0.02	0.14	0.13	0.05	0.07	**0.25**	**0.20**	0.02	4.3%
AHP Group of experts	0.03	0.11	0.02	0.15	0.08	0.07	0.08	**0.26**	**0.17**	0.03	4.3%
FAHP Expert Knowledge	0.00	0.09	0.00	0.18	0.14	0.00	0.02	**0.31**	**0.26**	0.00	6.7%
FAHP Group of experts	0.00	0.13	0.00	0.19	0.05	0.03	0.06	**0.32**	**0.22**	0.00	6.8%

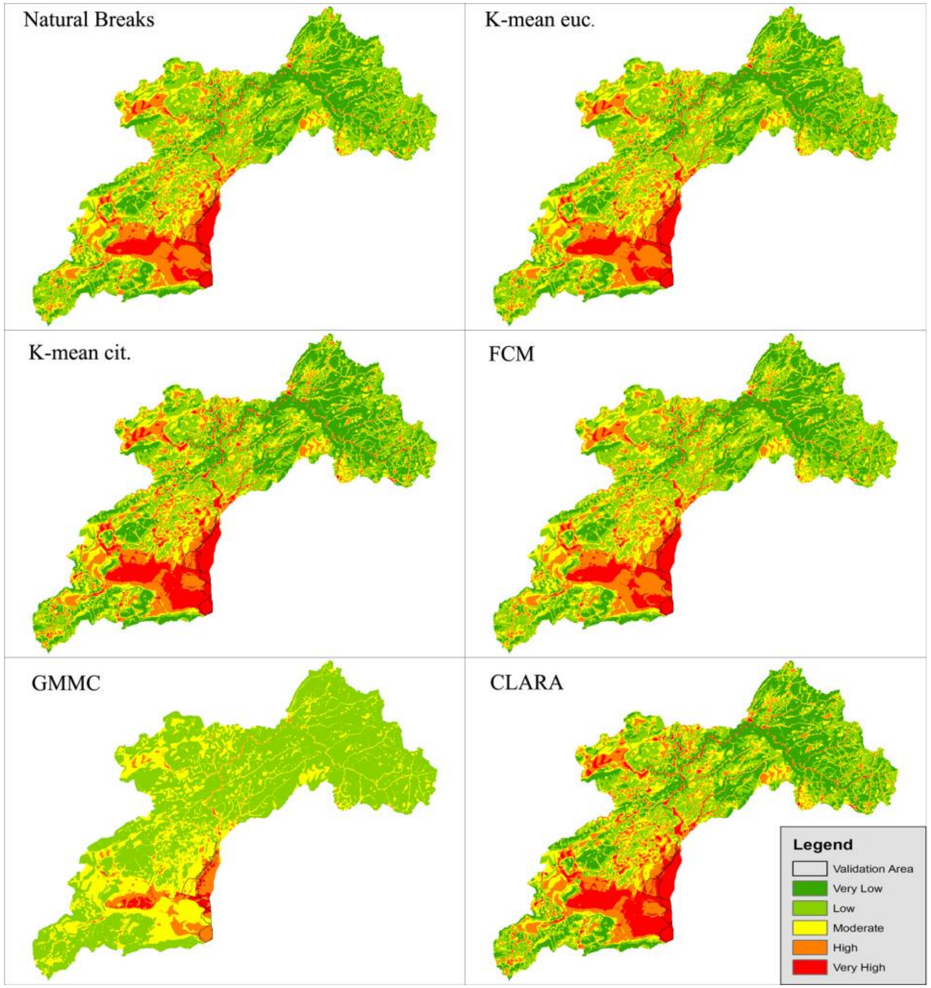
Papaioannou, et al, 2015

Final Maps of Potential Flood Prone Areas

AHP - Group of Experts - 1st approach



FAHP - Group of Experts - 1st approach



Papaioannou, et al, 2015

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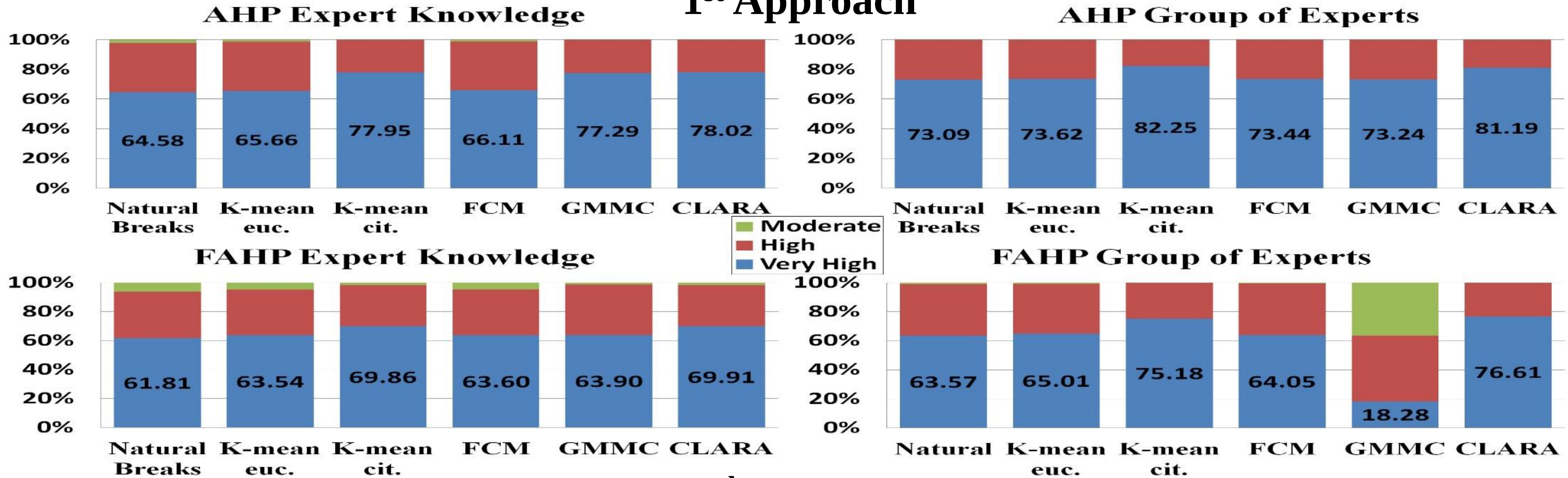
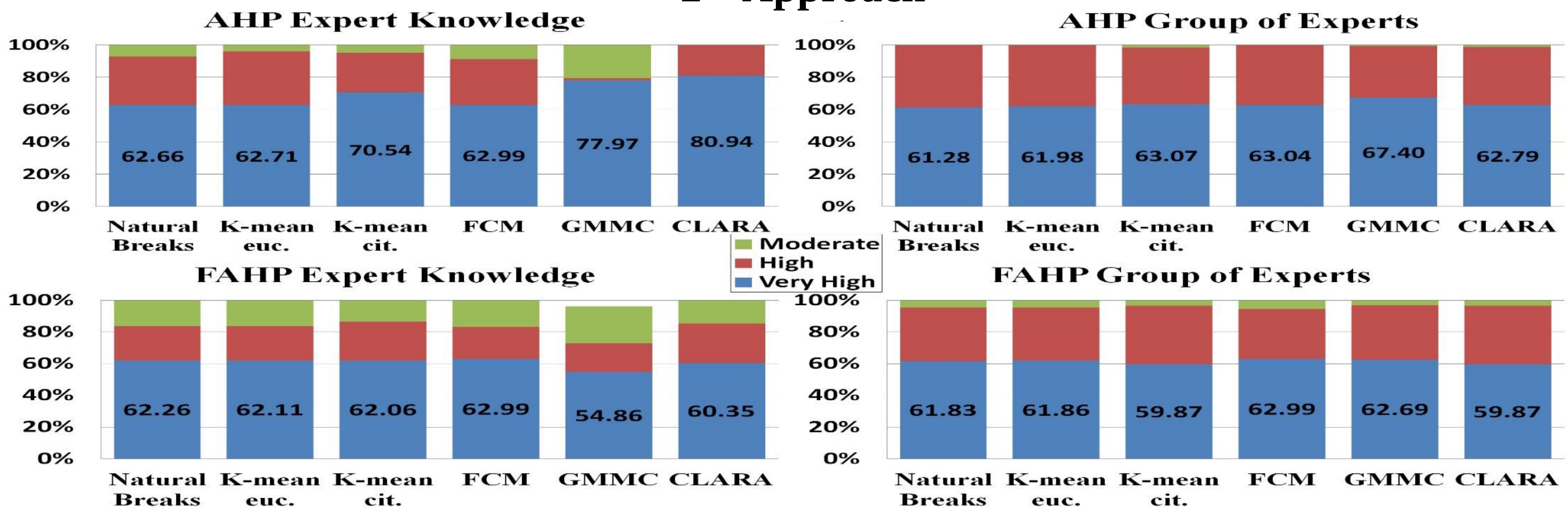
Validation (Classes participation % on validation area)

1st Approach



2nd Approach



Papaioannou, et al, 2015

Concluding Remarks

- An objective GIS-based spatial multi-criteria evaluation framework has been developed and applied at catchment scale for the mapping of potential flood prone areas.
  - 1st Approach-Normalized criteria
  - K-means cit. and CLARA clustering techniques
  - AHP
  - Group of experts
  - 10 proposed indexes

Papaioannou, et al, 2015

A framework to assess wetlands' potential as Nature-based Solutions

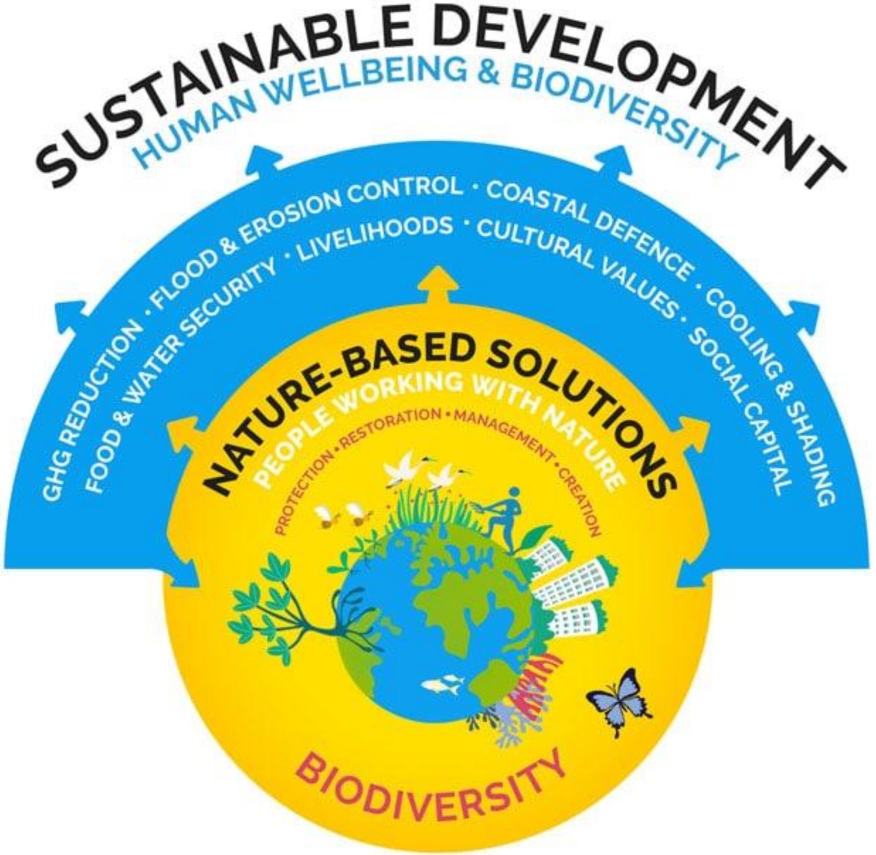
- What are Nature based Solutions (NbS)? - Focus on Ireland
- Wetlands as a promising NbS
- Ecosystem Services
- Current situation and practices
- How to evaluate the performance of wetlands for different services?
- Presentation of a tool to achieve this with an easy, user-friendly, and low-cost way
- Conclusions - generalisation

Alamanos & Papaioannou, et al, 2020

Nature-based solutions (NbS)

NbS are actions that involve the **protection, restoration or management of natural and semi-natural ecosystems**;

- working with nature to address societal challenges, providing benefits for both human well-being and biodiversity



- Plethora of Ecosystem Services (ES)
- From NbS we can derive a plethora of ES → direct and indirect benefits

Alamanos & Papaioannou, et al, 2020

https://www.naturebasedsolutionsinitiative.org/what-are-nature-based-solutions/

NbS in Ireland

gov.ie Departments Consultations Publicatio

Publication

Climate Action and Low Carbon Development (Amendment) Bill 2020

From Department of the Environment, Climate and Communications
Published on 7 October 2020
Last updated on 11 January 2021

The Climate Action and Low Carbon Development (Amendment) Bill is an ambitious piece of legislation. It commits us, in law, to move to a climate resilient and climate neutral economy by 2050.

The Programme for Government commits to a 7% average yearly reduction in overall greenhouse gas emissions over the next decade, and to achieving net zero emissions by 2050. This Bill will drive implementation of a suite of policies to help us achieve this goal.

NbS received extra support in the recent publication of the Climate Action and Low Carbon Development (Amendment) Bill in Ireland

It allows funding for climate action to be granted for projects that *“support projects that seek to increase the removal of greenhouse gas, particularly nature-based solutions that enhance biodiversity”*

Alamanos & Papaioannou, et al, 2020

What do we want from a NbS?

Another definition of NbS:

"Solutions that are inspired and supported by nature, which are **cost-effective**, simultaneously **provide** environmental, social and economic **benefits** and **help build resilience**.
Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through **locally adapted**, **resource-efficient** and **systemic interventions**."

Questions:

- How to use them right to achieve the sustainable management and the resilient systems?

- What measures and works can we make to derive all these benefits?

Alamanos & Papaioannou, et al, 2020

https://ec.europa.eu/info/research-and-innovation/research-area/environment/nature-based-solutions_en

Wetlands/ Peatlands

- 1.46 million ha of peat soils (1/5 of land area)
- <15% is protected
- 25% state-owned:

333,000 ha Coillte; 80,000 ha Bord na Móna; 42,000 ha NPWS

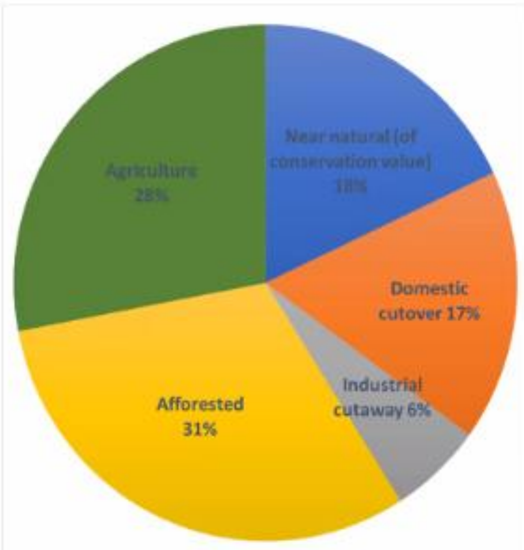


Figure 1: Estimates of area of peatland in Ireland under major land use classifications.

The state of Irish peatlands

- Most peatlands (82 %) are drained and utilised for other purposes
  - Few extraction sites have been rewetted
  - It is unknown how much peatland used for forestry and agriculture has been rewetted
- Only 18% of peatlands are considered to be of conservation value
  - Only a small proportion of these have been rewetted and restored
- Rewetting combined with other restoration techniques (e.g. reseeding or transplanting of essential peatland species) can speed up revegetation and improvements in water quality.

Peatlands = a type of wetlands (peat soils)

ES = highest Carbon storage capacity, climate change mitigation, stormwater retention, nutrient filtering, climate stability, flora and fauna, soil improvement, timber, raw materials, habitats, culture, etc.

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https://www.iucn.org/resources/issues-briefs/peatlands-and-climate-change

Problems

Significant wetland loss in Ireland the last decades

- limited or no solid broader management and planning, because of the lack of the specific knowledge required to estimate their Ecosystem Services (ES) potential
- Conservationists support the rewetting of peatlands/wetlands, but still we cannot quantify the benefits

To consider wetlands as Nature-based solutions (NbS), policymakers need to know their effectiveness on the ES of interest.

- Technical solutions' performances can be easily known from their design studies (e.g. water treatment ability, retention ponds capacity, etc.).
- With wetlands this cannot be the case because their performance depends on various factors (physical, geomorphological, hydrological, climatological, vegetation, soil, surrounding land uses, inflows, initial concentrations, connectivity with other water bodies, infiltration, etc.).

Subsequently, it is tough to compare them with other technical solutions on the same basis and with equal certainty.

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Research question

Provide a tool for the estimation of wetlands' effectiveness:

- fast,
- cost-free,
- easy and user-friendly, built on simple and well-known tools,
- considering most of the factors that determine it (depending each ES studied),
- in order to provide policymakers with more info on such NbS, and make the comparison of alternative options fairer.

A novel approach, based on classic techniques:

- Geographic Information Systems (GIS) are used to map the factors that affect wetlands' effectiveness (criteria),
- combined with Multi-Criteria Analysis (MCA) (to assign weights to those criteria), and produce a map with classified wetland potential performances on the ES of interest
- Catchment scale (compatibility)

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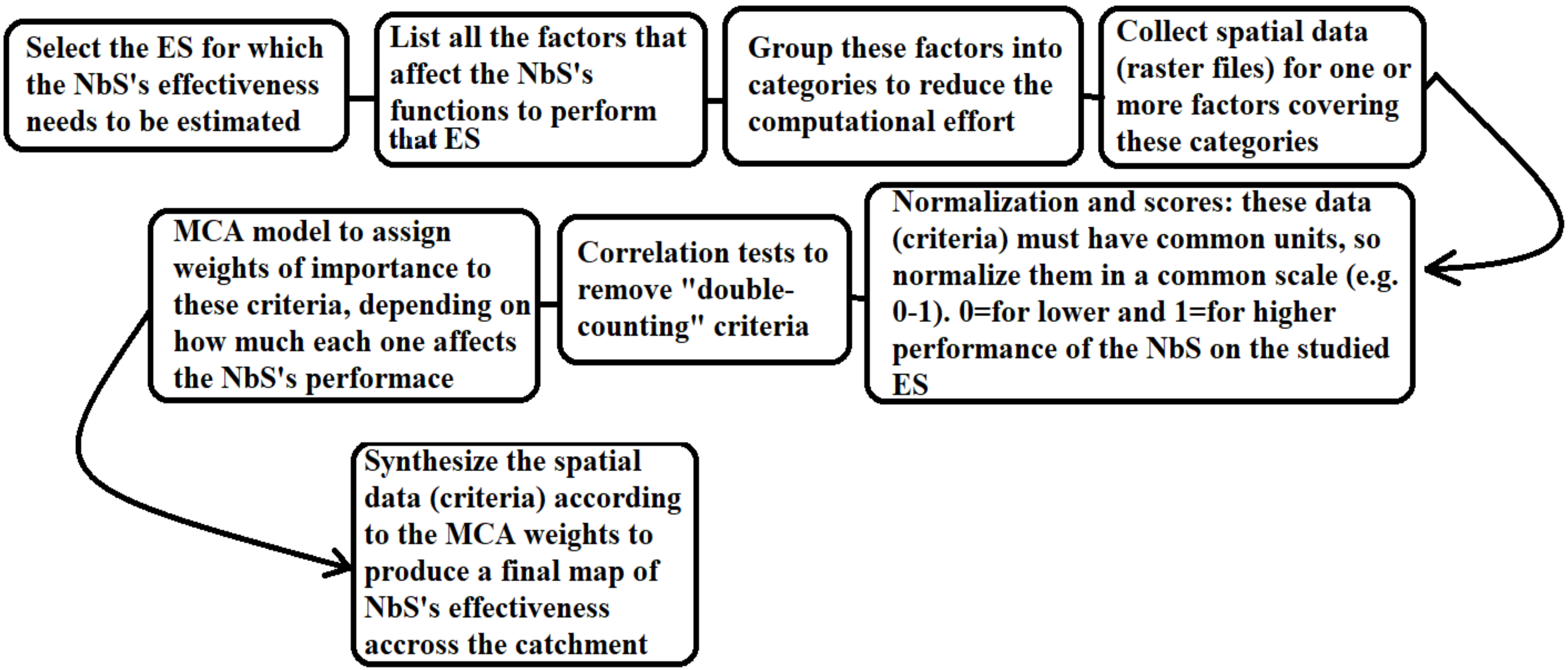
Conceptual flowchart



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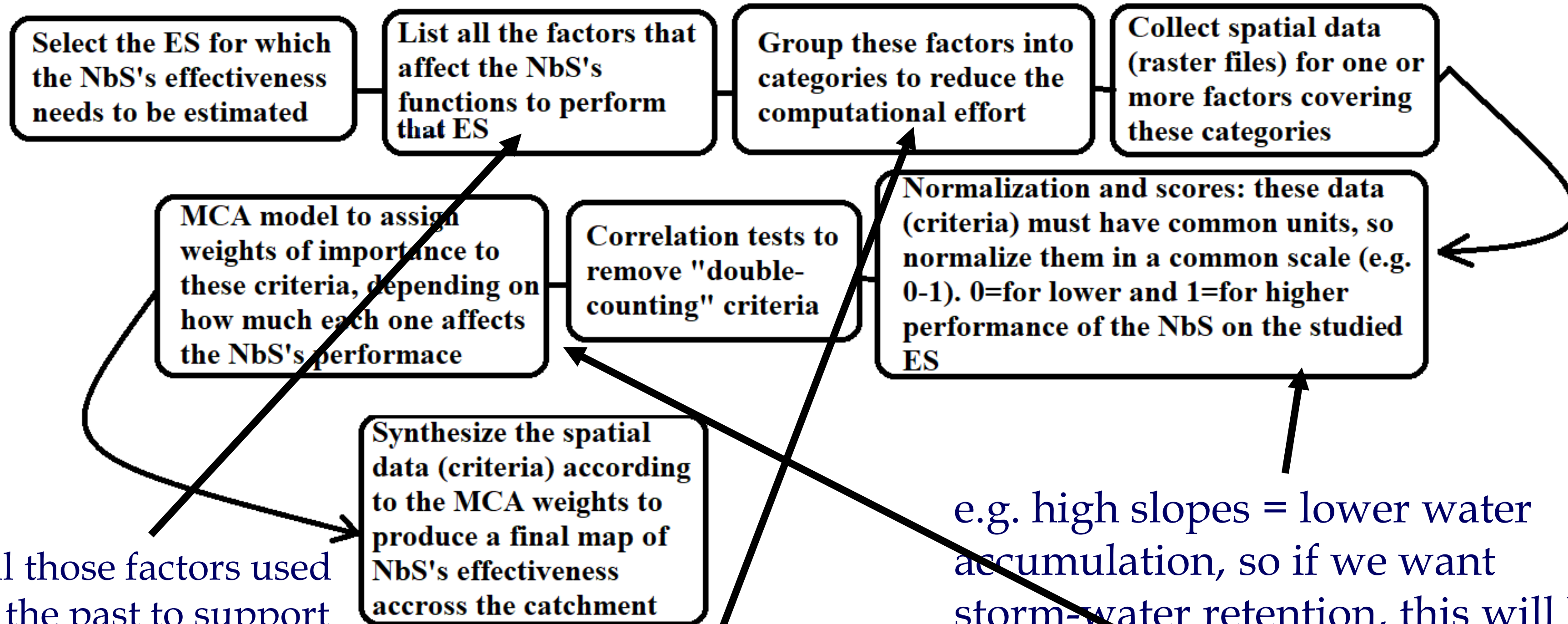
Conceptual flowchart



e.g. high slopes = lower water accumulation, so if we want storm-water retention, this will be low (towards 0)

All those factors used in the past to support effectiveness estimates, those that make estimations difficult, make each study case-specific, and prevent more general assessment,

Categories such as:
-Land-use criteria,
-Soil and vegetation criteria,
-Climatic criteria,
-Landscape/topography criteria
-etc

AHP works well with 5-10 criteria and can use qualitative comparisons among them

All the above must be according to the literature and the expert’s judgement

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ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ

Case Study Application

Grand River Watershed, Ontario, Canada

- Faces intense wetland loss (conversion to more profitable farmland)
- Legislations for reducing phosphorus (P) concentration from surface waters (Grand River flows into Lake Erie – eutrophication, reduce P by 40%)
- Wetlands as a NbS to reduce P

How efficient they are? Where must we protect them and where we can replace them with farmland?

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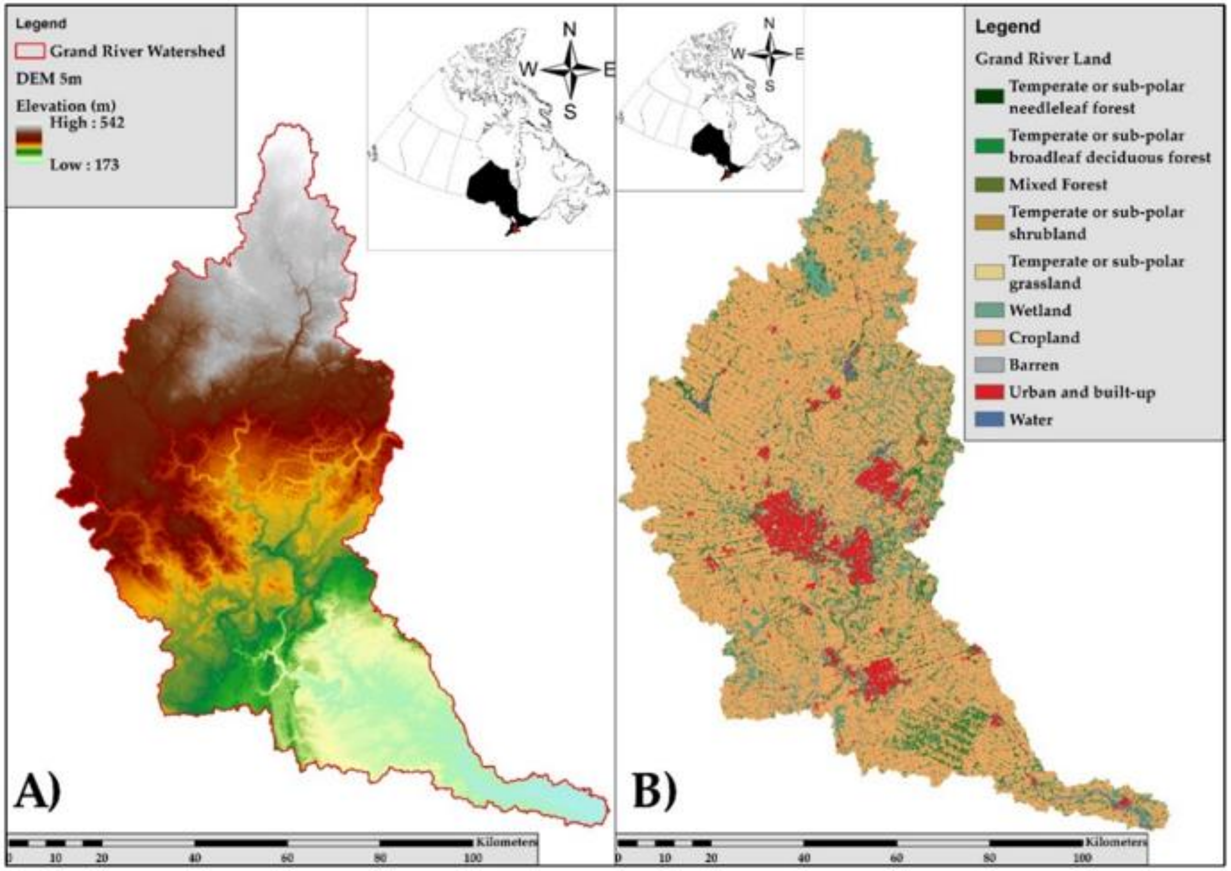

Case Study Application
ES = Efficiency for P filtering

Catchment scale: wetlands are parts of a wider ecosystem that functions in a coupled and interactive way with nature's and human's activities

Listing the factors/ Grouping them into categories:

- Land-use criteria: surrounding land uses majorly affect its performance, inflows' quantity and quality.
- Soil and vegetation criteria: soil type, vegetation type and density result in different nutrient-absorbing capacities.
- Climatic criteria: temperature, precipitation, sunny hours, ice coverage, etc. Meteorological factors affect the speed of the processes and the response of other factors (such as soil and vegetation).
- Landscape/topography criteria: DEM-related parameters which allow the calculation of slope, aspect, Topographic Position Index (TPI), Topographic Wetness Index (TWI), overland flow distance, etc. These factors show the water concentration inside the watershed, topographic features, and are important elements to consider for wetlands acting as sources or sinks of nutrients. Also, flow rates and accumulation (or the time that phosphorus stay in the wetland) can be indirectly addressed.

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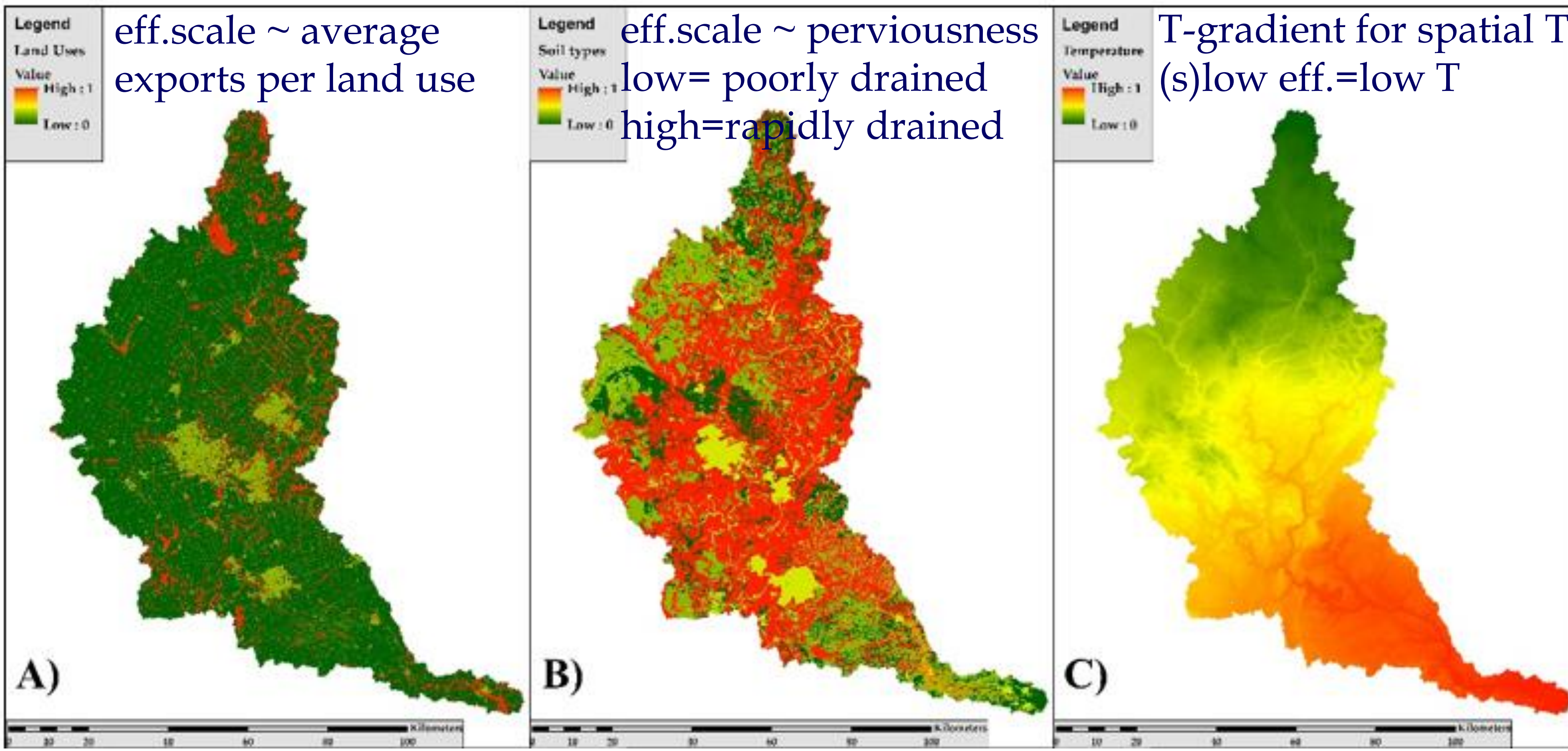
Final set of criteria – Normalization & scoring (0-1, low-high scale)

Final set of criteria with spatial data (data availability & correlation tests): Land Cover, Soil Type for Soil, Temperature, Slope, TPI and TWI.



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Final set of criteria – Normalization & scoring (0-1, low-high scale)

- small number of criteria makes the computational process simpler
- avoids double-effects on the evaluation process since they stand for different drivers
- all of them are in agreement with other studies

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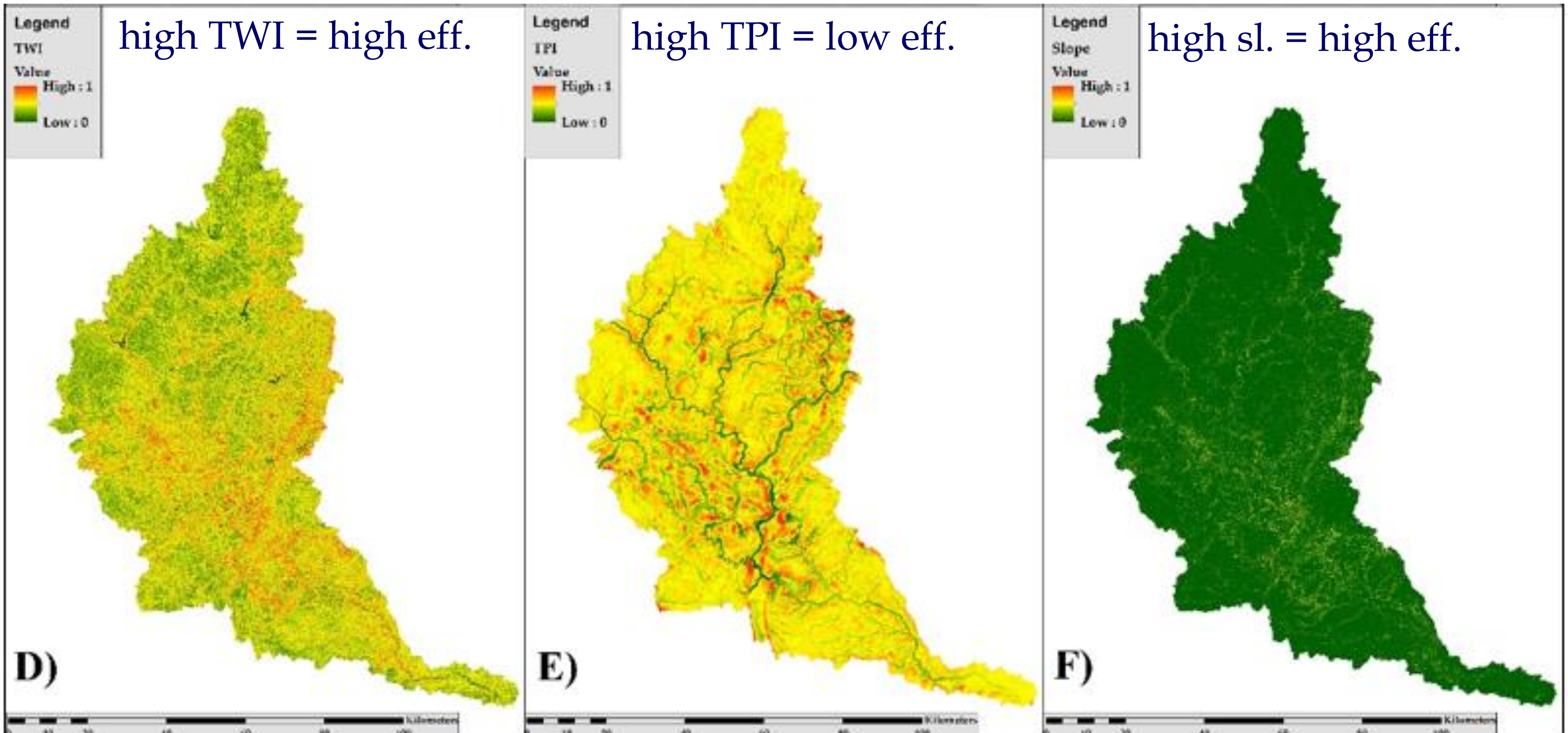


Case Study Application

MCA model – How important is each layer (criterion)?

AHP – pairwise comparisons 6x6 matrix (Table 1) →

- The right principal eigenvector was calculated for the matrix
- Synthesis of preferences determines which criterion has the higher priority and effect on the estimated result (consistency)
- Through the comparison relations the criteria were weighted (aij), for each map (wj) (Table 2)
- A spatial value occurred for each grid's cell, i.e. the potential effectiveness (i)

(raster calculator- GIS) →

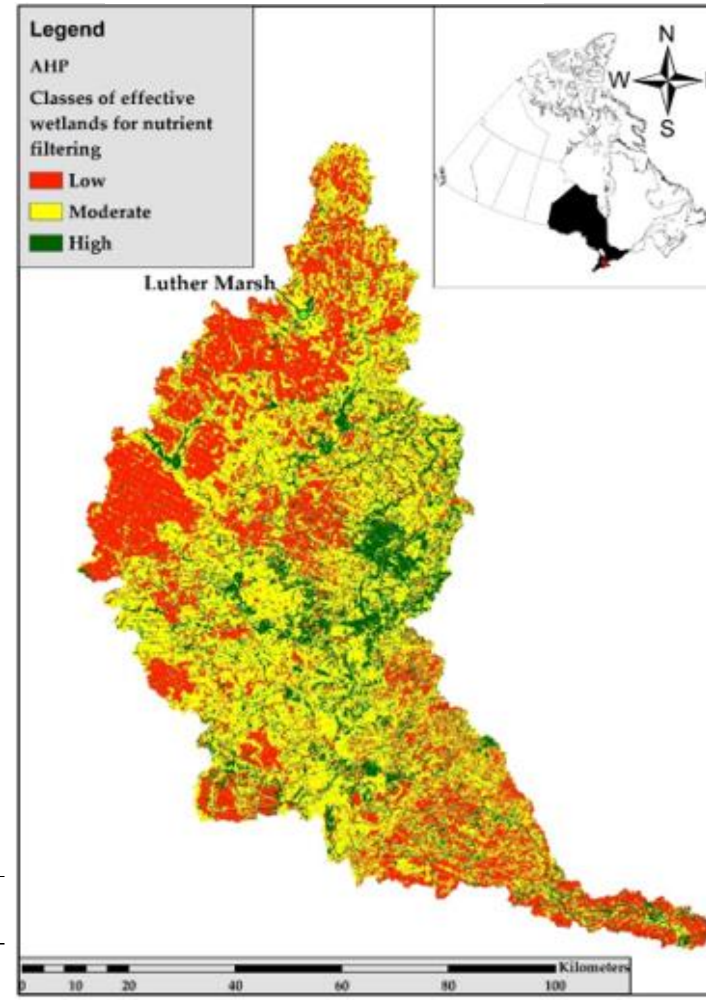
$$A^{i}_{AHP} = \sum_{j=1}^{6} a_{ij} \cdot w_j$$

Table 1. Example of AHP pairwise comparison using the Saaty scale.

	Temperature	TWI	TPI	Slope	Soil type	Land uses
Temperature	1	2	1/6	3	1/6	1/7
TWI	1/2	1	1/7	1	1/7	1/8
TPI	6	7	1	7	1/2	1/3
Slope	1/3	1	1/7	1	1/8	1/9
Soil type	6	7	2	8	1	1/3
Land uses	7	8	3	9	3	1

Table 2. Relative weights of the criteria, R.I, and C.R., as resulted from the AHP.

Priority Vector							Randomness Index (RI)	Consistency Ratio (C.R.)
Criteria	Temperature	TWI	TPI	Slope	Soil type	Land uses	Criteria n = 6	CR = 7.72%
Weights	0.06	0.03	0.20	0.03	0.25	0.42	RI = 1.24	



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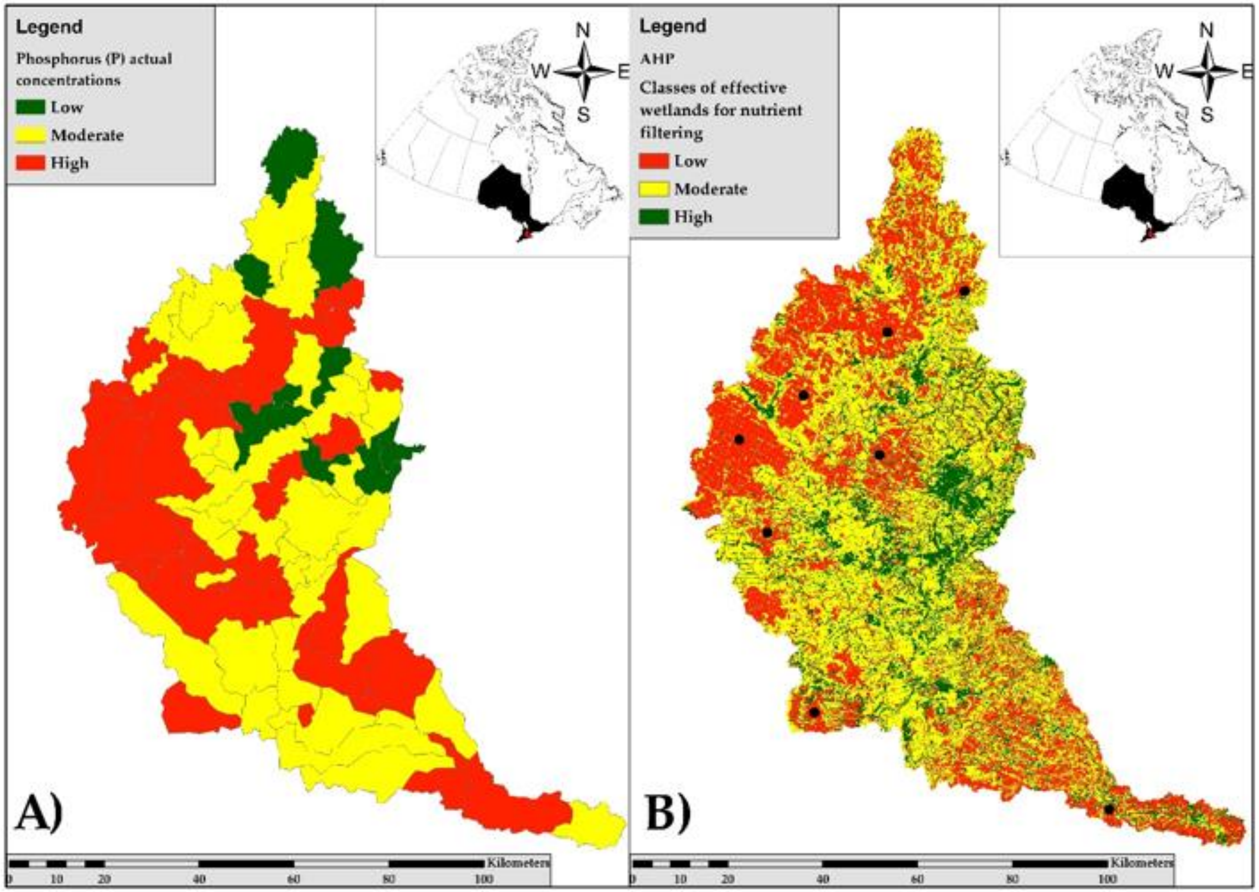
Validation



Indirect validation (e.g. nutrient filtering compared with nutrients modelled concentrations or estimated exports)

OR

Direct validation (e.g. storm-water retention compared with modelled floodplains)

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Conclusions

- Operational tool – it can be applied for any ES and similar problems on the identification of potential areas

preliminary estimator to detect locations of interest

- Objective & scientific logic to represent the "experts' judgement" process

- Easy and user-friendly tool: GIS/ or GIS + MS Excel/ or GIS + coding
- Cost-free + easy data manipulation
- Promotes the creation of spatial databases

Future research: quantify the ES through modelling

- e.g. flood or SWAT model → both are compatible with GIS → allows model-building expansion

- Quantification → validation → fairer comparisons of NbS with technical ones

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Thank you for your attention