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Politecnico di Torino
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EXPO 2015

October 14, 2015

Water resources system analysis: tools and challenges

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Outline

- Scientific and practical challenges in modeling water resources systems (Part 1)
- Example application: “A Hybrid Model Tree (MT) – Genetic Algorithm (GA) Scheme for Toxic Cyanobacteria Predictions in Lake Kinneret” (Part 2)
- Questions

Outline

Part 1

1. Introduction
2. Water resources systems basic components
3. Simulation tools
4. Optimization tools
5. Systems perspective
6. Integration methodologies

Part 2

7. Example application

Outline

1. Introduction
- Water resources systems basic components
- Simulation tools
- Optimization tools
- Systems perspective
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- Example application

Introduction

- <u>General:</u> water resources systems analysis – operations research (OR) of "water components" (e.g., reservoirs, rivers, watersheds, groundwater, distribution systems, etc.), as standalone or integrated, for single or multiobjective problems, deterministic or stochastic

- <u>Specific:</u> water distribution systems analysis (water security), watershed management, surface water

- <u>Tools:</u> "traditional" OR (LP, NLP), data driven modeling (neural networks, model trees), evolutionary computation (Genetic Algorithms, Ant Colony, Cross Entropy) – single/multiobjective

Introduction

- The scientific and practical **challenge** in dealing **quantitatively with water resources management problems** is in taking into consideration from a **systems perspective**, social, economical, environmental, and technical dimensions, and integrating them into **a single framework for trading - off in time and in space competing objectives**

- Inherently, such problems involve **modeling of water quantity and quality** for **water resources systems components**, such as: surface water, groundwater, water distribution systems, reservoirs, rivers, lakes, and others, **as stand alone or linked elements**

Introduction

- **Conceptual issues** which should be overcomed for constructing and solving a water resources management problem

- **Description of available tools** for dealing with water resources management problems: available **simulation programs** (e.g., WMS, GMS, SWAT, AVGWLF, EPANET), **optimization methodologies** (e.g., simulated annealing, genetic algorithms, ant colony, cross entropy, non-linear programming, linear programming)

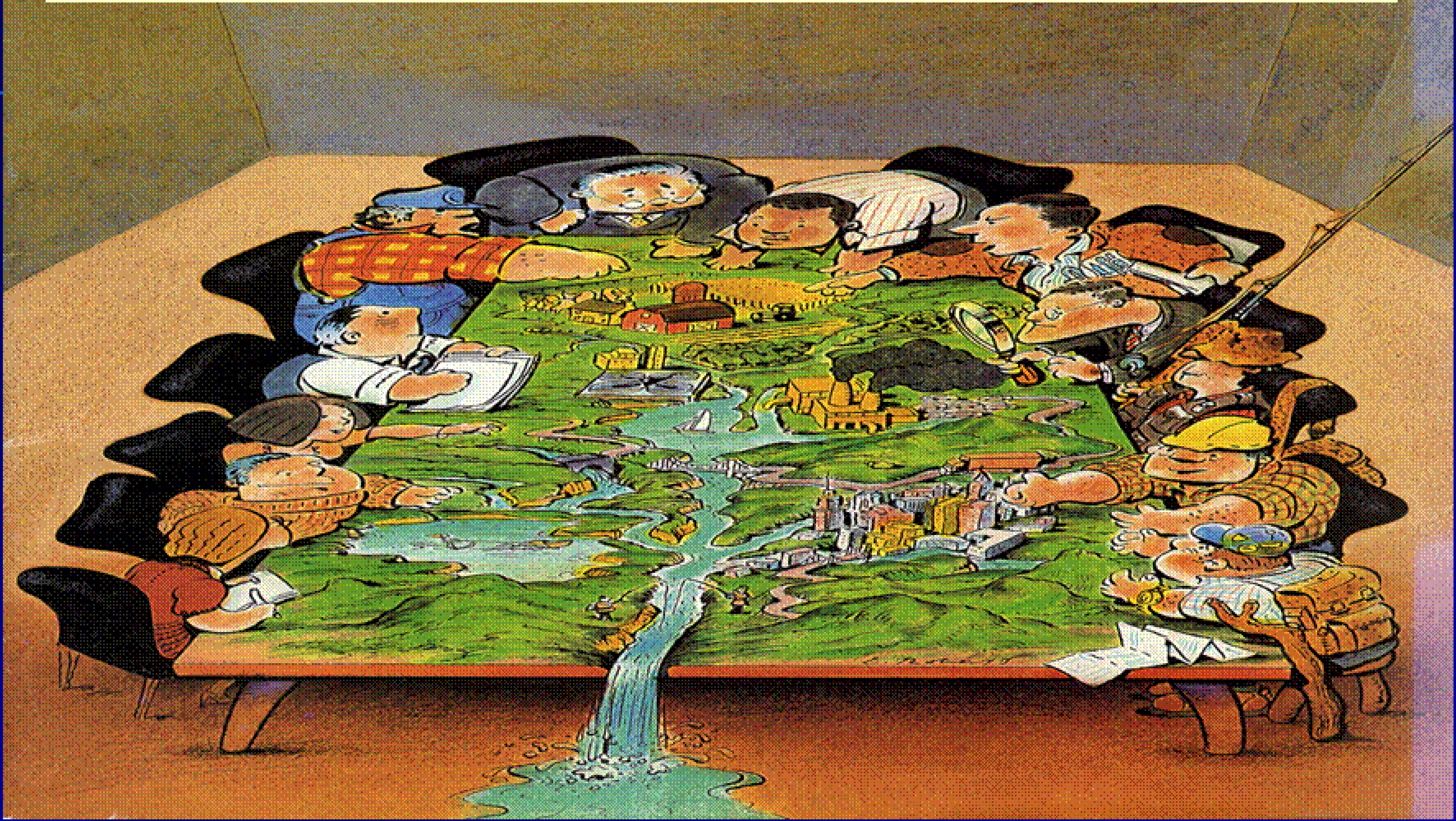
- **Integration approaches: "embedding" ; "linking" ; "hybridizing"**

- **Case study** for demonstrating the **"hybridizing"** approach

Outline

- Introduction
- **2. Water resources systems basic components**
- Simulation tools
- Optimization tools
- Systems perspective
- Integration methodologies
- Example applications

Loucks, Daniel P.; Beek, Eelco van; Stedinger, Jery R.; Dijkman, Jozef P.M.; Villars, Monique T. (2005). "Water resources systems planning and management: an introduction to methods, models and applications." Studies and reports in hydrology; 680 p., illus.



"Everything" interacts within river basins

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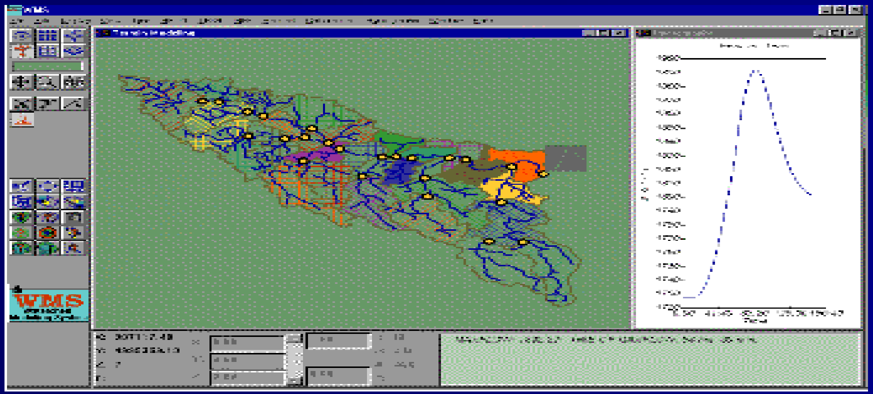
Simulation tools

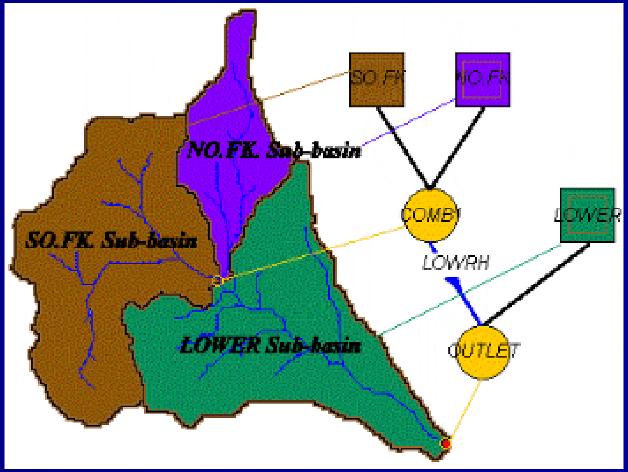
- Surface water – WMS, BASINS, others

<u>WMS – Watershed Modeling System</u>

Merging information obtained from terrain models and GIS with lumped parameter traditional hydrologic analysis models such as HEC-1 and TR-20, having an ability to take advantage of digital terrain for hydrologic data development

WMS uses three primary data sources for model development: 1. Geographic Information Systems (GIS) Data 2. Digital Elevation Models (DEMs) 3. Triangulated Irregular Networks (TINs)





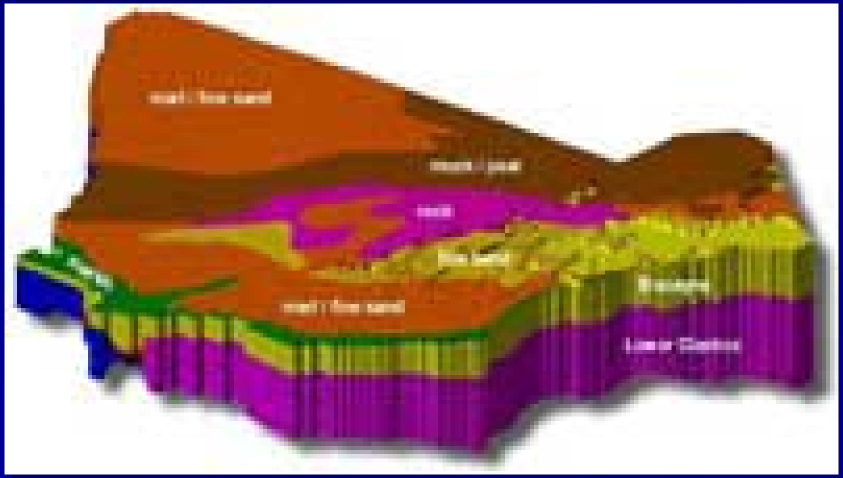
http://www.ems-i.com/

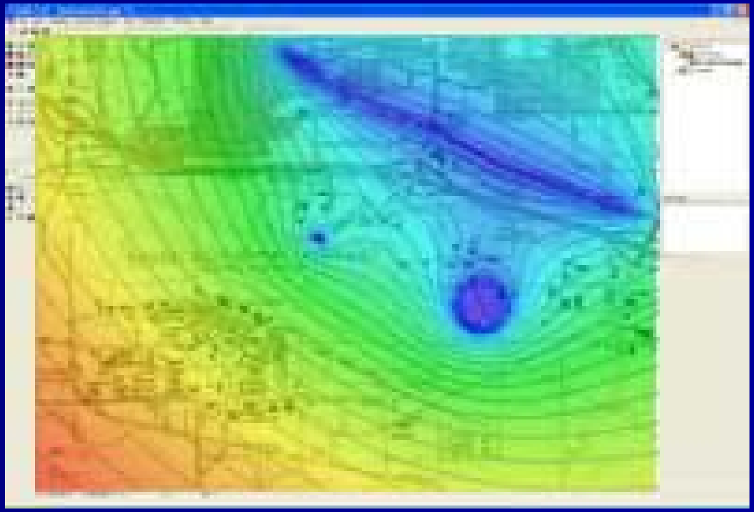
Simulation tools

- Groundwater – GMS, Visual MODFLOW, others

  GMS – Groundwater Modeling System

  Providing **GIS tools for groundwater simulation** including site characterization, model development, calibration, post-processing, and visualization, supporting both finite-difference and finite-element models in 2D and 3D including links to **MODFLOW, MODPATH**, and others





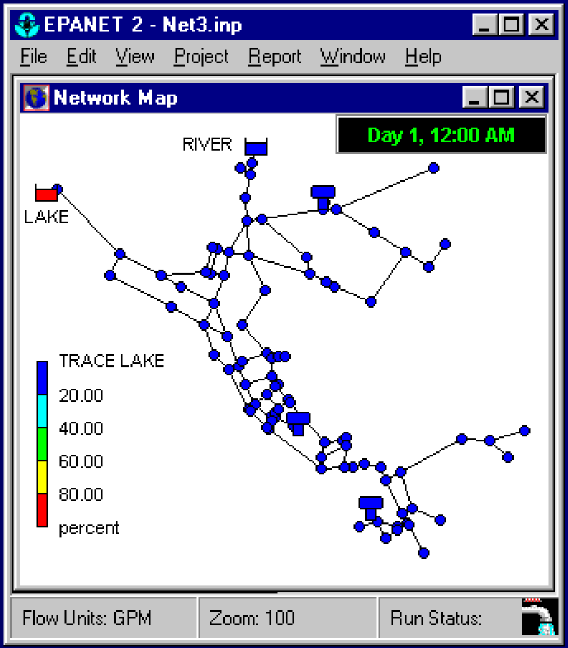
http://www.ems-i.com/

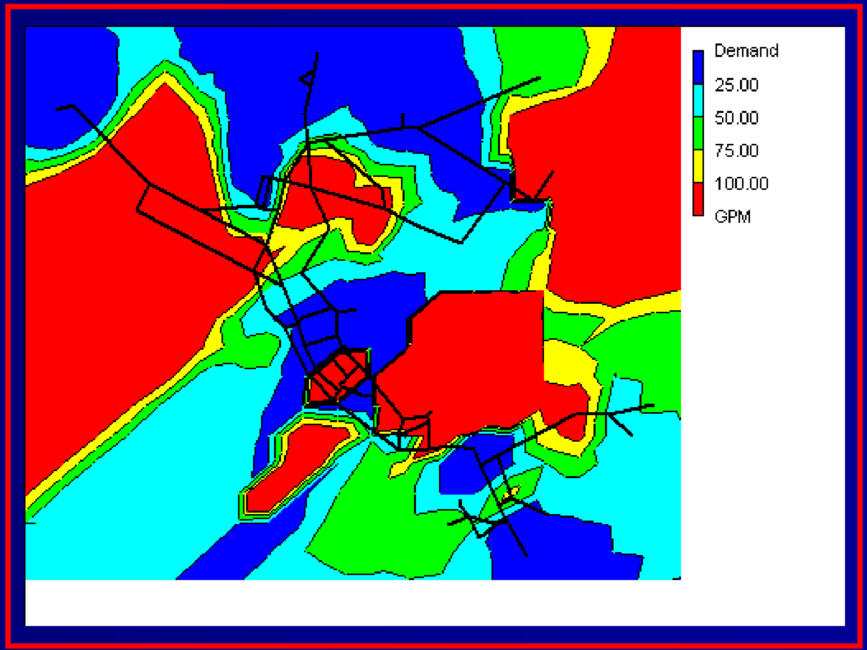
Simulation tools

- Water networks – EPANET, WaterCad, others

  EPANET

  Performing **extended period simulation of hydraulic and water-quality behavior** within pressurized pipe networks consisting of pipes, consumers, pumps, valves and storage tanks





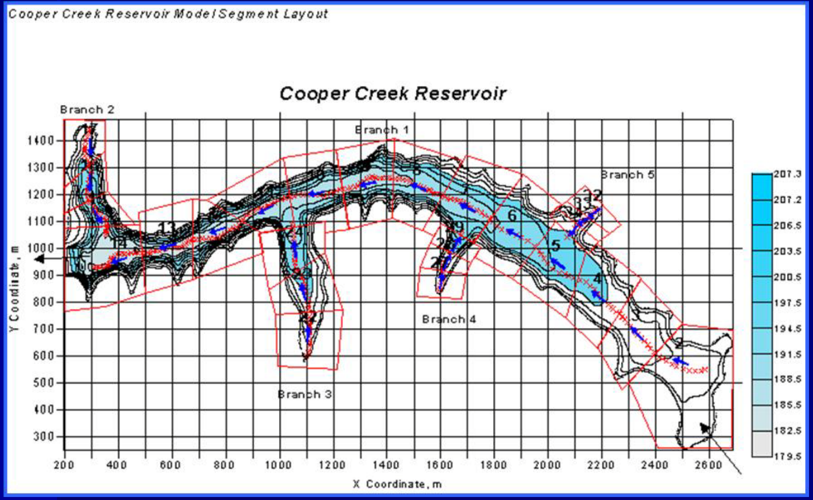
http://www.epa.gov/nrmrl/wswrd/epanet.html

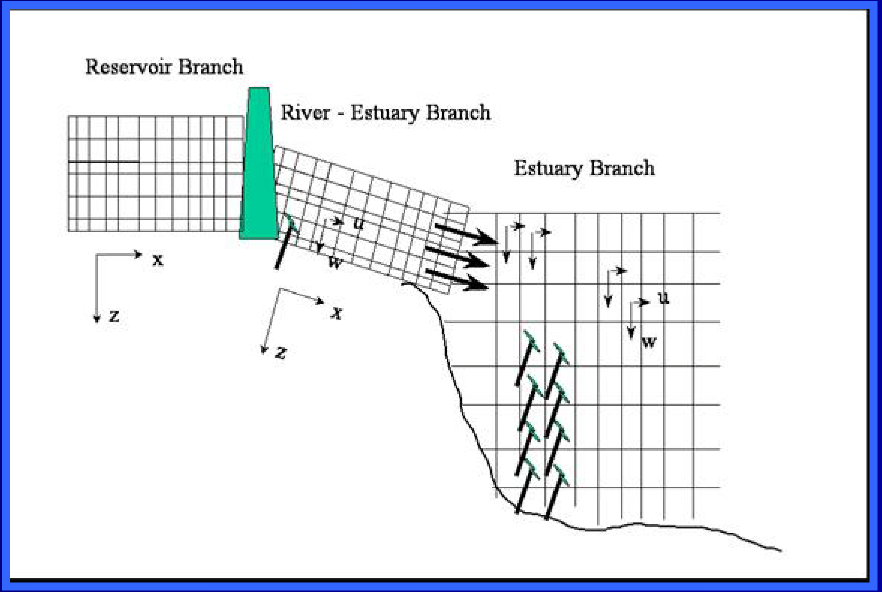
Simulation tools

- Lakes and reservoirs – CE-QUAL-W2, ELCOM, others

<u>CE-EQUAL-W2</u>

A two-dimensional , longitudinal/vertical, **hydrodynamic and water quality model for reservoirs, lakes and estuaries, which** models basic eutrophication processes such as temperature-nutrient-algae-dissolved oxygen-organic matter and sediment relationships





http://www.ce.pdx.edu/w2/

CE-QUAL-W2 Hydrodynamic equations

X- momentum

$$\frac{\partial UB}{\partial t}+\frac{\partial UUB}{\partial x}+\frac{\partial WUB}{\partial z}=gB\sin\alpha_s$$
$$+gB\cos\alpha_s\frac{\partial\eta}{\partial x}-\frac{gB\cos\alpha_s}{\rho}\int_\eta^z\frac{\partial\rho}{\partial x}\partial z+\frac{1}{\rho}\frac{\partial B\tau_{xx}}{\partial x}+\frac{1}{\rho}\frac{\partial B\tau_{xz}}{\partial z}+qBU_x$$

Continuity

$$\frac{\partial UB}{\partial x}+\frac{\partial WB}{\partial z}=qB$$

Water level

$$B_\eta\frac{\partial\eta}{\partial t}=\frac{\partial}{\partial x}\int_\eta^h UBdz-\int_\eta^h qBdz$$

Equation of state

$$\rho = f(T, TDS, SS) = \rho_T + (\Delta\rho_{sal} \text{ or } \Delta\rho_{TDS}) + \Delta\rho_{SS}$$

Turbulent Advective Diffusion

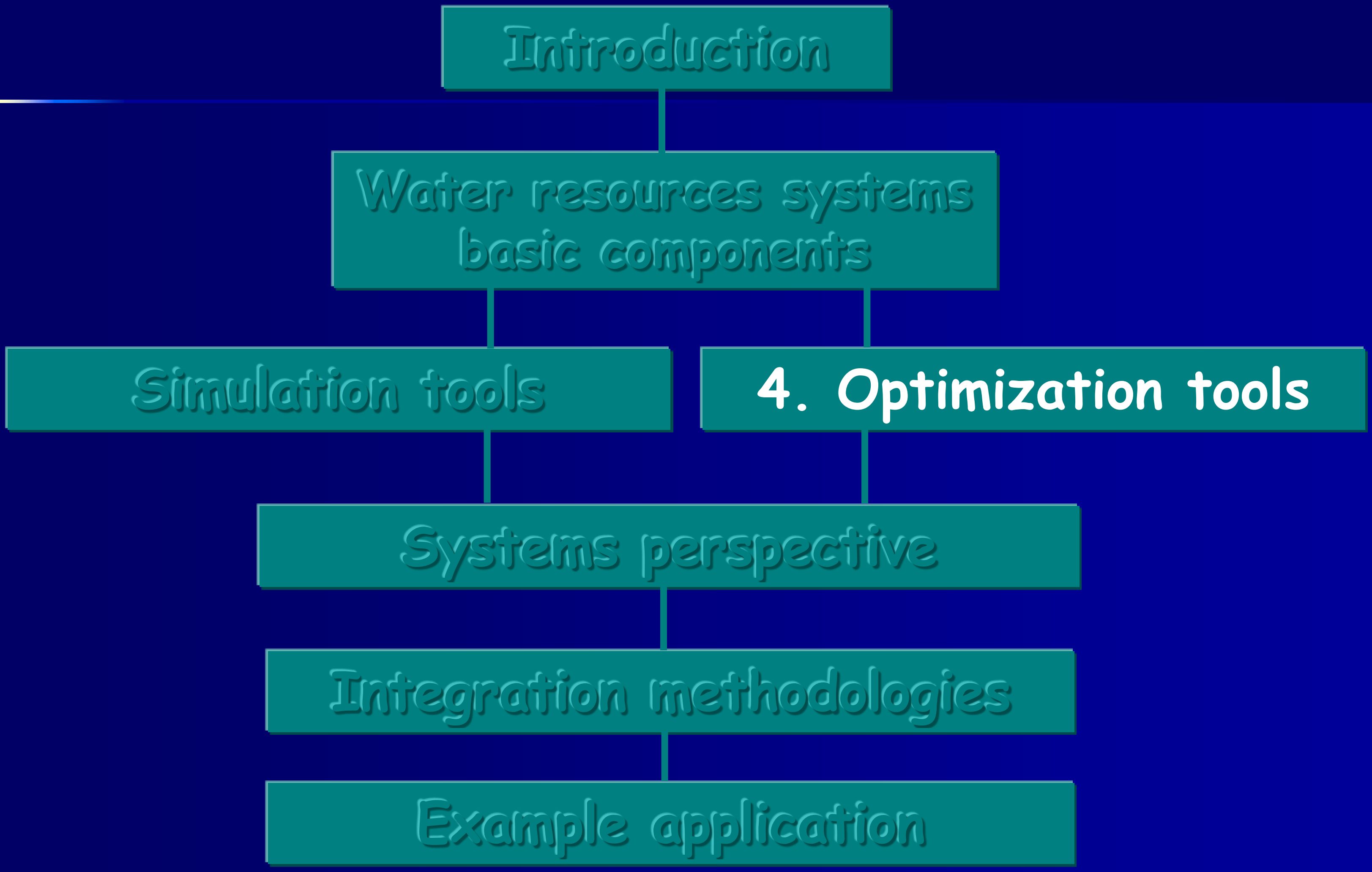
$$\frac{\partial B\Phi}{\partial t}+\frac{\partial UB\Phi}{\partial x}+\frac{\partial WB\Phi}{\partial z}-\frac{\partial\left(BD_x\frac{\partial\Phi}{\partial x}\right)}{\partial x}-\frac{\partial\left(BD_z\frac{\partial\Phi}{\partial z}\right)}{\partial z}=q_\Phi B+S_\Phi B$$

Two observations:

- The physical representation of water resources elements might be quite complex

This directs the possible solution methods and approaches employed for optimizing water resources systems

Outline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Optimization tools

Two main categories: (1) Classical (2) Heuristic

- **Classical:** LP (Linear Programming), NLP (Nonlinear Programming, e.g. GRG = General Reduced Gradient), Dynamic Programming, others

Advantages: provide analytical tools to solve optimization problems; **Limitations:** restricted (number of constraints, decision variables, model properties)

- **Heuristic:** Simulated Annealing, Genetic Algorithms, Ant Colony, Tabu Search, Cross Entropy, others

Advantages: not restricted; **Limitations:** no analytical assurance of an optimal solution, highly computational intensive

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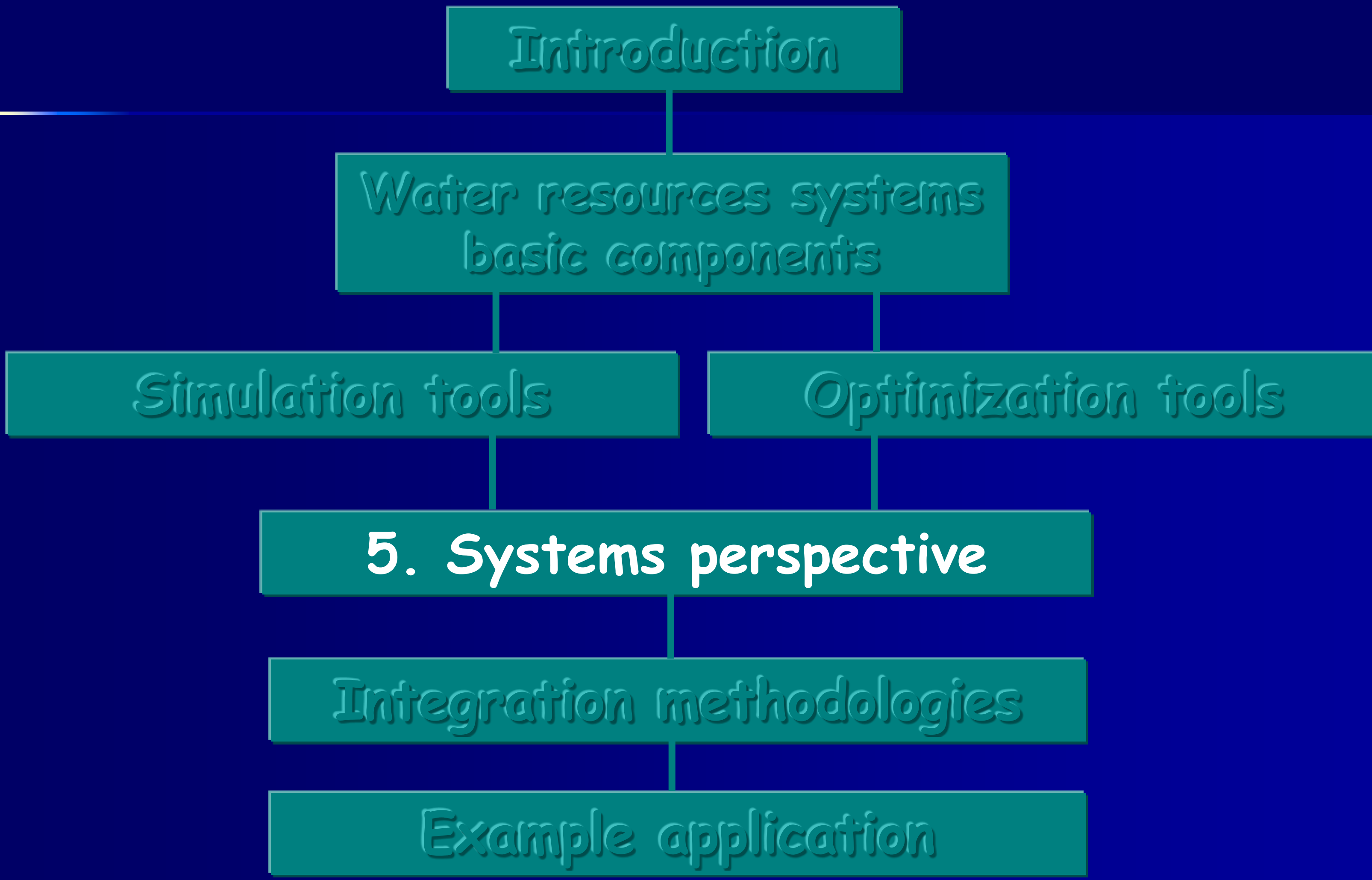
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Systems perspective

- The goal is to find a **Pareto optimal** solution set or a non-dominated solution set

- Each solution in the Pareto optimal set is optimal in the sense that **it is not possible to improve one objective without making at least one of the others worse**

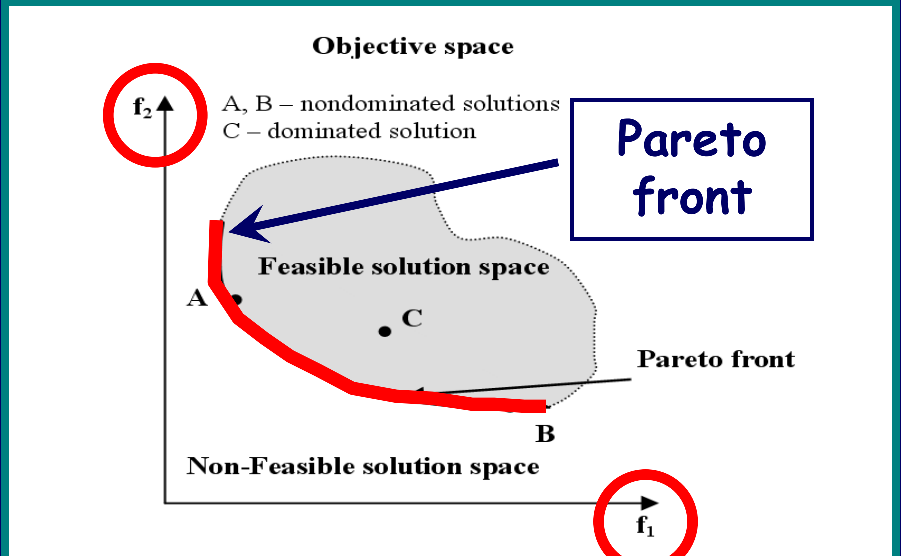
Optimize: $F(x) = \left(f_1(x), f_2(x), \ldots, f_M(x)\right)^T$

Subject to:

$g_i(x) > 0, \quad i = 1, 2, \ldots, k \qquad k$ Inequality constraints

$e_j(x) = 0, \quad j = 1, 2, \ldots, l \qquad l$ Equality constraints

where $x = \left(x_1, x_2, \ldots, x_n\right)^T$ is the vector of decision variables



Pareto front of a two-objective minimization problem

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- **6. Integration methodologies**
- Example applications
- Challenges

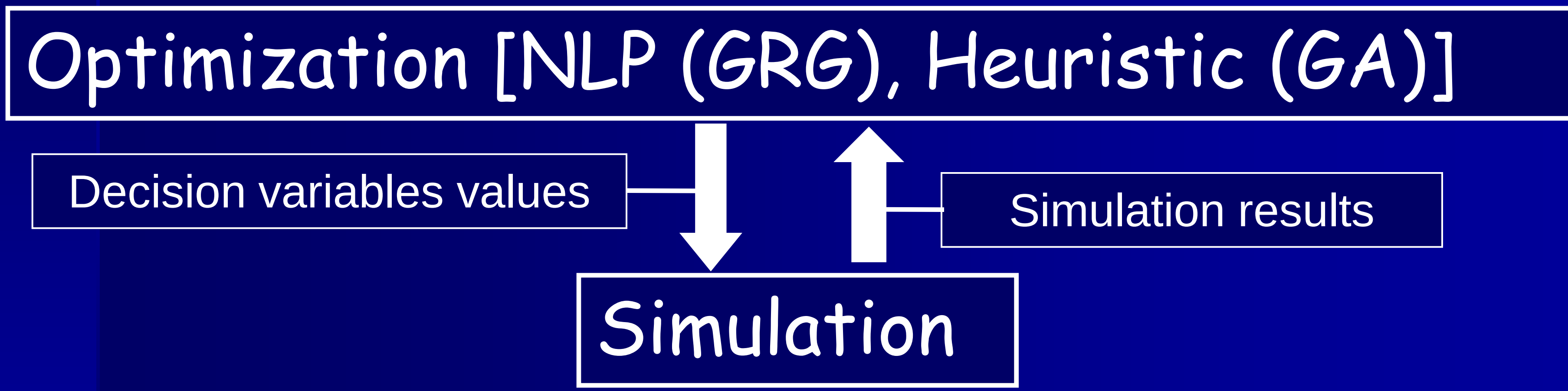
Integration methodologies

Three basic approaches:

- ❑ **Embedding** – direct; traditional
- ❑ **Simulation – Optimization (NLP) (Late 1980's)**
- ❑ **Simulation – Optimization (Heuristic) (Last decade)**
- ❑ **Hybrid modeling: Simulation - Data Driven Modeling – Heuristic Optimization (Lately)**

Integration methodologies

- Simulation – Optimization (NLP) (Late 1980's) ; Simulation – Optimization (Heuristic) (Last decade)



If the simulation stage is time consuming then **the optimization process can become endless** (e.g., a one 5 minute simulation duration for 100 GA generations with 100 strings at each generation, will result a computational time effort of about **35 days**)

Integration methodologies

- Hybrid modeling: Simulation - Data Driven modeling – Heuristic Optimization (Lately)

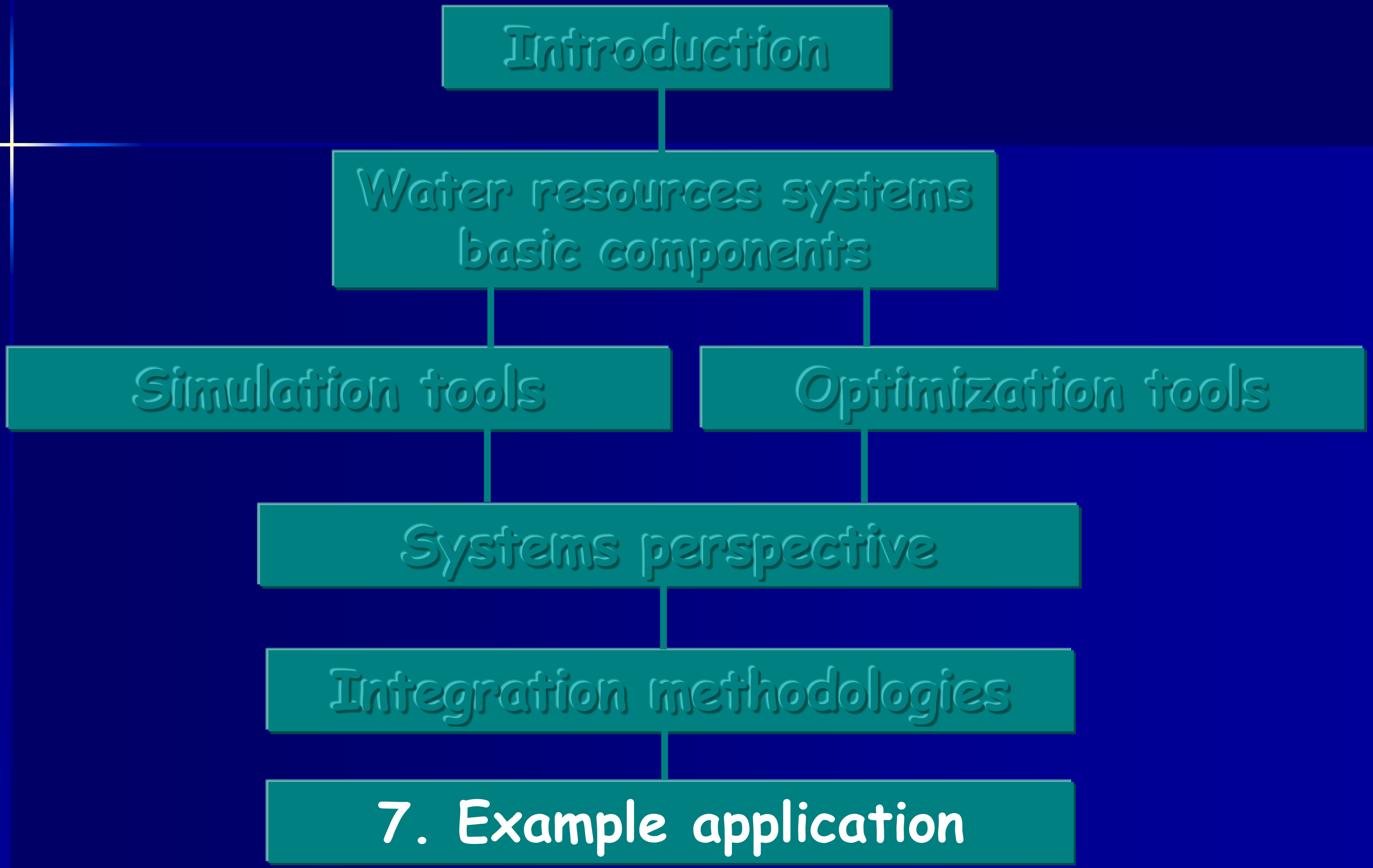
Optimization [NLP (GRG), **Heuristic (GA)**]

Decision variables values

Simulation results

Simplified Simulation + **Data Driven Modeling**

Outline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A Hybrid Model Tree (MT) – Genetic Algorithm (GA) Scheme for Toxic Cyanobacteria Predictions in Lake Kinneret

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[2] Lake Kinneret Watershed Unit, Mekorot, Israel National Water Company, Israel

Introduction

- This work presents **a hybrid model tree (MT) - genetic algorithm (GA) scheme for toxic Cyanobacteria (Blue Algae) predictions** in Lake Kinneret (Sea of Galilee), which is the most important surface water resource in Israel
- For **more than 30 years, up to 1994,** there have been no major problems with respect to the water quality of the lake
- In 1994 **toxic Cyanobacteria (blue algae)** blooms appeared, which suggests that the future water quality of the lake might be at risk

Introduction

- A **full physical understanding** of the reasons for the toxic Cyanobacteria blooms **is lacking**
- This study suggests **a data driven modeling approach**, relying on the vast existing data base of the lake, to explore the **possible major factors** causing the toxic Cyanobacteria to bloom, and **to predict** their possible appearance
- The suggested model is **a hybrid model-trees (MT) genetic algorithm (GA) scheme**
- A few words about **Lake Kinneret, model-trees (MT), and genetic algorithms (GA's) ---**

Lake Kinneret

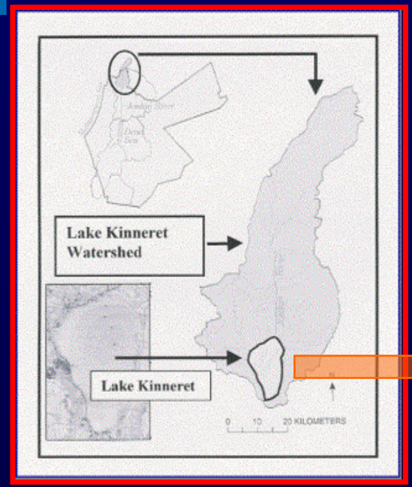
Lake Kinneret – the Sea of Galilee

32:50N, 35:35E; -209 m above sea level.

A warm, monomictic lake, located at the northern end of the Afro. Syrian Rift Valley in Northern Israel.

PHYSICAL DIMENSIONS

Surface area - 170 km^2
Volume - 4 km^3 (4000 MCM)
Maximum depth - 43 m
Mean depth - 25.6 m
Length of shoreline – 53 km
Residence time - 4.8 yr
Catchment area - 2,730 km^2



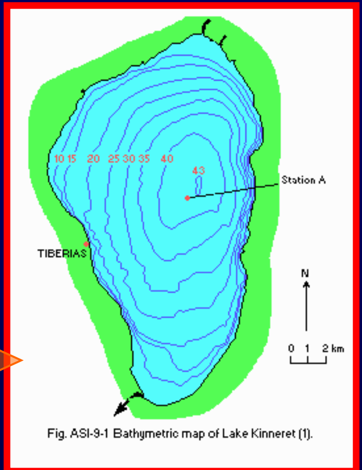
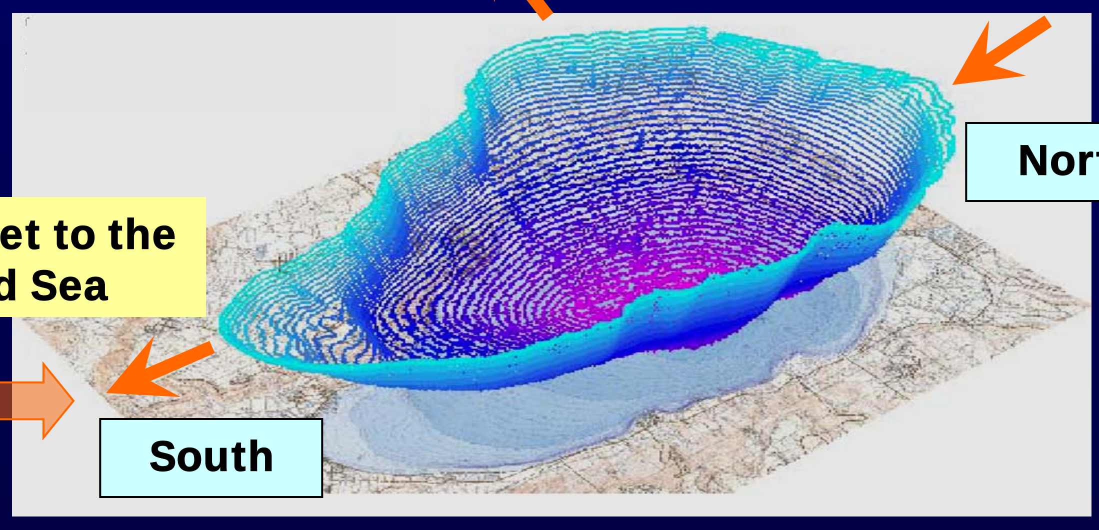


Fig. ASI-9-1 Bathymetric map of Lake Kinneret (1).

Lake Kinneret

3D Bathymetry illustration of Lake Kinneret

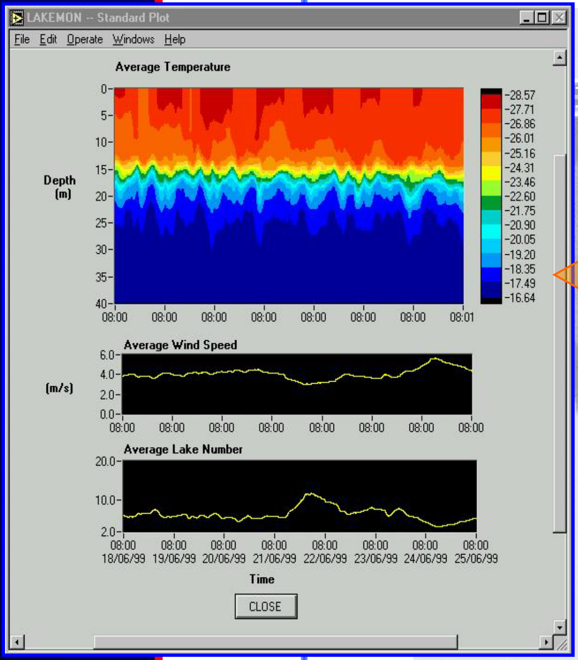
[KLL report (2001)]

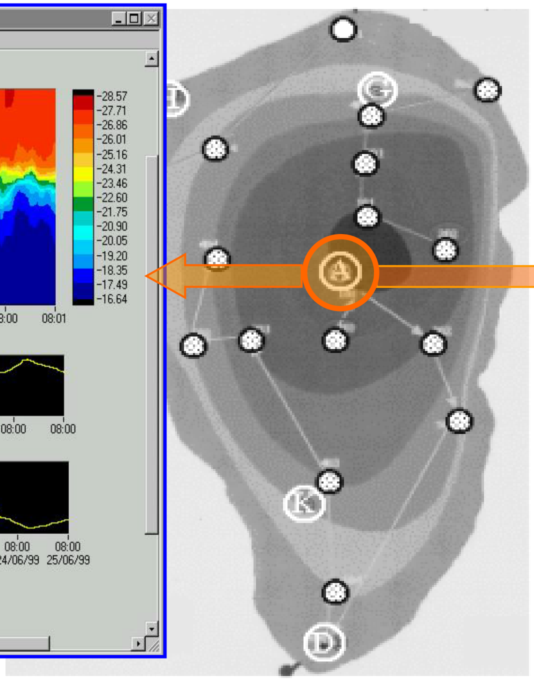


The largest natural fresh surface water in Israel providing approximately 35% of its annual drinking water, a proportion that is constantly increasing.

Monitored Data

LDS- Wind recorder, Short & long-wave radiation, air temp, thermister chain & radio antenna installed at sta. A sends real-time data to KLL





Legend

- Mekorot beginning of month moni[…]
- Mekorot **mid** month monitoring campaign stations
- (K) KLL monitoring station K

Methodology

Input (Database)

1. Physical
2. Chemical
3. Biological
4. External loading

- Each of the parameters is measured on a **fortnight basis**

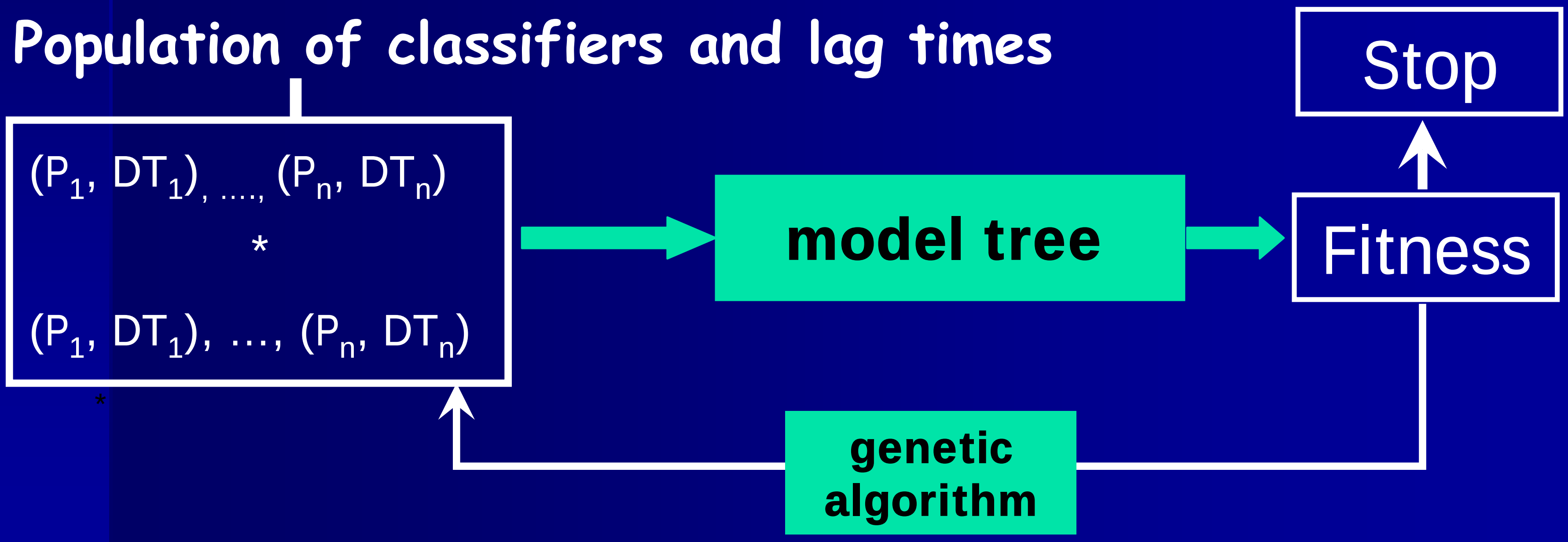
- **what classifiers** should be chosen so as to **maximize** the model **prediction** ability ?

- the **model trees** are **predicting;** the **GA** searches the **best classifiers**

north through the Jordan River (e.g., Nitrate, Nitrogen, Phosphorus, etc.)

Methodology

An **iterative scheme** for searching the **optimal set of classifiers** and their corresponding lag times which **maximizes the model prediction ability** for a given database component



Methodology

DATABASE

Physical	Chemical	Biological	External loading
1… n_1	1… n_2	1… n_3	1… n_4

Stage A. INITIALIZATION

* Choose randomly a predefined number of parameters from the database (e.g., one parameter from each database group OR any four parameters).
* Choose randomly a time lag for each of the chosen parameters (e.g., three weeks).
* *Repeat* until a set of parameters and corresponding time lags are selected (i.e., setting the first GA population).

Stage B. MODEL TREE (MT) CONSTRUCTION

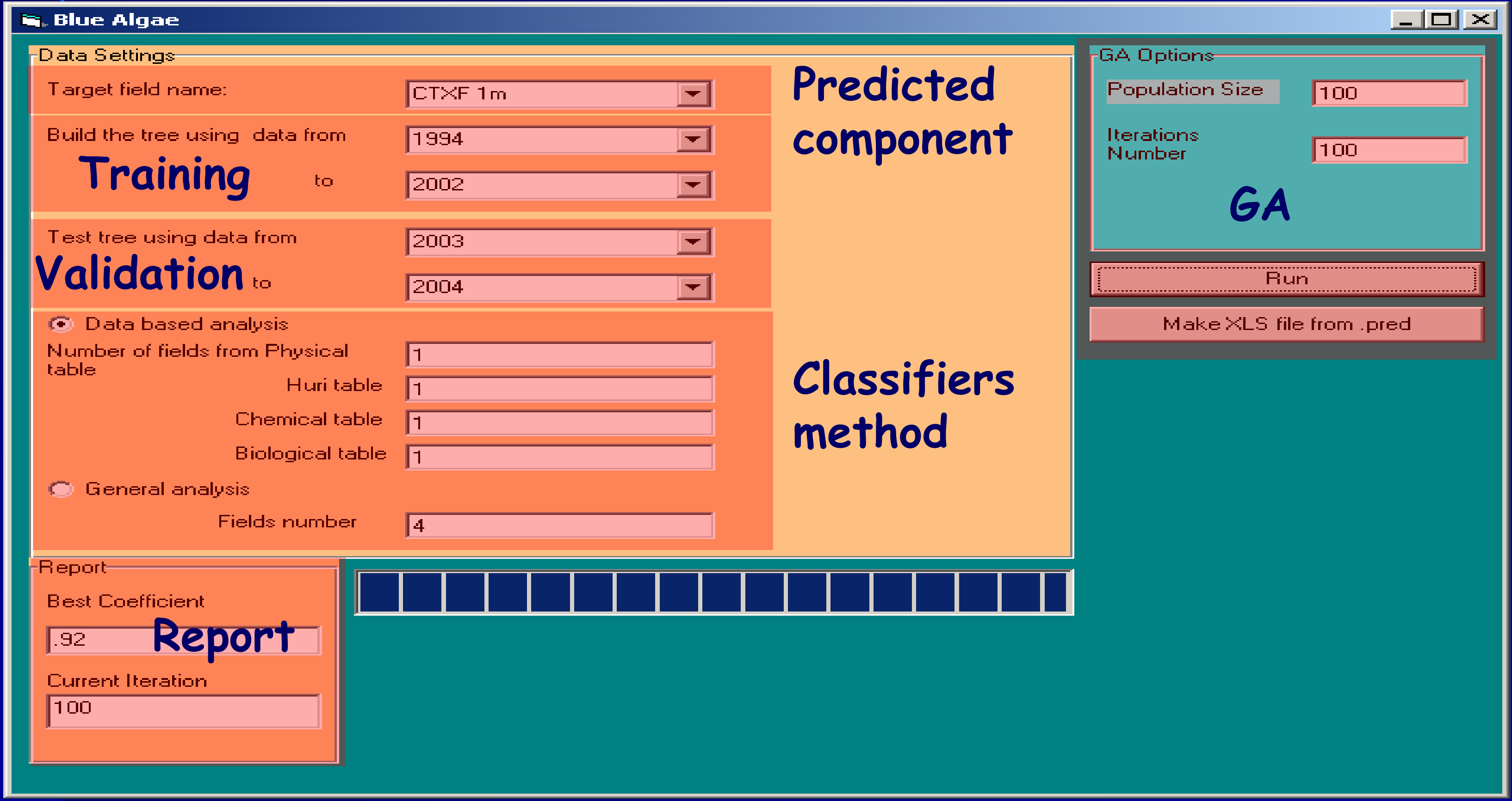
* Build a model tree for each of the selected parameters and time lags (i.e., the GA strings) using Cubist (Quinlan, 1993) for predicting a chosen parameter (e.g., Toxic Nitrogen Fixing Cyanobacteria Algae).
* Assign each string a fitness equal to its correlation coefficient calculated by Cubist using a predefined cross validation dataset.

Stage C. GENETIC ALGORITHM (GA)

* Perform *Selection, Crossover, and Mutation* on the current population using optiGA (Salomons, 2002).
* Construct a new population of strings (i.e., parameters and time lags).
* *Check* if STOPPING conditions are met. If stopping conditions are met define the corresponding highest correlation coefficient string as the OPTIMAL solution (i.e., parameters and time lags), *otherwise* go back to Stage B.

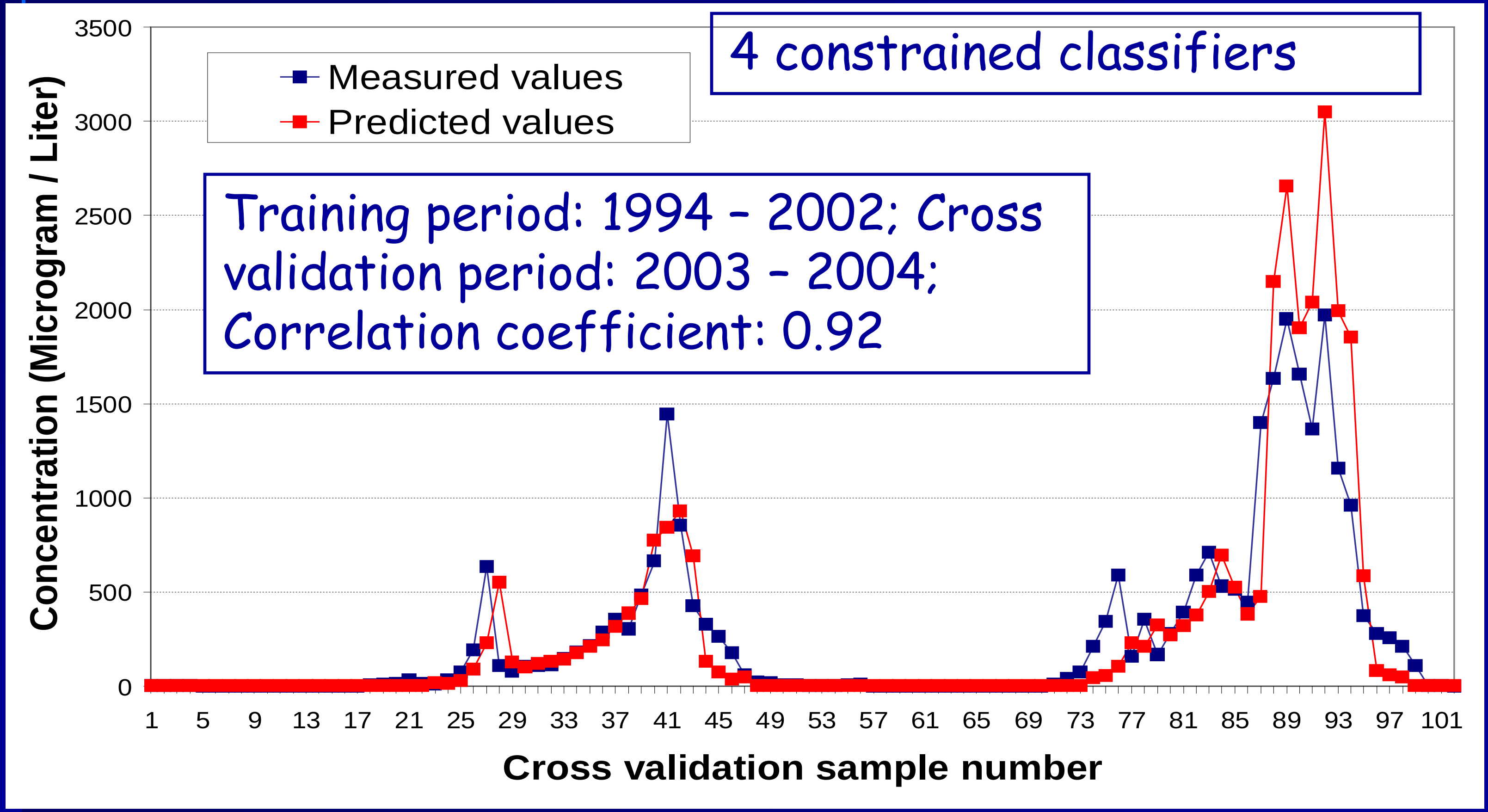
Methodology

The methodology is cast in a program entitled **KAPM (Kinneret Algae Prediction Model),** it's main interface menu is:



Application

Predicting (CTXF 1m) Toxic Nitrogen Fixing Cyanobacteria Algae blooms at station A (deepest point in the lake) at a depth of 1 m (validation results):



Application

Optimal model tree rules:

```
Rule 1:
  IF
      WTemp <= 26.55
      CTXF 5m <= 71.23
  THEN
      CTXF 1m = 3.91

                              ...
                              ...

Rule 13:
  IF
      WTemp > 26.81
      CTXF 5m > 725.00
      CTXF 5m <= 1328.42
  THEN
      CTXF 1m = -208.3 + 38 (WTemp) - 855 (NTOT 5-10) +
                + 0.38 (CTXF 5m)
Rule 14:
  IF
      NTOT (Huri) <= 1.90
      NTOT 5-10 <= 0.37
      CTXF 5m > 725.00
  THEN
      CTXF 1m = 792.54 + 0.38 (CTXF 5m)
Rule 15:
  IF
      CTXF 5m > 1328.42
  THEN
      Output = 4463.67 - 1.06 (CTXF 5m)
```

Conclusions

- The methodology and application of **a coupled model trees (MT) – genetic algorithm (GA) scheme** for predicting blue-algae blooms in Lake Kinneret **was presented and demonstrated**

- The model was able to **satisfactorily predict blue-algae blooms** using a database which incorporates physical, chemical, biological, and external loading data for the lake

- One of the possible extension options of the model is to explore the tradeoff between the model prediction ability versus the optimal correlation coefficient (i.e., fitness) using **multi-objective optimization**, assuming that these two objectives compete

Thanks!

Questions?