Integrated optimisation for reservoir operation using Genetic Algorithms
GA Aquator

Lydia Vamvakeridou-Lyroudia
Mark Morley
Josef Bicik
Dragan Savic
Godfey Walters

Chris Green
Peter Edgley
Will Clark

University of Exeter-CWS
L.S.Vamvakeridou-Lyroudia@ex.ac.uk
D.Savic@ex.ac.uk

Oxford Scientific Software
chris.green@oxscisoft.com

09/12/2008

What is this presentation about?

- AQUATOR: (OXSCISOFT)
  - Water supply system simulation software
  - In use by several UK water companies
- Genetic Algorithms: (University of Exeter-CWS)
  - Genetic Algorithms software for optimisation (generic software)
- Project: Linking AQUATOR with Genetic Algorithms, and applying them for the optimisation single reservoir systems for use by United Utilities
  - 2 Test case studies

Previous steps

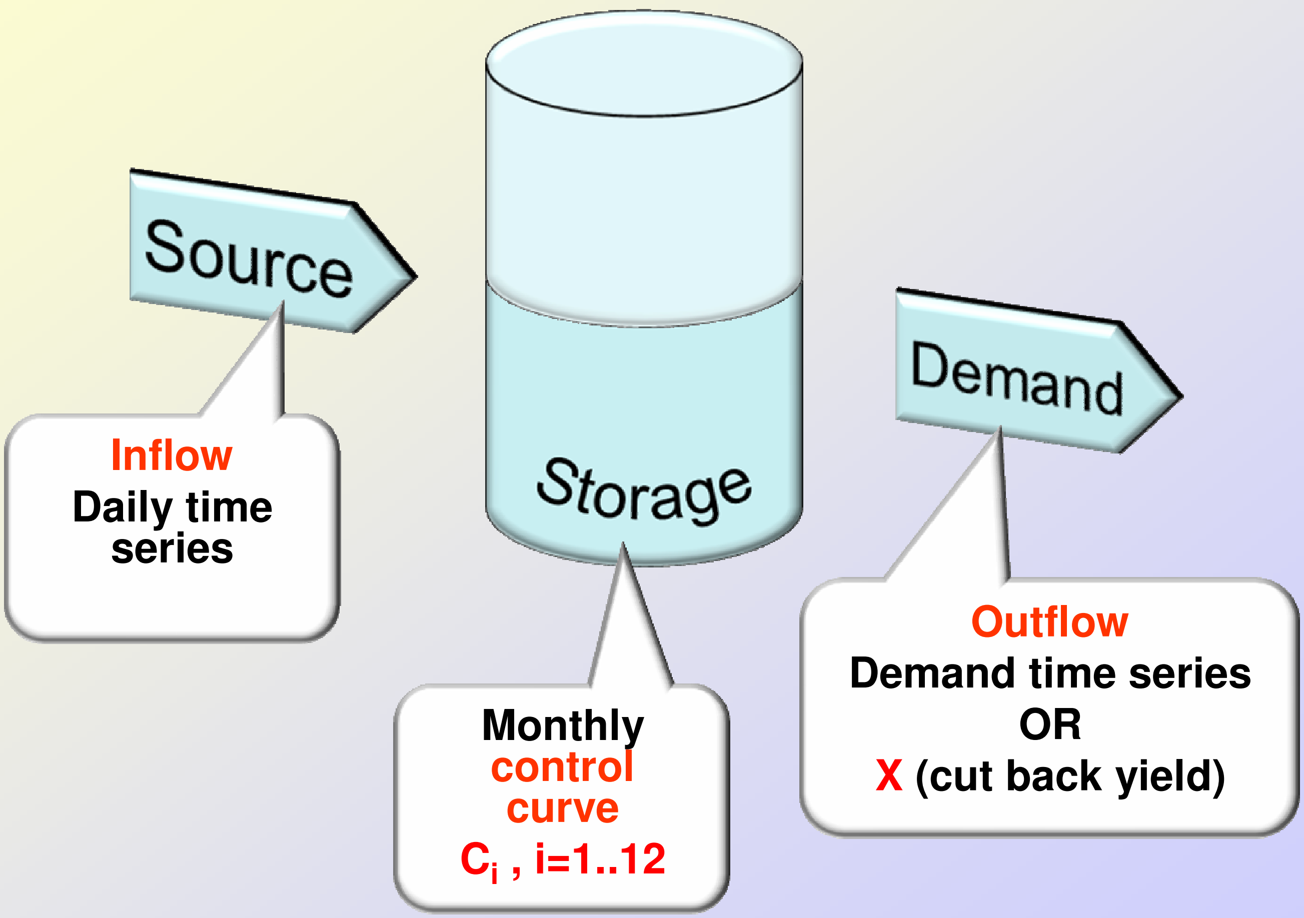
- Barnacre system (UU) :
    - ❑Test case study
- AQUATOR: (OXSCISOFT)
    - ❑ (VBA – Excel controlled)
- GANET_XL: (University of Exeter-CWS)
    - ❑Genetic Algorithm platform for optimisation (generic software – Add-in for Excel)
- Objective: Linking AQUATOR with GANET_XL , and applying them for the optimisation of Barnacre system

Outcomes

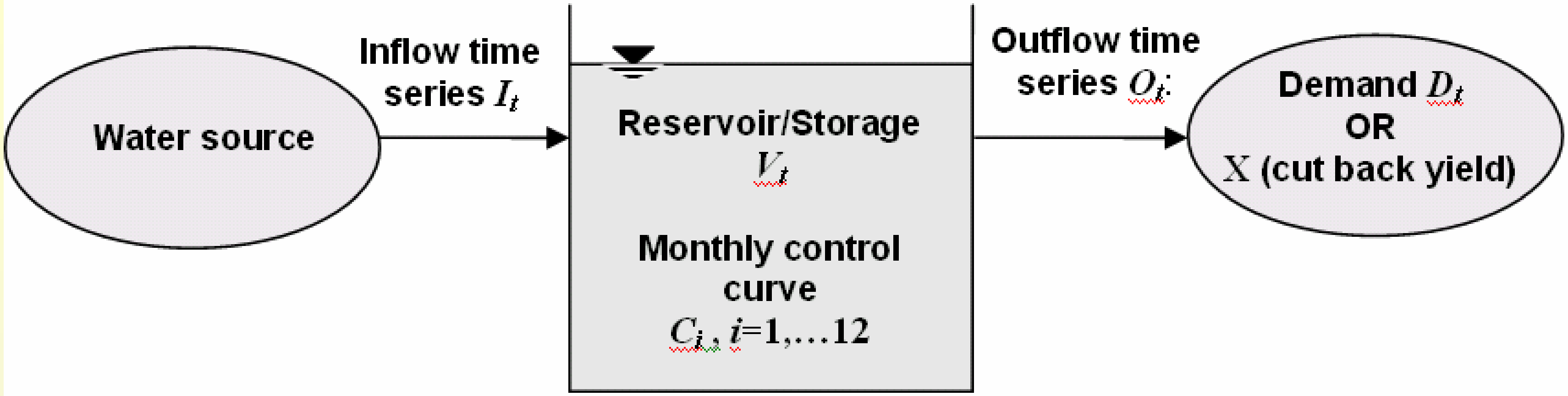
- Preliminary report
  - ❑May 2006
  - ❑Successful
- Initial Proposal
  - ❑ September 2006
- Proposal
  - ❑July 2008
  - ❑GA module integrated to AQUATOR
  - ❑ Reducing run time by applying distributed computing
  - ❑2 case studies (Barnacre System and Watergrove & Springmill)

Centre for Water Systems

Single reservoir system



Single reservoir system

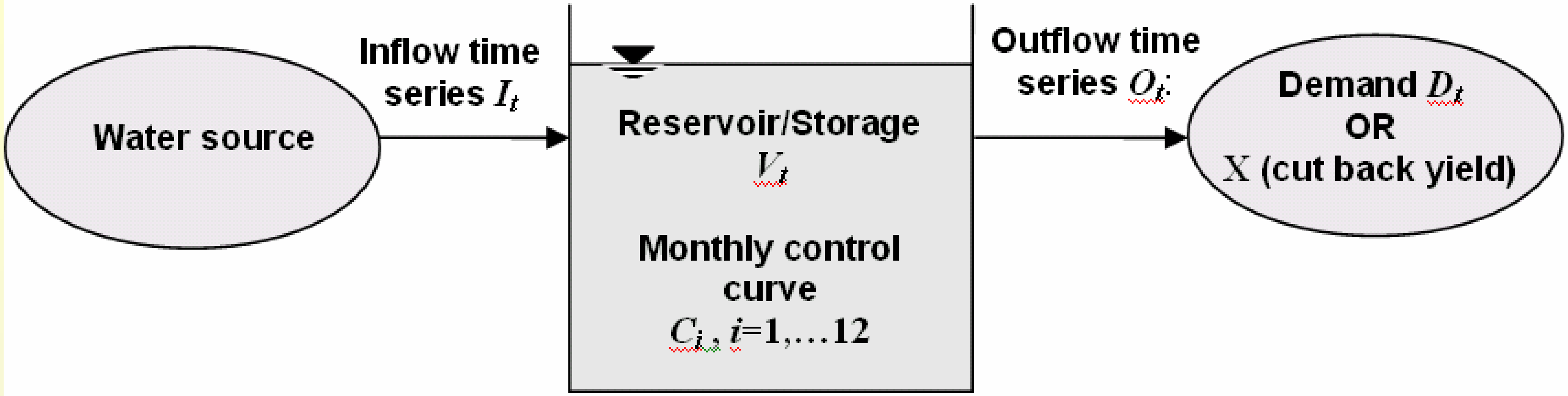


$$V_t = V_{t-1} + I_t - O_t \qquad \forall t, \quad t = 1,\ldots n$$

$$V_{\min} \le V_t \le V_{\max}$$

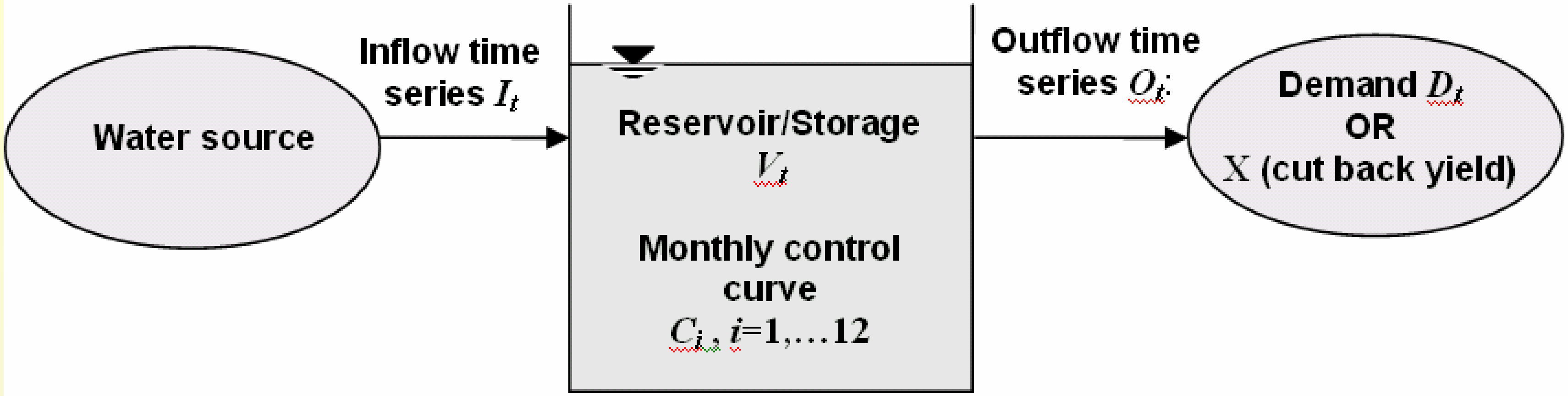
$$C_{\min}(\%) = \frac{V_{\min}}{V_{\max}} \times 100 \qquad C_{\max} = 100\%$$

Single reservoir system



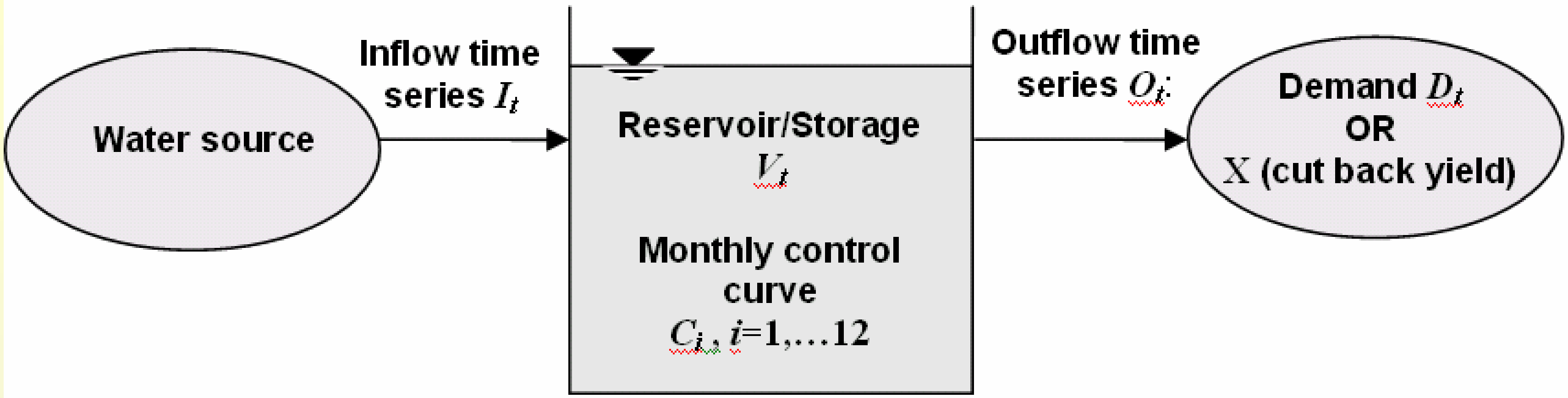
$$\text{Water demand } W_t \qquad W_t = \begin{cases} D_t & if \quad \dfrac{V_t}{V_{\max}} \times 100 \geq C_i \\ X & if \quad \dfrac{V_t}{V_{\max}} \times 100 < C_i \end{cases} \qquad \forall t, \quad t = 1, \ldots n$$

Single reservoir system



- If V_t<Vmin → O_t < Water demand W_t → ***Failure*** + ***Water deficit***
- If Vt<Vmax → Spill→***Failure…***
- Water companies apply deterministic approach, based on historic (existing) input and demand data series

Single reservoir system



- Previous approach by Water Companies (2 steps)
  - Parameter X defined initially, by trials, as the max value with Ci=100% for all months, with no failures
  - Then (endless) trial-and-error manual computations (EXCEL) to estimate proper values for each Ci (12 values) or (using a DP algorithm, in some cases)

Genetic Algorithms (GA)

- Optimisation method suitable
  - For "hard" problems (non-linear/discrete/non convex)
  - For "difficult" decision variables
  - For "strange" constraints
  - For discrete search space/variables
  - For one (single) or more (multi-) objective problems
  - Directed random search
- Based on Darwinian evolution principles ("Survival of the fittest")
- Solutions can be reproduced (repeatable)

Single objective GA

- Decision variables (unknowns): (Multiple control curves now possible)
    - ➢X (cutback yield)
    - ➢Ci, i=1,12 (monthly control curve components)
- Total: 13 unknowns = string of 13 decision variables for 1 control curve
- 13*2=26 unknowns = string of 26 decision variables for 2 control curves, …3*13=39 for 3 control curves….
- Objective function: max V (Yield/total volume)
- Shape Constraints for the control curve: No supply deficits (SD=0) / failures (NF=0), limits to the number of changes in a year/magnitude of change… ←NEW

Shape constraints (GA)

- Magnitude of change in consecutive months → *DC*

$$dc_i = \begin{cases} \left|C_i - C_{i-1}\right| & for \quad i = 2, \ldots 12 \\ \left|C_i - C_{12}\right| & for \quad i = 1 \end{cases}$$

$$DC = \max\left\{dc_i, i = 1, \ldots 12\right\}$$

- Number of changes in a year> significant *step* → *NC*

$$nc_i = \begin{cases} 1 & if \quad dc_i \geq step \\ 0 & if \quad dc_i < step \end{cases}$$

$$NC = \sum_{i=1}^{12} nc_i$$

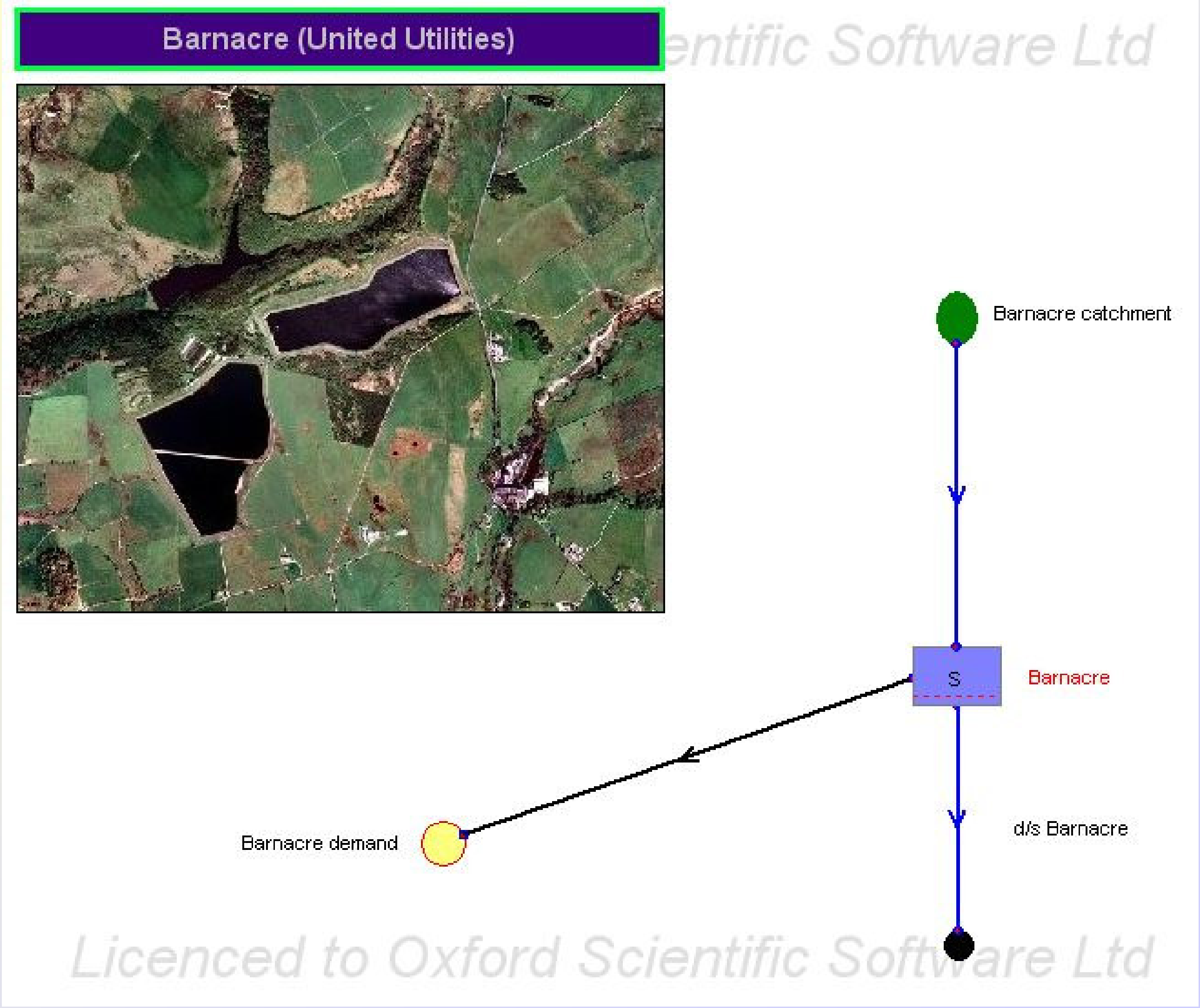
- These two shape parameters introduced as secondary Objective functions for the GA

Multi-objective GA

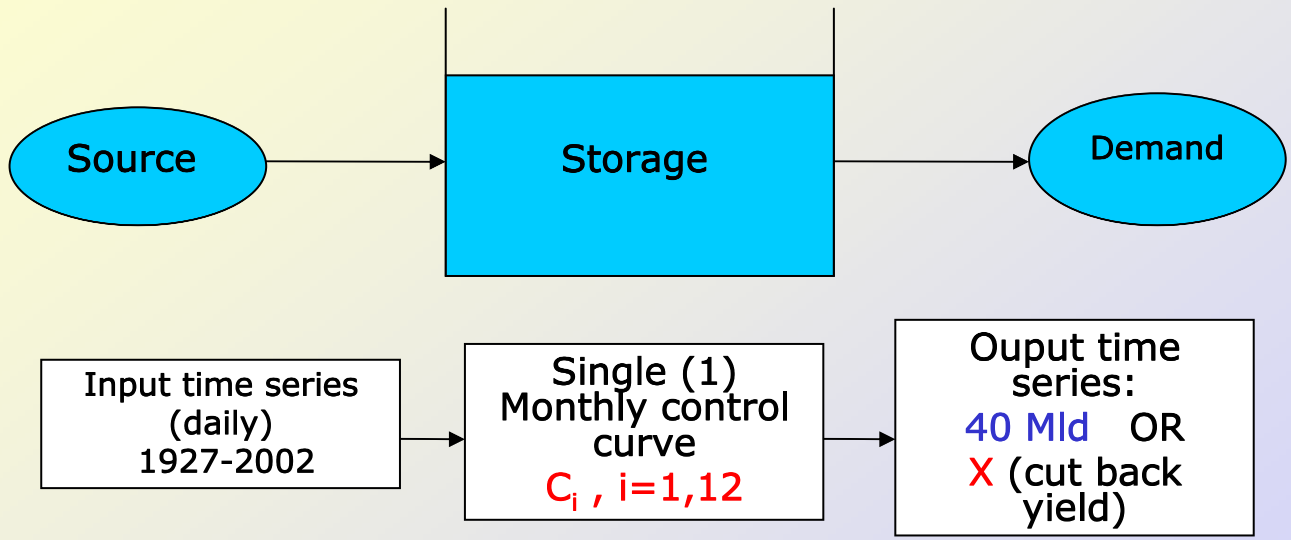
- Objective function (1): max V (Yield/total volume)
  - AND
- Objective function (2): min NC (number of changes in the control curve in a year)
  - AND/OR
- Objective function (3): min DC (magnitude of changes in the control curve for consecutive months)
- Constraints: No supply deficits (SD=0) / failures (NF=0), limits to the number of changes in a year, control curve discretisation step… (any other)

- Trade-off curve of non-inferior solutions (Pareto points)

Case study 1: Barnacre system

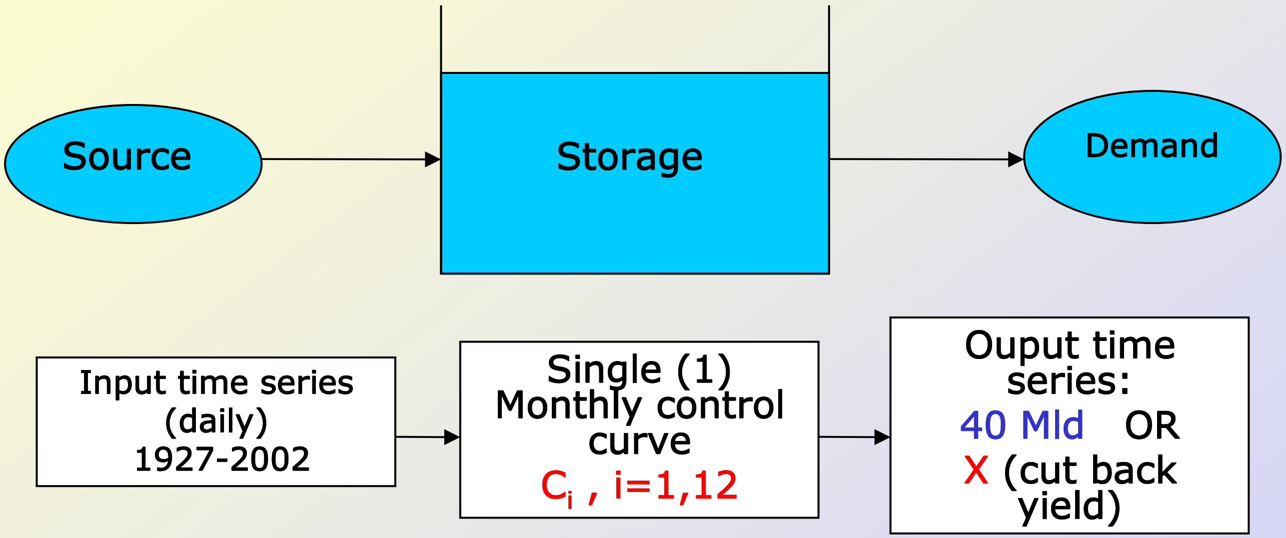


Barnacre system test problem



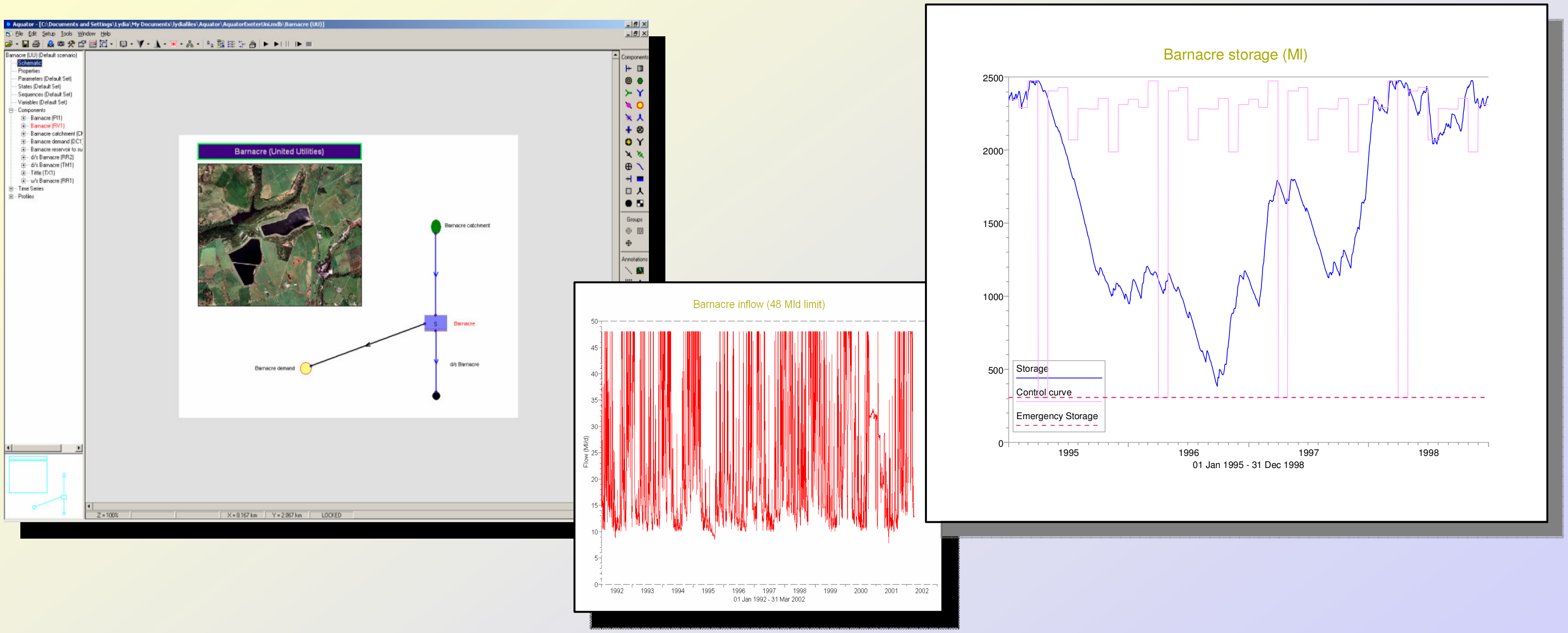
- Single reservoir
- No energy costs taken into account (gravity fed)
- Target: Maximising yield (water volume) AND
- No deficits/No spills → No failures
- Decision variables (Unknowns): X and C_i, i=1,12
- Initial optimal solution given by UU for comparison/testing

Barnacre system test problem



- Control curve (monthly) C_i , i=1,12
- Ci % of max water volume (reservoir capacity)
- If storage > Ci → Outflow= 40 Mld
- If storage < Ci → Outflow= X (cutback yield)
- If storage < minimum → deficit (To be avoided)

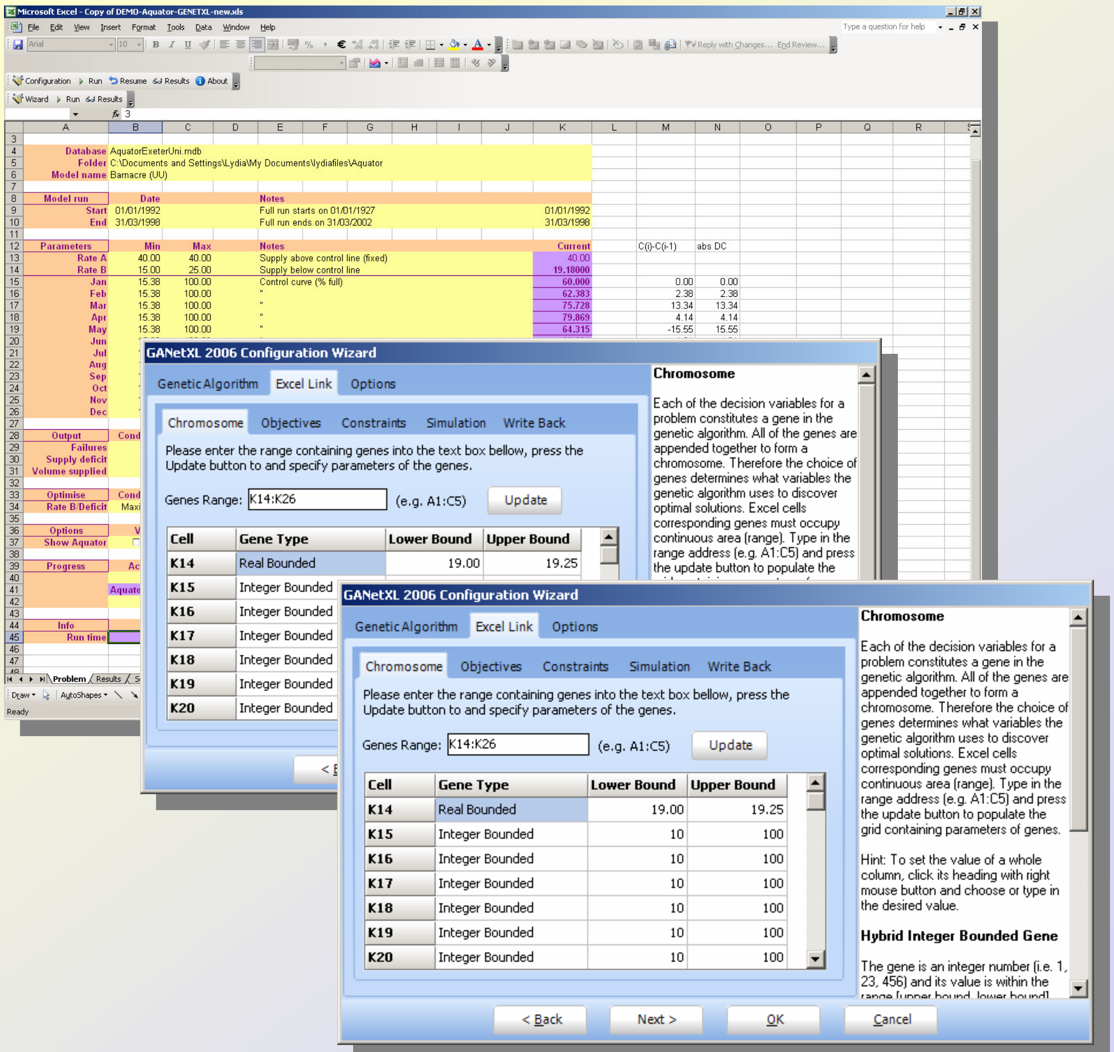
AQUATOR+BARNACRE



- AQUATOR:Water supply system simulation software (VBA – Excel controlled)
- Barnacre system loaded at AQUATOR
- Simulation results successful for 1927-2002

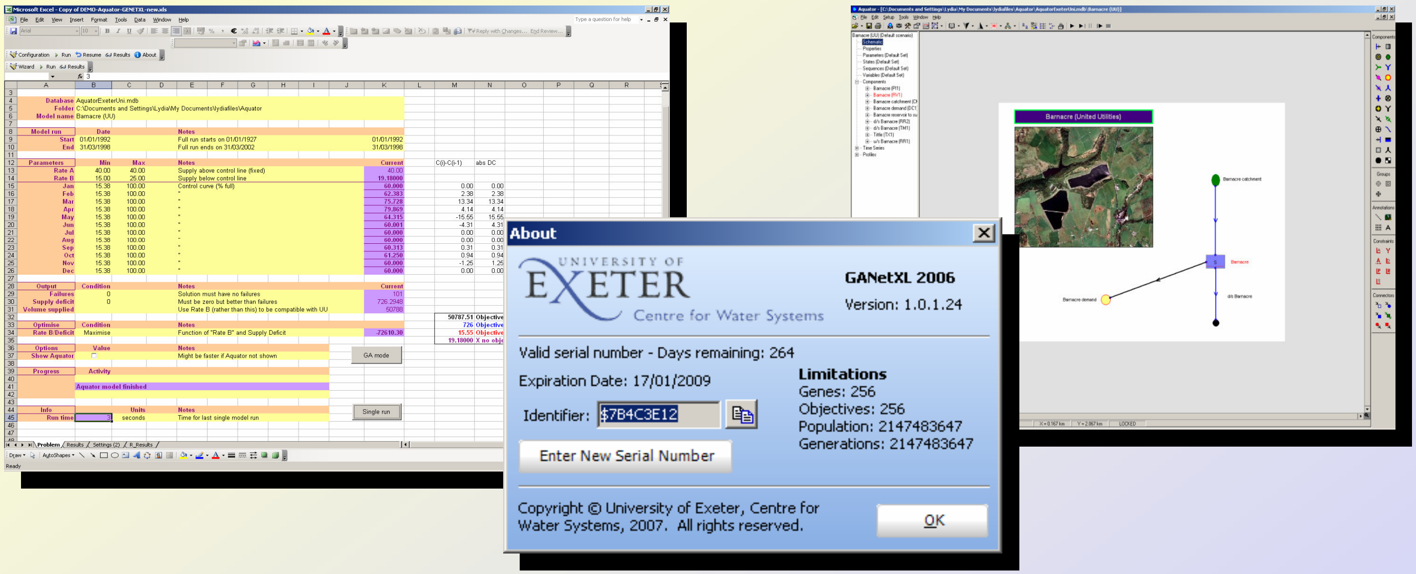
UNIVERSITY OF EXETER
Centre for Water Systems

GANET-XL



- •Generic platform for optimisation with Genetic Algorithms
- •Performing single objective and multiobjective optimisation
- •Add-in for Excel: (VBA – Excel controlled)
- •Dialog box
- •On screen running

AQUATOR+GANET_XL+Barnacre



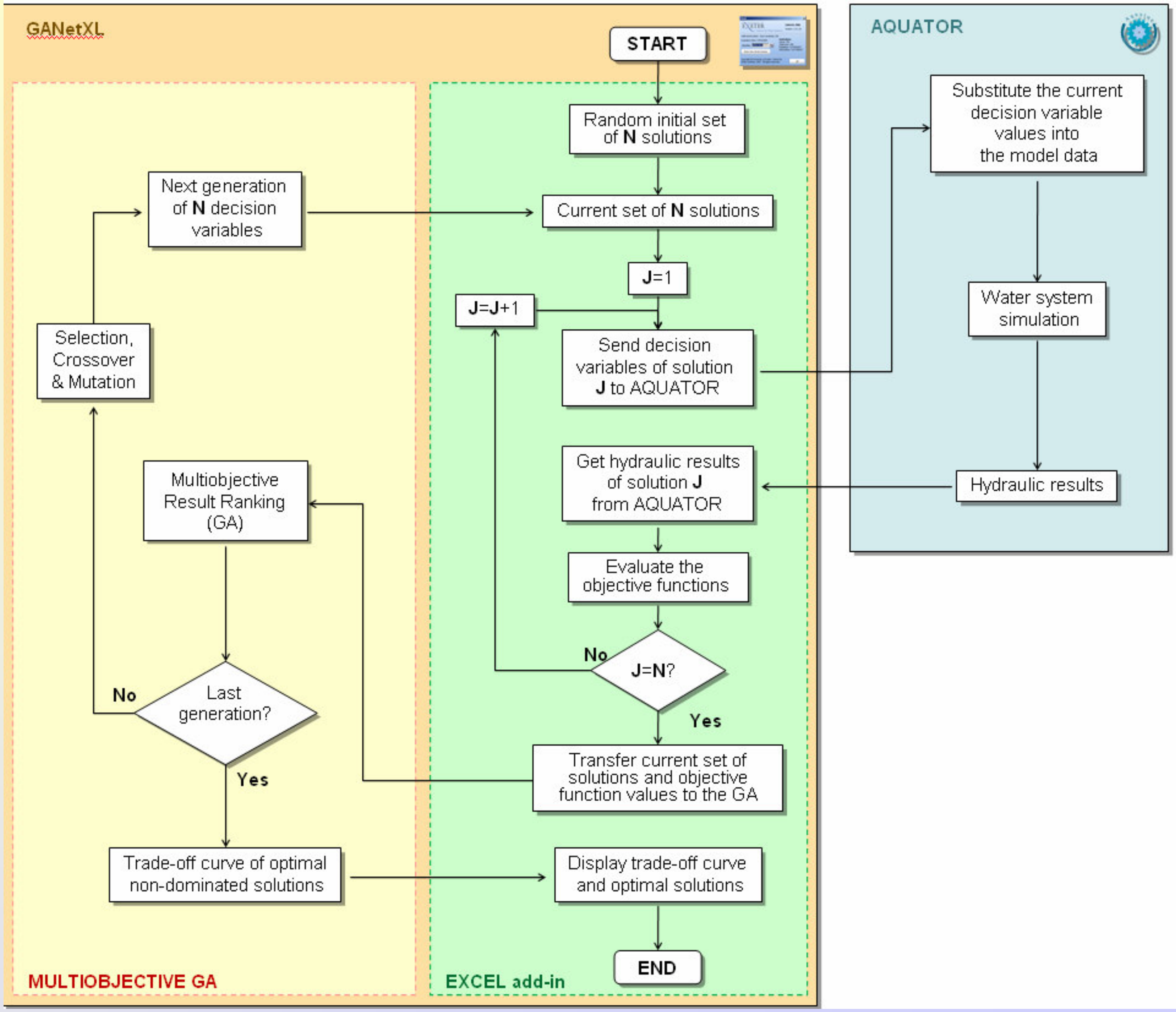
- AQUATOR: Additional/special control spreadsheet/macros prepared so as to "communicate" with GANET_XL. Successfully combined

- Applied for Barnacre system for optimisation

- For the critical period 1992-1998 to reduce the simulation run time (and checking for all)

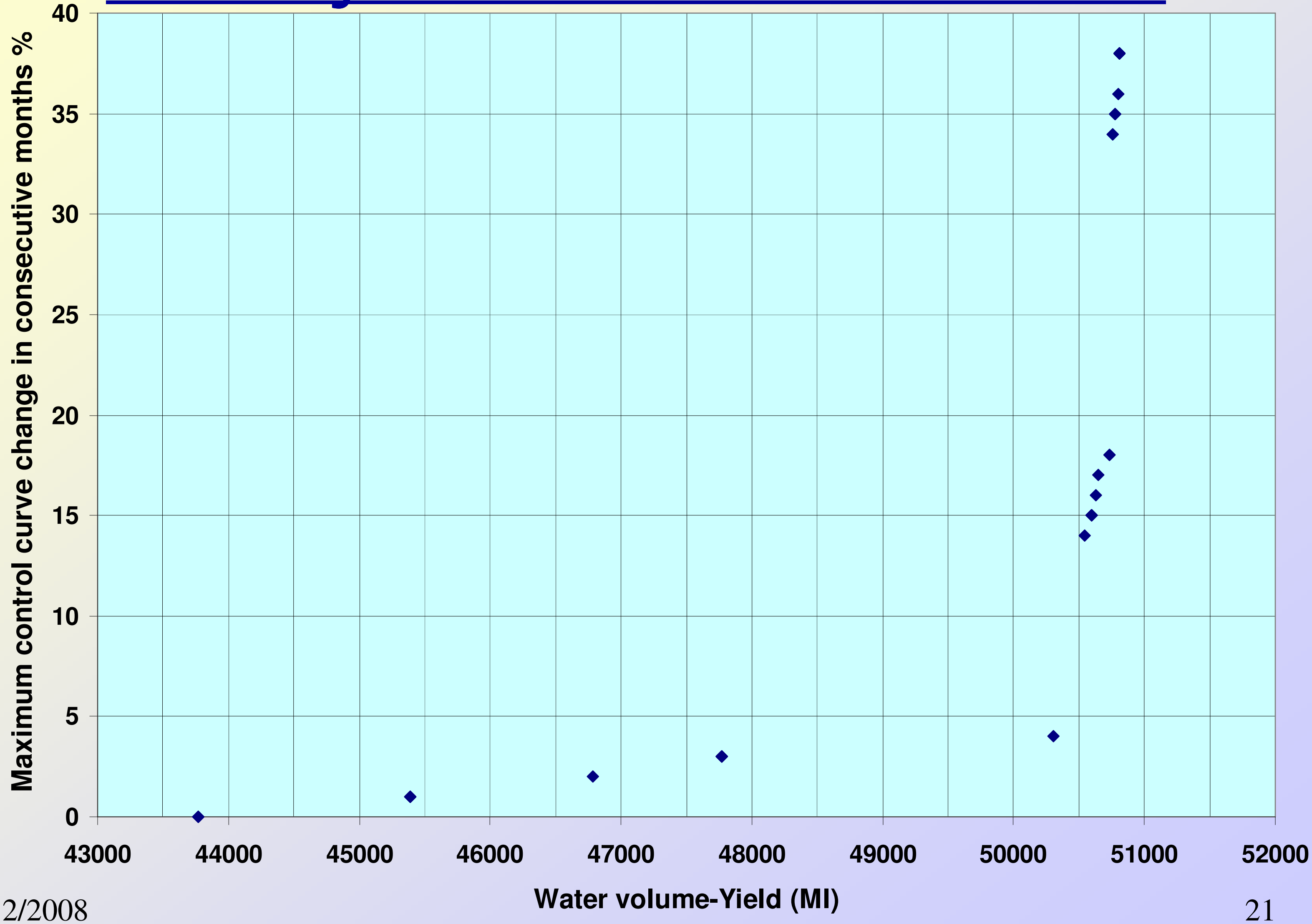
- Successful results (…)

Structure



GANetXL
START
Random initial set of N solutions
Current set of N solutions
J=1
J=J+1
Send decision variables of solution J to AQUATOR
Get hydraulic results of solution J from AQUATOR
Evaluate the objective functions
J=N?
No
Yes
Transfer current set of solutions and objective function values to the GA
Display trade-off curve and optimal solutions
END
EXCEL add-in
Next generation of N decision variables
Selection, Crossover & Mutation
Multiobjective Result Ranking (GA)
Last generation?
No
Yes
Trade-off curve of optimal non-dominated solutions
MULTIOBJECTIVE GA
AQUATOR
Substitute the current decision variable values into the model data
Water system simulation
Hydraulic results

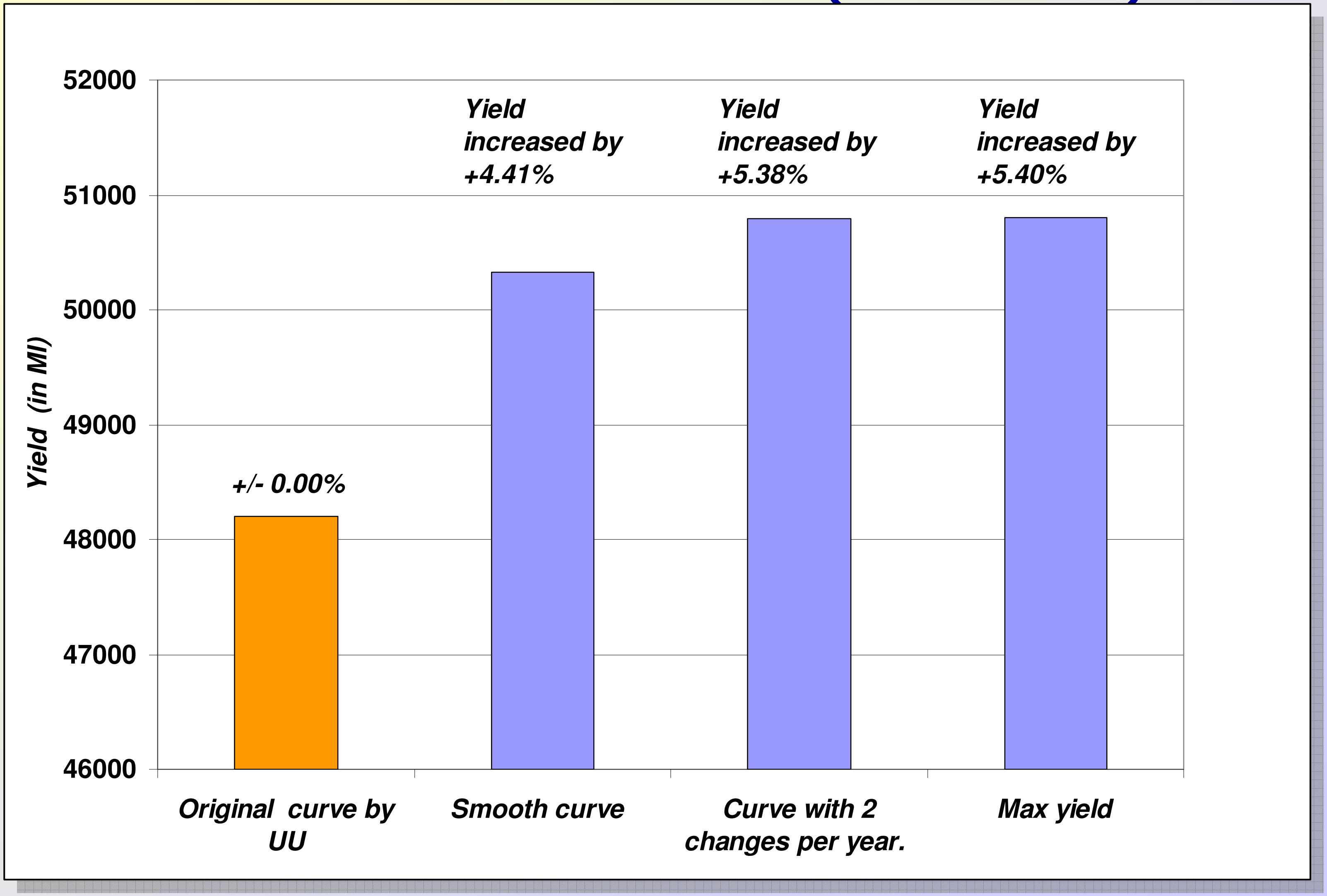
Multiobjective GA-Trade-off curve



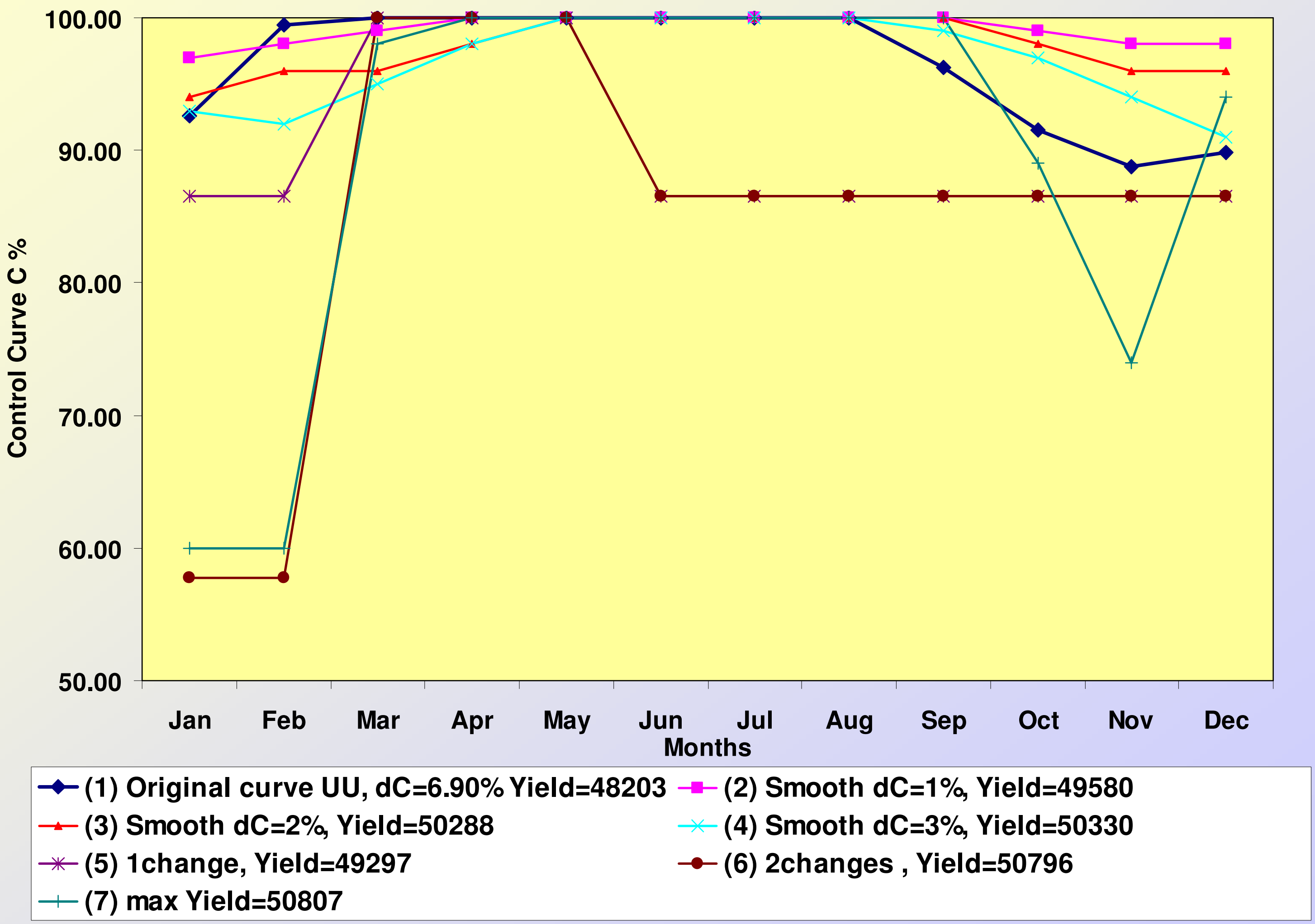
Selected Solutions for Barnacre

1992-1998	Original UU	Smooth curve	Smooth curve	Smooth curve	Min changes	Min changes	Max yield
max dC%	6.90	1.00	2.00	3.00	1 change 13.45	2changes 42.28	38.00
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Rate A	40.00	40.00	40.00	40.00	40.00	40.00	40.00
Rate B=X	19.1800	19.12898	19.03226	19.00012	19.18536	19.18536	19.12691
Jan	92.60	97.00	94.00	93.00	86.55	57.72	60.00
Feb	99.50	98.00	96.00	92.00	86.55	57.72	60.00
Mar	100.00	99.00	96.00	95.00	100.00	100.00	98.00
Apr	100.00	100.00	98.00	98.00	100.00	100.00	100.00
May	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Jun	100.00	100.00	100.00	100.00	86.55	86.55	100.00
Jul	100.00	100.00	100.00	100.00	86.55	86.55	100.00
Aug	100.00	100.00	100.00	100.00	86.55	86.55	100.00
Sep	96.30	100.00	100.00	99.00	86.55	86.55	100.00
Oct	91.50	99.00	98.00	97.00	86.55	86.55	89.00
Nov	88.80	98.00	96.00	94.00	86.55	86.55	74.00
Dec	89.80	98.00	96.00	91.00	86.55	86.55	94.00
Failures	0	0	0	0	0	0	0
Deficit	0	0	0	0	0	0	0
Volume	48203	49580	50288	50330	49297	50796	50807
Volume increase %	0.00	2.86	4.32	4.41	2.27	5.38	5.40

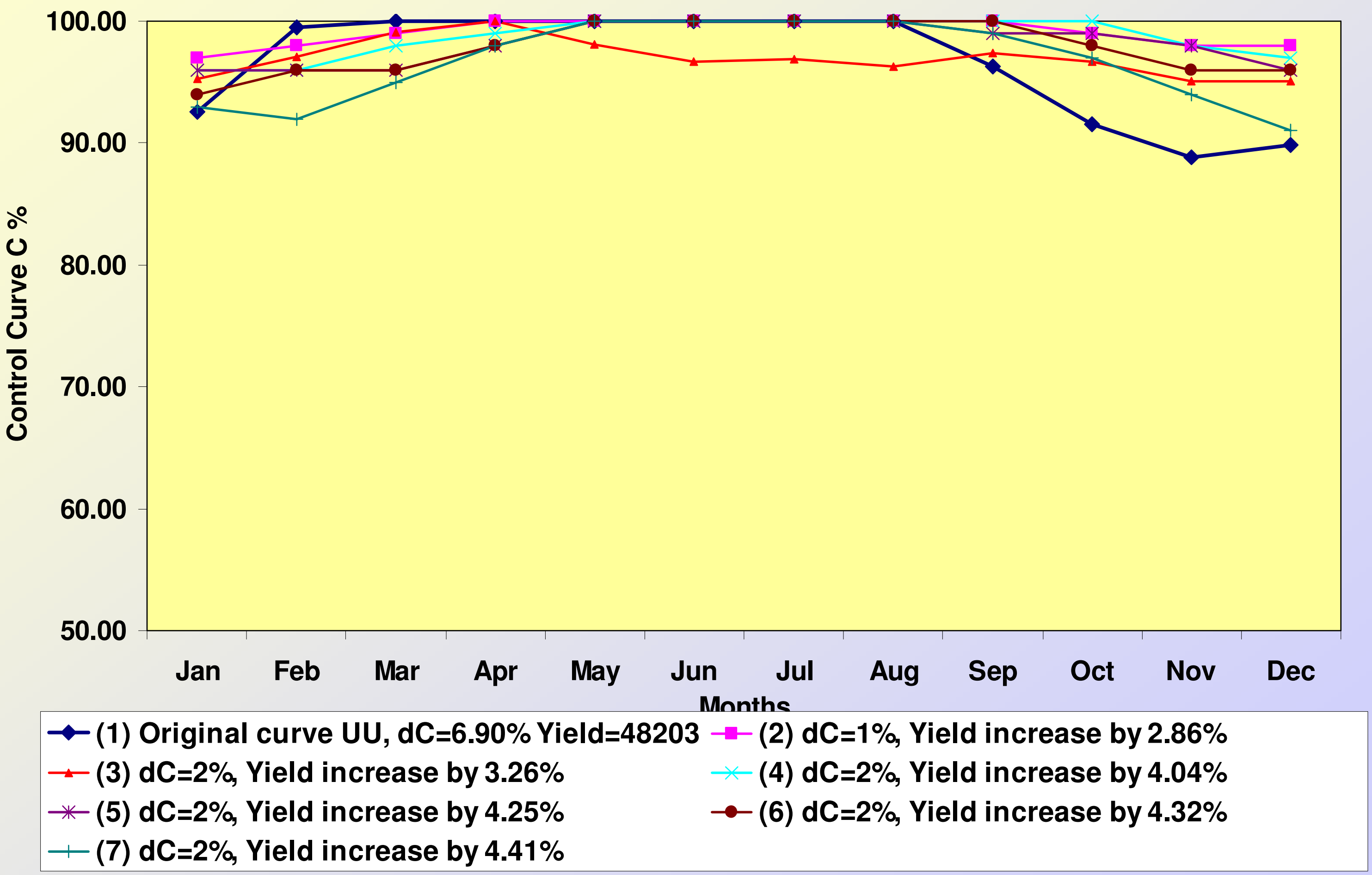
Different control curves (Barnacre)



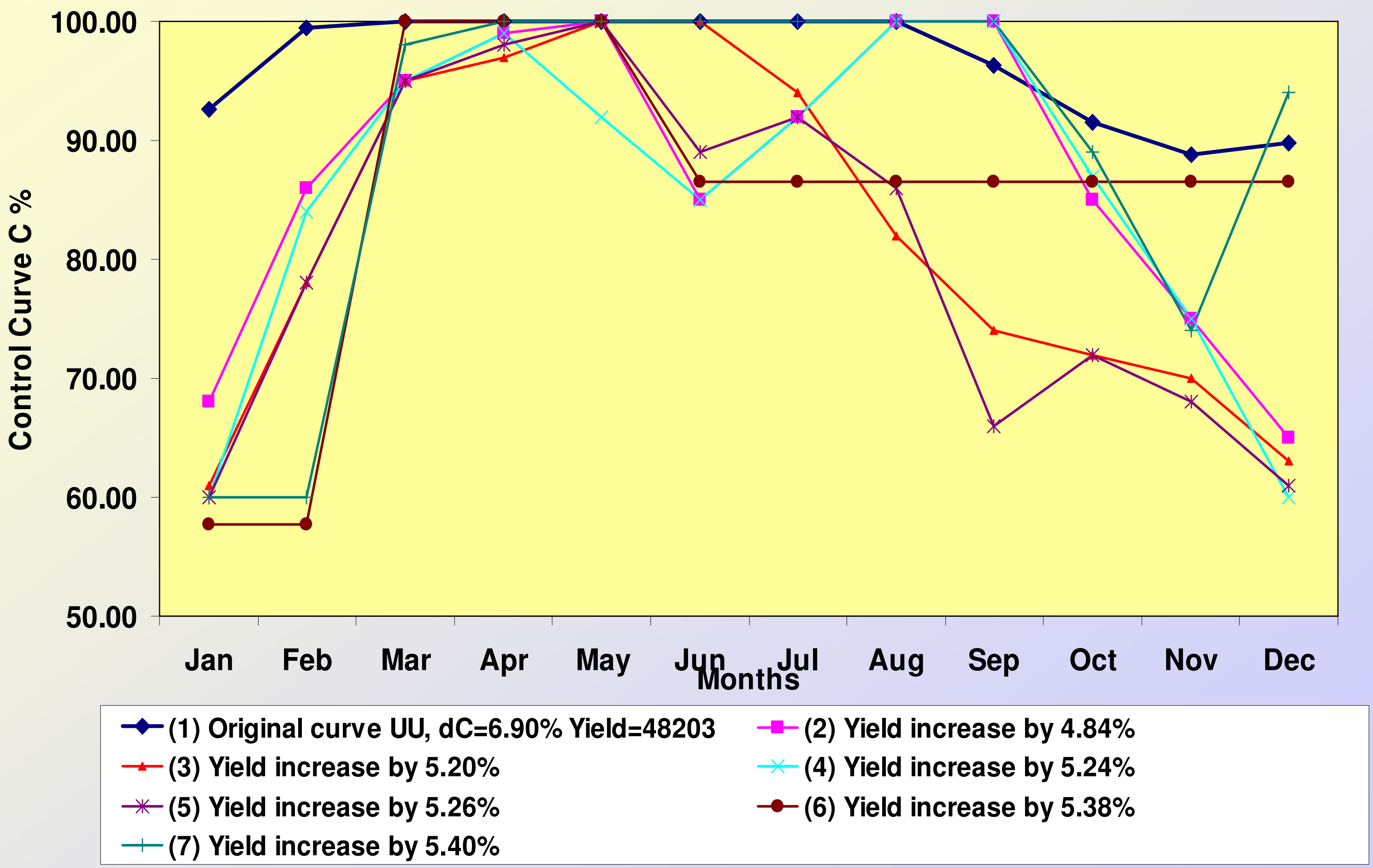
Different control curves (Barnacre)



Smooth control curves (2) (Barnacre)



Increased yield (3) (Barnacre)



AQUATOR+GANET_XL outcomes…

Advantages:

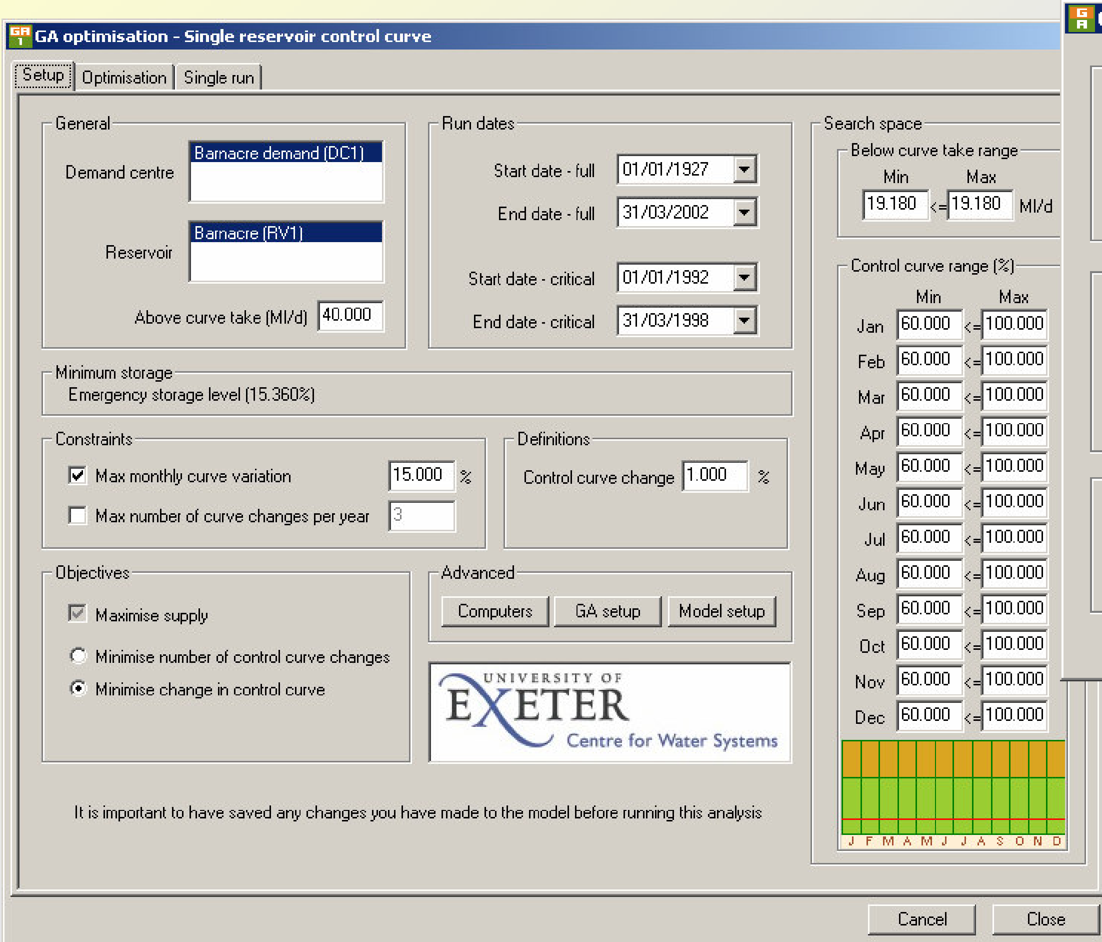
- AQUATOR and GANET_XL can be combined and integrated
- It can improve results (volume and "smoothness" of the curve)
- Optimisation in one step (X and Ci simultaneously), even for complex systems with multiple reservoirs
- Any other objective/constraint can be added
- Convinced UU to proceed…

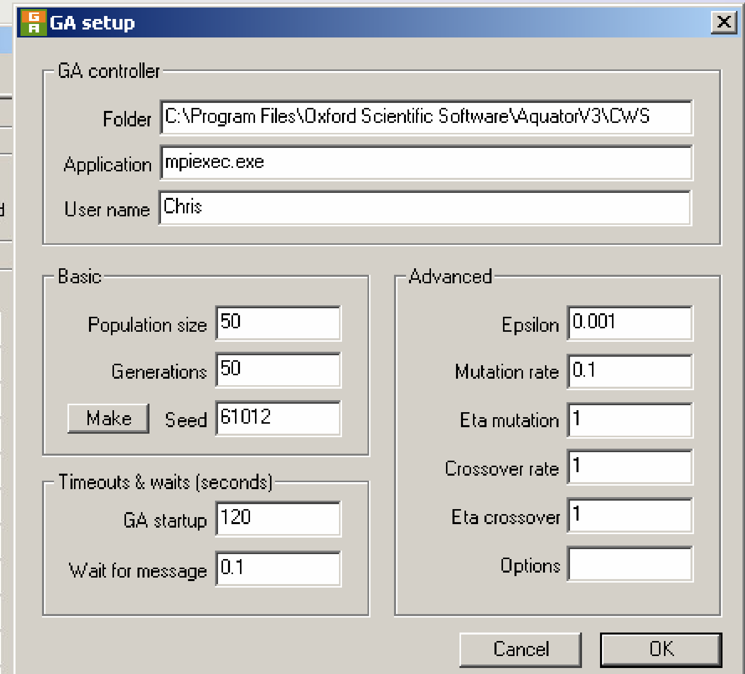
Problem:

- Time needed (thousands of generations/AQUATOR simulations) → distribution to computers in parallel →NEXT!
- Shortening the time by critical period concept and other techniques …

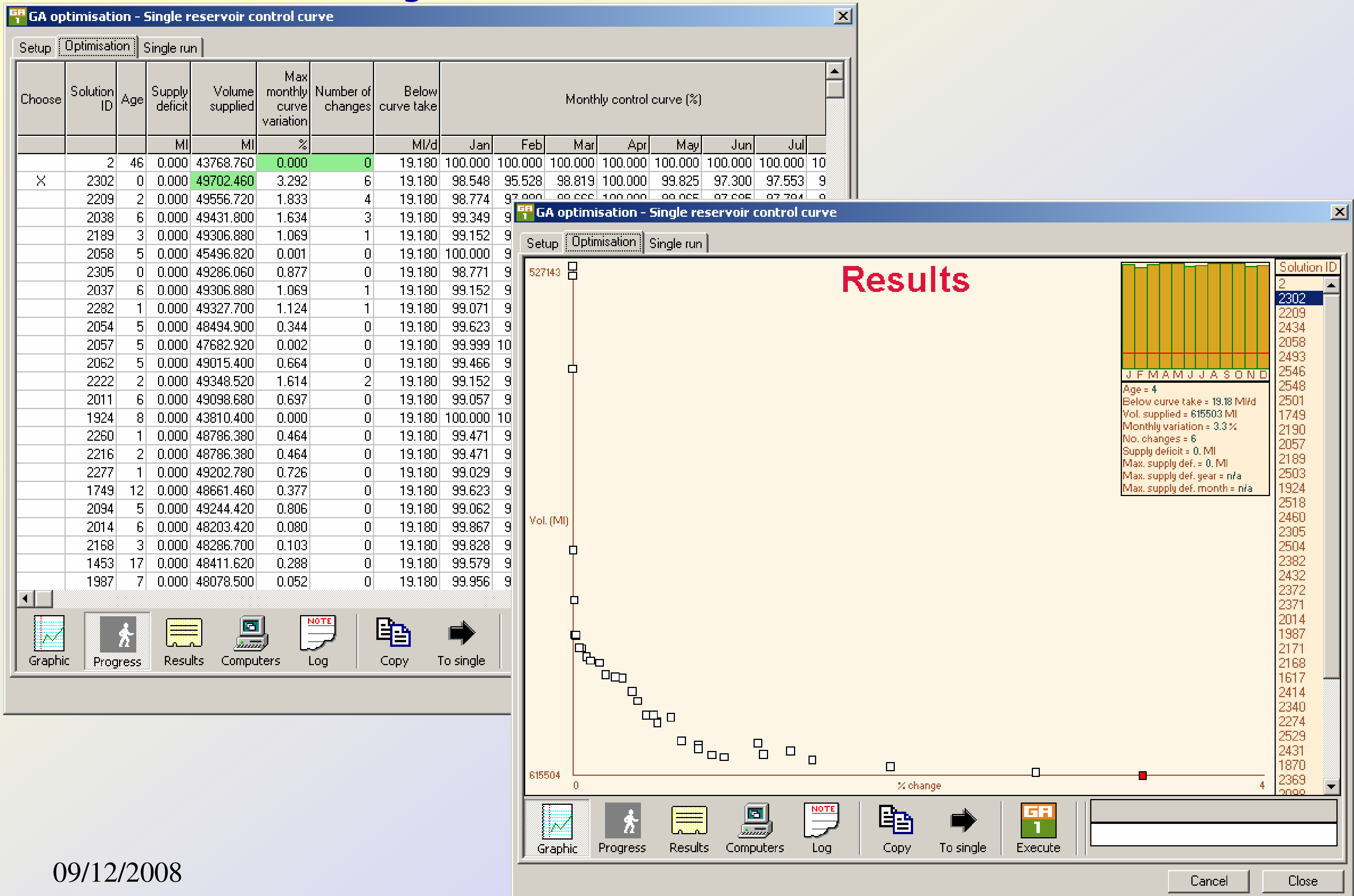
Next step: GA-Aquator: Integration

- GA Optimisation developed as add-in to AQUATOR
- Activated through AQUATOR (GA-Aquator)
- Optimisation set up by the user (menus in AQUATOR)





Multiobjective GA-Trade-off curve



GA optimisation - Single reservoir control curve

Setup | Optimisation | Single run

Choose	Solution ID	Age	Supply deficit	Volume supplied	Max monthly curve variation	Number of changes	Below curve take	Monthly control curve (%)							
			Ml	Ml	%		Ml/d	Jan	Feb	Mar	Apr	May	Jun	Jul	
	2	46	0.000	43768.760	0.000	0	19.180	100.000	100.000	100.000	100.000	100.000	100.000	100.000	10
X	2302	0	0.000	49702.460	3.292	6	19.180	98.548	95.528	98.819	100.000	99.825	97.300	97.553	9
	2209	2	0.000	49556.720	1.833	4	19.180	98.774							
	2038	6	0.000	49431.800	1.634	3	19.180	99.349	9						
	2189	3	0.000	49306.880	1.069	1	19.180	99.152	9						
	2058	5	0.000	45496.820	0.001	0	19.180	100.000	9						
	2305	0	0.000	49286.060	0.877	0	19.180	98.771	9						
	2037	6	0.000	49306.880	1.069	1	19.180	99.152	9						
	2282	1	0.000	49327.700	1.124	1	19.180	99.071	9						
	2054	5	0.000	48494.900	0.344	0	19.180	99.623	9						
	2057	5	0.000	47682.920	0.002	0	19.180	99.999	10						
	2062	5	0.000	49015.400	0.664	0	19.180	99.466	9						
	2222	2	0.000	49348.520	1.614	2	19.180	99.152	9						
	2011	6	0.000	49098.680	0.697	0	19.180	99.057	9						
	1924	8	0.000	43810.400	0.000	0	19.180	100.000	10						
	2260	1	0.000	48786.380	0.464	0	19.180	99.471	9						
	2216	2	0.000	48786.380	0.464	0	19.180	99.471	9						
	2277	1	0.000	49202.780	0.726	0	19.180	99.029	9						
	1749	12	0.000	48661.460	0.377	0	19.180	99.623	9						
	2094	5	0.000	49244.420	0.806	0	19.180	99.062	9						
	2014	6	0.000	48203.420	0.080	0	19.180	99.867	9						
	2168	3	0.000	48286.700	0.103	0	19.180	99.828	9						
	1453	17	0.000	48411.620	0.288	0	19.180	99.579	9						
	1987	7	0.000	48078.500	0.052	0	19.180	99.956	9						

09/12/2008

GA-Aquator

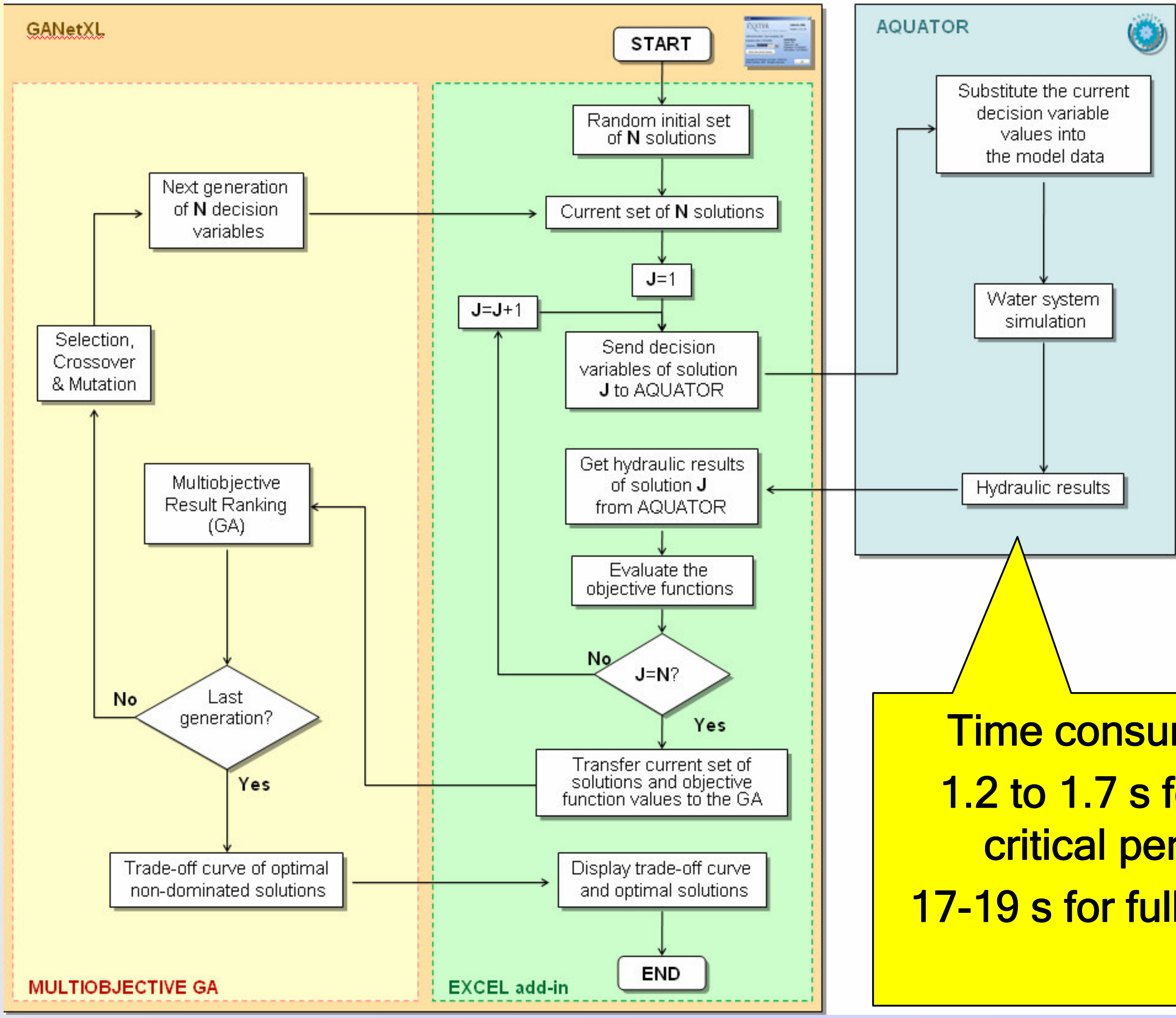
Problem:

- Time needed (thousands of generations/AQUATOR simulations) → distribution to computers in parallel

Shortening the time by

- Critical period concept
  - Optimising for a short critical period
  - Checking (internal for GA-Aquator) for full period
- Improving the GA … (new version-OMNI Optimiser)
  - Larger population (100-200)
  - ‘Near optimal’ results in 150-300 generations (instead of 3000)
- Distributed computing (computers working in parallel)…

Structure



Time consuming:

1.2 to 1.7 s for the critical period

17-19 s for full period

GA-Aquator

Problem:

- Time needed (thousands of generations/AQUATOR simulations) → distribution to computers in parallel

Shortening the time by

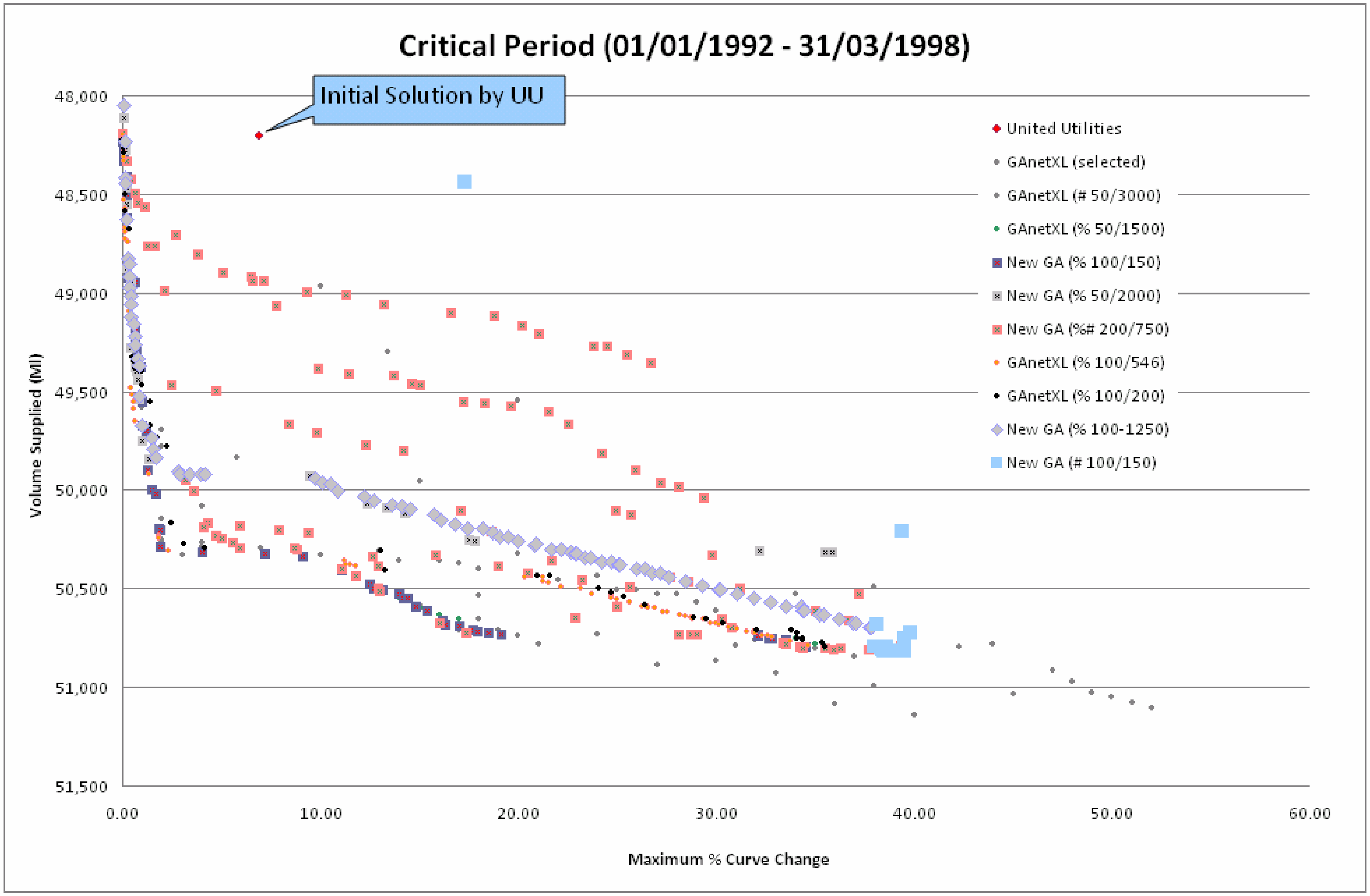
- Critical period concept
  - Optimising for a short critical period
  - Checking (internal for GA-Aquator) for full period
- Improving the GA … (new version-OMNI Optimiser)
  - Larger population (100-200)
  - 'Near optimal' results in 150-300 generations (instead of 3000)
- Distributed computing (computers working in parallel)…

GA-optimiser

Improving the GA

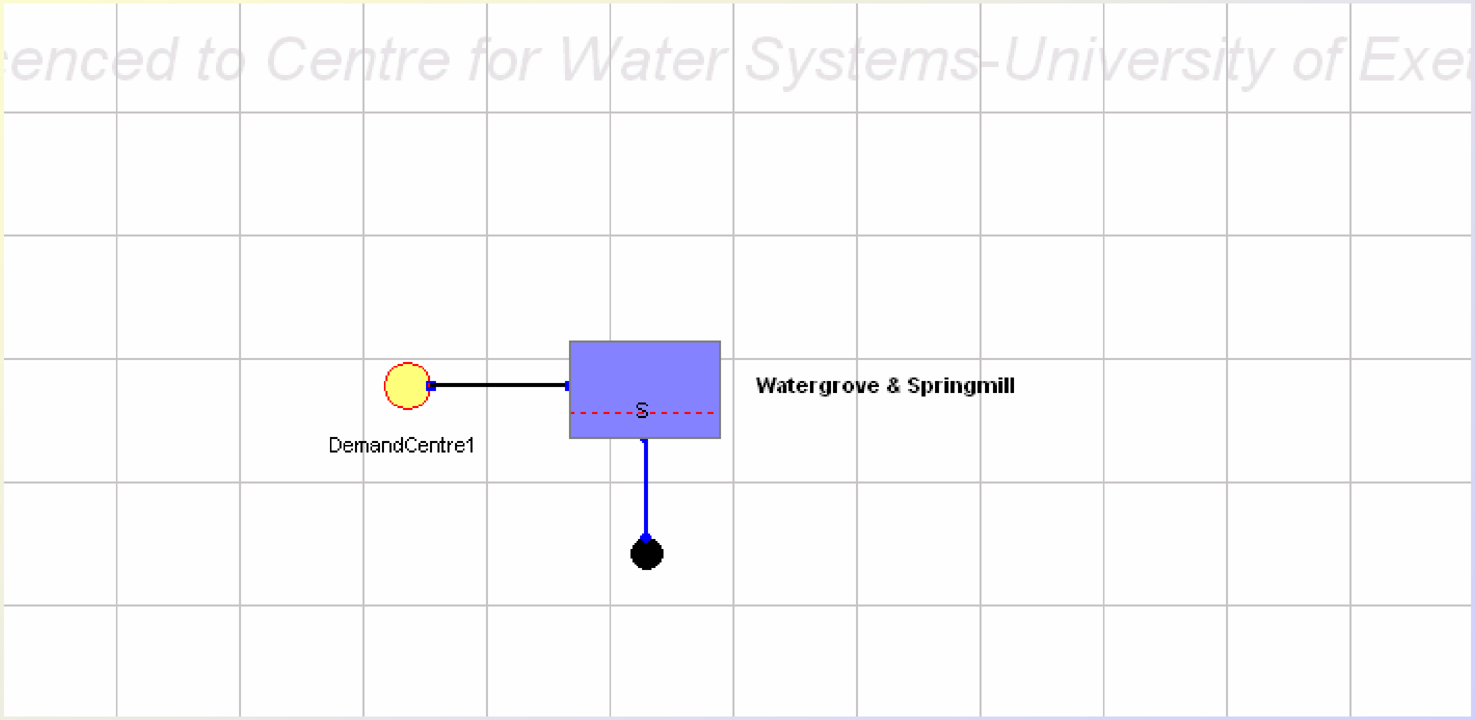
- Omni-Optimiser… New..
- Universal (single + multi) objective optimisation
- Maintains variability in objective and decision space
- Robust and disruptive mutation operator
- Deb, K., and Tiwari, S. (2008). "Omni-optimizer: A generic evolutionary algorithm for single and multi-objective optimization." *European Journal of Operational Research"*, 185(3), 1062-1087.
- Applied in GA-Aquator for larger population (100-200) than GANET_XL (20-50)
- 'Near optimal' results in 150 generations (instead of 3000) in under 1 hr (+distributed computing)

New GA-trade-off curves (Barnacre)

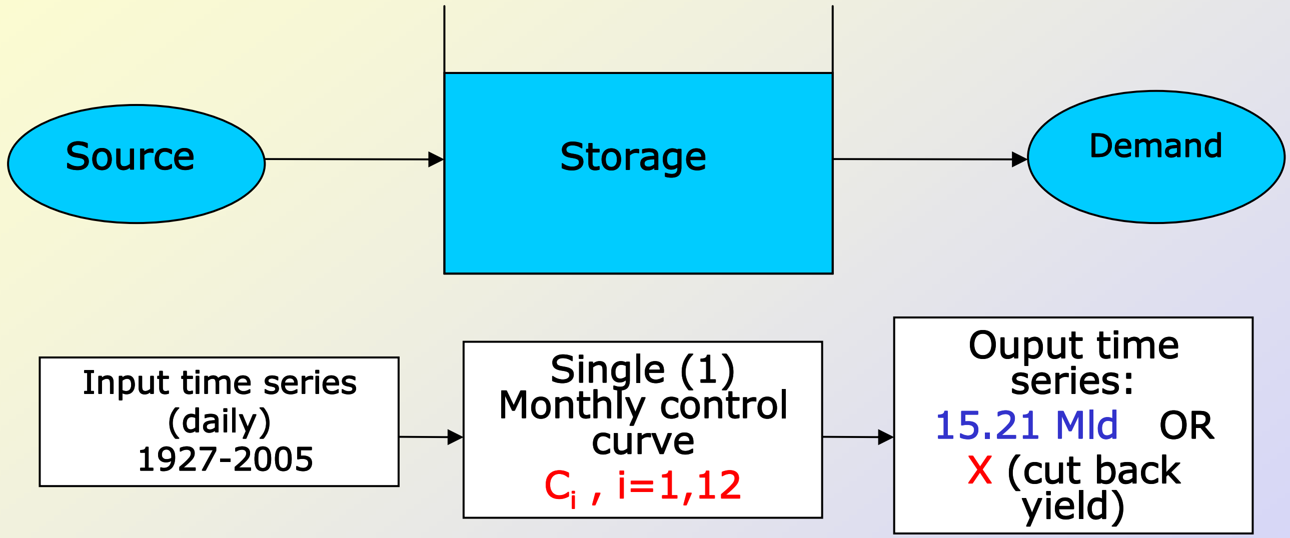


2nd case study

Watergrove & Springmill system

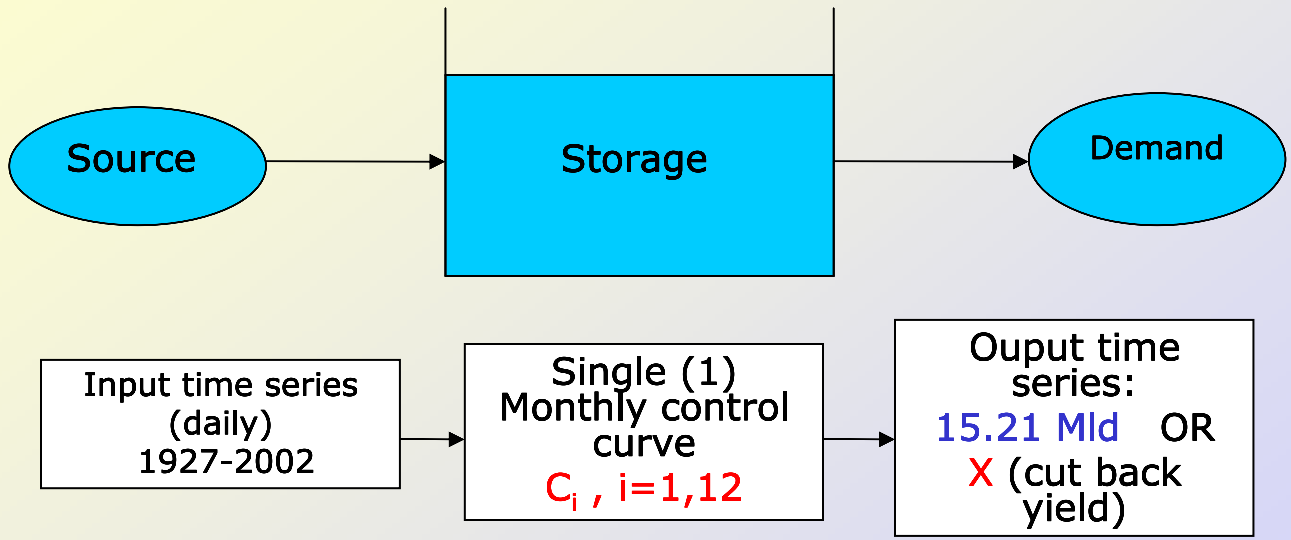


W&S system test problem



- Single reservoir
- Spills /No energy costs taken into account (gravity fed)
- Target: Maximising yield (water volume) AND No deficits
- Decision variables (Unknowns): X and C_i, i=1,12
- Initial optimal solution given by UU (X fixed at UU request)

W&S system test problem

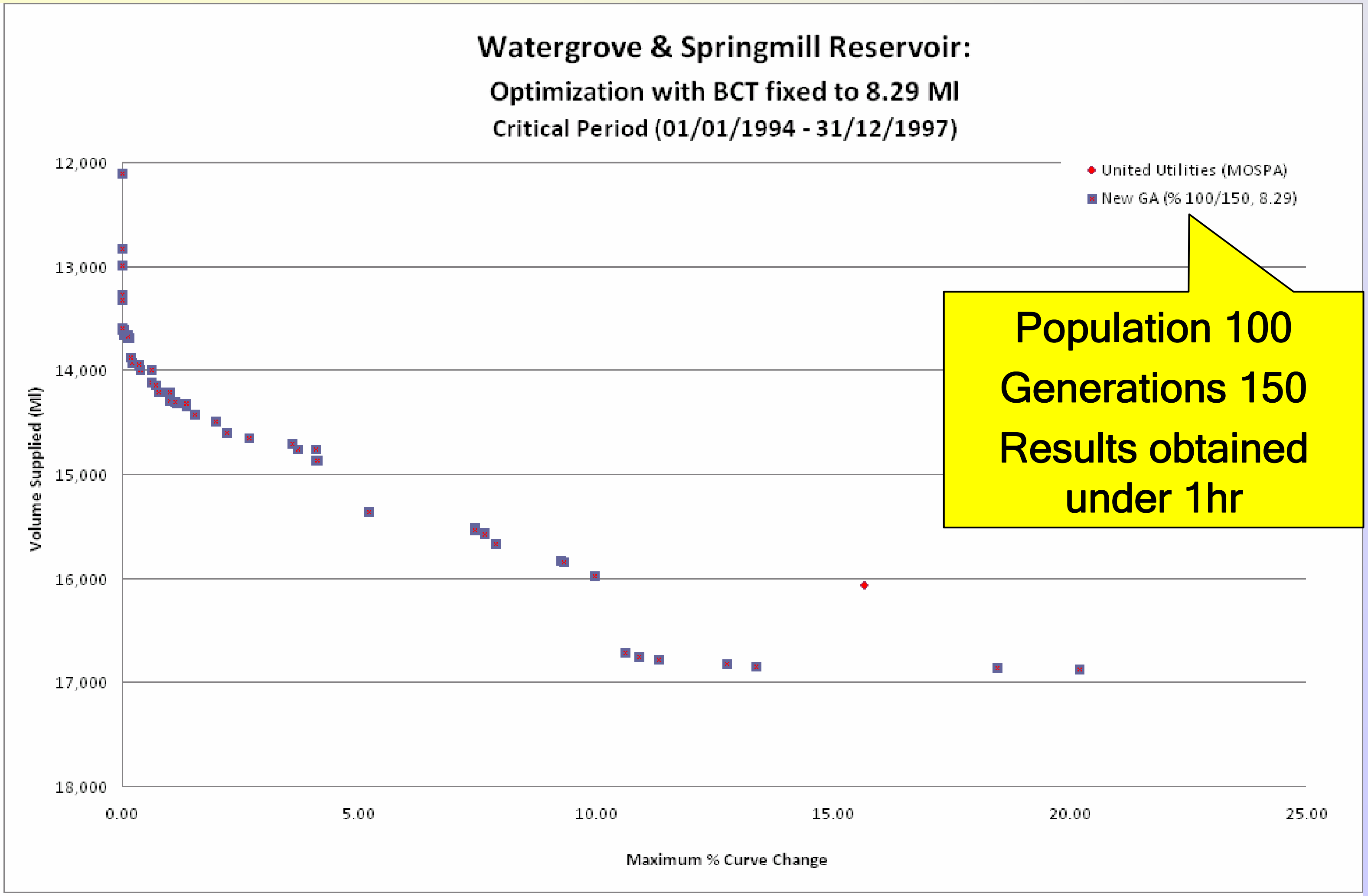


- Control curve (monthly) C_i , i=1,12
- Ci % of max water volume (reservoir capacity)
- If storage > Ci → Outflow= 15.21 Mld
- If storage < Ci → Outflow= X=8.29 (cutback yield)
- If storage < minimum → deficit (To be avoided)
- If storage > maximum → spills (To be avoided)

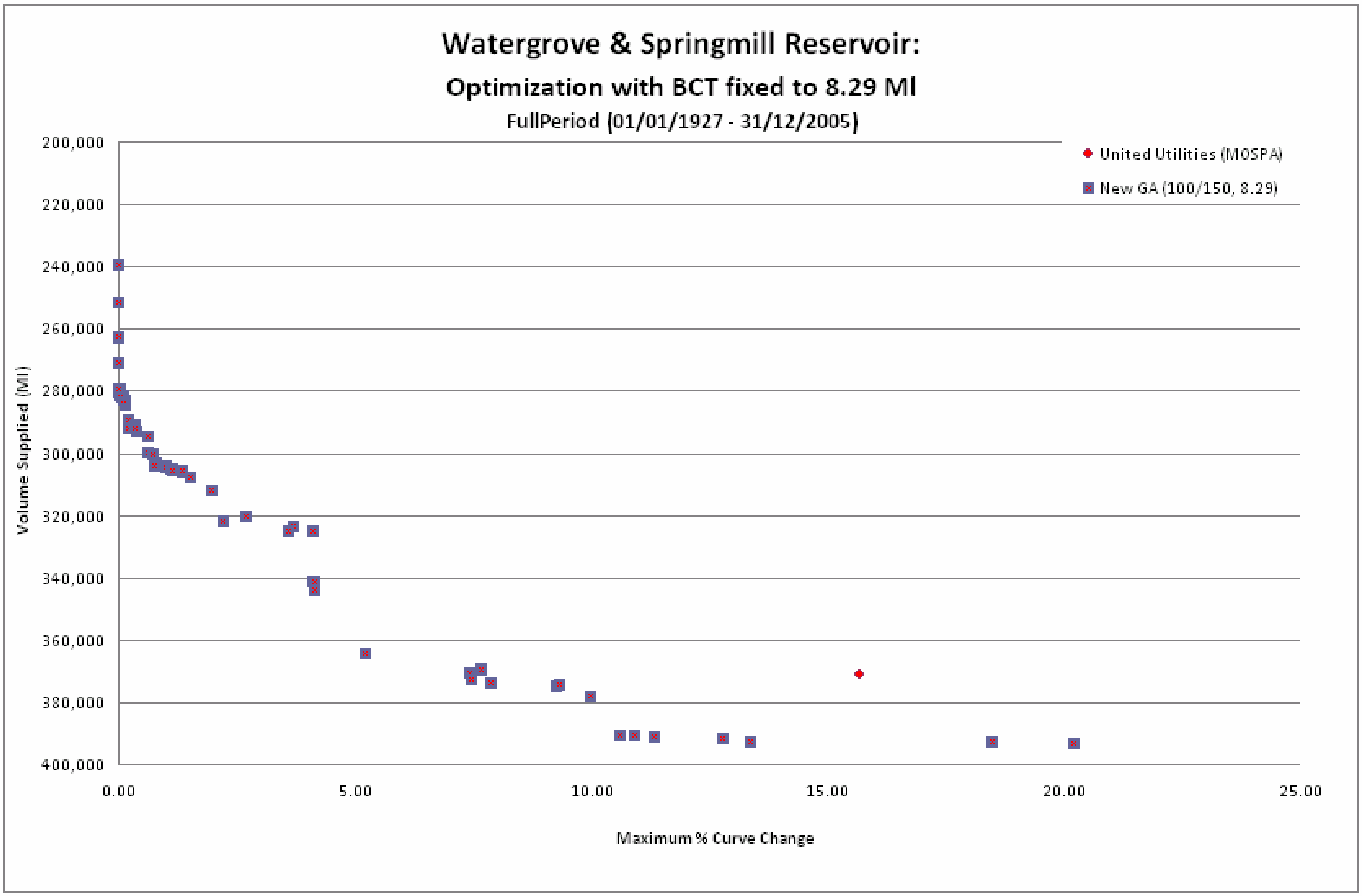
Selected Solutions for W&S

1993-1997	Original UU	Smoother curve	Smoother curve	Smoother curve	Smoother curve	Max yield	Max yield
max dC%	15.67	10.90	11.32	12.77	13.38	18.48	20.21
		(2)	(3)	(4)	(5)	(6)	(7)
Rate A	15.21	15.21	15.21	15.21	15.21	15.21	15.21
Rate B=X	8.2900	8.29000	8.29000	8.29000	8.29000	8.29000	8.29000
Jan	72.24	68.47	68.47	62.60	66.73	51.17	49.37
Feb	84.92	77.89	76.98	69.48	69.26	69.65	69.58
Mar	92.99	84.08	84.08	82.26	82.63	87.68	82.44
Apr	97.16	94.80	94.90	94.96	95.33	95.34	95.33
May	100.00	90.57	91.19	91.19	89.44	89.44	91.23
Jun	98.66	87.55	87.55	87.55	86.25	86.83	84.57
Jul	87.76	76.96	76.24	75.48	76.37	76.28	75.95
Aug	72.09	68.03	66.88	66.94	67.13	66.85	66.85
Sep	60.30	58.35	58.35	58.62	57.45	57.56	57.43
Oct	52.53	55.70	55.70	55.98	54.24	52.85	54.18
Nov	54.77	50.10	50.10	49.94	49.54	49.54	49.54
Dec	61.64	57.57	57.91	57.63	53.76	50.90	58.12
Failures		0	0	0	0	0	0
Deficit		0	0	0	0	0	0
Volume	16077	16748	16783	16824	16852	16866	16880
Volume increase %		4.18	4.39	4.65	4.82	4.91	4.99
Volume full period	371165	390659	391171	391662	392901	392597	393226
Volume increase % full period		5.25	5.39	5.52	5.86	5.77	5.94

Trade-off curve for W&S/Critical period



Trade-off curve for W&S (Full period)



GA-Aquator

Advantages/Conclusions:

- AQUATOR and GA have been combined and integrated
- It can improve results (volume and "smoothness" of the curve)
- Optimisation in one step (X and Ci simultaneously), even for complex systems with multiple reservoirs
- Multiple objectives in order to 'shape' the curve.
- Interest by the Water Companies ("real" problem)
- Distributed computing applied
- Improved MOGA + gaining experience

GA-Aquator

Next steps:

- Optimising for Reservoir System with multiple curves

  (to start with UU in the spring)

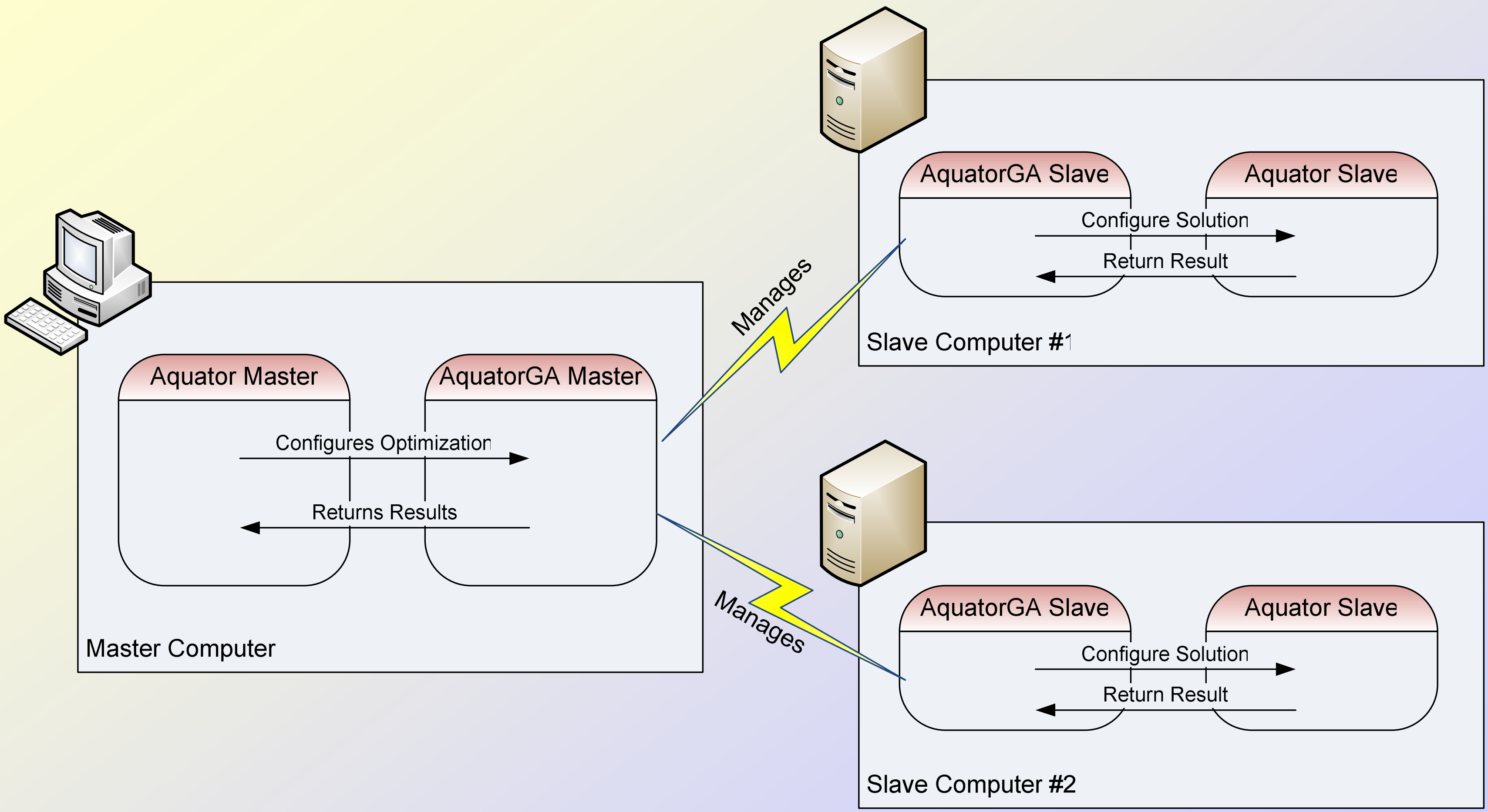
- Extending to multiple reservoirs through AQUATOR
- Extending to other Water Companies
- Extending similar techniques and experience for integrating GA to other "commercial" water system software

GA-Aquator

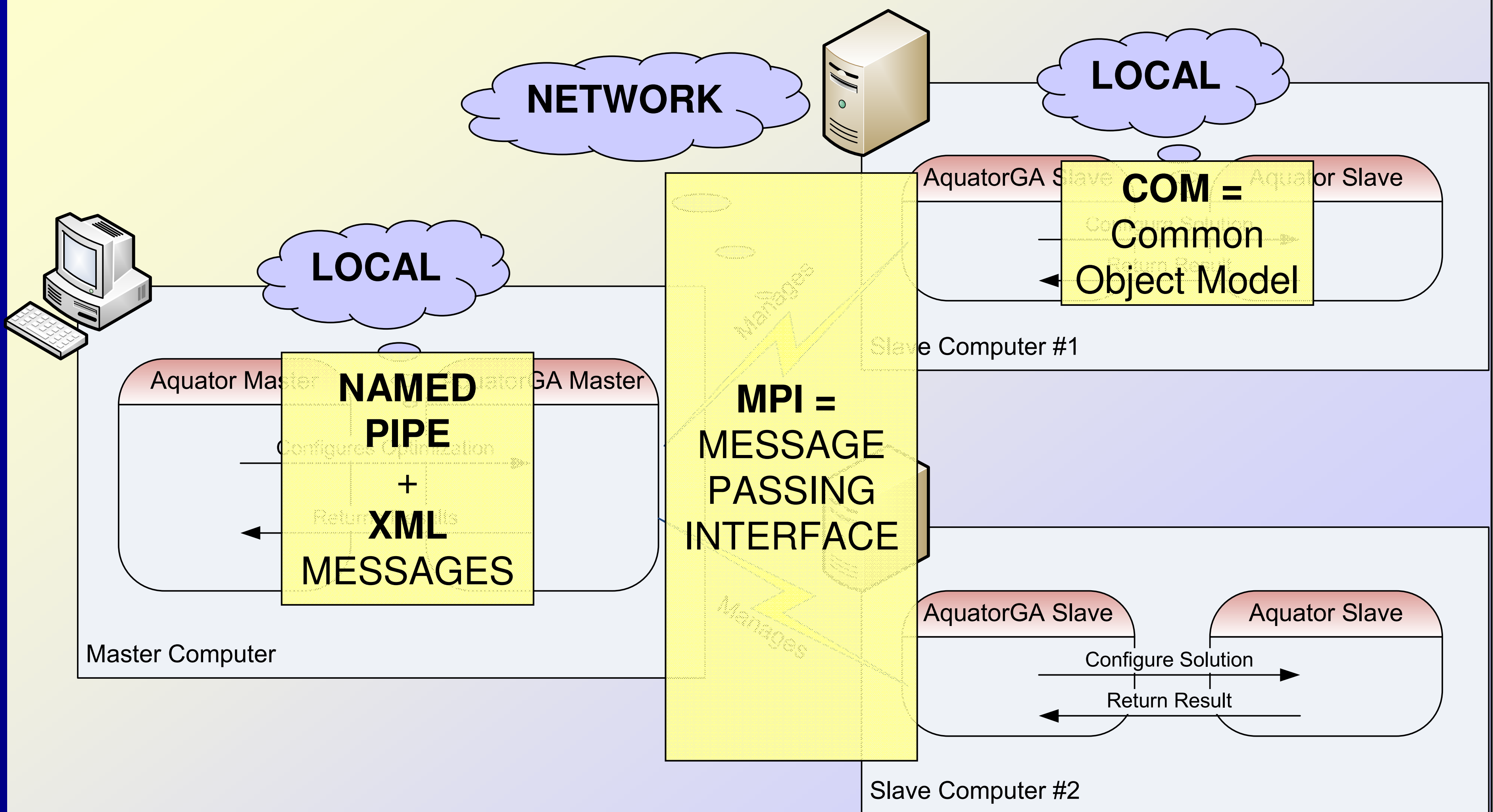
- Demonstration…
- Distributed computing for GA-AQUATOR

By Josef Bicik…

Ditsributed computing for GA-Aquator



Inter-Process Communication



Inter-Process Communication

- MPI – Message Passing Interface
  - Communication protocol for parallel computing
  - Widely adopted
  - Available on ZEN (Physics supercomputer)
  - Mostly distributed communication
- Pipes
  - Bi-directional communication between 2 processes
  - Behaves like a normal file but data only in memory
  - Supported by operating system (POSIX)
  - Mostly local communication

UNIVERSITY OF EXETER
Centre for Water Systems

AQUASTRESS

Thank you for your attention

Links

- MPI - http: //www.mcs.anl.gov/research/projects/mpich2/
- ZEN Supercomputer - http://newton.ex.ac.uk/features/supercomputer.html
- Omni optimizer - http://linkinghub.elsevier.com/retrieve/pii/S0377221706006291
  http://www.iitk.ac.in/kangal/seminar/omni.ppt