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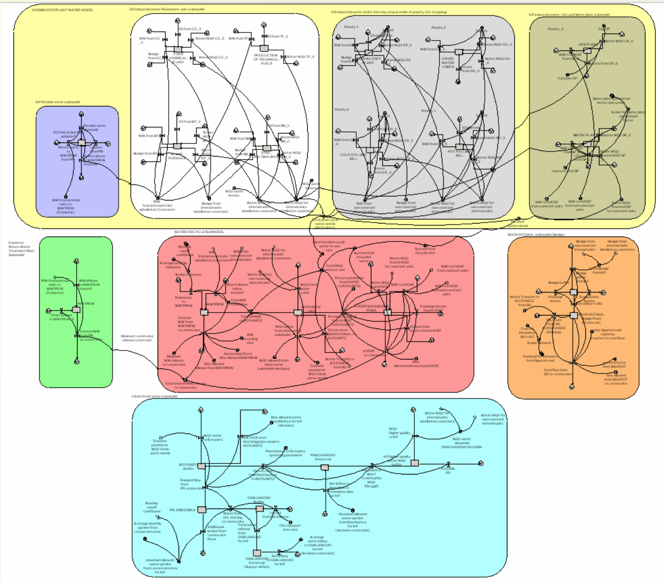
System Dynamics Modelling for the Simulation of Complex Water Systems



Dr Lydia S. Vamvakeridou-Lyroudia

SDM: System Dynamics Modelling

1. SDM Overview
2. Simple example
3. SDM in AQUASTRESS
4. Case studies (2)
5. Running demo…

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SDM: System Dynamics Modelling

System Dynamics Modelling (SDM) or Systems Thinking

- **Methodology for analyzing, studying and managing**
- **Complex Systems**
- **When formal analytical methods do not exist**
- **(or are hard to apply)**
- **By linking feedback mechanisms (loops and iterations)**
- **Breaking down the problem into sub-systems and sub-models**
- **In a way similar to the conceptual thinking of non-programmers (conceptual models)**
- **No analytical formal simulation model necessary**

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SDM: System Dynamics Modelling

Based on conceptual/graphical representation of relations among different system components.

- ***Visualisation using specialised software (interface)***
- ***Models built gradually starting with few components, adding complexity interactively***
- ***Differential equation + Integration simulated in a "friendly" way***
- ***Different time scales for different subsystems***

Suitable for developing a model in participatory process

Acting as *Decision Support Tools (DST)* for stakeholders (non-engineers) and experts for examining alternatives/scenarios

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SDM: System Dynamics Modelling

History/Applications

- ***Industrial long-term management problems (Forrester 1961)***
- ***Business strategy and policy problems***
- ***Ecology / Complex environmental systems***
- ***Complex water systems***
- ***Participatory process***

Several Specialised software tools for visualisation….

- ***SIMILE (www.simulistics.com)*** **(← Used here)**
- ***VENSIM (www.vensim.com)*** **(← Used here)**
- ***STELLA (www.iseesystems.com)***
- ***SIMULINK(www.mathworks.com) (MATLAB)***
- ***POWERSIM (www.powersim.com)***
- ***MODELMAKER (www.modelmakertools.com) (BORLAND)***

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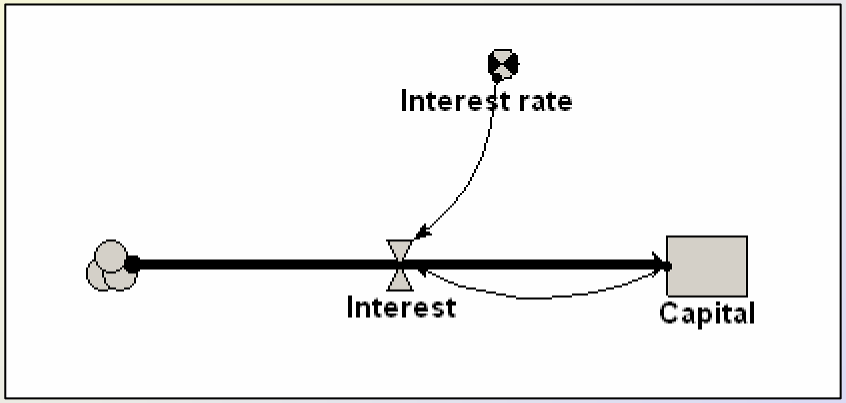
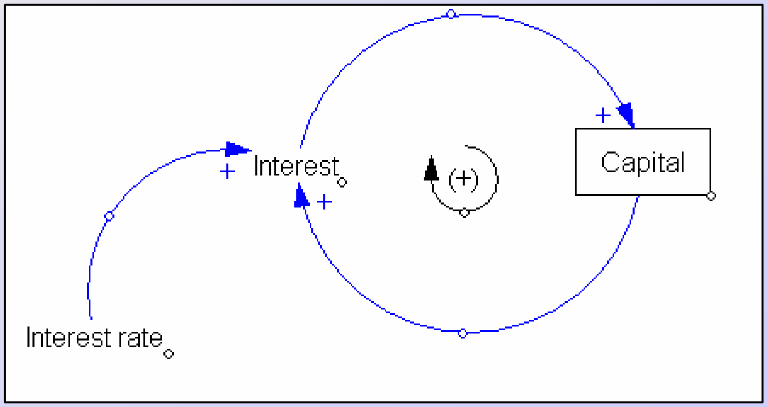
SDM: System Dynamics Modelling

Each SDM model consists of:

- **Stocks/Compartments** (Levels-State variables)
- **Connectors** (Arrows)
- **Flows/Influences** (Rates)
- **Converters** (Auxiliaries/Parameters)
- **Decision processes** (Priorities/Allocation/Relations)





Flow diagram

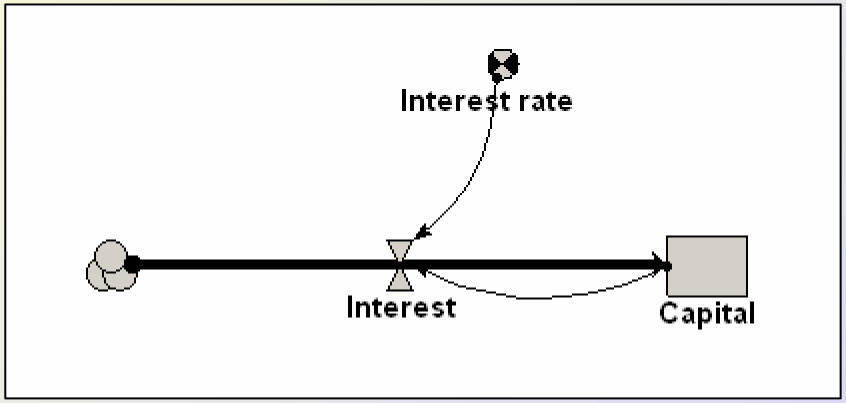
Causal Loop diagram

SDM: System Dynamics Modelling

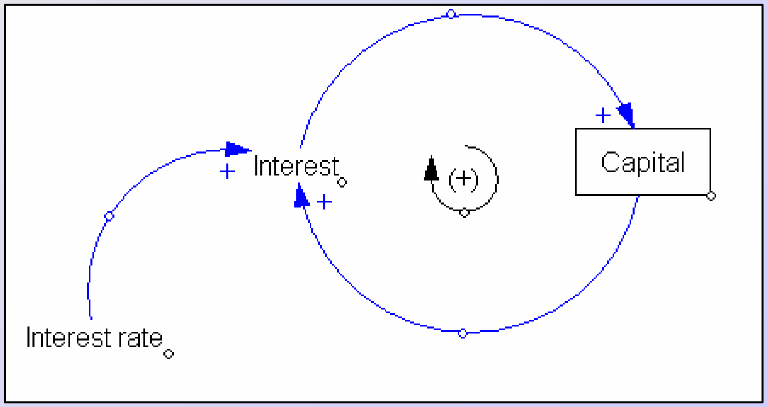
Flow diagram: For quantitative (numerical) model/simulation

Causal Loop diagram: For qualitative (conceptual) model

- **For each system, both Flow and Causal Loop diagrams can be drawn**
- **Causal loop helpful for studying "causality"**



Flow diagram



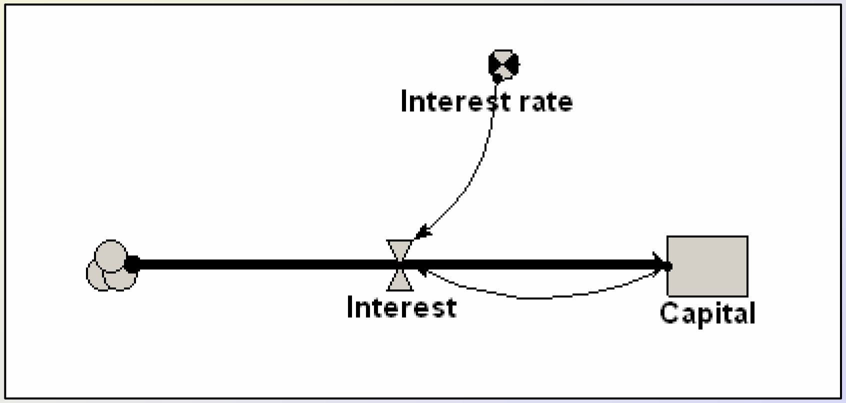
Causal Loop diagram

SDM: System Dynamics Modelling

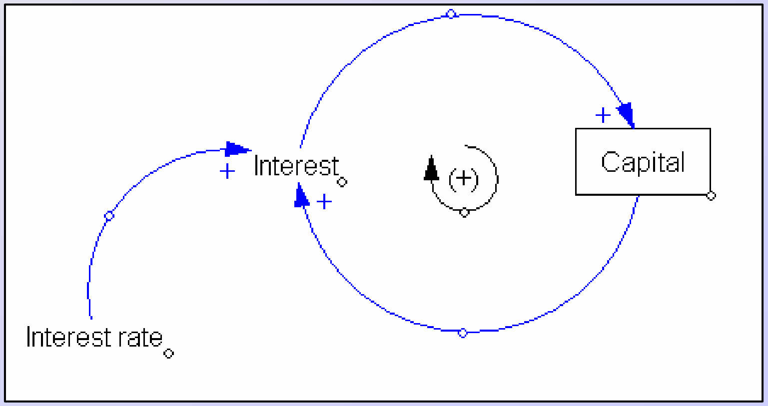
Analytical expression (i.e. $C_t=C_o(1+a)^t$) *NOT needed*

Data needed:

- **Drawing "Capital" as Stock, "Interest" as Flow, "Interest rate" as Parameter, "arrows" as influences**
- **Initial value for "Capital" (e.g. 10000)**
- **Interest rate (e.g. 10%)**
- **Relation: Interest=Capital*Interest_rate**



Flow diagram



Causal Loop diagram

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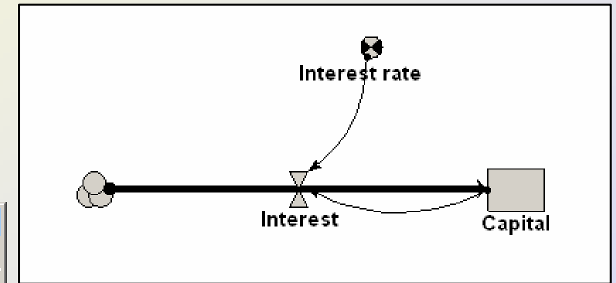
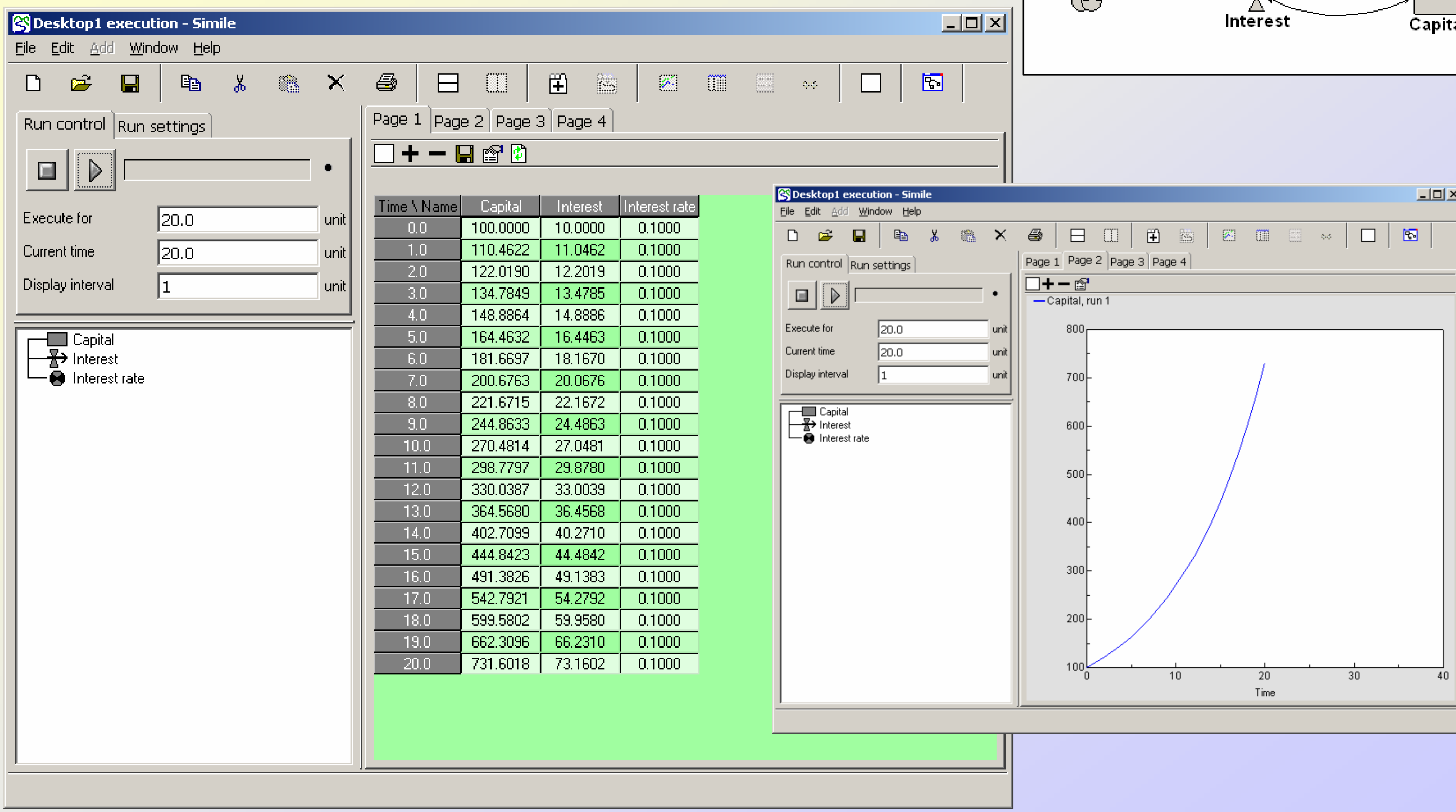
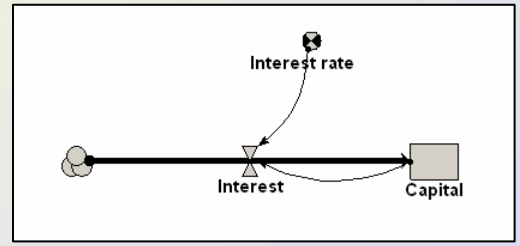
SDM: Simple example

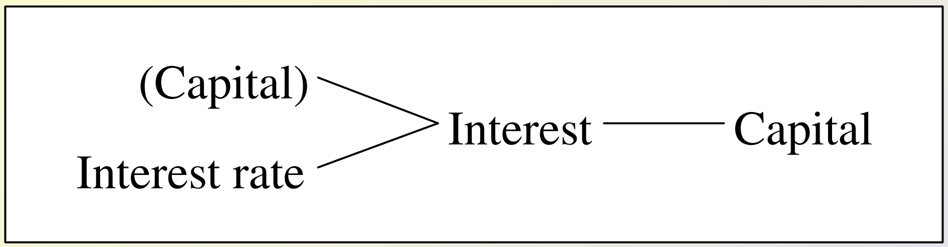


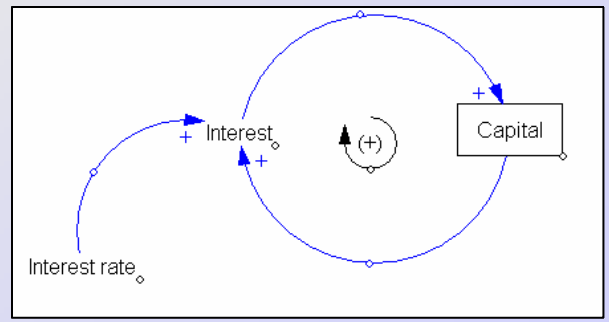


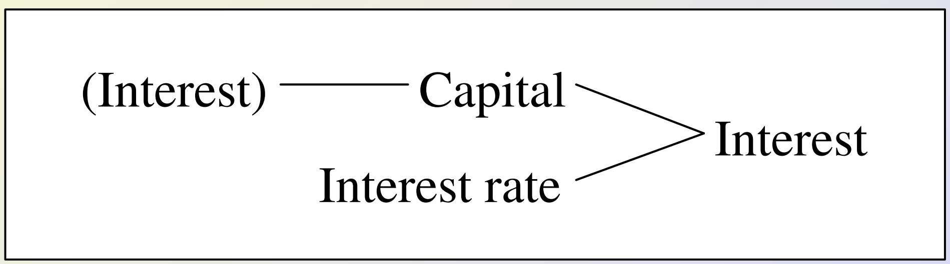
Time \ Name	Capital	Interest	Interest rate
0.0	100.0000	10.0000	0.1000
1.0	110.4622	11.0462	0.1000
2.0	122.0190	12.2019	0.1000
3.0	134.7849	13.4785	0.1000
4.0	148.8864	14.8886	0.1000
5.0	164.4632	16.4463	0.1000
6.0	181.6697	18.1670	0.1000
7.0	200.6763	20.0676	0.1000
8.0	221.6715	22.1672	0.1000
9.0	244.8633	24.4863	0.1000
10.0	270.4814	27.0481	0.1000
11.0	298.7797	29.8780	0.1000
12.0	330.0387	33.0039	0.1000
13.0	364.5680	36.4568	0.1000
14.0	402.7099	40.2710	0.1000
15.0	444.8423	44.4842	0.1000
16.0	491.3826	49.1383	0.1000
17.0	542.7921	54.2792	0.1000
18.0	599.5802	59.9580	0.1000
19.0	662.3096	66.2310	0.1000
20.0	731.6018	73.1602	0.1000

SDM: Simple example-Causality

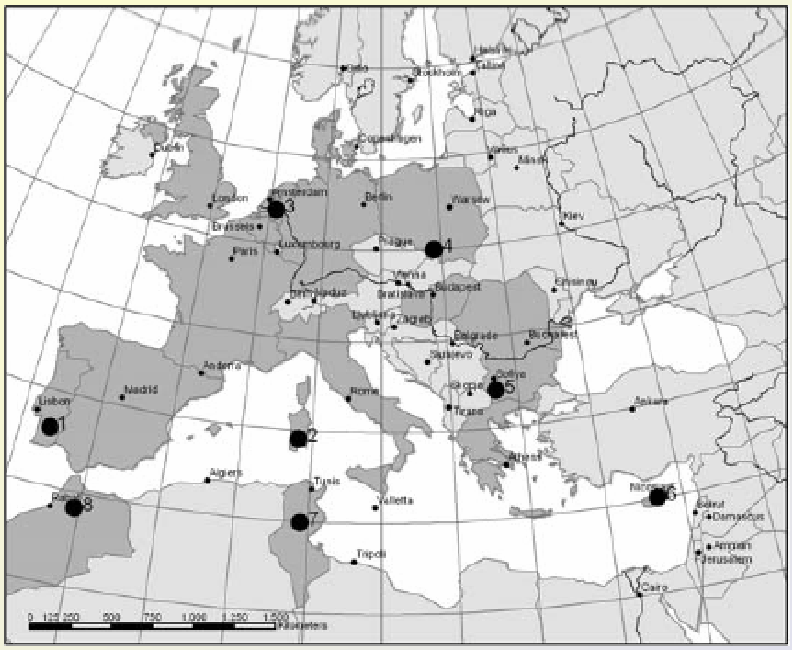








SDM in AQUATRESS



AquaStress

(http://www.aquastress.net)

- **Mitigation of Water Stress through new Approaches to Integrating Management, Technical, Economic and Institutional Instruments**
- **EC FP6 IP project (2005-2009)**
- **€ 14 million budget**
- **35 partners**
- **8 (very) different test sites/case studies**

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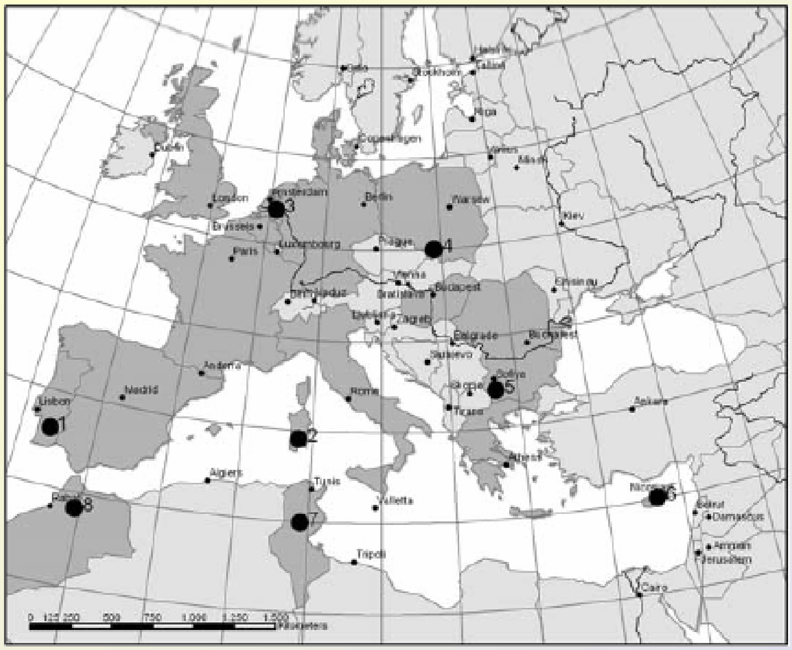
AQUASTRESS

SDM in AQUATRESS



Within AQUASTRESS several Technical Options are investigated for mitigating water stress:

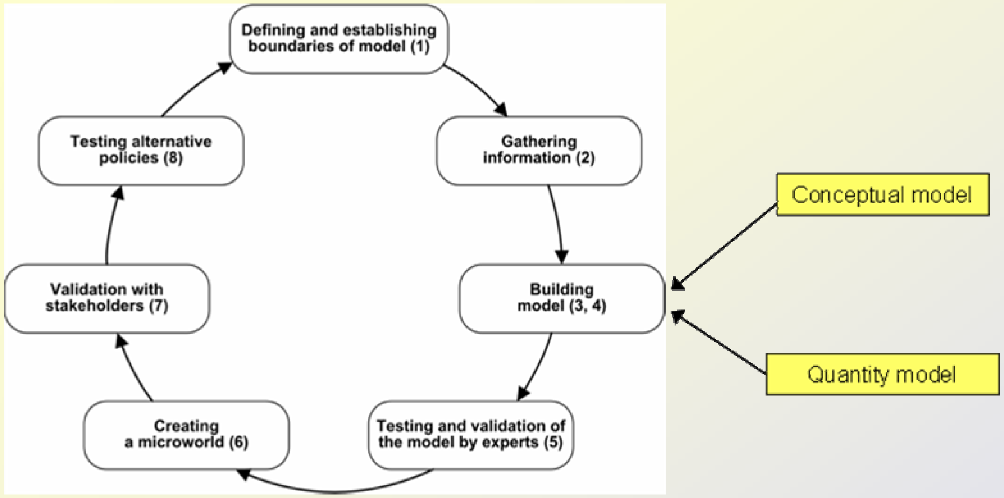
From the technical point of view each of these options are separately

- ***Examined* (State-of-the-art methodologies, techniques)**
- ***Assessed* (Results, quantities, costs)**
- ***Considered* for each test site (local feasibility)**

They are then combined using Conceptual and System Dynamics Modelling to simulate the water systems for each case study

SDM models: low in detail, high in integration

SDM : Method of application



For each case study separately

- **Identify a problem/system within the case study**
- **Develop a dynamic hypothesis explaining the cause of the problem (SDM -Conceptual model)**
- **Build a computer simulation model (SDM Quantitative model)**
- **Test the model (Validation)**
- **Use the model to produce and assess alternative policies**
- **With interactive process (Experts→stakeholders→experts→stakeholders…)**

University of Exeter Centre for Water Systems — AQUASTRESS

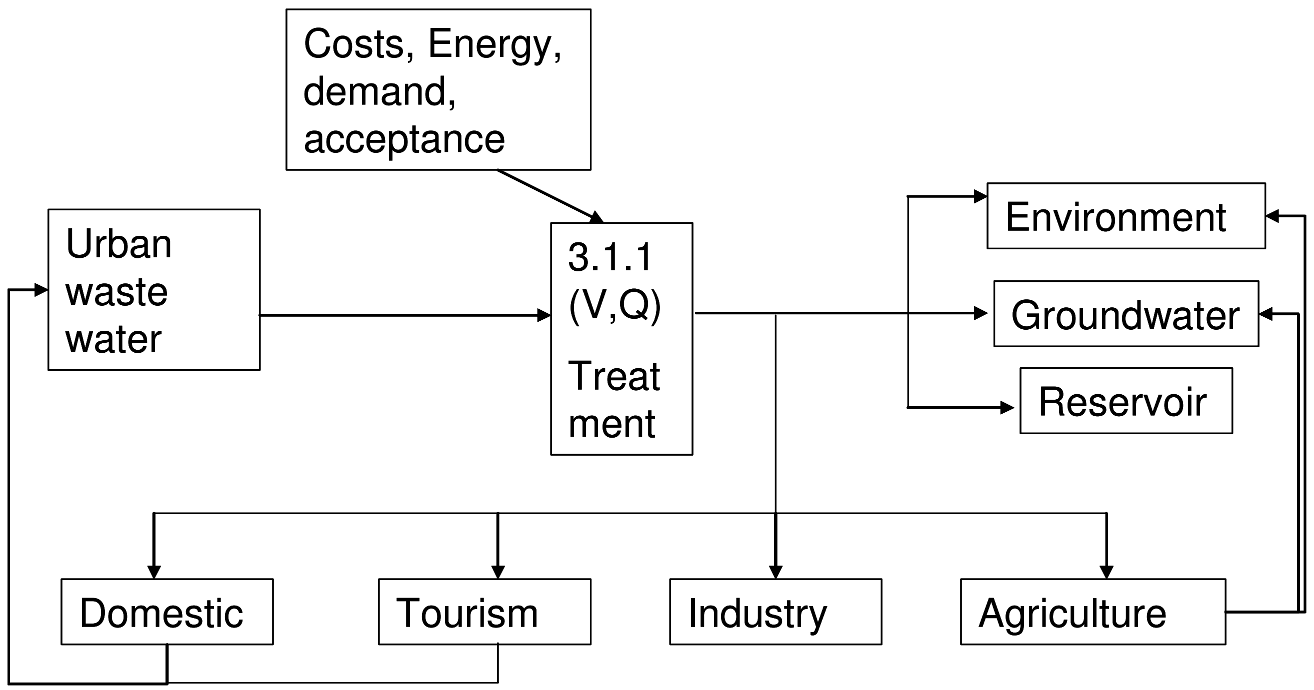
SDM – AQUASTRESS: Component Types (1/2)

(1)	(2)	(3)	(4)	(5)
AQUASTRESS terminology	Water Resources	Water Resources	Water losses	Water users
Type of water system model component	Water bodies	Resources	Losses	Water users
SDM Functional type	Stocks	Converters: Inflows	Converters: Outflows	Converters: Outflows
Brief functional description	Storage/ Water sources	Water inputs to the system	Losses	Water users/ Water consumption
Abbreviation	S	I	L	U
Dimension/Units	Volume - Mass	Volume/time	Volume	Volume/time
Component Abbreviation	Reservoir RES	Precipitation (Rainfall) P	Evapo-transpiration ET	Agriculture AWU
Component Abbreviation	Groundwater- Aquifer GW	Surface runoff SR	Groundwater losses GL	Industry IWU
Component Abbreviation	Sea SEA	Groundwater flow GF		Domestic DWU
Component Abbreviation		Urban Waste water UWW		Environment EWU
Component Abbreviation				Tourism/ Leisure TWU

SDM – AQUASTRESS: Component types (2/2)

(1)	(2)	(3)	(4)	(5)	(6)
AQUASTRESS terminology			Options	Options	Options
Type of water system model component			Quantitative manipulator	Qualitative manipulator	Transfer (mass flow)
SDM Functional type			Converters	Converters	Converters
Brief functional description	AQUASTRESS Option Code	Abbreviation	Option that alters the volume	Option that alters the quality (e.g. concentration)	Option for Re-allocation without altering the volume
Abbreviation			V	Q	T
Dimension/Units			Volume/time	Concentration	Volume/time
Waste water re-use	O3.1.1	OWWR	✓	✓	
Desalination	O3.1.2	ODES	✓	✓	
Drainage water re-use	O3.1.4	ODWR			✓
Water table management	O3.2.1	OWTM	✓		✓
Groundwater remediation	O3.2.2	OGRR		✓	
Surface water control	O3.2.3	OSWC	✓		✓
Enhanced reservoir management	O3.2.4	OERM	✓	✓	✓
Minimising water losses	O3.3.1	OMWL	✓		
Process optimisation in industry	O3.3.2	OPOI	✓	✓	✓
Domestic Water Use and conservation	O3.3.3	ODUC	✓		
Irrigation water management	O3.4.1	OIWM	✓	✓	✓
Tailoring crop patterns	O3.4.2	OTCP	✓		
Less water intensive processes	O3.4.3	OLWI	✓		

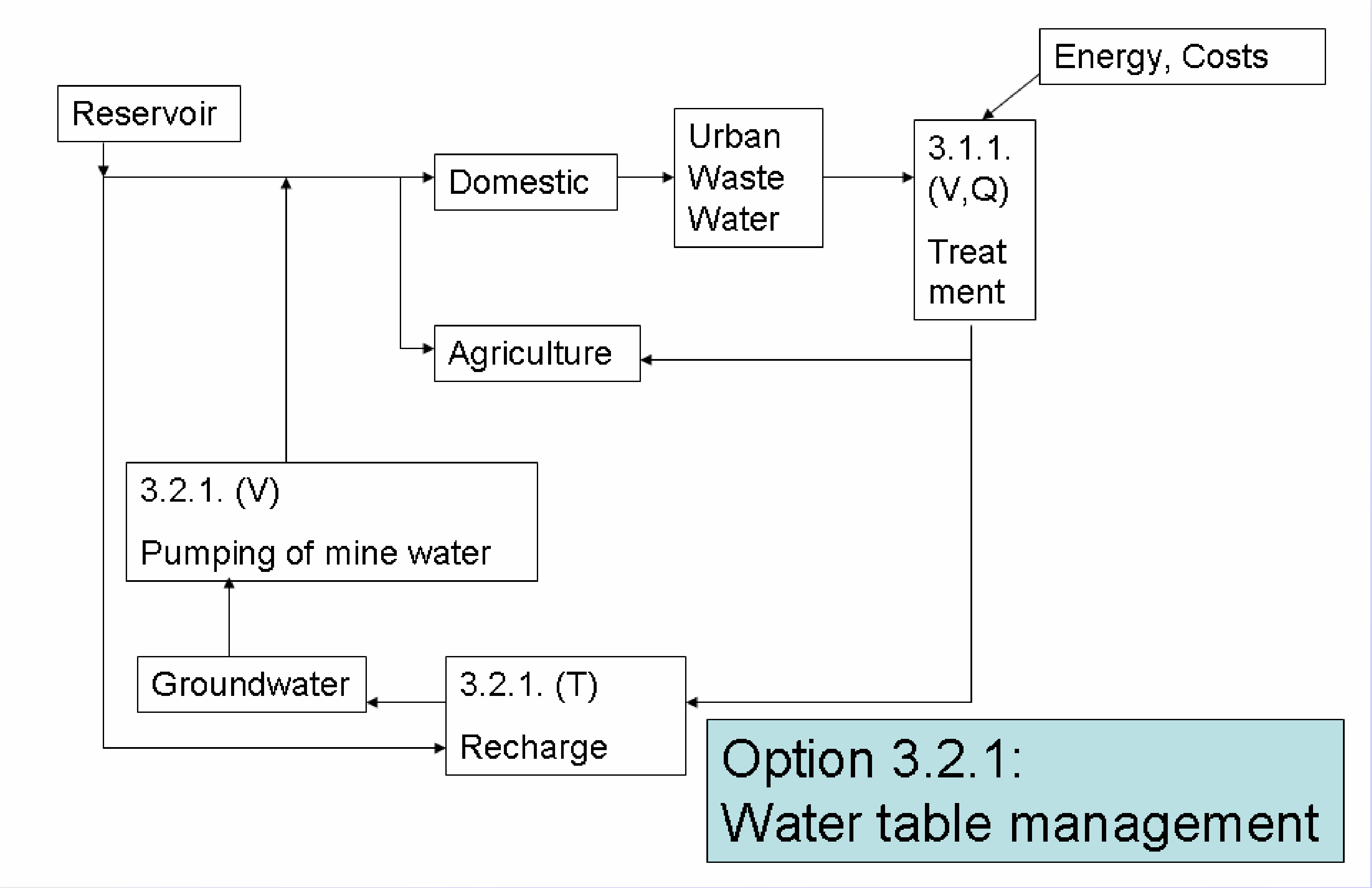
SDM – Conceptual model for technical options- Example (1)



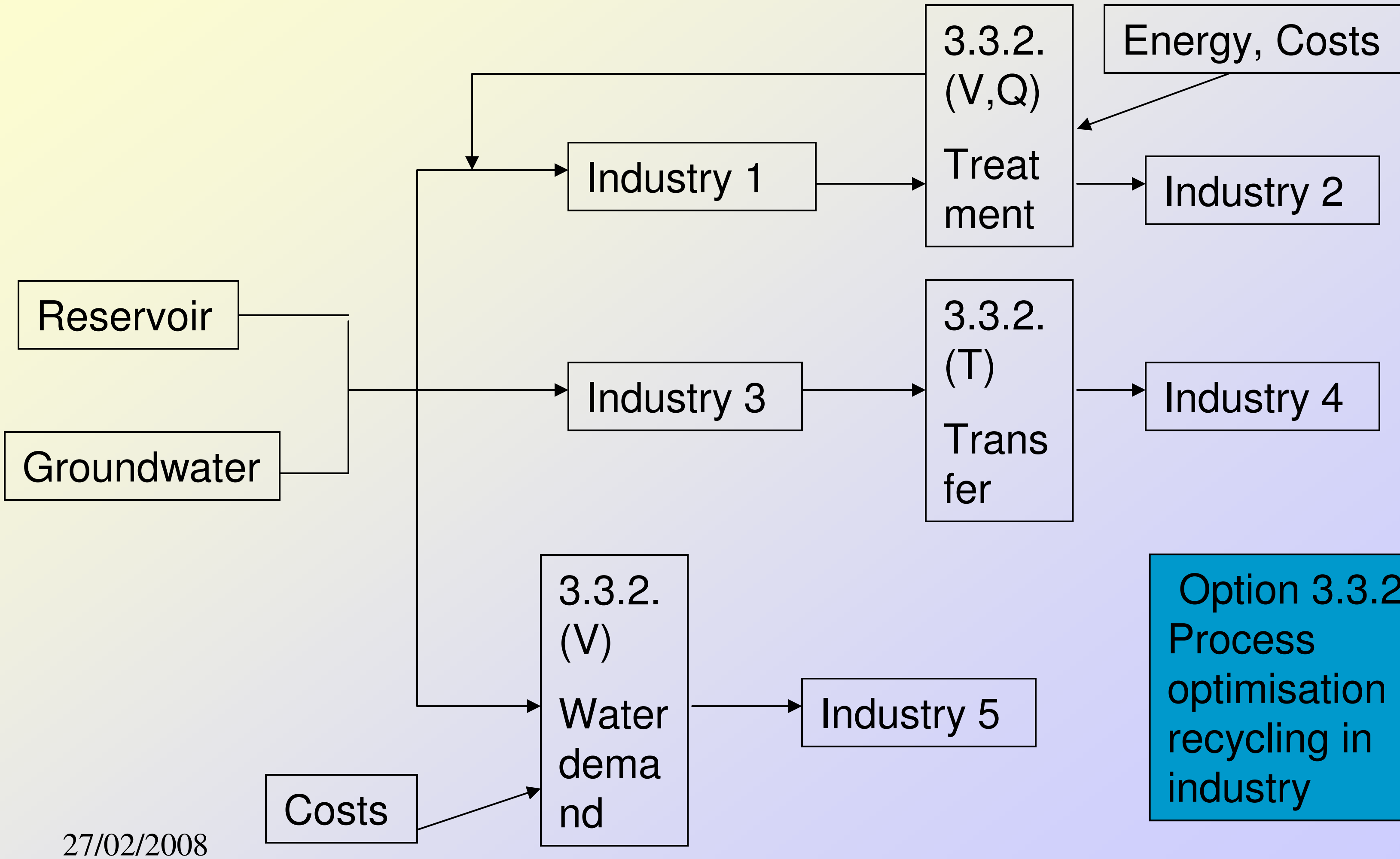
Option 3.1.1.

Waste water re-use

SDM – Conceptual model for technical options-Example (2)



SDM – Conceptual model for technical options- Example (3)



Option 3.3.2
Process optimisation and recycling in industry

AQUASTRESS SDM: Case studies

1. Kremikovtzi plant water system – (Bulgaria)

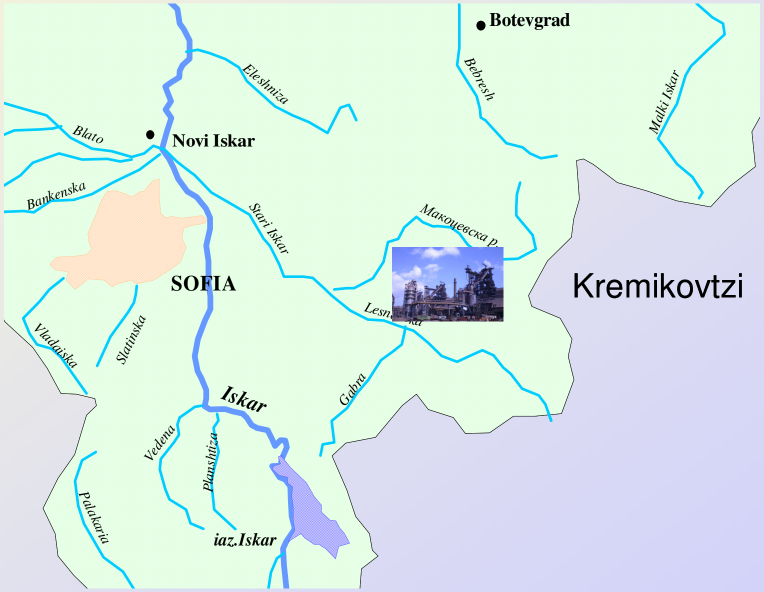
- *Industrial (competitive) water use – limited water resources*
- *Improve the rate of water re-use*
- *Study operational policies for dry and very dry years*

2. Merguellil catchment (valley) aquifer management – (Tunisia)

- *Hydrological model (group of small dams+1 large dam)*
- *Study agricultural water use*
- *Improve aquifer recharge and management*

Kremikovtzi system: Industrial water re-use

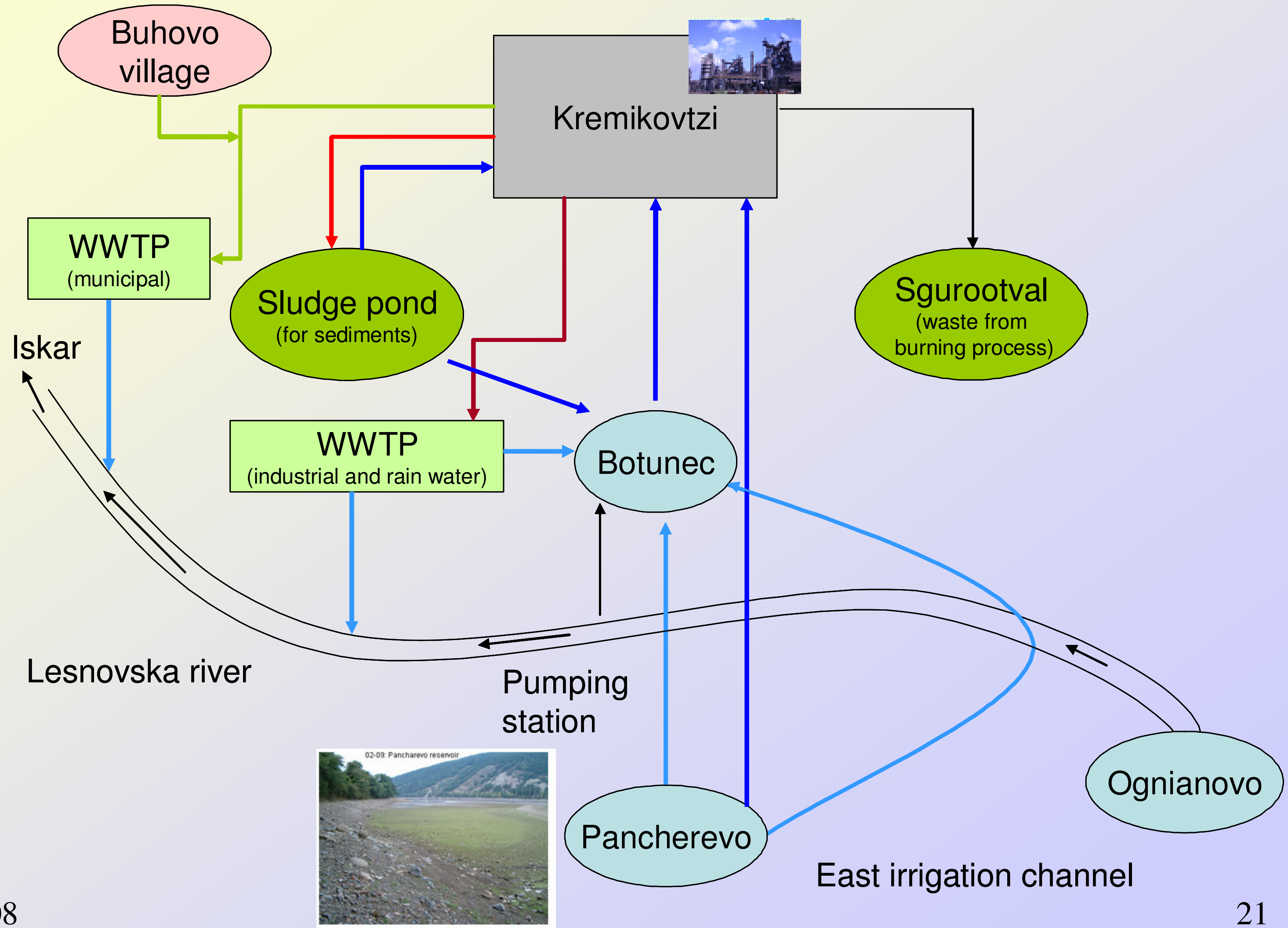
- **The industrial plant of Kremikovtzi consist on of the biggest water consumers and water pollutants in the Sofia region.**
- **Water demands for the plant amound to 550 million m³ / year, a significant percentage of which is recycled within the plant.**
- **The plant takes about 50-60 million m3 /year fresh water from two nearby reservoirs**



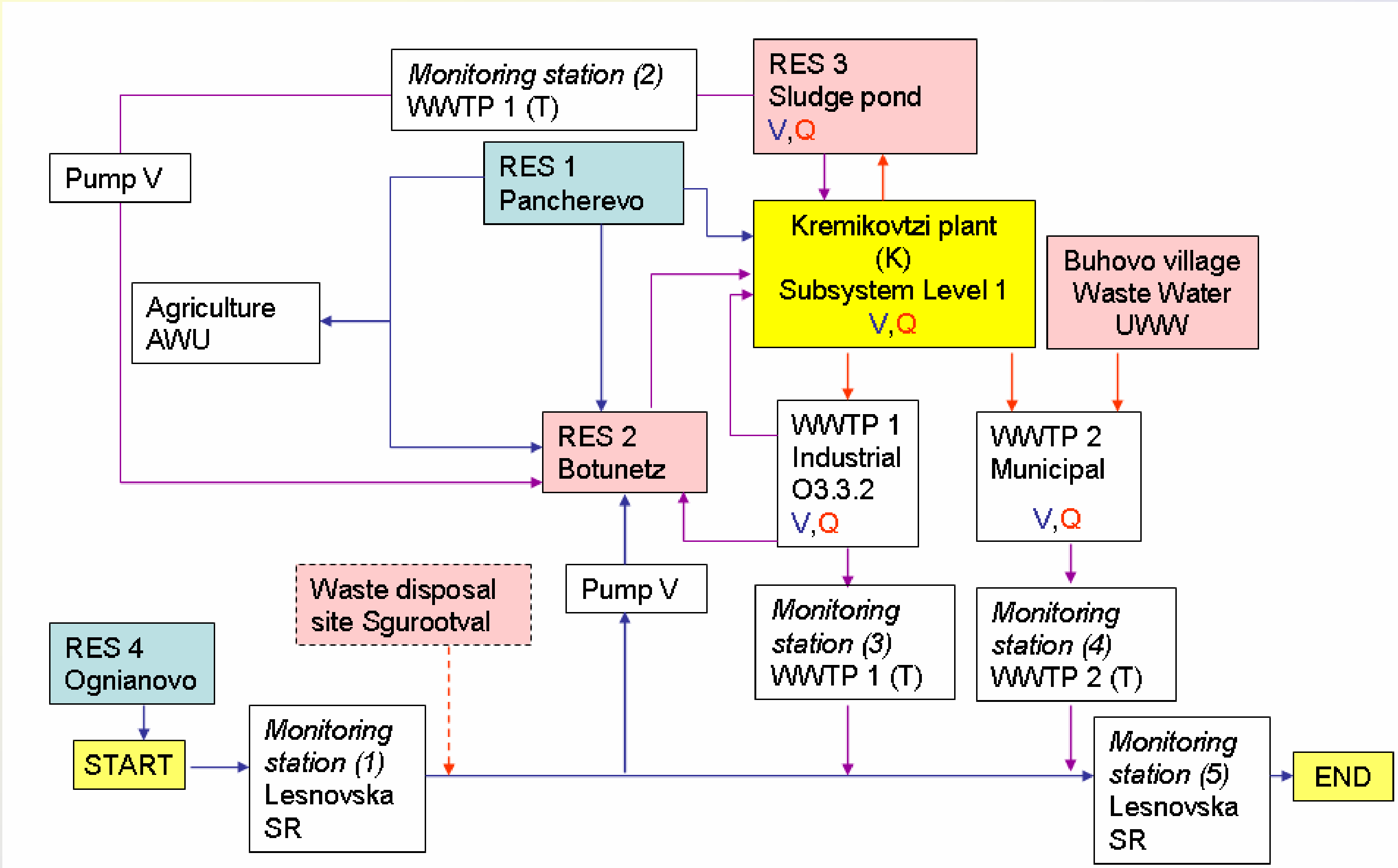
The SDM model aims at defining operating scenarios, and propose water saving measures, so as to:

1. ***Reduce the plant fresh water needs***
2. ***Improve the rate of water re-use***
3. ***Study operational policies for dry and very dry years***

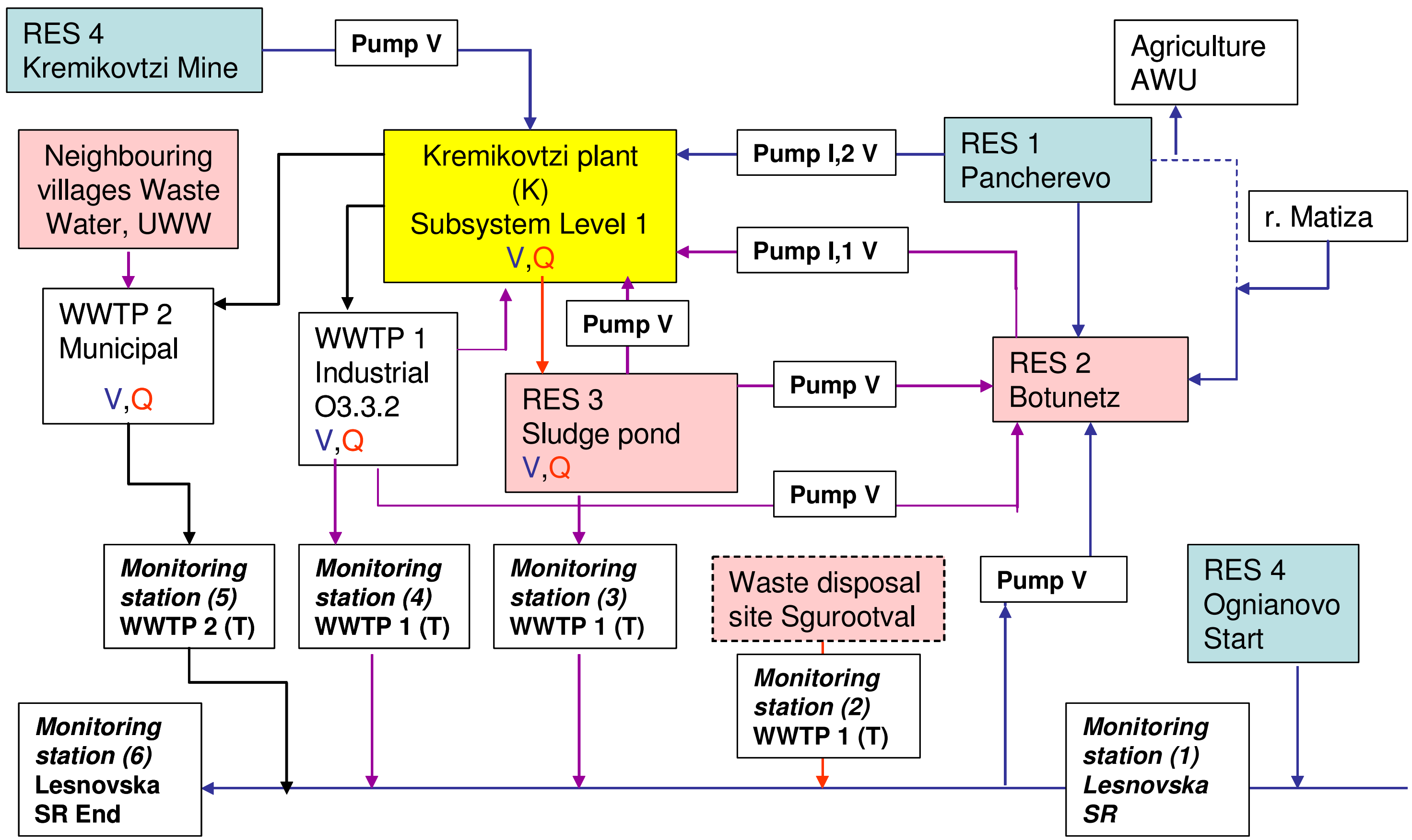
Case study: Kremikovtzi water system



Kremikovtzi conceptual model initial-July 2006- (1)



Kremikovtzi conceptual model October 2006- (2)



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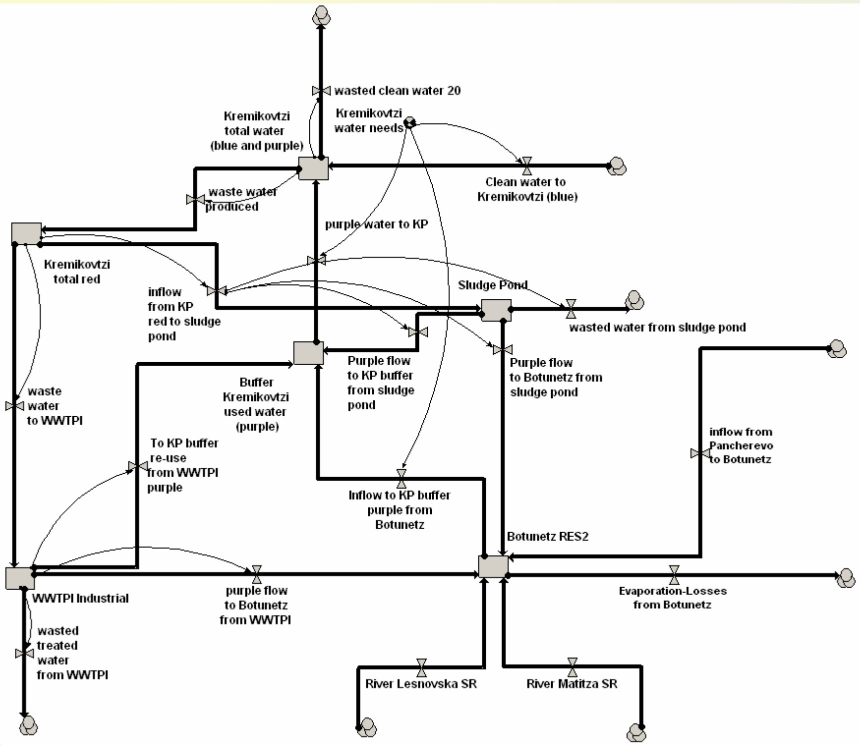
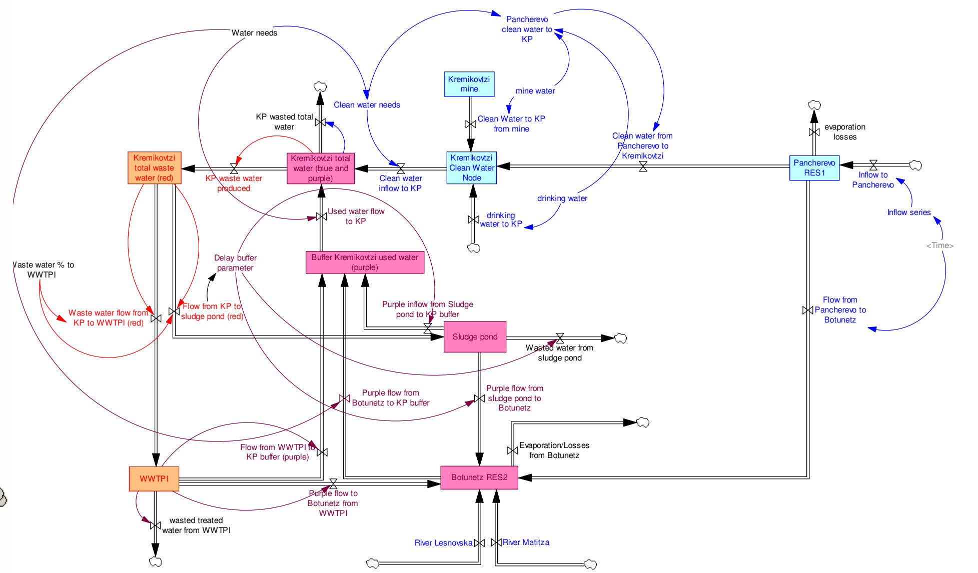
SDM: Initial SDM models

Initial SDM models for water quantities using different software tools (WB3-WB4-JWT-November 2006)

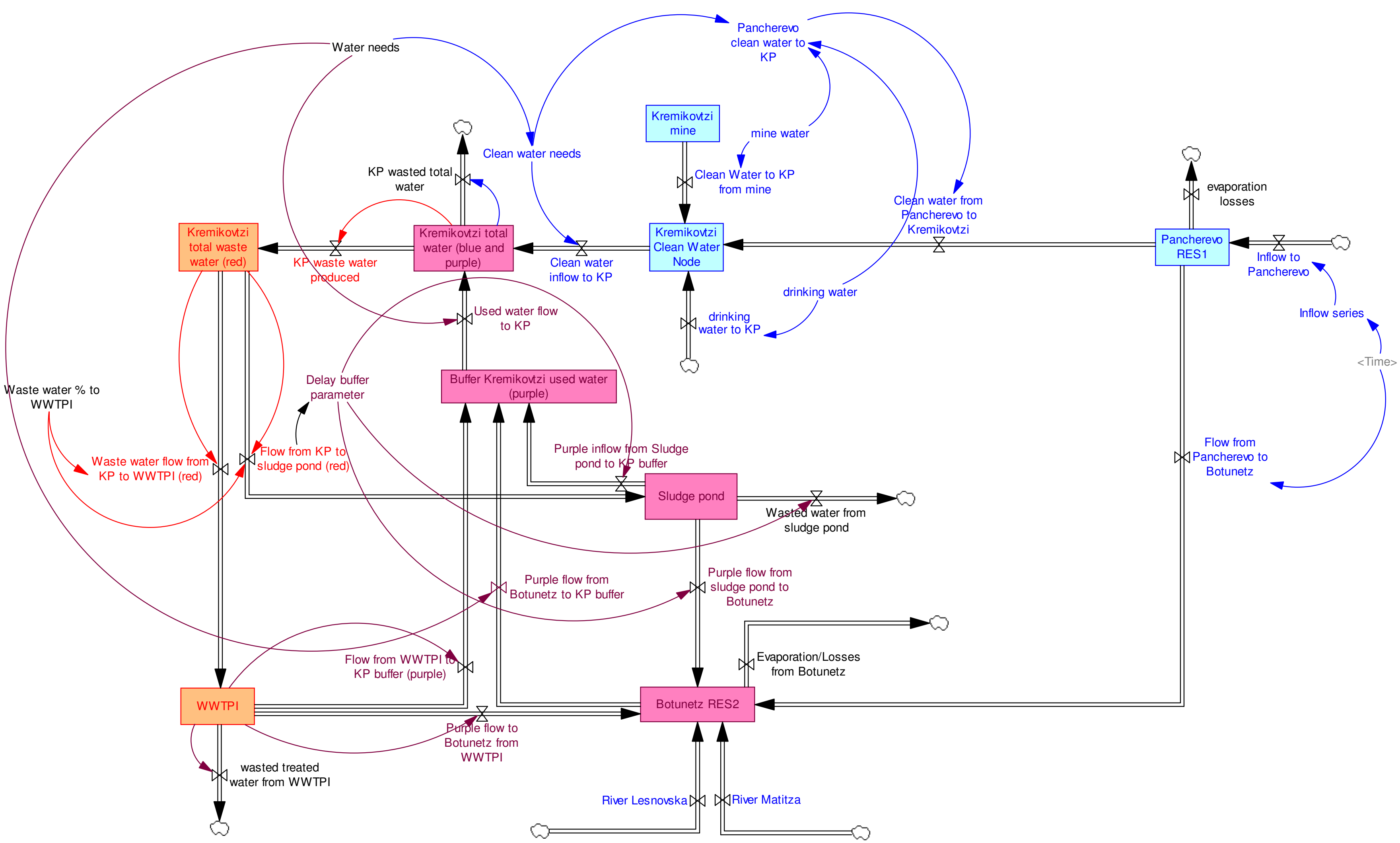


SIMILE

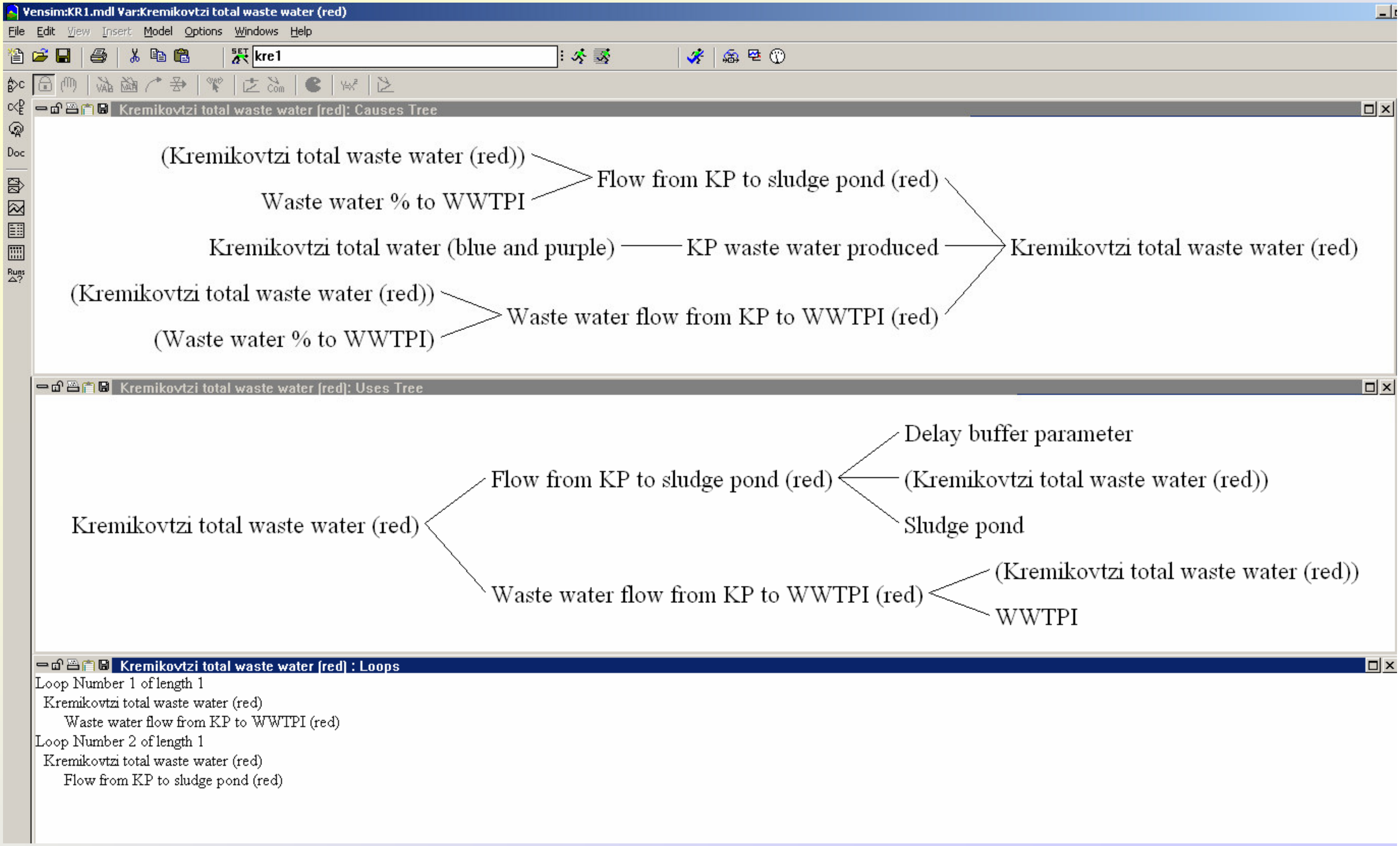


VENSIM

SDM model in VENSIM (November 2006- (3)



Causalities with VENSIM



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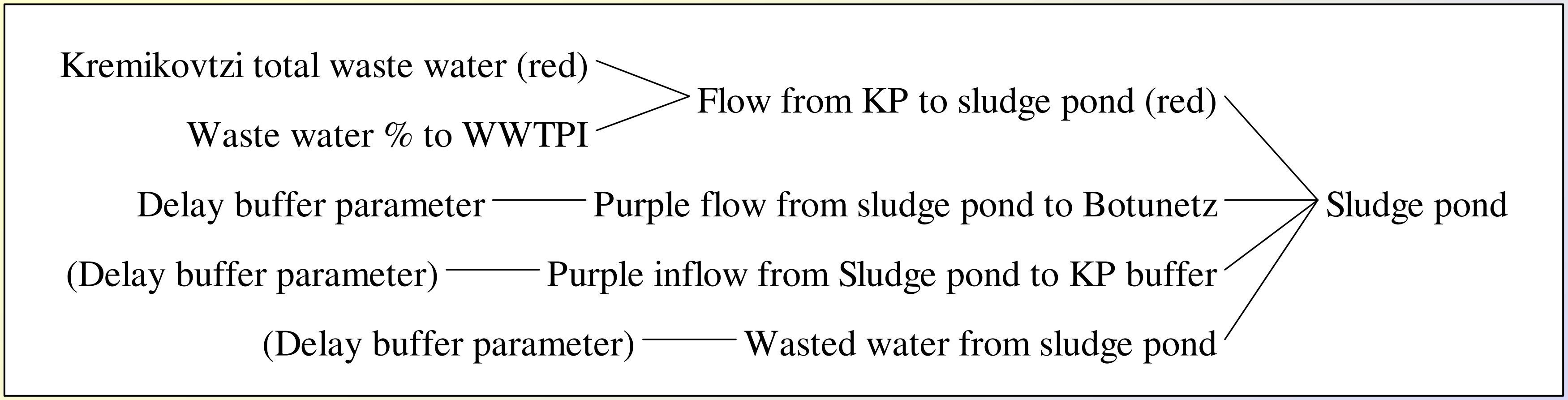
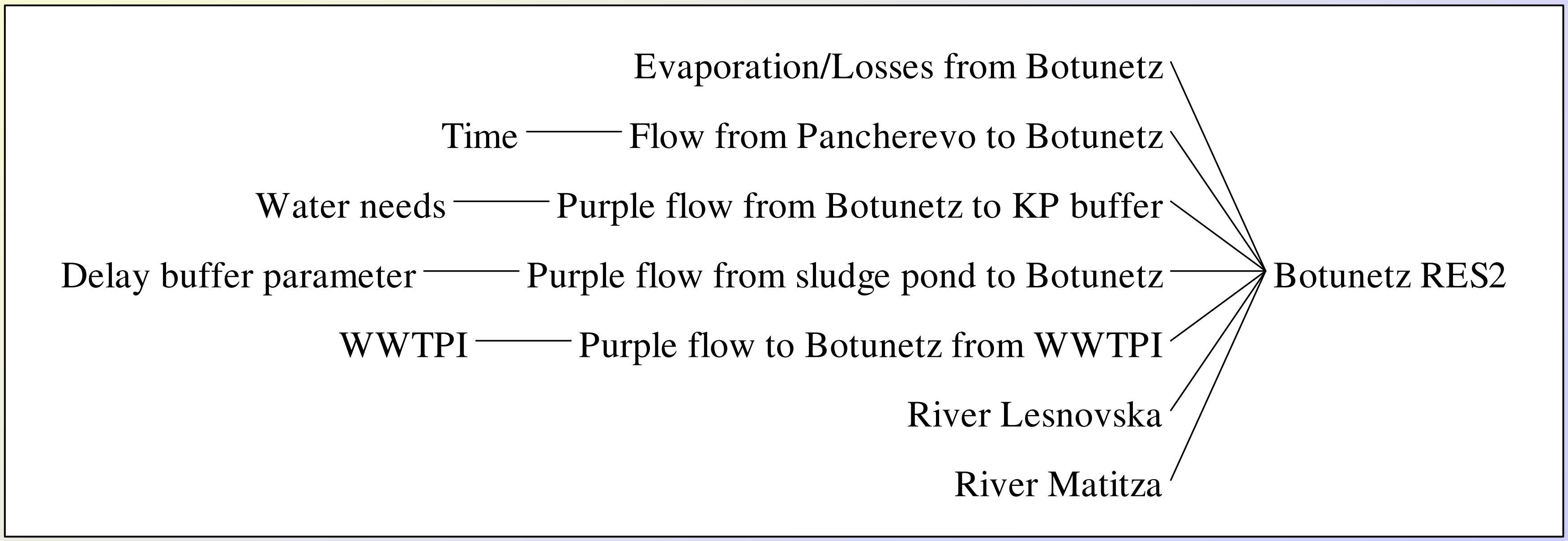
AQUASTRESS

Causalities with VENSIM





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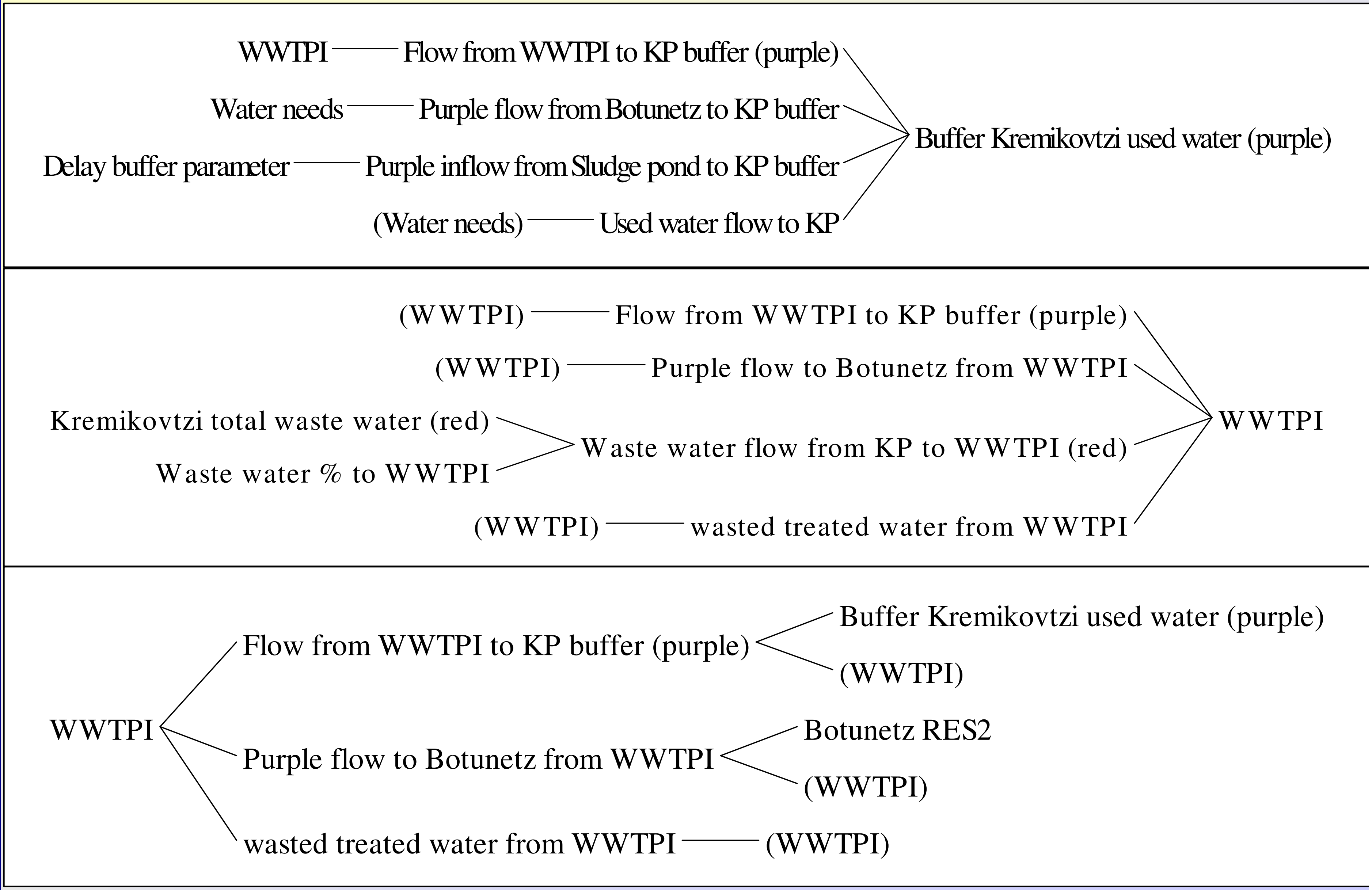
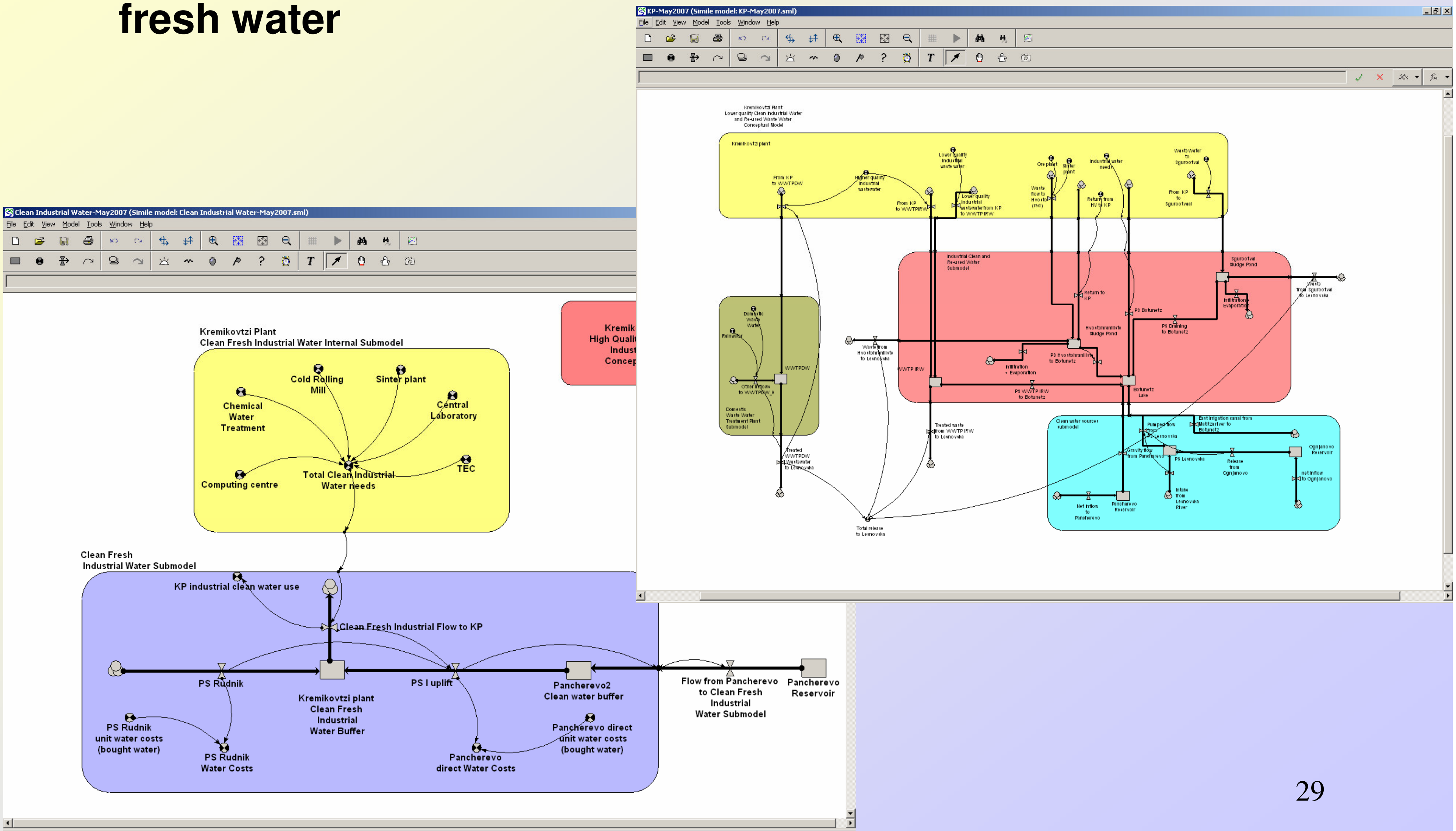
AQUASTRESS

Causalities with VENSIM



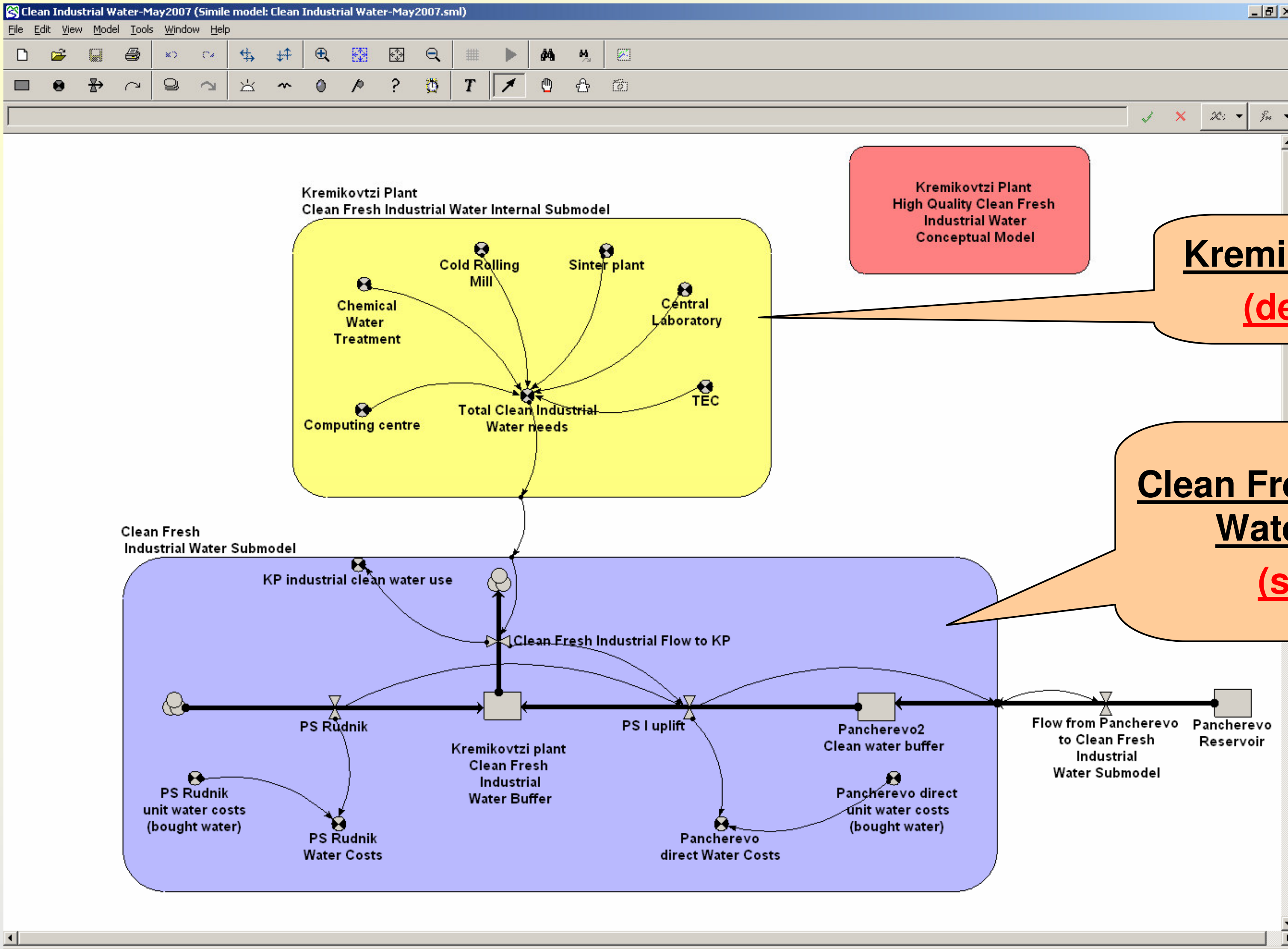
SDM: Intermediate SDM Models

(May 2007-July 2007) Separate models for higher and lower quality fresh water



SIMILE- May 2007-(4)

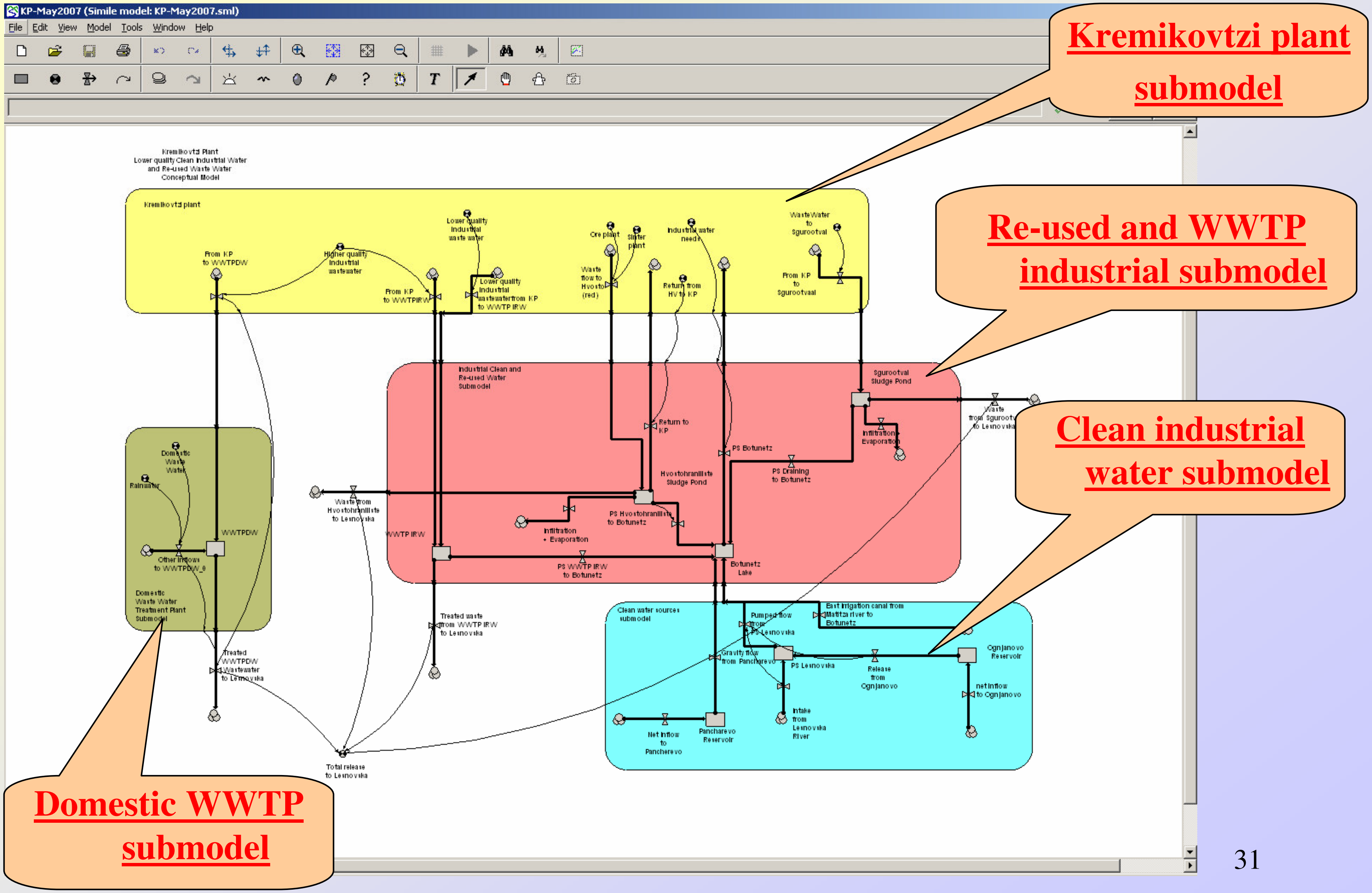
Clean industrial water model (2 sub-models)



Kremikovtzi plant (demands)

Clean Fresh Industrial Water Submodel (supply)

Re-used and waste water model



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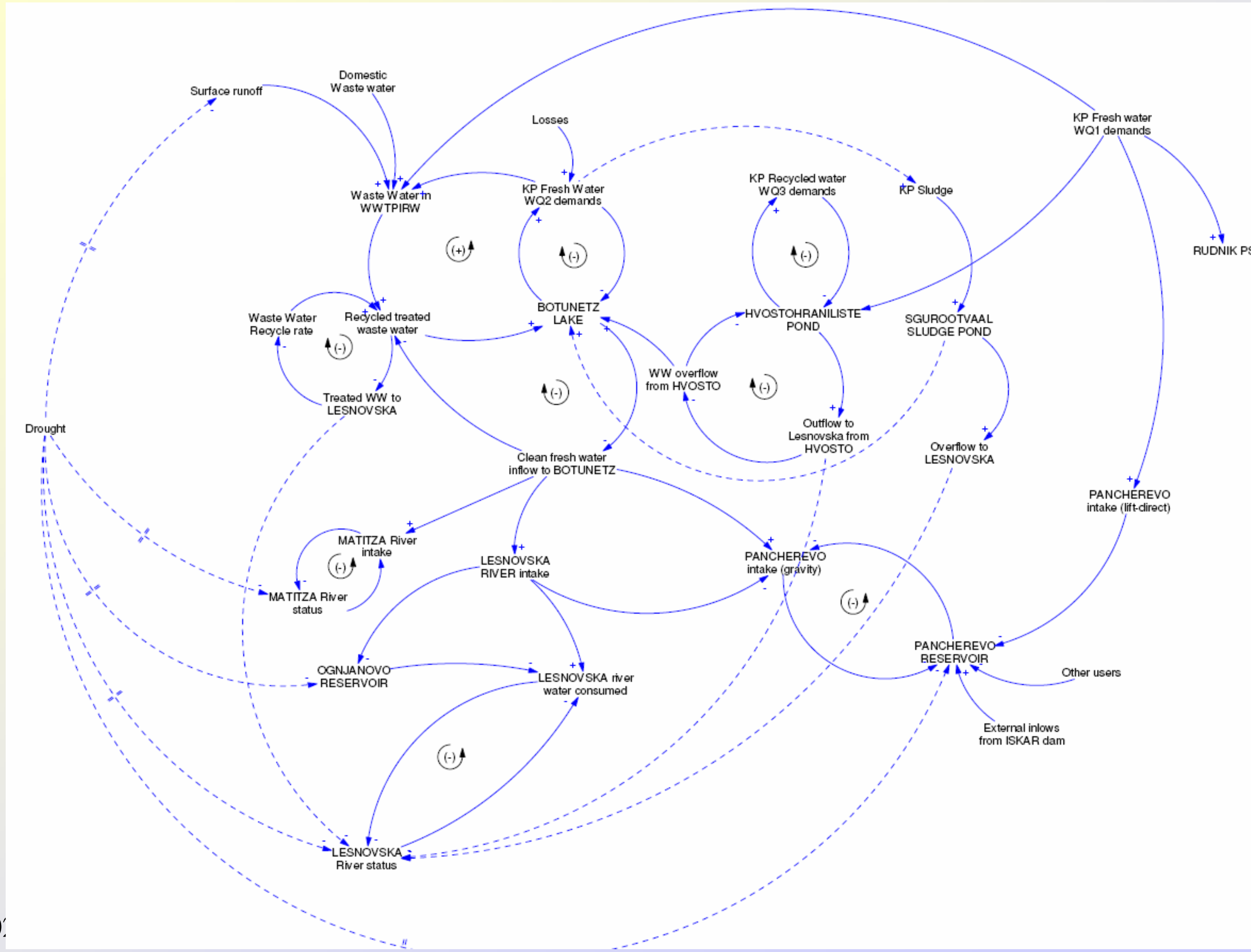
Final Model (Causal Loop Diagram)



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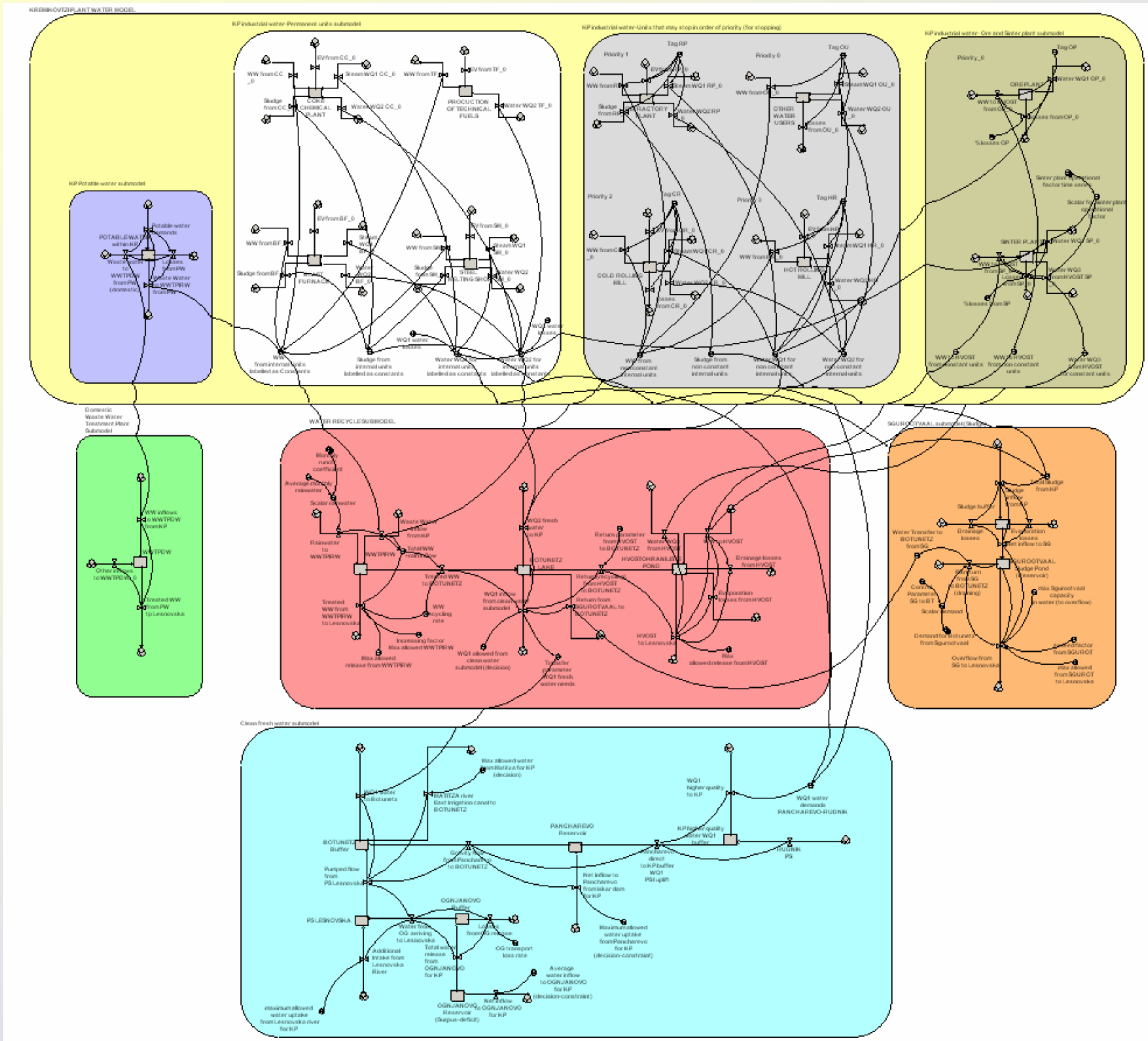
Final SDM Model Kremikovtzi



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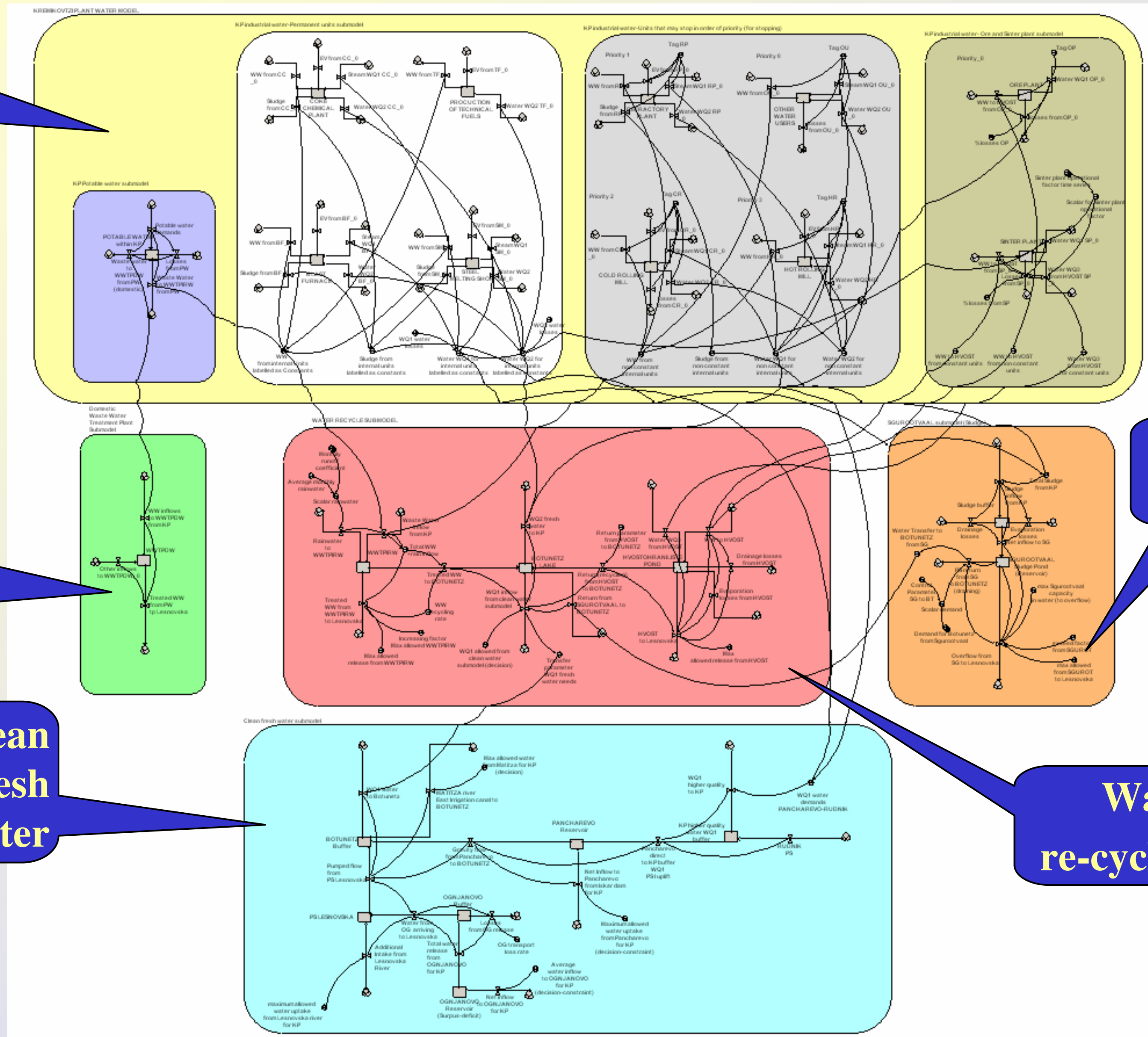
Final SDM Model Kremikovtzi

KP plant subsystem

Domestic Waste Water

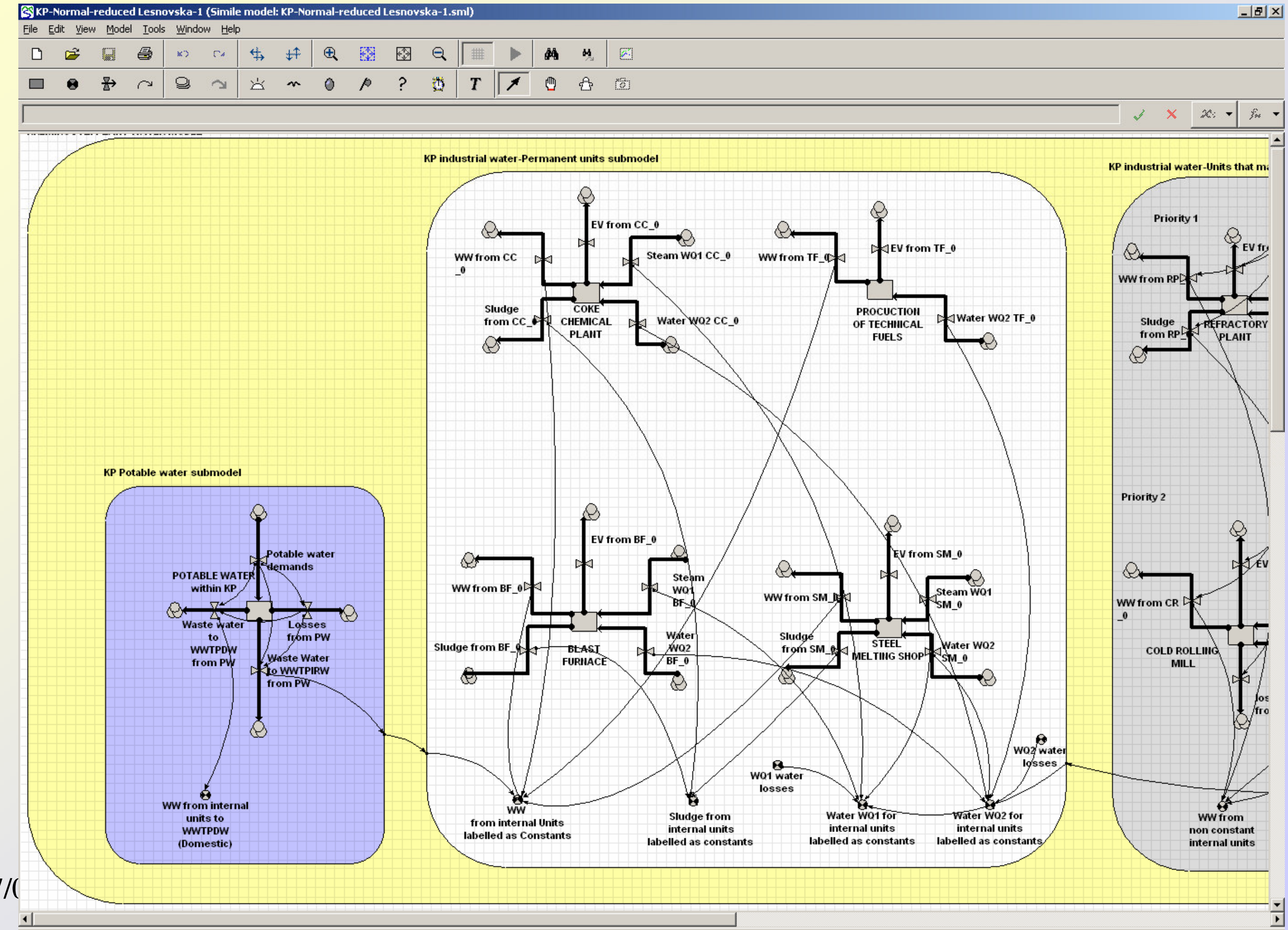
Clean Fresh Water



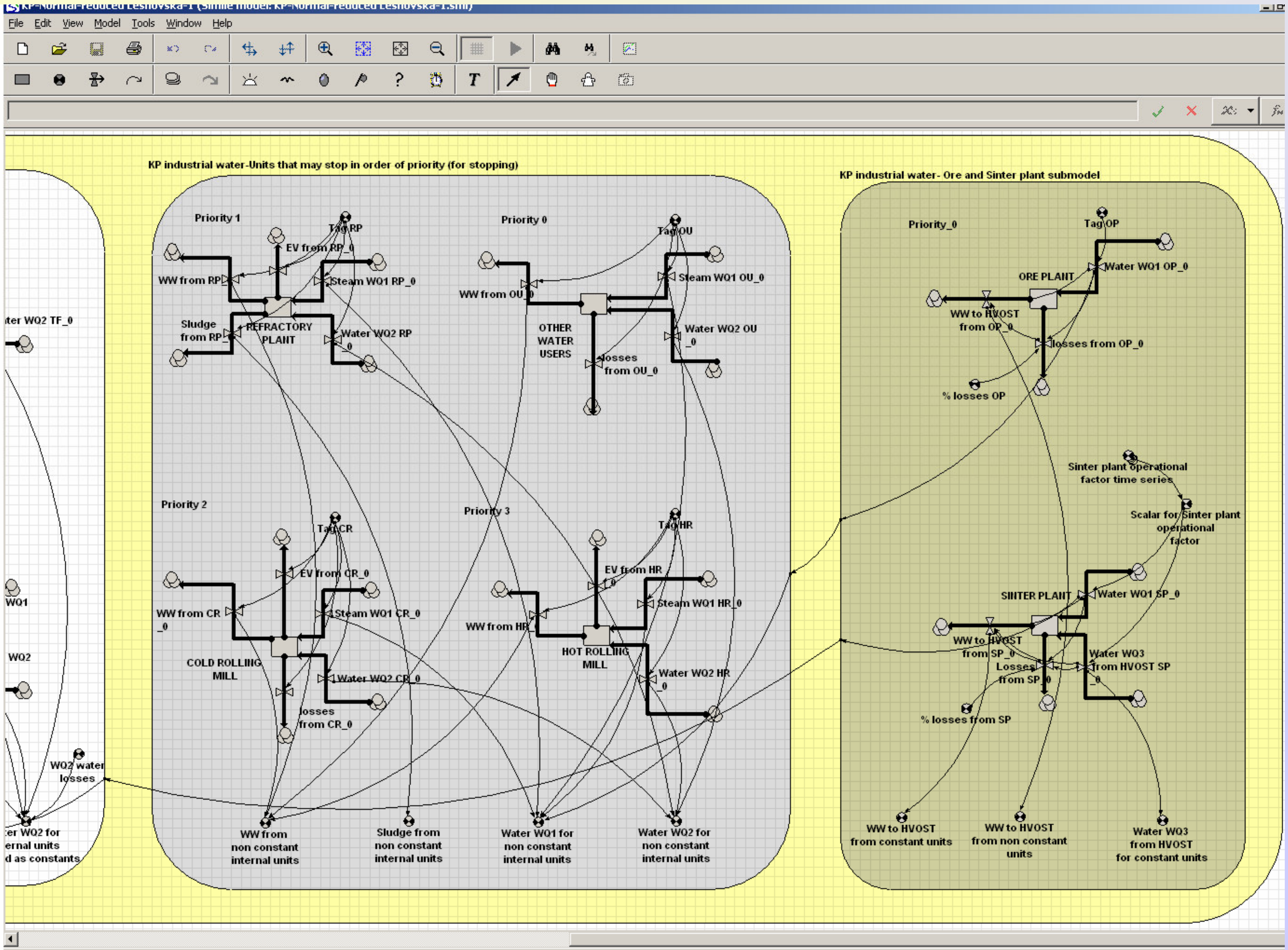
Sludge Pond

Water re-cycling

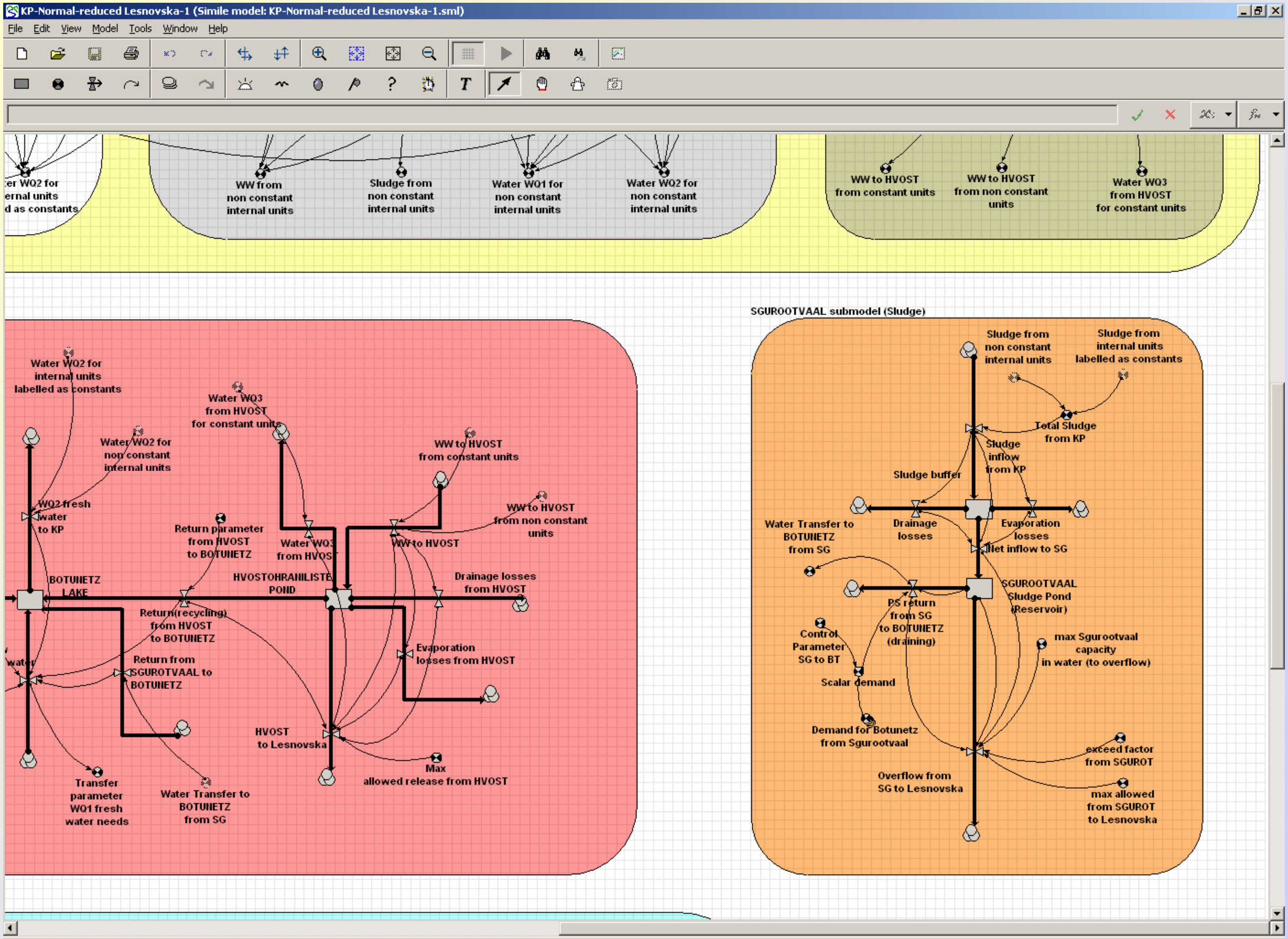
KP permanent units and potable water subsystems



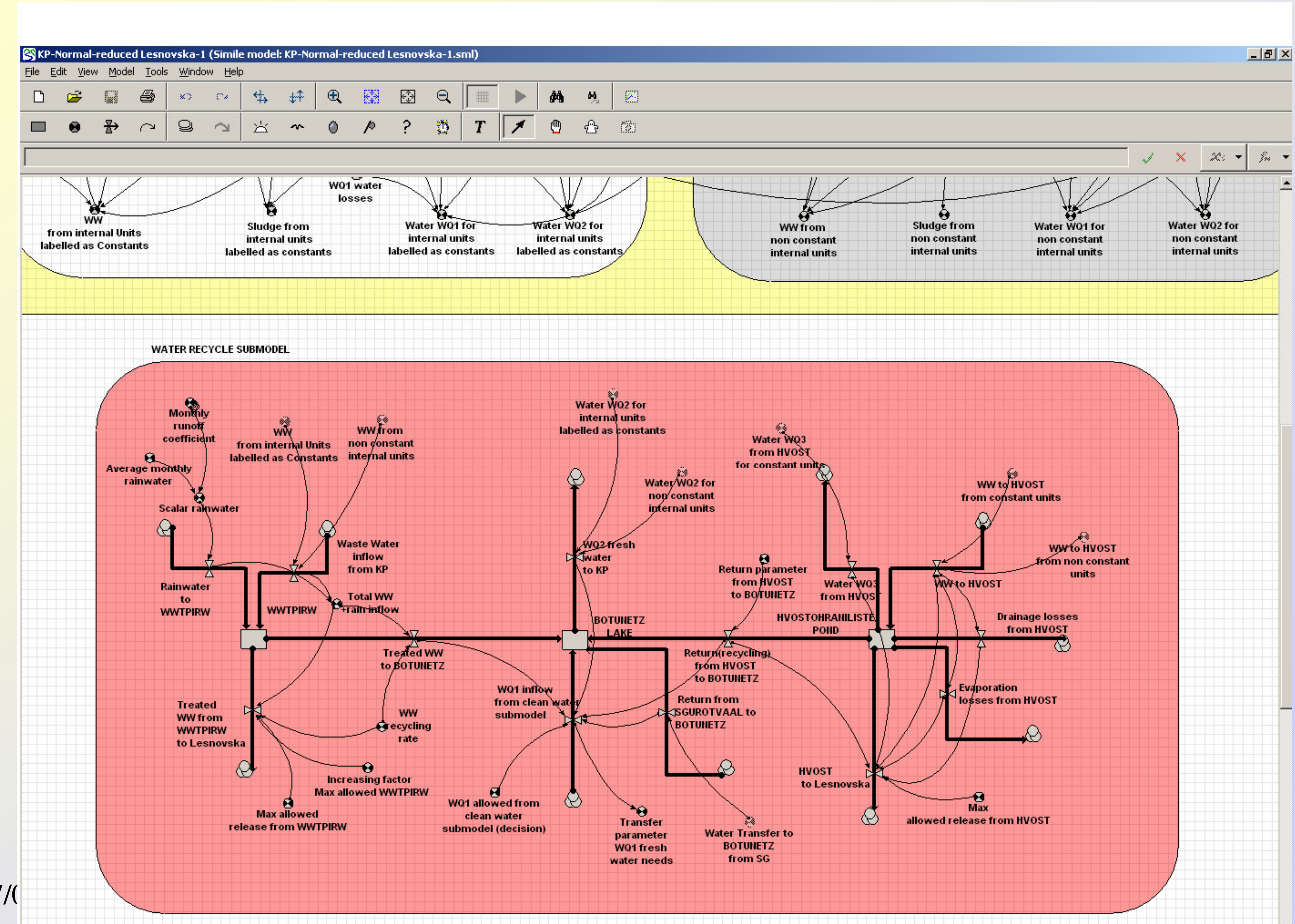
KP Non permanent units, Ore and Sinter plant units subsystems



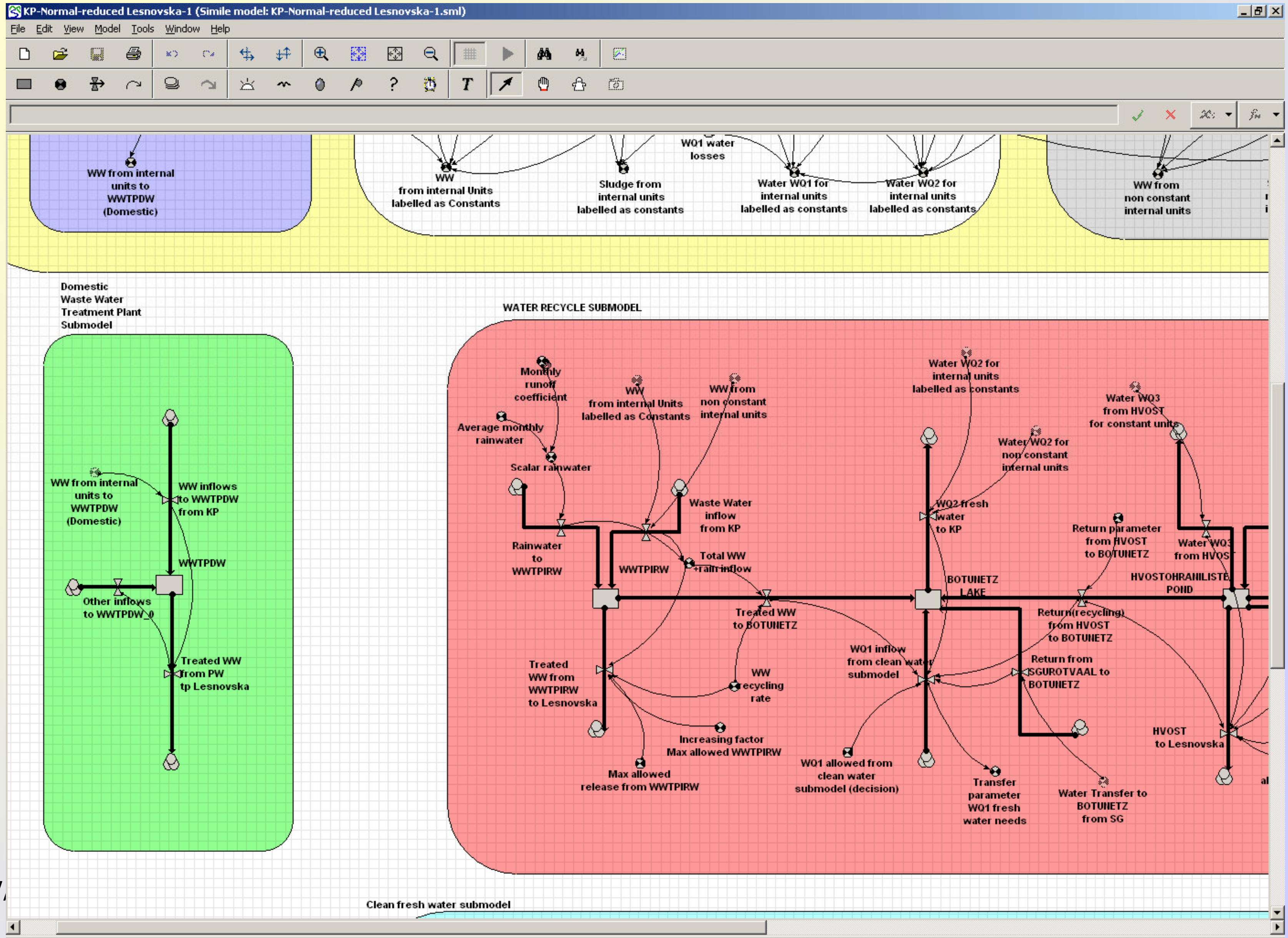
KP Sludge pond subsystem



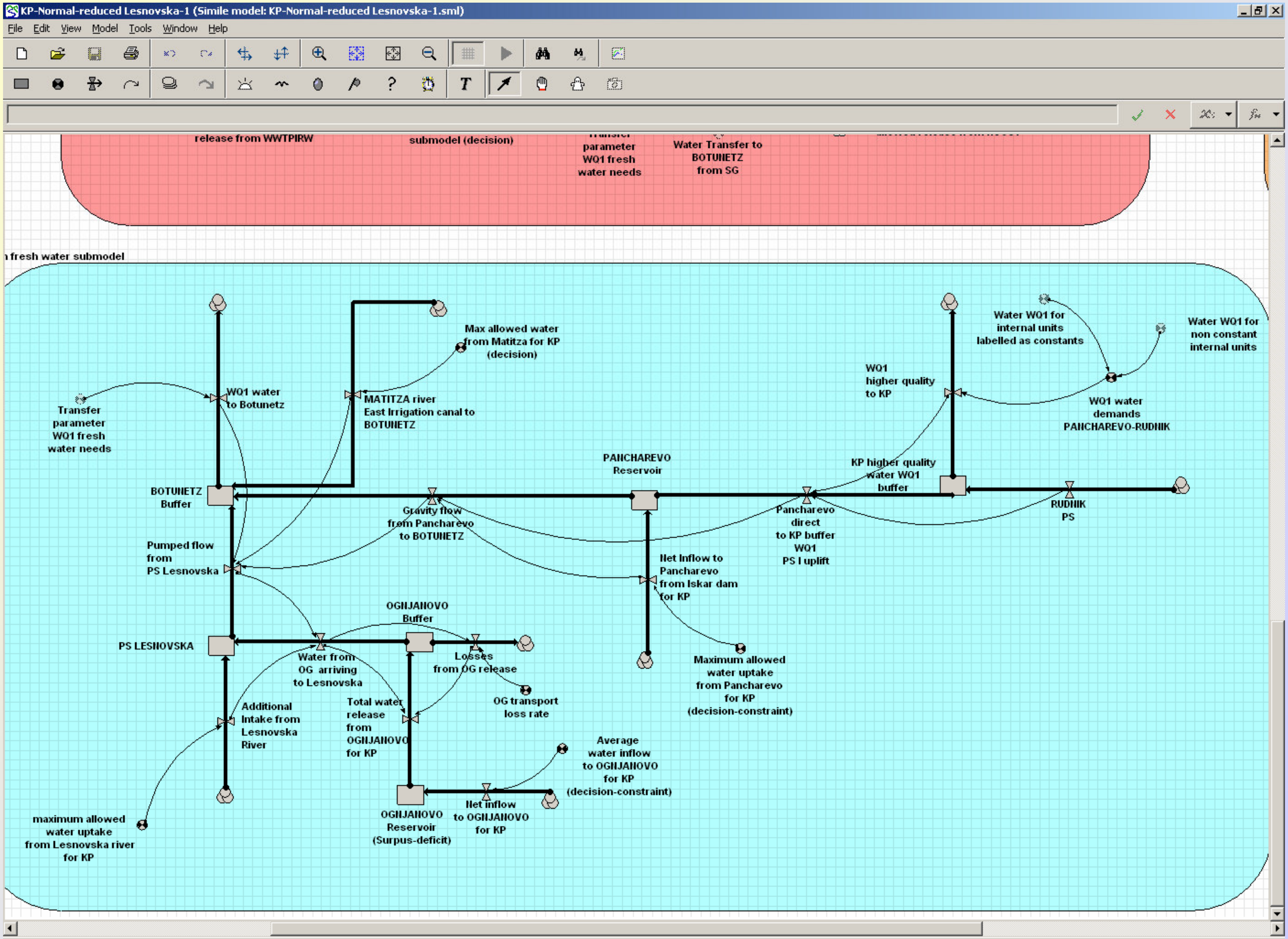
KP Water re-cycling subsystem



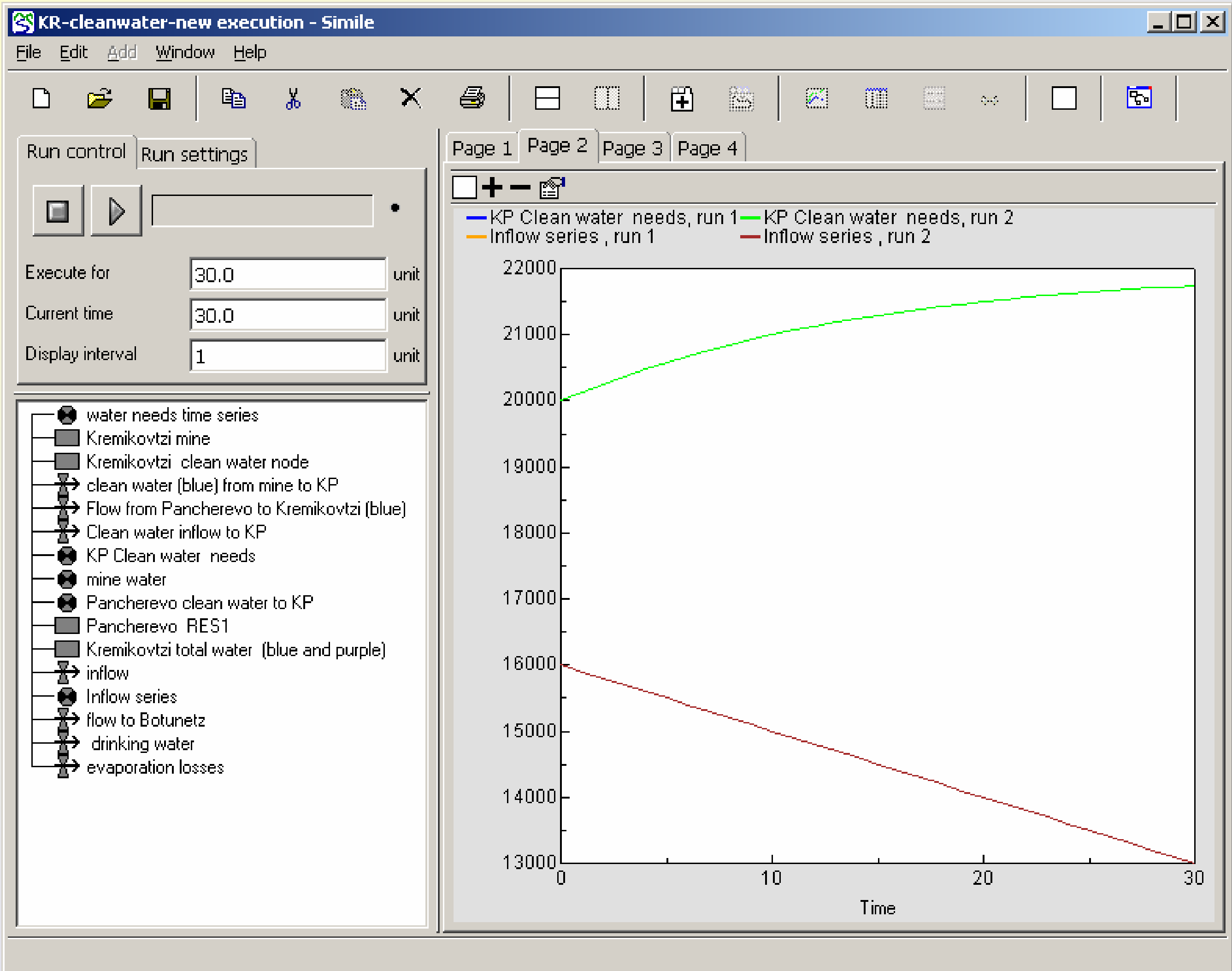
KP Domestic Waste Water Subsystem



KP Clean Fresh Water Subsystem



Generating scenarios with SIMILE



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AQUASTRESS

Generating scenarios with SIMILE

KR-PurpleRedWater-smallfonts execution - Simile

File Edit Add Window Help

Run control | Run settings

Execute for: 30.0 unit
Current time: 30.0 unit
Display interval: 1 unit

- Clean water to Kremikovtzi (blue)
- Botunetz RES2
- Sludge Pond
- Buffer Kremikovtzi used water (purple)
- WWTPI Industrial
- River Lesnovska SR
- River Matitza SR
- purple flow to Botunetz from WWTPI
- Purple flow to Botunetz from sludge pond
- Purple flow to KP buffer from sludge pond
- Inflow to KP buffer purple from Botunetz
- wasted treated water from WWTPI
- Kremikovtzi total water (blue and purple)
- purple water to KP
- inflow from Pancherevo to Botunetz
- Evaporation-Losses from Botunetz
- wasted water from sludge pond
- inflow from KP red to sludge pond
- Kremikovtzi water needs
- To KP buffer re-use from WWTPI purple
- Kremikovtzi total red
- waste water to WWTPI
- waste water produced
- wasted clean water 20
- Kremikovtzi water needs time series

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Time \ Name	Kremikovtzi water needs	To KP buffer re-use from WWTPI purple	Buffer Kremikovtzi used water (purple)	Sludge Pond	Botunetz RES2	Kremikovtzi total red	waste water to WWTPI	purple water to KP	inflow from KP red to sludge pond
0.0	40000.0000	14112.0000	0.0000	10000.0000	10000.0000	32000.0000	20160.0000	20000.0000	11840.0000
1.0	40264.1502	14112.0000	2112.0000	21840.0000	12911.2000	32000.0000	20160.0000	20132.0751	11840.0000
2.0	40511.9668	14112.0000	4736.7549	23024.0000	16261.5700	32000.0000	20160.0000	20255.9834	11840.0000
3.0	40744.2589	14112.0000	7287.1649	24208.0000	19462.3766	32211.3201	20293.1317	20372.1294	11918.1885
4.0	40961.8226	14205.1922	9767.8872	25470.1885	22516.7248	32409.5734	20418.0313	20480.9113	11991.5422
5.0	41165.4373	14292.6219	12280.4421	26735.3610	25440.7889	32595.4071	20535.1065	20582.7186	12060.3006
6.0	41355.8619	14374.5745	14823.0099	28003.2737	28236.5408	32769.4581	20644.7586	20677.9309	12124.6995
7.0	41533.8325	14451.3310	17393.8409	29273.7026	30905.8409	32932.3498	20747.3804	20766.9162	12184.9694
8.0	41700.0605	14523.1663	19991.2571	30546.4425	33450.4425	33084.6895	20843.3544	20850.0302	12241.3351
9.0	41855.2306	14590.3481	22613.6537	31821.3051	35871.9955	33227.0660	20933.0516	20927.6153	12294.0144
10.0	42000.0000	14653.1361	25259.4994	33098.1180	38172.0509	33360.0484	21016.8305	21000.0000	12343.2179
11.0	42134.9976	14711.7813	27927.3362	34376.7229	40352.0652	33484.1845	21095.0362	21067.4988	12389.1483
12.0	42260.8238	14766.5254	30615.7791	35656.9750	42413.4048	33600.0000	21168.0000	21130.4119	12432.0000
13.0	42378.0502	14817.6000	33323.5148	36938.7416	44357.3499	33707.9981	21236.0388	21189.0251	12471.9593
14.0	42487.2197	14865.2272	36049.2997	38221.9009	46185.0999	33808.6591	21299.4552	21243.6099	12509.2039
15.0	42588.8476	14909.6186	38791.9589	39506.3414	47897.7766	33902.4401	21358.5373	21294.4238	12543.9028
16.0	42683.4212	14950.9761	41550.3835	40791.9607	49496.4292	33989.7758	21413.5587	21341.7106	12576.2170
17.0	42771.4011	14989.4911	44323.5284	42078.6652	50982.0377	34071.0781	21464.7792	21385.7005	12606.2989
18.0	42853.2219	15025.3454	47110.4100	43366.3688	52355.5174	34146.7369	21512.4443	21426.6110	12634.2927
19.0	42929.2931	15058.7110	49910.1038	44654.9924	53617.7225	34217.1209	21556.7861	21464.6466	12660.3347
20.0	43000.0000	15089.7503	52721.7415	45944.4638	54769.4496	34282.5775	21598.0239	21500.0000	12684.5537
21.0	43065.7046	15118.6167	55544.5085	47234.7162	55811.4414	34343.4345	21636.3637	21532.8523	12707.0708
22.0	43126.7467	15145.4546	58377.6415	48525.6887	56744.3899	34400.0000	21672.0000	21563.3734	12728.0000
23.0	43183.4452	15170.4000	61220.4257	49817.3250	57568.9395	34452.5636	21705.1151	21591.7226	12747.4485
24.0	43236.0988	15193.5806	64072.1921	51109.5735	58285.6905	34501.3974	21735.8803	21618.0494	12765.5170
25.0	43284.9870	15215.1162	66932.3155	52402.3868	58895.2012	34546.7562	21764.4564	21642.4935	12782.2998
26.0	43330.3713	15235.1195	69800.2115	53695.7213	59397.9913	34588.8790	21790.9938	21665.1857	12797.8852
27.0	43372.4962	15253.6957	72675.3346	54989.5367	59794.5440	34627.9896	21815.6334	21686.2481	12812.3561
28.0	43411.5901	15270.9434	75557.1756	56283.7962	60085.3085	34664.2970	21838.5071	21705.7951	12825.7899
29.0	43447.8661	15286.9550	78445.2598	57578.4655	60270.7027	34697.9970	21859.7381	21723.9330	12838.2589
30.0	43481.5230	15301.8167	81339.1444	58873.5135	60351.1144	34729.2721	21879.4414	21740.7615	12849.8307

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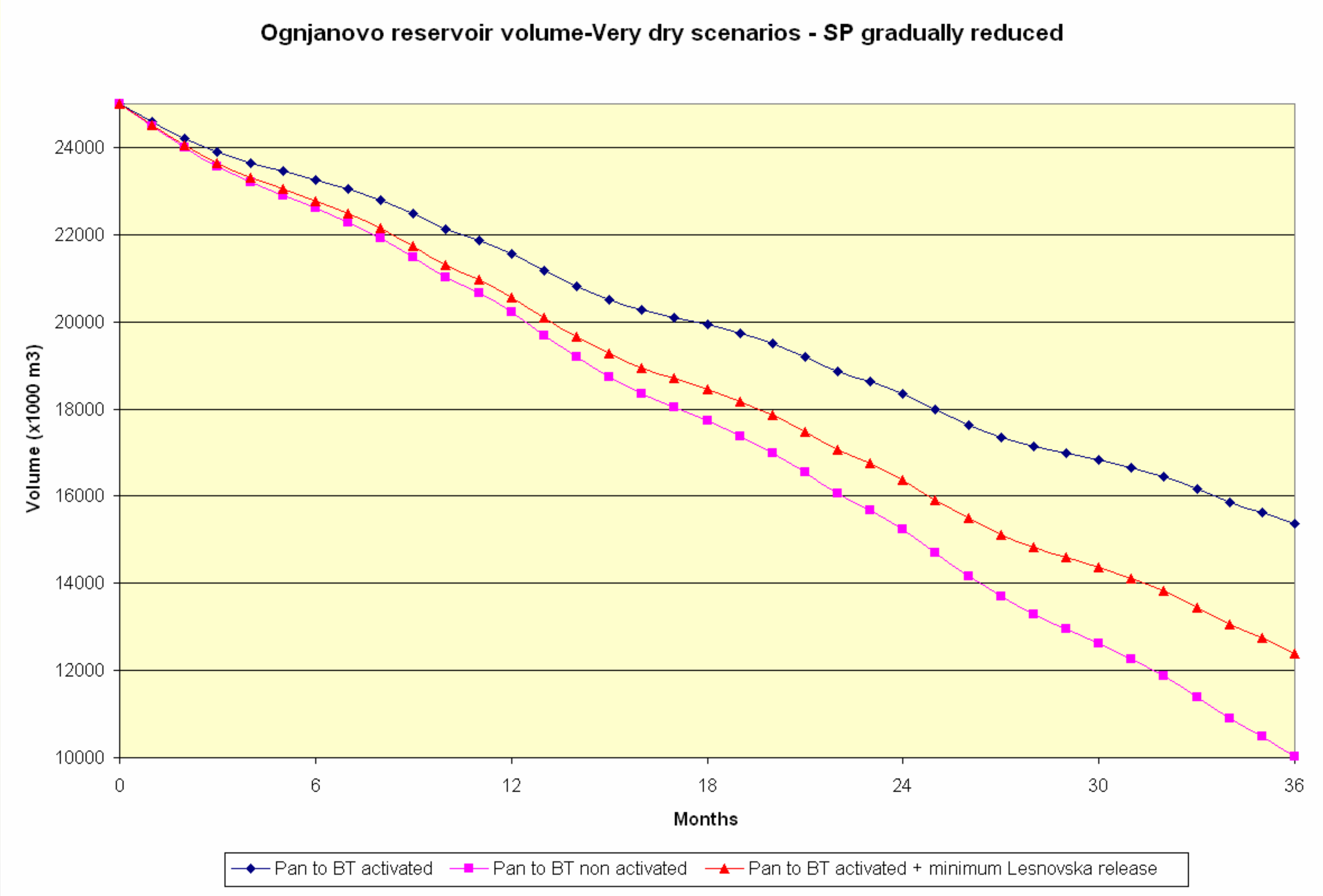
KP Results-Alternatives



KP Results-System total recycling rate

Very dry	All on	0.6276
95%	OP stops	0.6230
	OP stops+ Other water users (Priority 0)	0.6374
	OP stops+ Non permanent units (Priority 1)	0.6298
	OP stops+ Non permanent units (Priority 2)	0.6299
	OP stops+ Non permanent units (Priority 3)	0.6010
	OP stops+ Non permanent units (Priority 3)+ SP 5/6	0.5906
	OP stops+ Non permanent units (Priority 3)+ SP 4/6	0.5793
	OP stops+ Non permanent units (Priority 3)+ SP 3/6	0.5671
	OP stops+ Non permanent units (Priority 3)+ SP 5/6+Lesnovska release	0.5661
	OP stops+ Non permanent units (Priority 3)+ SP 4/6+Lesnovska release	0.5539
	OP stops+ Non permanent units (Priority 3)+ SP 3/6+Lesnovska release	0.5405
Dry	Recycle 90%+ Return WQ3	0.6224
	Recycle 90%	0.5785
Normal	Recycle 75%	0.5330
	Recycle 70%	0.5045
	Recycle 65%	0.4759
	Recycle 60%	0.4474

AQUASTRESS SDM: Case studies

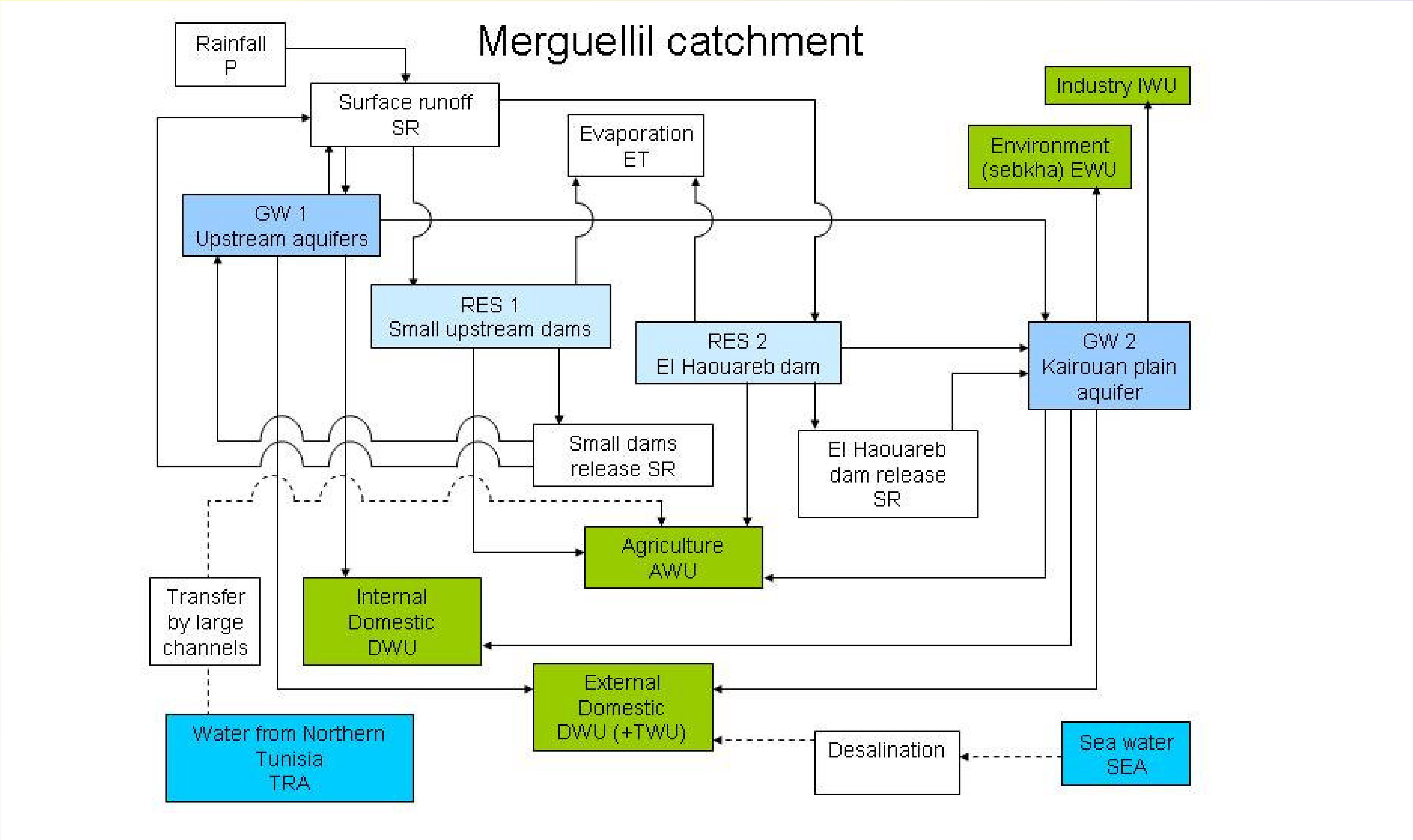
1. Kremikovtzi plant water system – (Bulgaria)

- *Industrial (competitive) water use – limited water resources*
- *Improve the rate of water re-use*
- *Study operational policies for dry and very dry years*

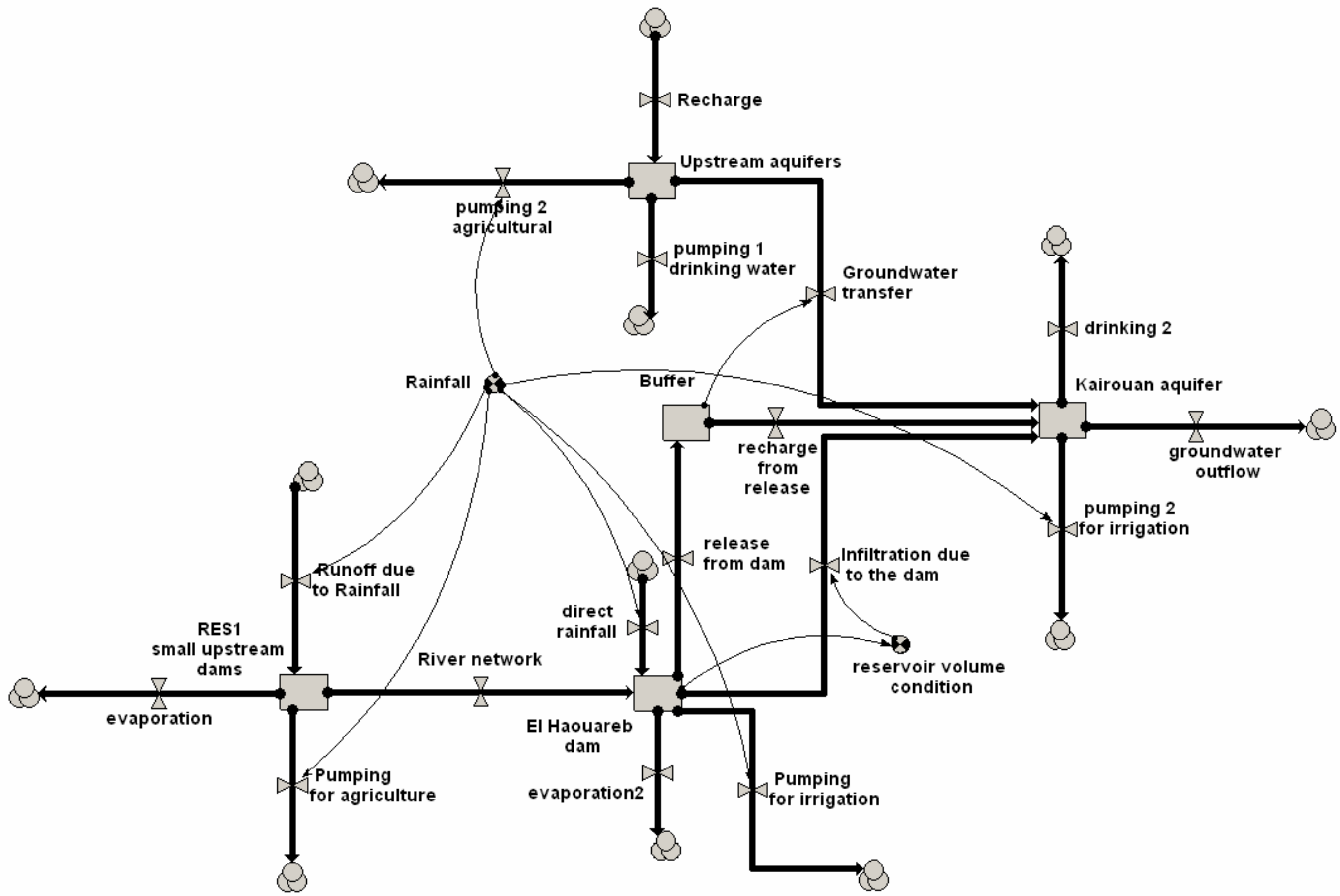
2. Merguellil catchment (valley) aquifer management – (Tunisia)

- *Hydrological model (group of small dams+1 large dam)*
- *Study agricultural water use*
- *Improve aquifer recharge and management*

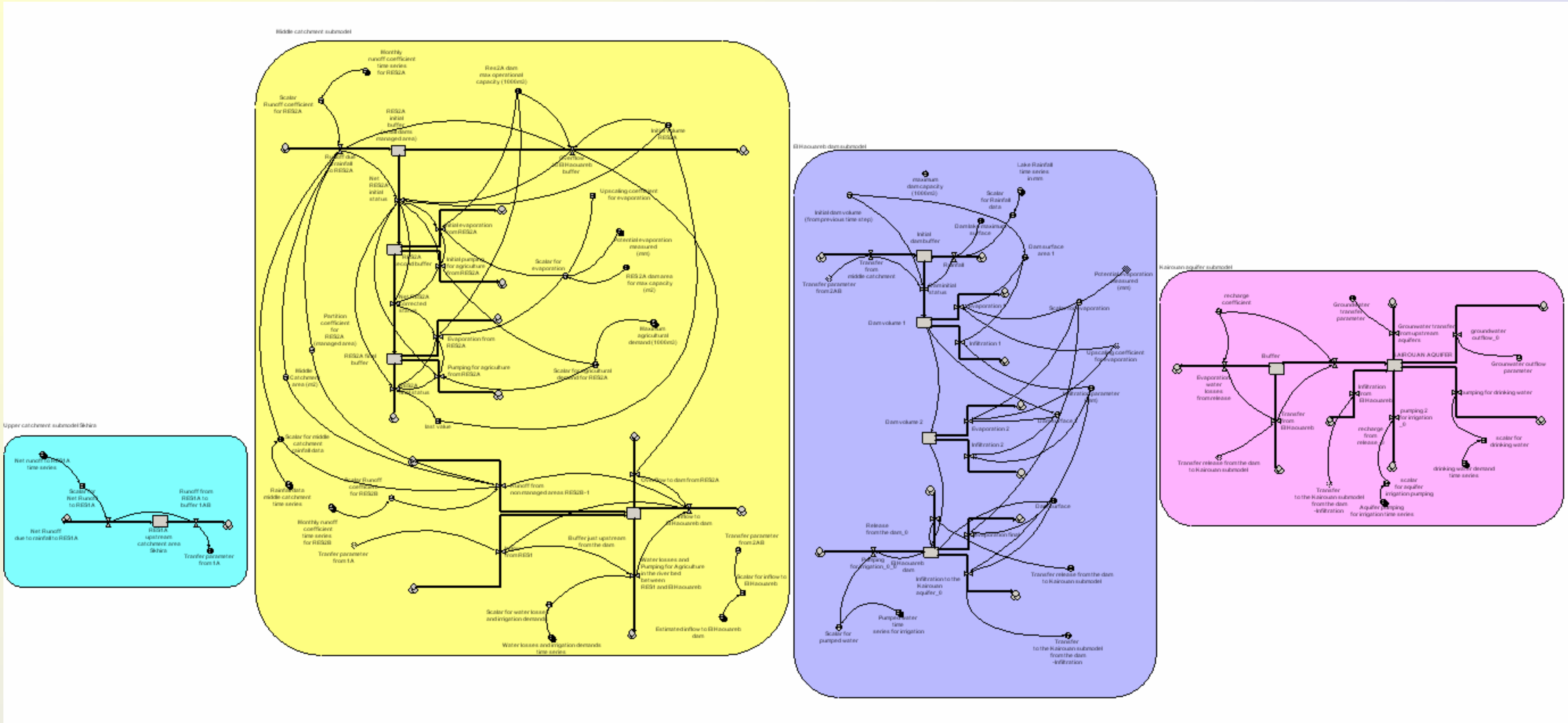
Merguellil conceptual model (Tunisia)



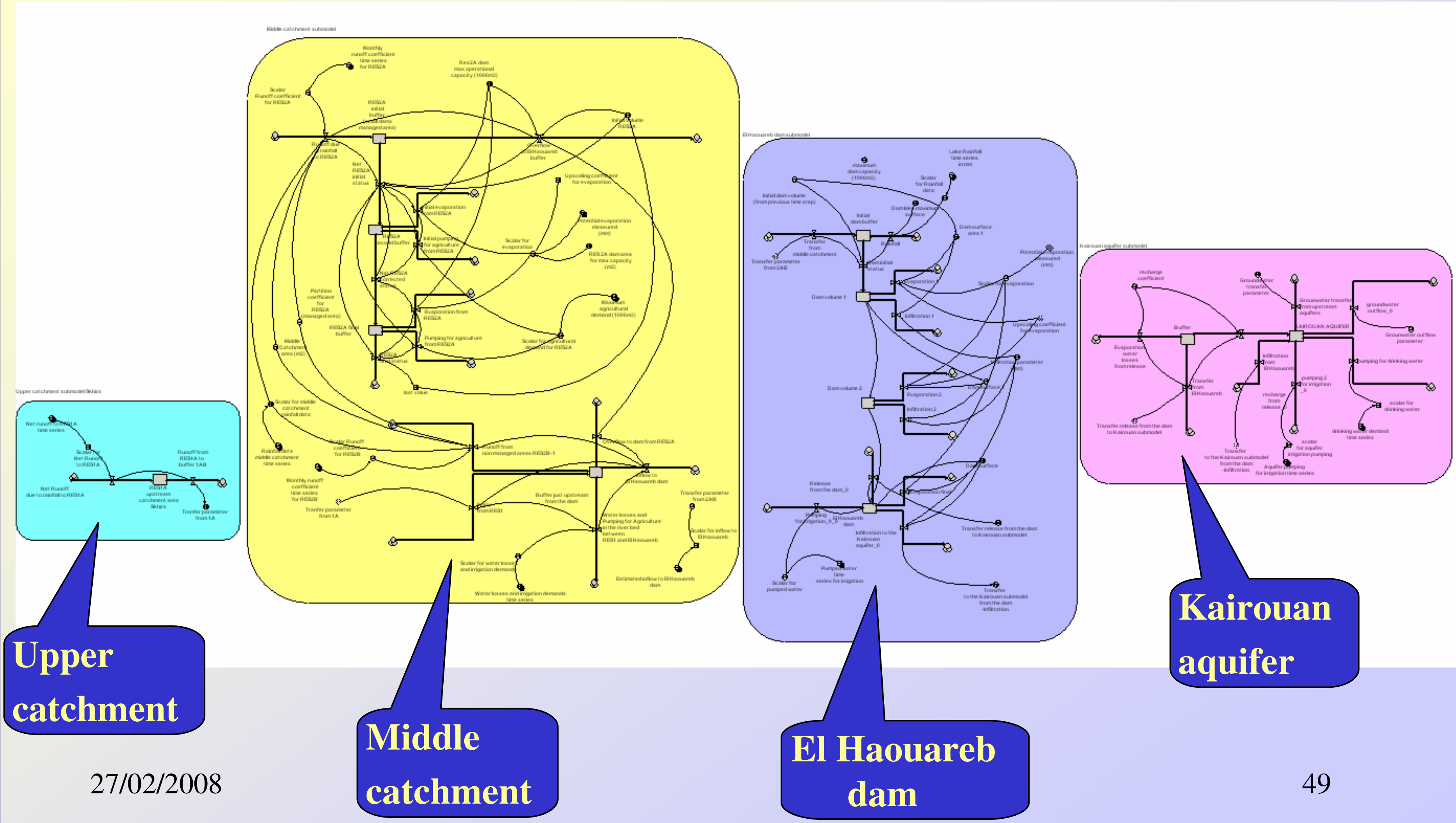
Merguellil SDM (Tunisia) Initial model



Merguellil SDM (Tunisia) final model



Merguellil SDM (Tunisia) final model



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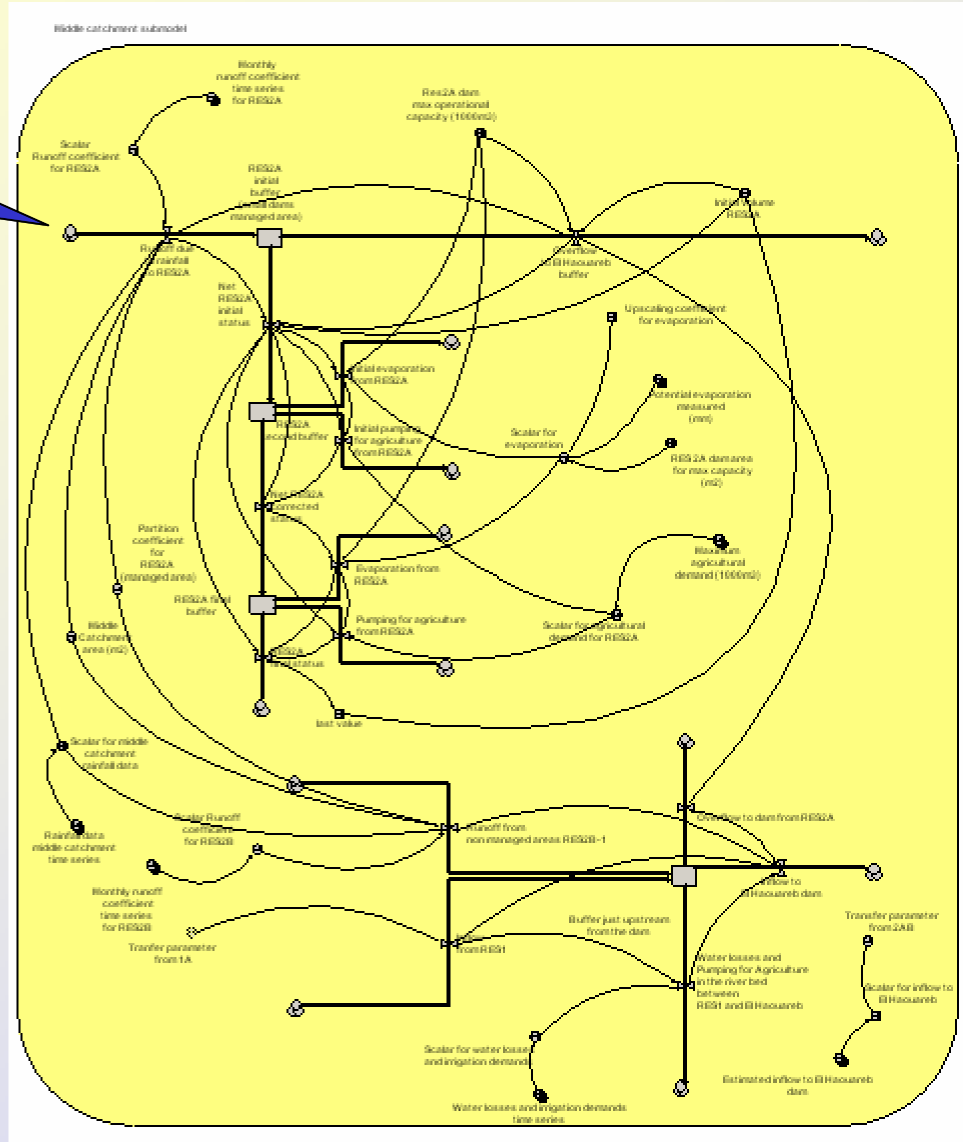
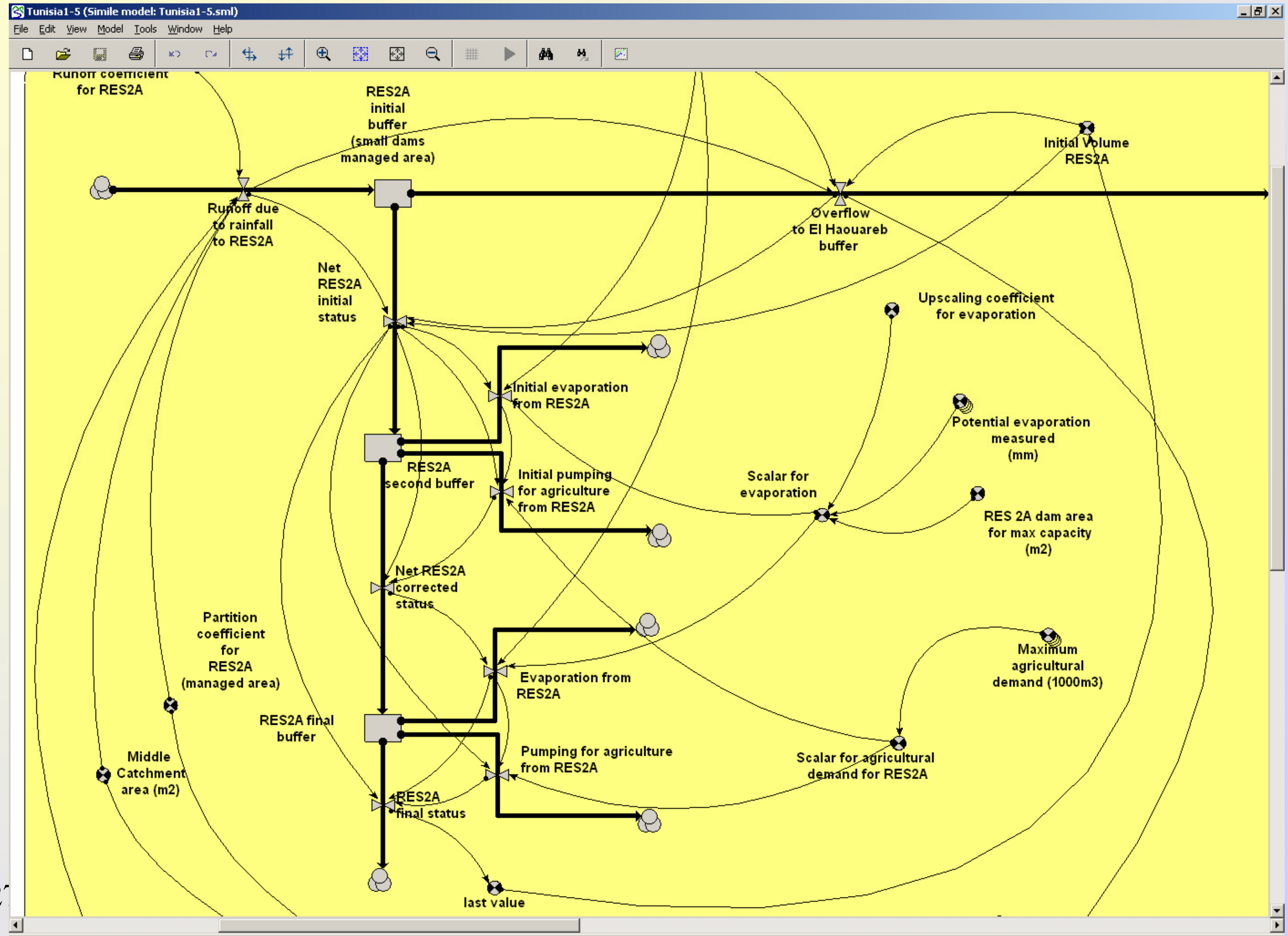
Merguellil SDM (Tunisia) final model

Middle catchment



Merguellil SDM (Tunisia) detail



SDM: Advantages/Disadvantages

Advantages

- Easy to build models for complex, "non-specific" systems
- Good graphics environment
- Easy to make others understand and get involved
- Easy to run and compare scenarios
- SDM: Modelling by "afterthought"
- Especially useful for "time series" runs

Disadvantages

- Iterative procedures within the same time step to be avoided
- Need for special "simulation schemes"/logic (e.g. continuity)
- Multiple variables for the same component need to be separated

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Time for demo display…