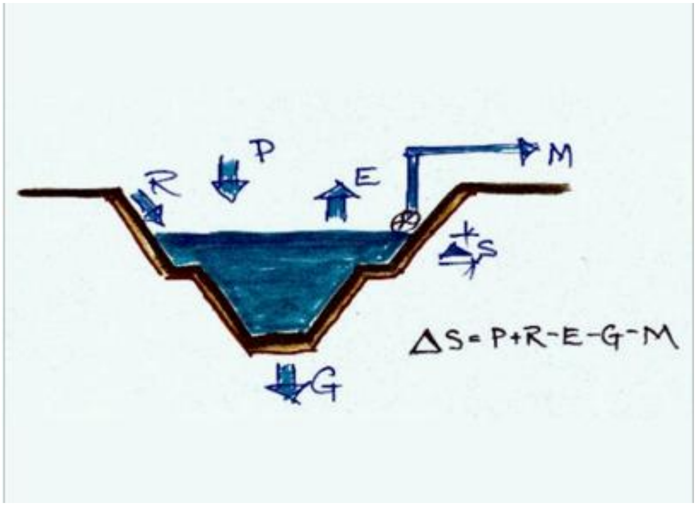
System dynamics modelling framework with specialized water management modules



WaterSmart seminar/Green Mining Programme 28.8.2015

SYKE’s auditorium, Helsinki

Juhani Korkealaakso, VTT

Recent developments in system dynamic modelling allow integration and assessment of all the factors and processes that may impact water management at the mine site → Goldsim programming platform as an example

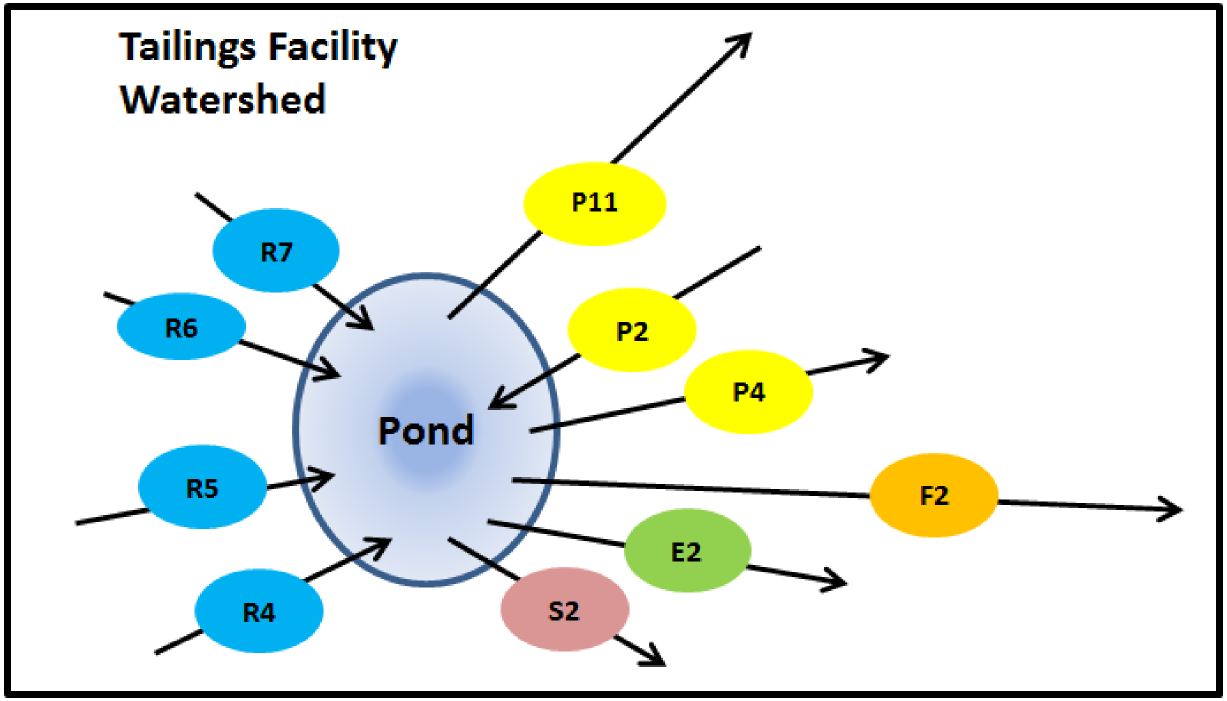
- It is possible to extend the water balance calculations to include dynamic and probabilistic (uncertainty and sensitivity analysis) simulations as well as mass balances of water quality and further to include also the geochemical transport and reactions in variably saturated porous media
- It is possible to extend, define and edit the water balance calculations for the varying planning and operational needs of different life cycle phases of the mining project
- It is possible to link and integrate databases and external programs like mineral process simulators, reactive, hydrochemical transport models, 3D surface, seepage and groundwater flow models etc. into the system platform and into the overall dynamic calculations
- It is possible to combine monitoring information into water balance modelling and to continuously update model predictions and parameters always when new measurements are available. It is possible to carry out multitask optimizations and with weather forecasts produce flow etc. forecasts
- It is possible to program own process modules like climate generators, detailed waste pile and tailing structures and processes, etc. and produce own mine-specific software with client-specific user interfaces and control panels

Water management on a mining operation begins with an understanding of where the water comes from and where it goes…

The conventional water balance is deterministic and only about water flows…

The deduction of flows to and from the specific operating unit within the mine water circuit – to account for all inflows, outflows and losses across the unit and calculating the unknown flow as the balancing flow

F2= R7+R6+R5+R4+P2-P11-P4-E2-S2



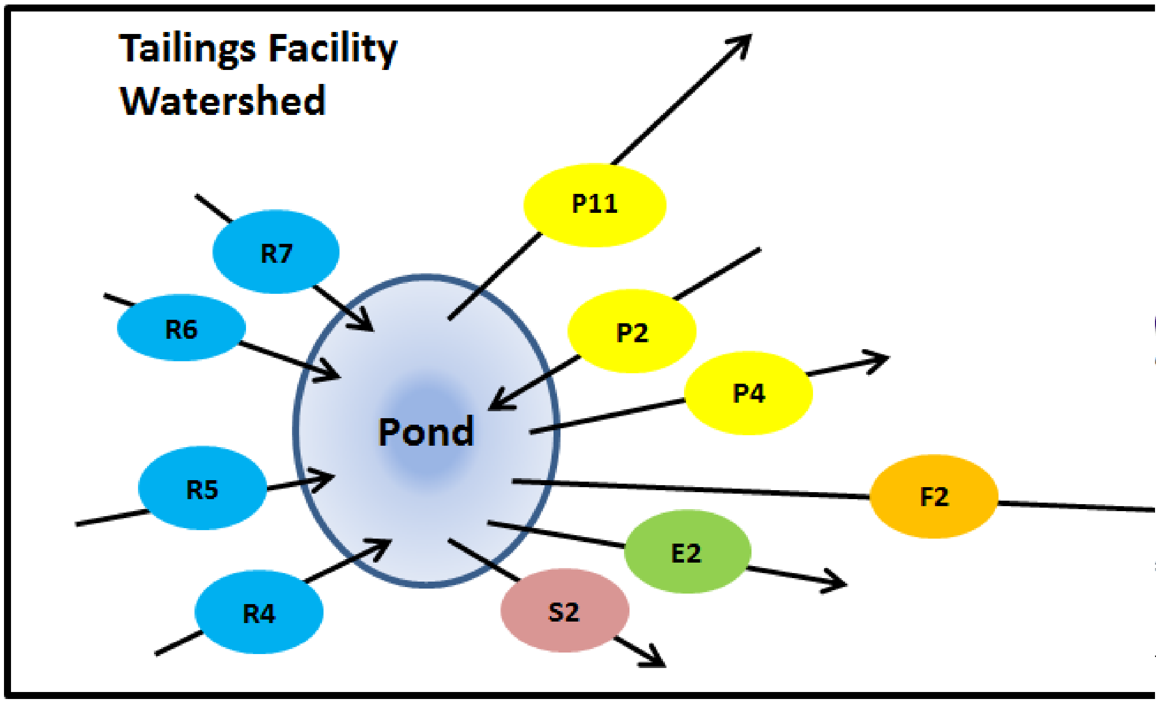
- **R4** runoff from natural ground
- **R5** runoff from prepared ground
- **R6** precipitation direct to the pond & wet tailings
- **R7** runoff from dry tailings beach
- **P2** discharge from thickener to tailings disposal facility
- **P11** reclaim water from the tailings impoundment to the mill rikastushiekka-altaalta rikastamolle
- **P4** water retained in the consolidated tailings mass
- **E2** evaporation from the tailings pond & wet tailings
- **F2** surface flow from the tailings pond to the collection pond at the water treatment plant
- **S2** seepage from the tailings pond

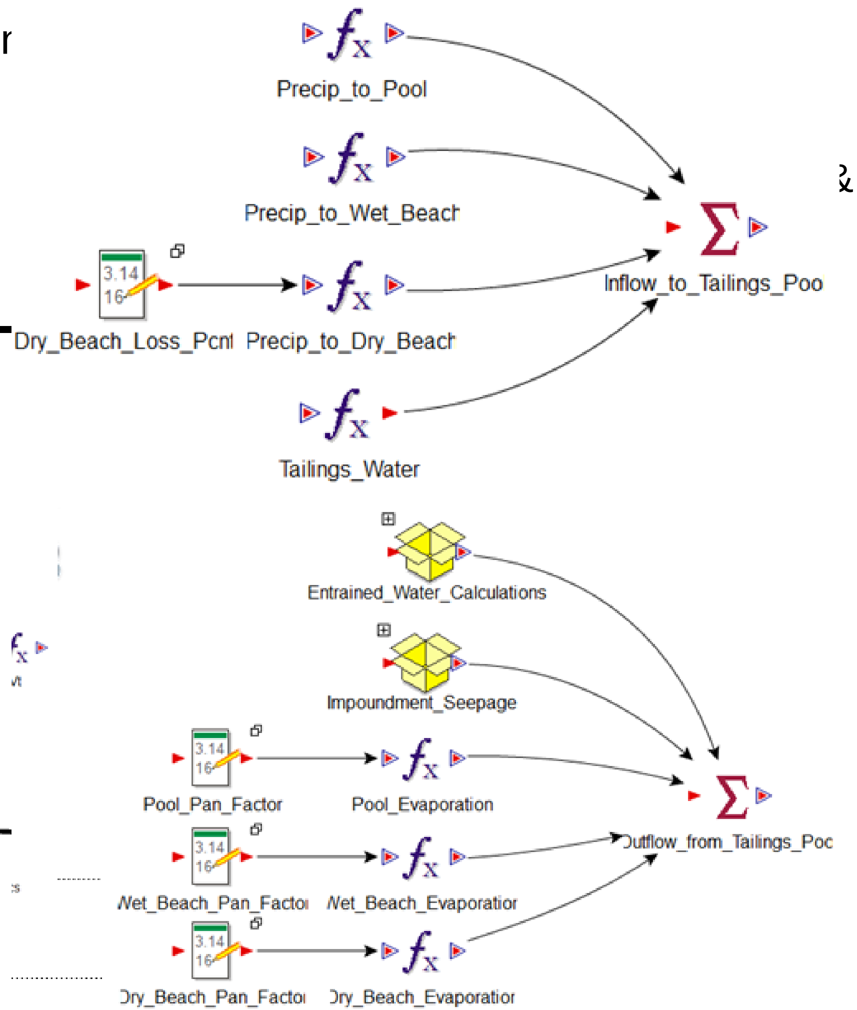
Water management on a mining operation begins with an understanding of where the water comes from and where it goes…

…also in system dynamic programming

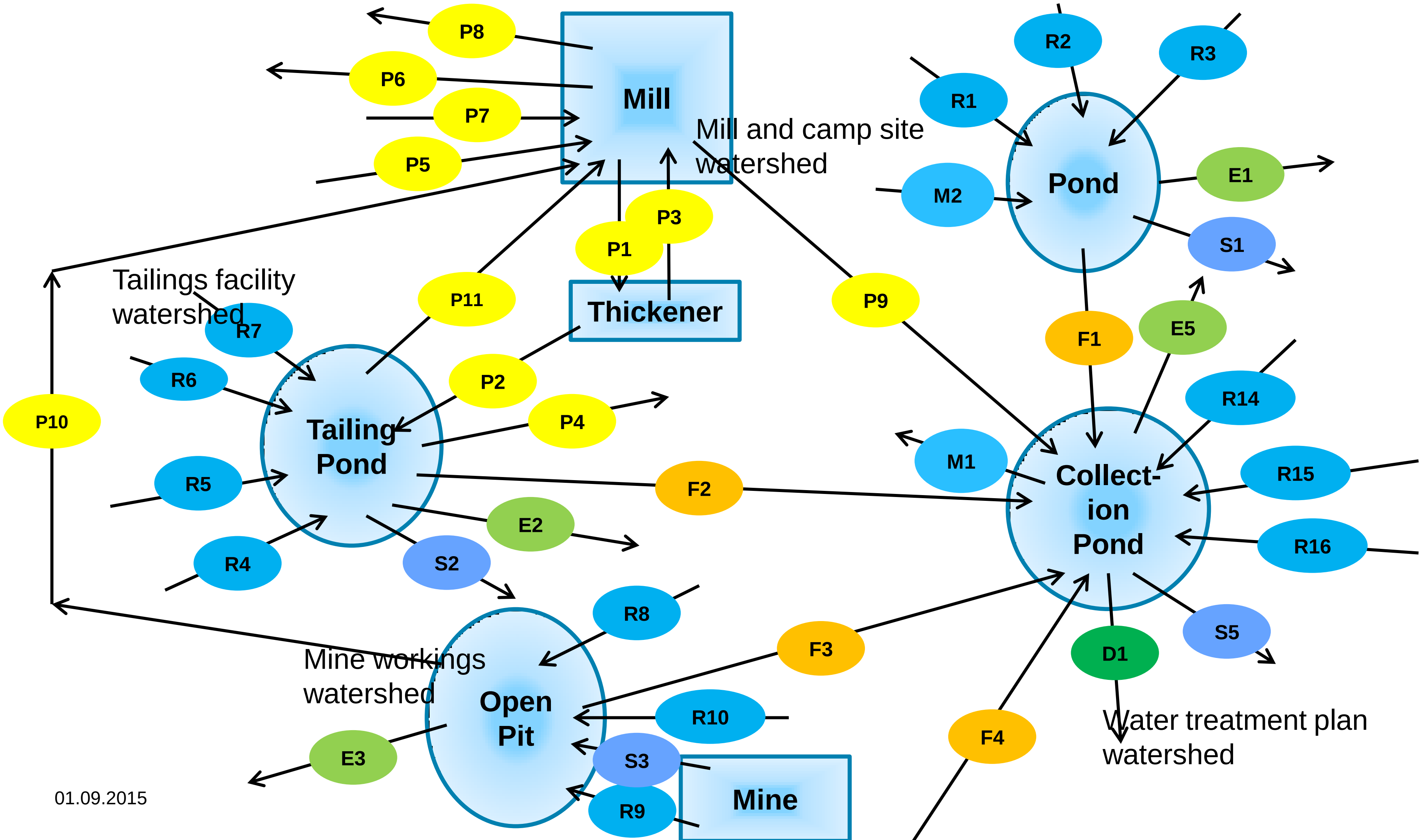
The deduction of flows to and from the specific operating ur within the mine water circuit – to account for all inflows, outflows and losses across the unit and calculating the unknown flow as the balancing flow

F2= R7+R6+R5+R4+P2-P11-P4-E2-S2





Water balance summary of flows is obtained simply by connecting flows from each sub-watershed sheet



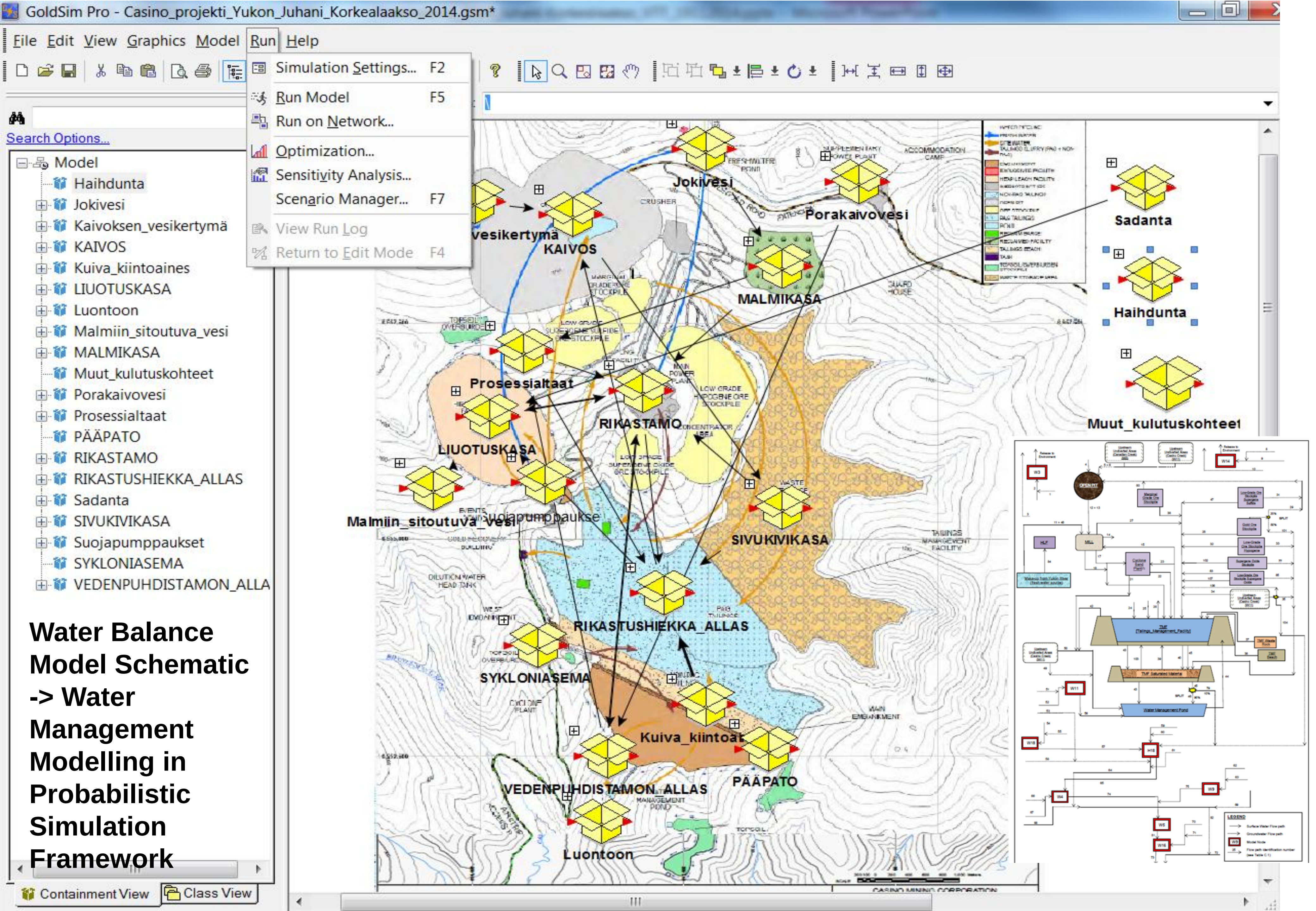
A modular approach to modelling water flow and quality using Goldsim Platform and Programming

- GoldSim is a user-friendly, highly graphical, object-oriented program for programming and carrying out dynamic, probabilistic mine-specific water balance and mass balance simulations of each mine component and the mine site as a whole.

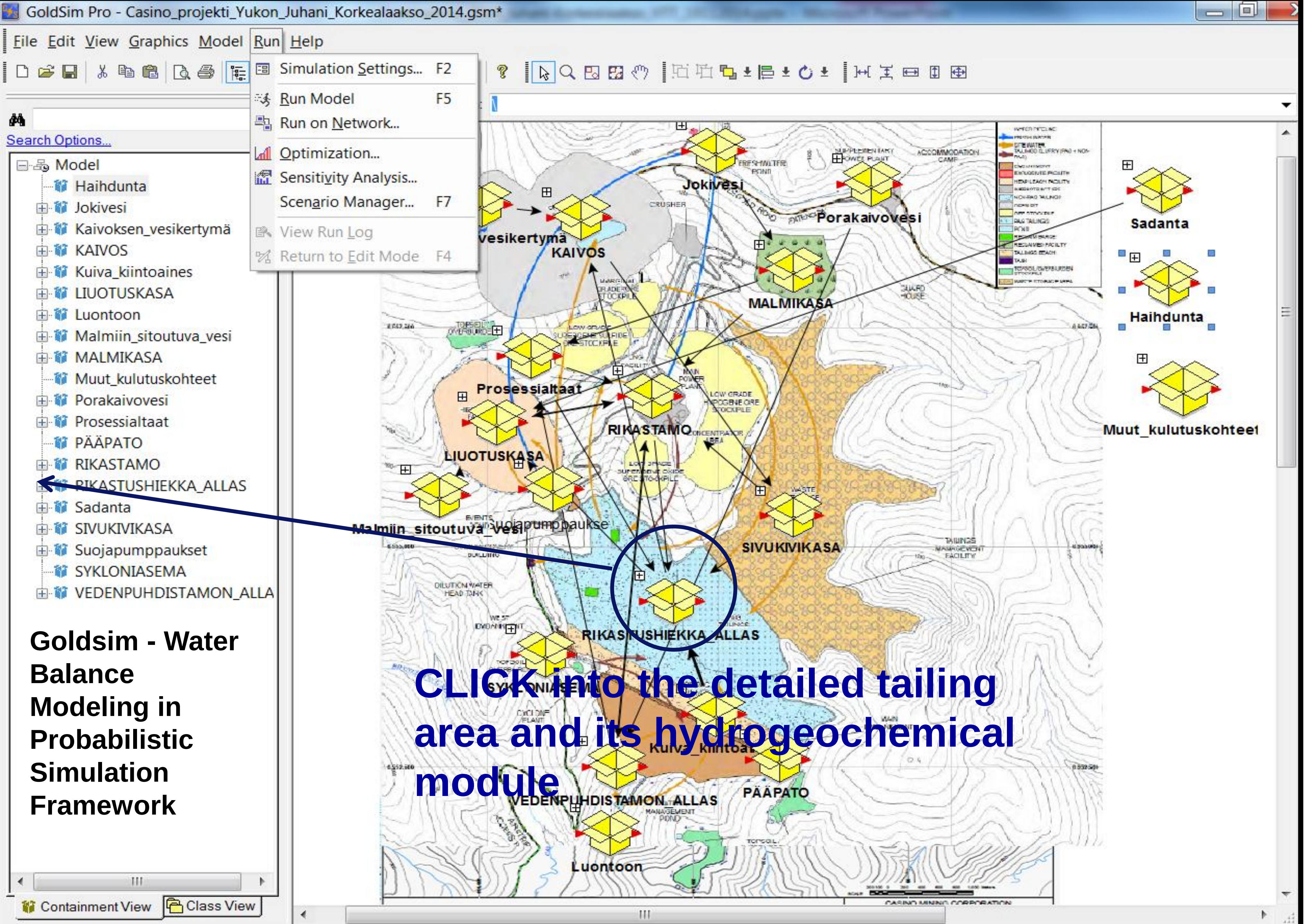
- Goldsim is based on the principle of mass balance. A body of water is modelled by the ”reservoir” element in the model. Water quantity mass balance is always maintained

- Water quality is modelled by linking chemical loadings to the water balance. In Goldsim, the concentrations and transport of the concerned chemical species are modelled by the contaminant transport ”cell” elements, which are linked with the corresponding water balance ”reservoir” elements. Mass balance is always maintained for the ”cell”:.

- Goldsim has been developed to model complex environmental systems and has been extensively and successfully applied to simulate water resource management, mining operation, contaminant transport, and radioactive waste management. Yukon Goverment and Environment (2013): ”Goldsim is a standard modelling tool in the water resources and mining industries”.

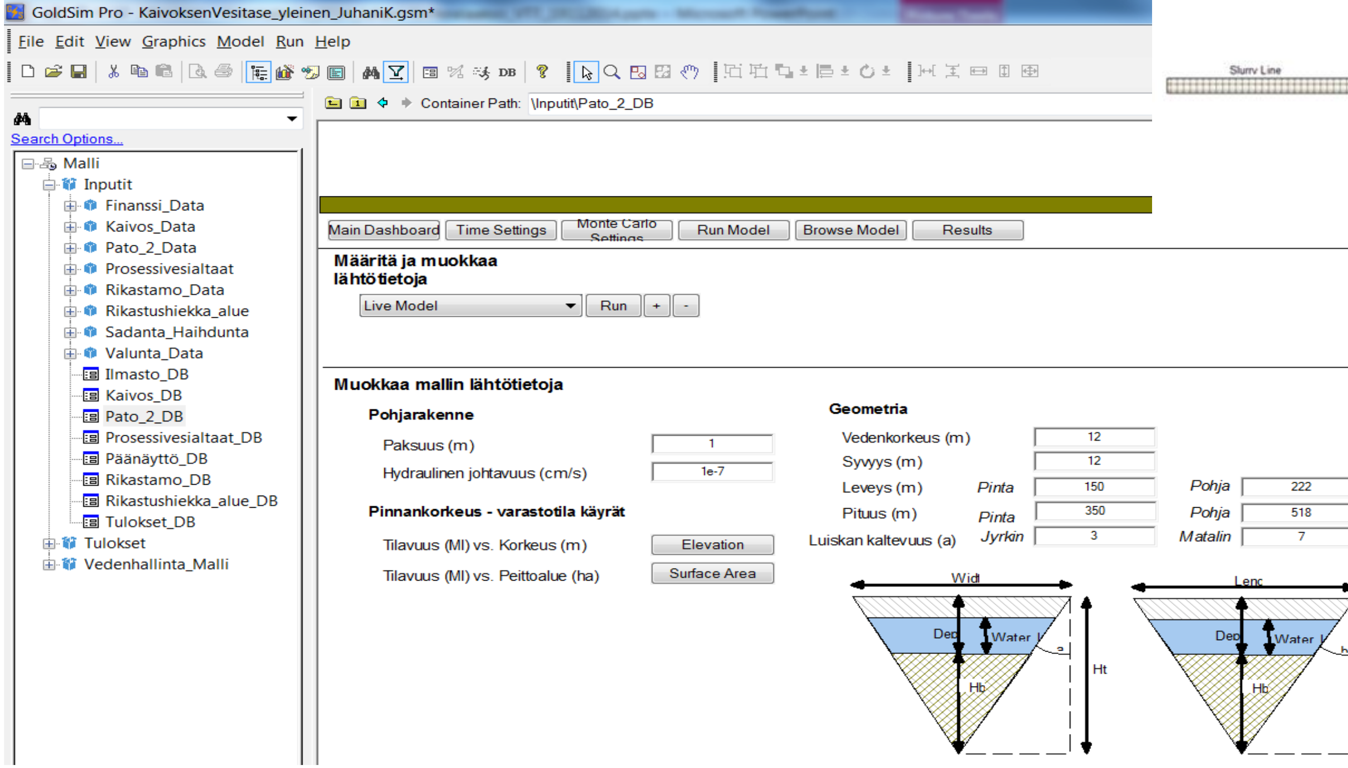


Water Balance Model Schematic -> Water Management Modelling in Probabilistic Simulation Framework

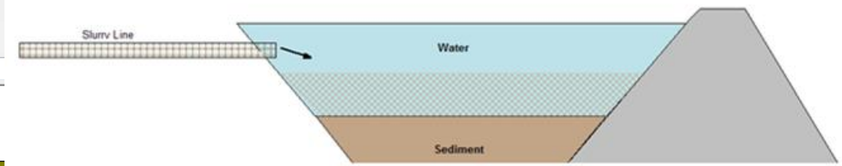


Goldsim - Water Balance Modeling in Probabilistic Simulation Framework

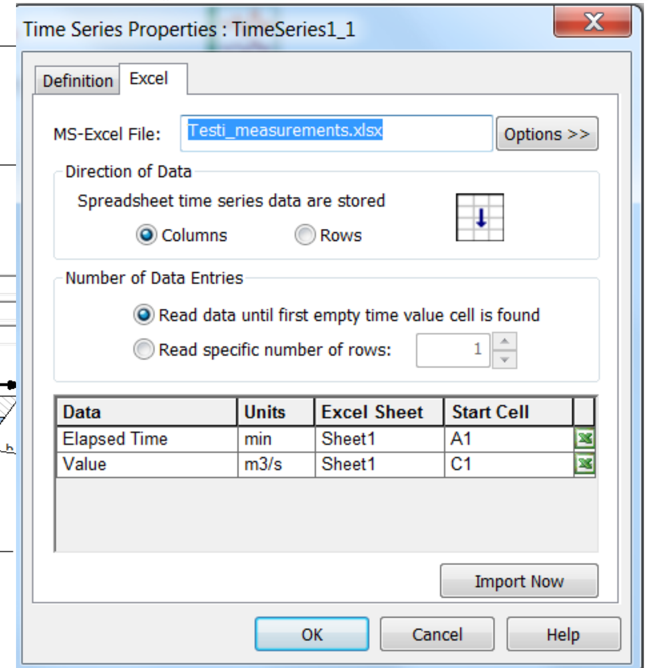
CLICK into the detailed tailing area and its hydrogeochemical module



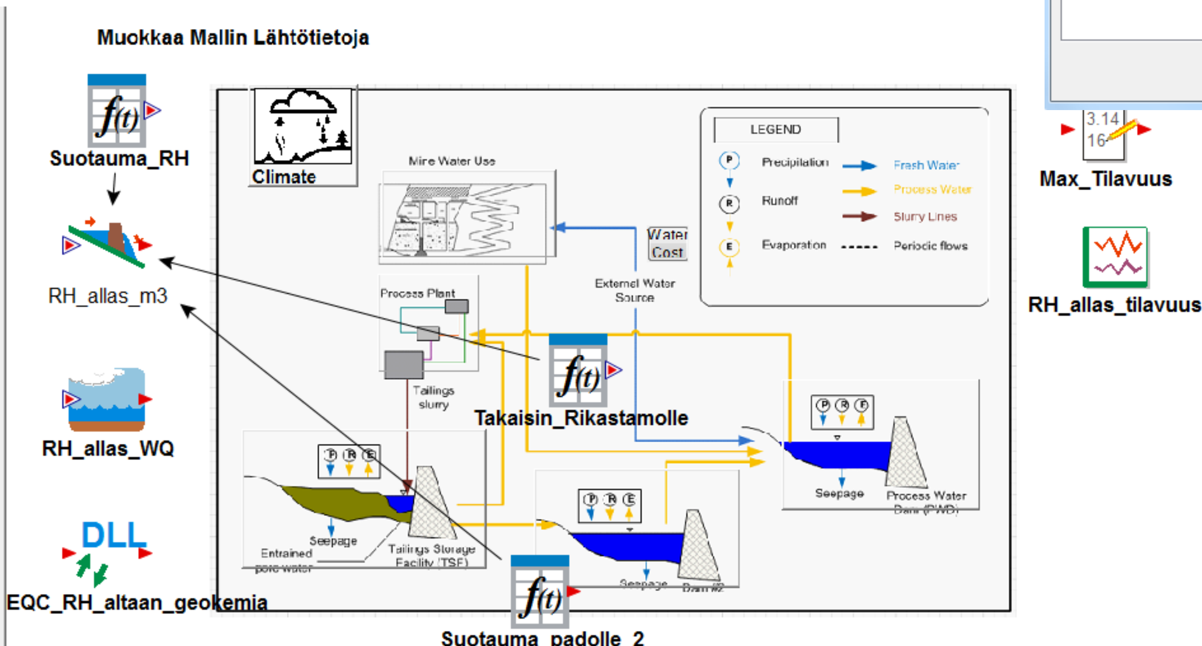
GoldSim Pro - KaivoksenVesitase_yleinen_JuhaniK.gsm*
File Edit View Graphics Model Run Help
Container Path: \Inputit\Pato_2_DB
Search Options...
Malli
Inputit
Finanssi_Data
Kaivos_Data
Pato_2_Data
Prosessivesialtaat
Rikastamo_Data
Rikastushiekka_alue
Sadanta_Haihdunta
Valunta_Data
Ilmasto_DB
Kaivos_DB
Pato_2_DB
Prosessivesialtaat_DB
Päänäyttö_DB
Rikastamo_DB
Rikastushiekka_alue_DB
Tulokset_DB
Tulokset
Vedenhallinta_Malli
Main Dashboard
Time Settings
Monte Carlo Settings
Run Model
Browse Model
Results
Määritä ja muokkaa lähtötietoja
Live Model
Run
Muokkaa mallin lähtötietoja
Pohjarakenne
Paksuus (m) 1
Hydraulinen johtavuus (cm/s) 1e-7
Pinnankorkeus - varastotila käyrät
Tilavuus (Ml) vs. Korkeus (m) Elevation
Tilavuus (Ml) vs. Peittoalue (ha) Surface Area
Geometria
Vedenkorkeus (m) 12
Syvyys (m) 12
Leveys (m) Pinta 150 Pohja 222
Pituus (m) Pinta 350 Pohja 518
Luiskan kaltevuus (a) Jyrkin 3 Matalin 7
Water
Hb
Ht



Slurry Line
Water
Sediment

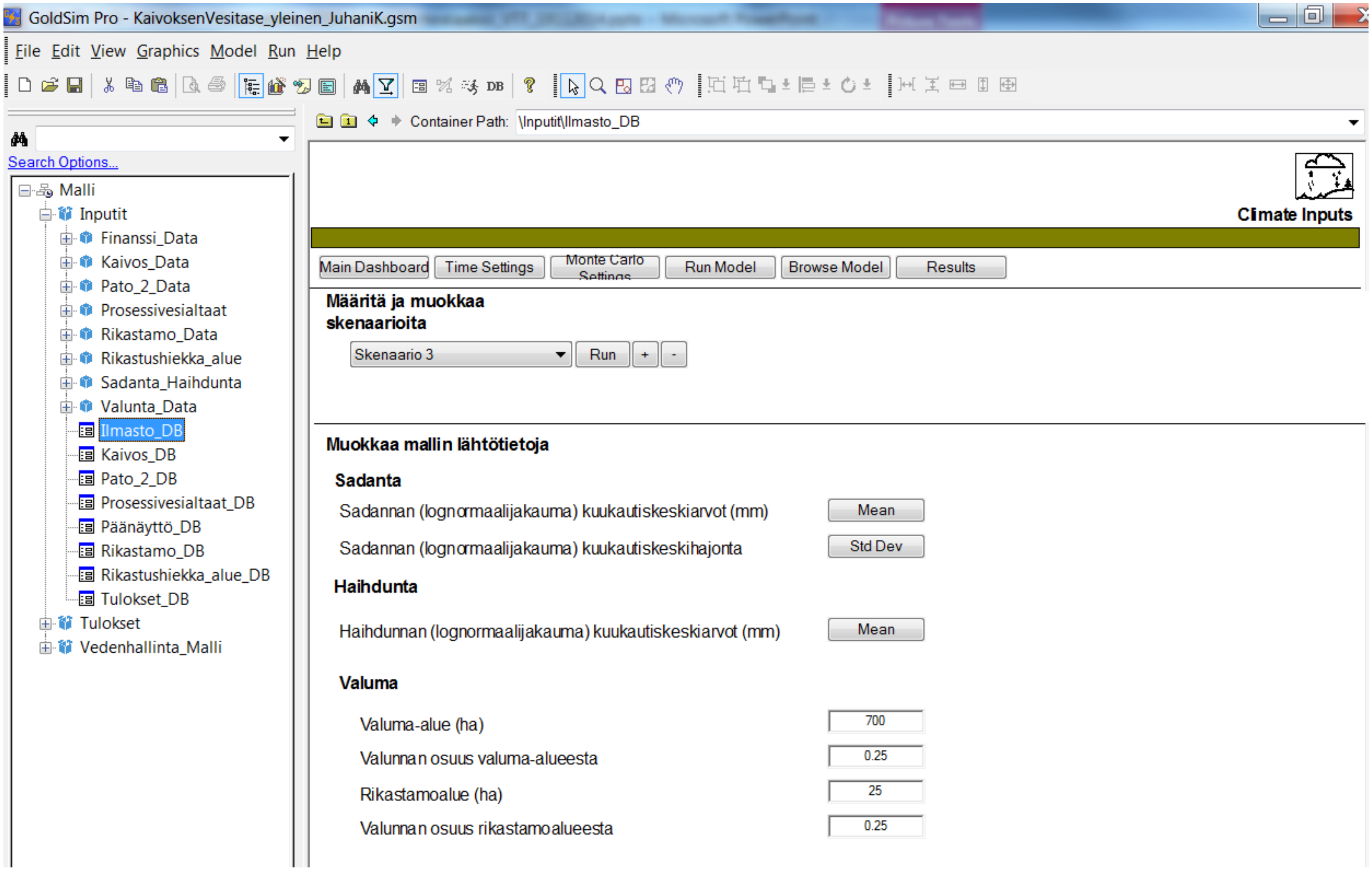


Time Series Properties : TimeSeries1_1
Definition
Excel
MS-Excel File: Testi_measurements.xlsx
Options >>
Direction of Data
Spreadsheet time series data are stored
Columns
Rows
Number of Data Entries
Read data until first empty time value cell is found
Read specific number of rows: 1
Data | Units | Excel Sheet | Start Cell
Elapsed Time | min | Sheet1 | A1
Value | m3/s | Sheet1 | C1
Import Now
OK
Cancel
Help



Muokkaa Mallin Lähtötietoja
Suotauma_RH
RH_allas_m3
RH_allas_WQ
DLL
EQC_RH_altaan_geokemia
Climate
Mire Water Use
Water Cost
External Water Source
LEGEND
Precipitation
Runoff
Evaporation
Fresh Water
Process Water
Slurry Lines
Periodic flows
Process Plant
Tailings slurry
Takaisin_Rikastamolle
Seepage
Entrained pore water
Tailings Storage Facility (TSF)
Process Water Dam (PWD)
Suotauma_padolle_2
Max_Tilavuus
RH_allas_tilavuus

User Interface for Climate Generator



Example output of probabilistic simulation

GoldSim customer companies in 40 countries (http://www.goldsim.com/Web/Solutions/Customers/):

- Mining (59); Nuclear Waste Management (41);
- Water Resource Management (20);
- Engineering and Management Consulting (121);
- Regulatory and Research Organizations (79);…

WHY…

- Free Player/Viewer/exe to customer's customer;
- Dashboards/client-specific interfaces;
- Evolves continuously in response to customer's needs (since 2002 -> now version 11.1);
- Numerical process models/simulators can be dynamically integrated to a common platform through Dynamic Link Library-DLL (inside each common time-step), databases, spreadsheets…

Mining

Adani Mining (Australia)
Agnico Eagle Mines (Mexico)
Anglo American (South Africa, Ireland, China)
AngloGold Ashanti (US, Mali, South Africa)
ArcelorMittal (Luxembourg)
Barrick Gold Corporation (Argentina, Chile, United
BHP Billiton (South Africa)
Boddington Gold Mine (Australia)
Boliden Mineral (Sweden)
BMA Gregory Crinum Mine (Australia)
Bunge (Brazil)
Bureau d'Etudes Environnement, Mine et Geologie (Ivory
Carlota Copper Company
Chieftain Metals (Canada)
Codelco Andina (Chile)
Compania Minera Antamina (Peru)
Department of Primary Industries and Resources South Australia
Diavik Diamond Mines (Canada)
Energy Fuels
Evolution Mining (Australia)
Freeport McMoran Copper and Gold (United States, Chile, Congo, Peru)
Glencore (Australia, Peru)
Gold Fields (Peru, South Africa)
Goldcorp (Argentina, Canada, United States)
Groote Eylandt Mining Company Limited (Australia)
Hudbay (Peru)
Imperial Metals (Canada)
Katanga Mining (Democratic Republic of Congo)
Kennecott Utah Copper
Kinross Gold Corporation (Mauritania, United States)
Lundin Mining (Portugal, United Kingdom)
Minas de Oro Nacional (Mexico)
Minera Barrick Pierina (Peru)
Minera Buenaventura (Peru)
Minerals and Metals Group - MMG (Australia
Minsur (Peru)
Mosaic Fertilizer
New Gold (Mexico)
Newcrest Mining (Australia)
Newmont Mining Corporation (United States, Indonesia, Peru, Ghana)
Oyu Tolgoi (Mongolia)
Palaris Mining (Australia)
Peace River Coal (Canada)
Pilbara Iron (Australia)
Pinto Valley Mining
QIT Madagascar Minerals (Madagascar)
Queensland Alumina (Australia)
Rio Paracatu Mineracao (Brazil)
Rio Tinto Alcan (Australia, France)
Rio Tinto Technology and Innovation (United States, Australia)
Rio Tinto - Mineracao Corumbaense Reunida (Brazil)
Rio Tinto - Minera Peru Limitada (Peru)
Round Mountain Gold
Sibanye Gold (South Africa)
Sociedad Minera Cerro Verde (Peru)
Teck Resources (United States, Canada)
Thompson Creek Mining (Canada)
Twin Metals Minnesota
Vale (Australia, Brazil)

Engineering and Management Consulting

350 Strategy Ltd (United Kingdom)
Access Consulting Group (Canada)
…
Galson Sciences (United Kingdom)
GeoTrans, Inc.
Gilbert & Sutherland (Australia)
Halcrow (Australia)
Haley & Aldrich
Hansen Bailey Environmental Consultants (Australia)
Hatch (Canada, United States)
Herrera Environmental Consultants
HR Ingenieros Asociados (Peru)
Hyder Consulting (Australia)

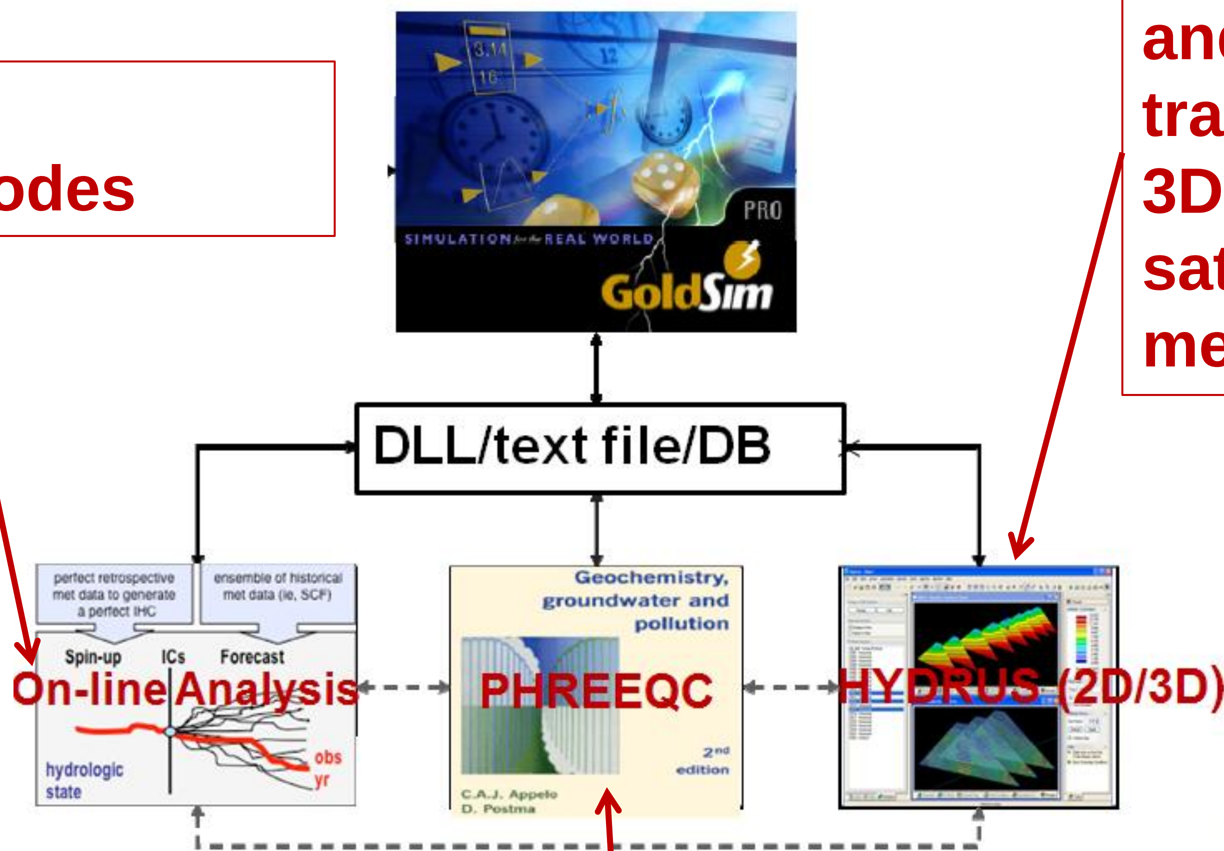
ILanda Water Services (South Africa)
…
SNC Lavalin (Canada)
SRK Consulting (Australia, Canada, South Africa, United Kingdom, United States)
Tailings Consultants Scandinavia (Sweden)
Tepco Systems Corporation (Japan)
Toyo Engineeing Corporation (Japan)
Visible Information Center (Japan)
Walsh Environmental Scientists and Engineers
Water Technology Pty Ltd (Australia)
WM Group (New Zealand)
WorleyParsons (Canada, Australia)
W. W. Wheeler and Associates

WaterSmart → New Modules for the Mine-Site Wide Water Quantity and Quality Modelling Environment

General Integrated Model Concept

Real-time and forecasting modes

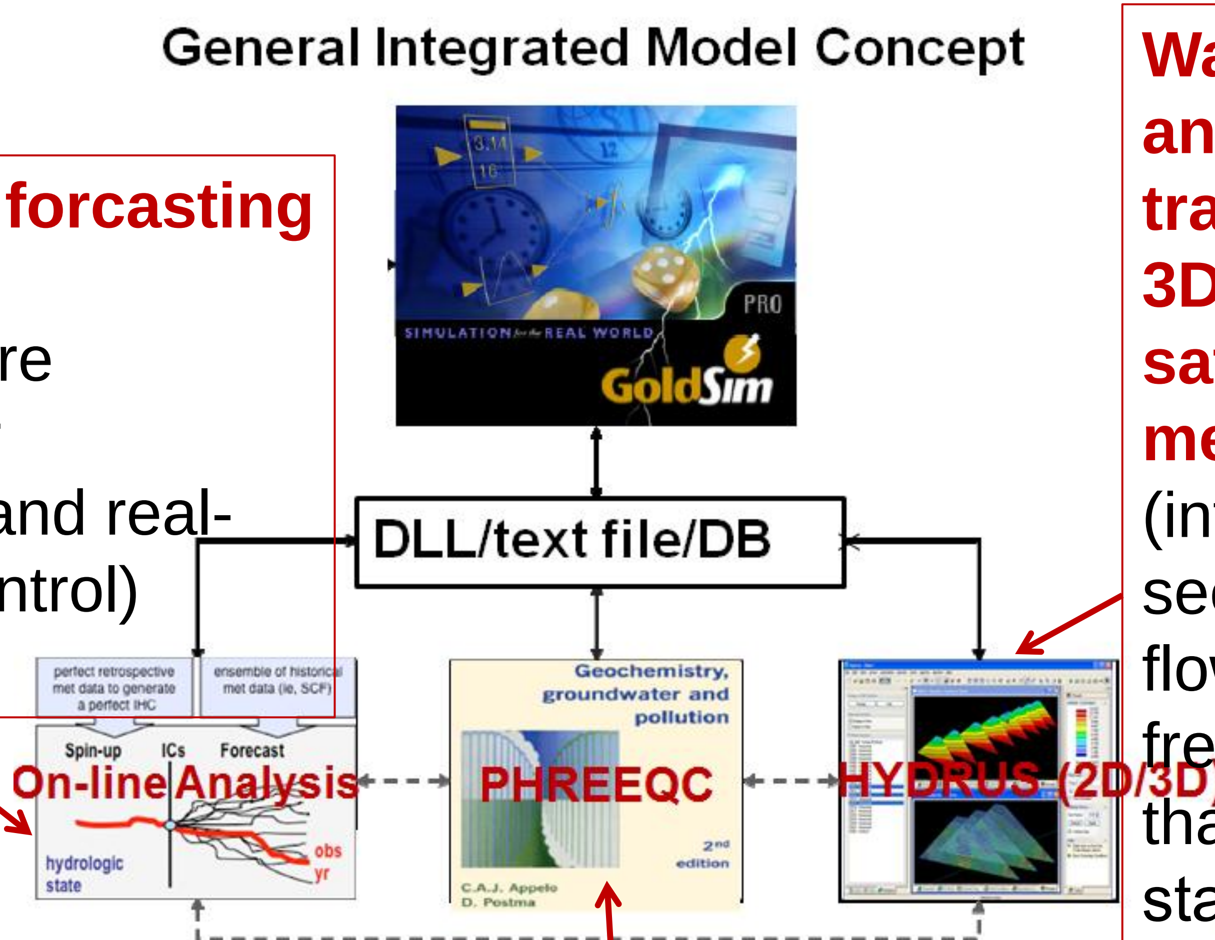
Water, heat, and solute transport in 3D in variably saturated media



Reactive Geochemistry

The development of new modules for the Mine-Site Wide Water Quantity and Quality Modelling Environment

Real-time and forcasting modes
→ towards more proactive water management (and real-time system control)



Reactive Geochemistry

Water, heat, and solute transport in 3D in variably saturated media (infiltration, seepage, gw flow, runoff, freezing-thawing, stability…in tailings, open pits, waste rock piles, soil/rock)

Hydrogeochemical Modelling (calculations of water chemistry, water-mineral interactions, speciation of water…) with PHREEQC

- **IF (SIMPLE MASS TRANSPORT and MIXING) THEN Goldsim contaminant transport tools**

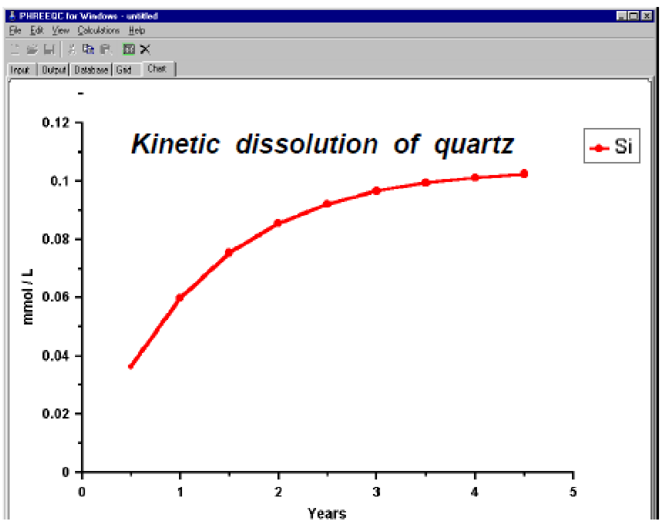
- **ELSE (REACTIVE GEOCHEMISTRY -> PHREEQC)**
  - **Aqueous Complexation**
  - **Acid-base and Redox Reactions**
  - **Cation Exchange Reactions**
  - **Surface Adsorption Reactions (double layer…)**
  - **Precipitation-Dissolution**
  - **Reactions with Organic Matter and Effects of Bacteria**
  - **Temperature and Pressure Changes,**

Aqueous, Gas, Mineral, Flow /Transport Coupling…

KINETICS, THERMODYNAMIC DATABASES

For kinetic calculations a rate equation must be programmed in BASIC using keyword **RATES**. The rate is called with keyword **KINETICS** which can also pass parameters to the rate. The BASIC functions are explained under keyword **RATES** in the PHREEQC manual.

```
#       Kinetic quartz dissolution
#
RATES
 Quartz                        # rate name
 -start
 #1 rem  dQu/dt = -k * (1 - Ω_Quartz).  k = 10^-13.7 mol/m2/s (25 C)
 #2 rem  parm(1) = A (m2), parm(2) = V (dm3) recalculate to mol/dm3/s

 10 moles = parm(1) / parm(2) * (m/m0)^0.67 * 10^-13.7 * (1 -  SR("Quartz"))
 20 save moles * time          # integrate. save and time must be in rate definition
                               # moles count positive when added to solution
 -end

KINETICS  # Sediment: 100% qu, grain size 0.1 mm, por 0.3, rho_qu 2.65 kg/dm3
 Quartz                        # rate name
 -formula SiO2
 -m0  102.7                    # initial moles of quartz
 -parms 22.7  0.162            # parameters for rate eqn. Here:
       # Quartz surface area (m2/kg sediment), water filled porosity (dm3/kg sediment)
 -step 1.58e8 in 10 steps      # 1.58e8 seconds = 5 years
 -tol 1e-8                     # integration tolerance, default 1e-8 mol

INCREMENTAL_REACTIONS true  # start integration from previous step

SOLUTION 1

USER_GRAPH
 -heading time Si; -axis_titles years mmol/L
 -axis_scale y_axis 0 0.12 0.02; -axis_scale x_axis 0 5
 -start
 10 graph_x total_time/3.1536e7
 20 graph_y tot("Si")*1e3
 -end
END
```



Currently 6 databases are provided with PHREEQC, PHREEQC.DAT is the smallest. WATEQ4F.DAT has additional data for heavy metals, the 2 MINTEQ.DAT files have a few more organic chemicals, and LLNL.DAT is a huge database with many minerals and large-range, temperature dependent equilibrium constants. PHREEQD.DAT contains tracer diffusion coefficients for solute species. The databases contain lists under keywords:

```
SOLUTION_MASTER_SPECIES                                     # always needed
#element  species   alk     gfw_formula    element_gfw
H         H+        -1.0    H              1.008
H(0)      H2        0.0     H
H(1)      H+        -1.0    0.0
E         e-        0.0     0.0            0.0
O         H2O       0.0     O              16.0
O(0)      O2        0.0     O
O(-2)     H2O       0.0     0.0
# ...the above elements must always be present in the database
Ca        Ca+2      0.0     Ca             40.08
Fe        Fe+2      0.0     Fe             55.847   # Fe+2 is primary redox species
Fe(+2)    Fe+2      0.0     Fe
Fe(+3)    Fe+3      -2.0    Fe
# The primary species reaction is repeated in SOLUTION_SPECIES, with log_k = 0
# etc...
SOLUTION_SPECIES
H+ = H+                           # H+ primary species
          log_k     0.0
          -gamma    9.0     0.0   # params for activity coefficient
          -dw       9.31e-9       # tracer diffusion coefficient (m²/s) at 25°C
Fe+2 = Fe+2                       # Fe+2 is the primary redox species for Fe
          log_k     0.0
          -gamma    6.0     0.0
          -dw       0.719e-9
Fe+2 = Fe+3 + e-                  # new species defined on the right of = sign
          log_k     -13.02
          delta_h 9.680     kcal # temp. dependency from Van 't Hoff eqn
          -gamma    9.0     0.0
# etc...
PHASES                            # Minerals
Calcite
 CaCO3 = CO3-2 + Ca+2
          log_k     -8.48
          delta_h -2.297 kcal
          -analytic  -171.9065  -0.077993  2839.319  71.595   # log_k vs temp
# etc...
EXCHANGE_MASTER_SPECIES
 X        X-                      # element, species
EXCHANGE_SPECIES
 X- = X-                          # reaction for master species with log_k = 0
          log_k     0.0
 Na+ + X- = NaX
          log_k     0.0
          -gamma    4.0     0.075
# etc...
SURFACE_MASTER_SPECIES            # element, species
 Hfo_s    Hfo_sOH
 Hfo_w    Hfo_wOH
SURFACE_SPECIES
 Hfo_sOH = Hfo_sOH                # reaction for master species with log_k = 0
          log_k     0.0
 Hfo_sOH + H+ = Hfo_sOH2+
          log_k     7.29          # = pKa1,int
```

Linking fundamental geochemistry and empirical observations for water quality predictions using GoldSim

Brent Usher[1], Roald Strand[1]. Chris Strachotta[1], Jim Jackson[2]

[1]*Klohn Crippen Berger (Ltd) PO Box 3276, South Brisbane QLD 4101 Australia, busher@klohn.com*
[2]*Compañía Minera Antamina S.A. Lima, Peru, jjackson@antamina.com*

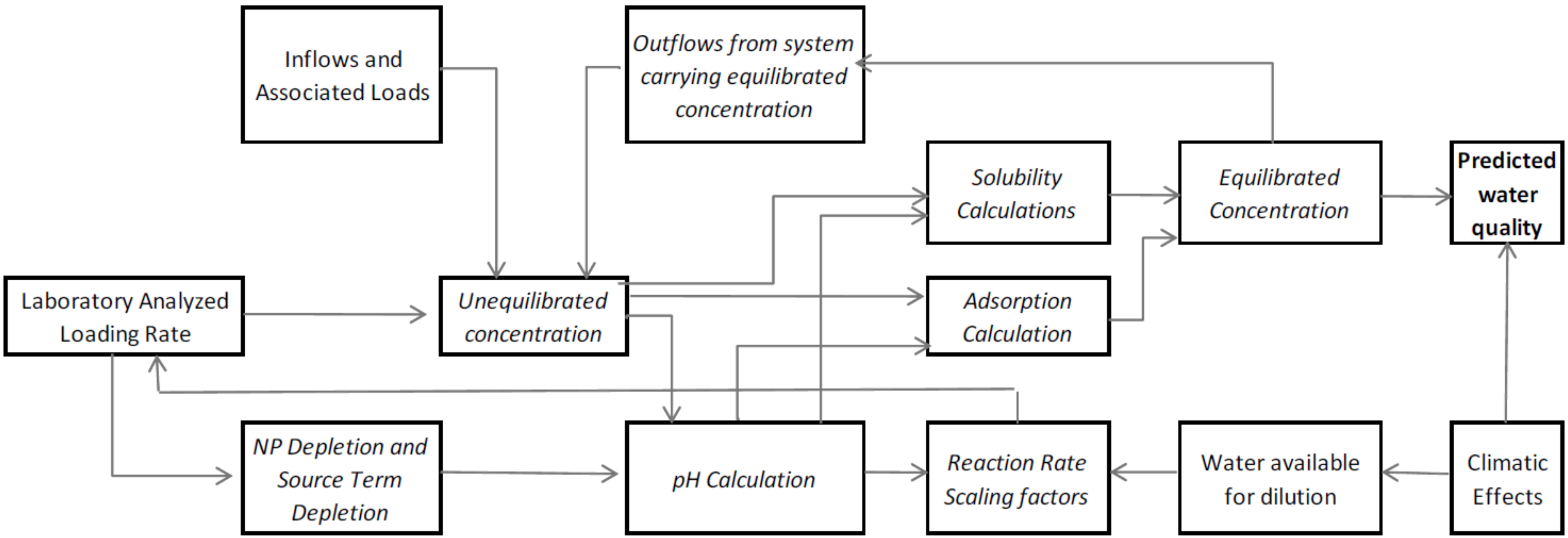
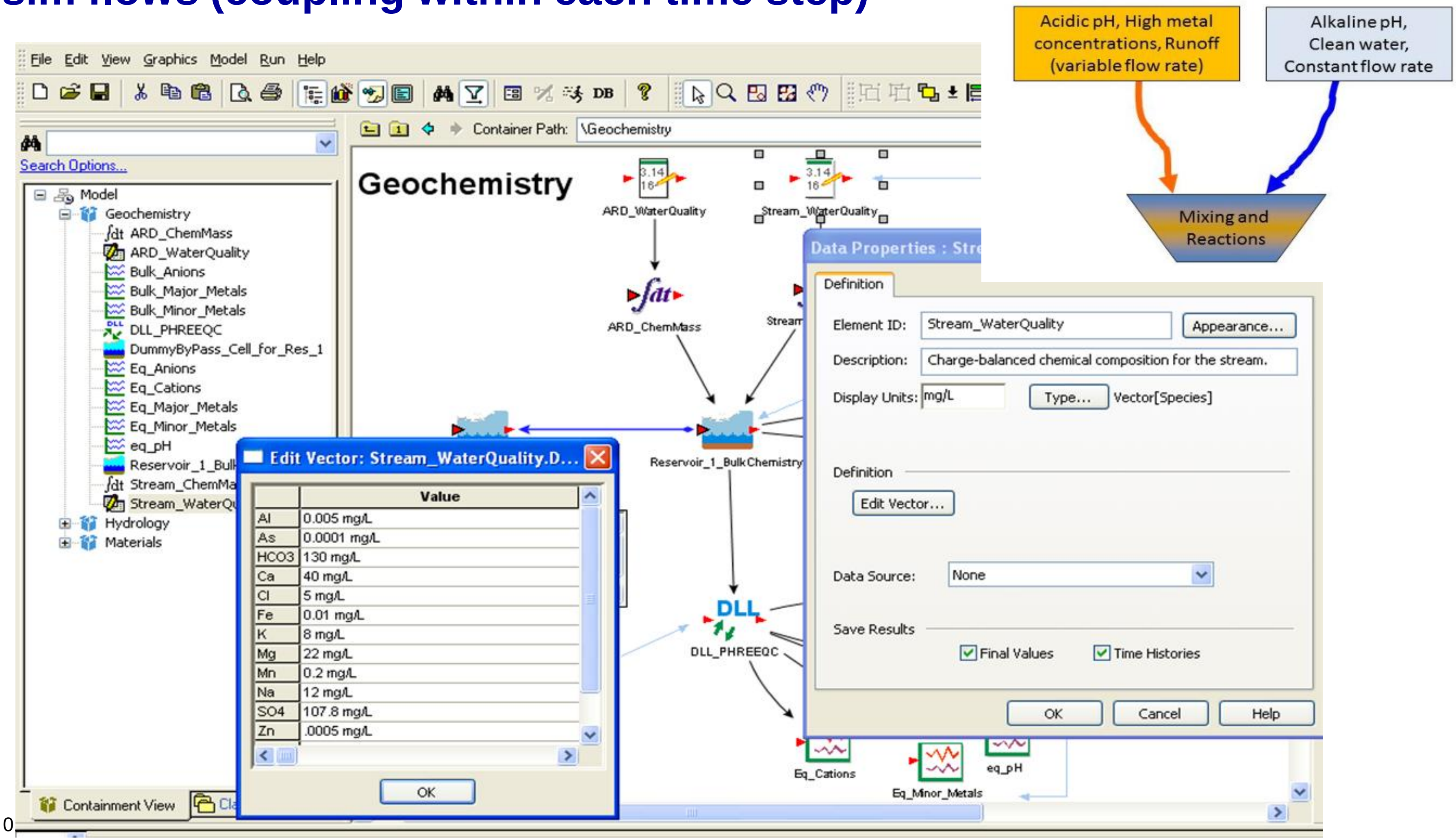


***Figure 1** Overview of water quality algorithm included in the model*

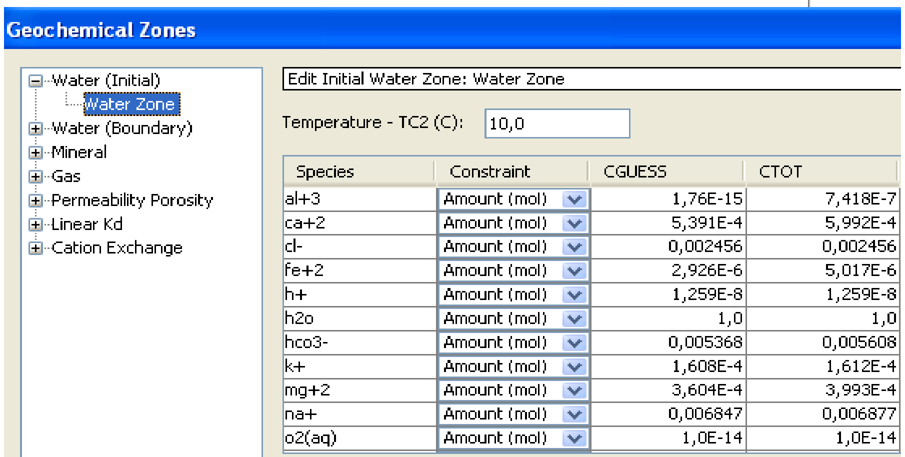
Reactive HydroGeochemical Module (soil and water, groundwater, waste rock, ore heaps, tailings…)

Direct Linkage of PHREEQC model (mixing, reactions, water-mineral interactions…) through Dynamic Link Libraries (External DLL Element) with the Goldsim flows (coupling within each time step)

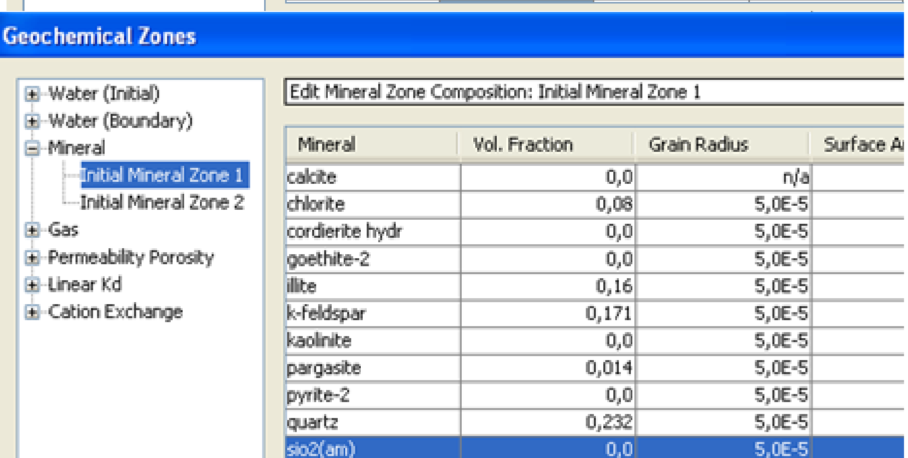


Example of Reactive HydroGeochemical Module -

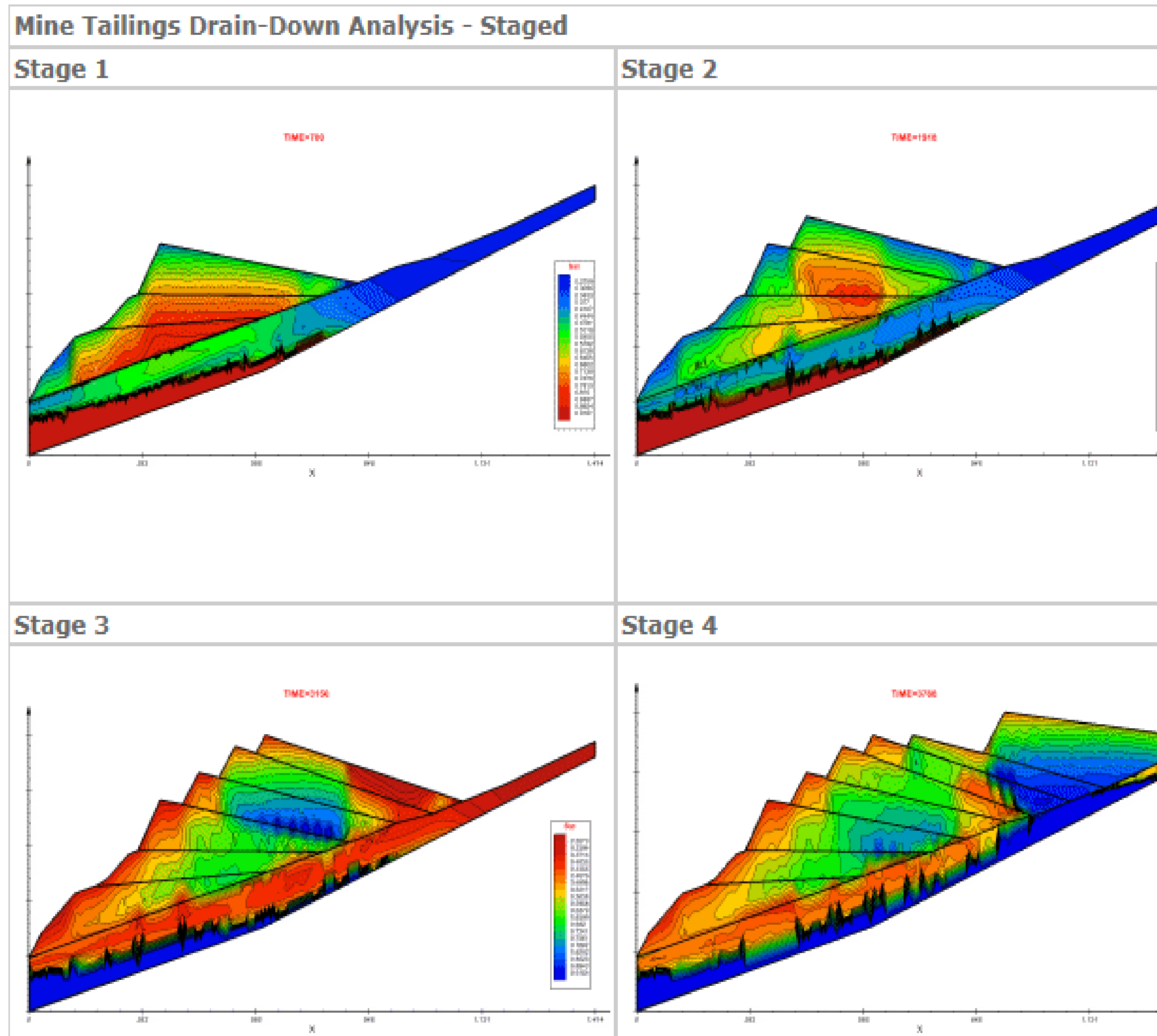
to investigate potential changes in pH and redox conditions and in buffering capacity as well as the hydrogeochemical processes related to tailings managem



Species	Constraint	CGUESS	CTOT
al+3	Amount (mol)	1,76E-15	7,418E-7
ca+2	Amount (mol)	5,391E-4	5,992E-4
cl-	Amount (mol)	0,002456	0,002456
fe+2	Amount (mol)	2,926E-6	5,017E-6
h+	Amount (mol)	1,259E-8	1,259E-8
h2o	Amount (mol)	1,0	1,0
hco3-	Amount (mol)	0,005368	0,005608
k+	Amount (mol)	1,608E-4	1,612E-4
mg+2	Amount (mol)	3,604E-4	3,993E-4
na+	Amount (mol)	0,006847	0,006877
o2(aq)	Amount (mol)	1,0E-14	1,0E-14



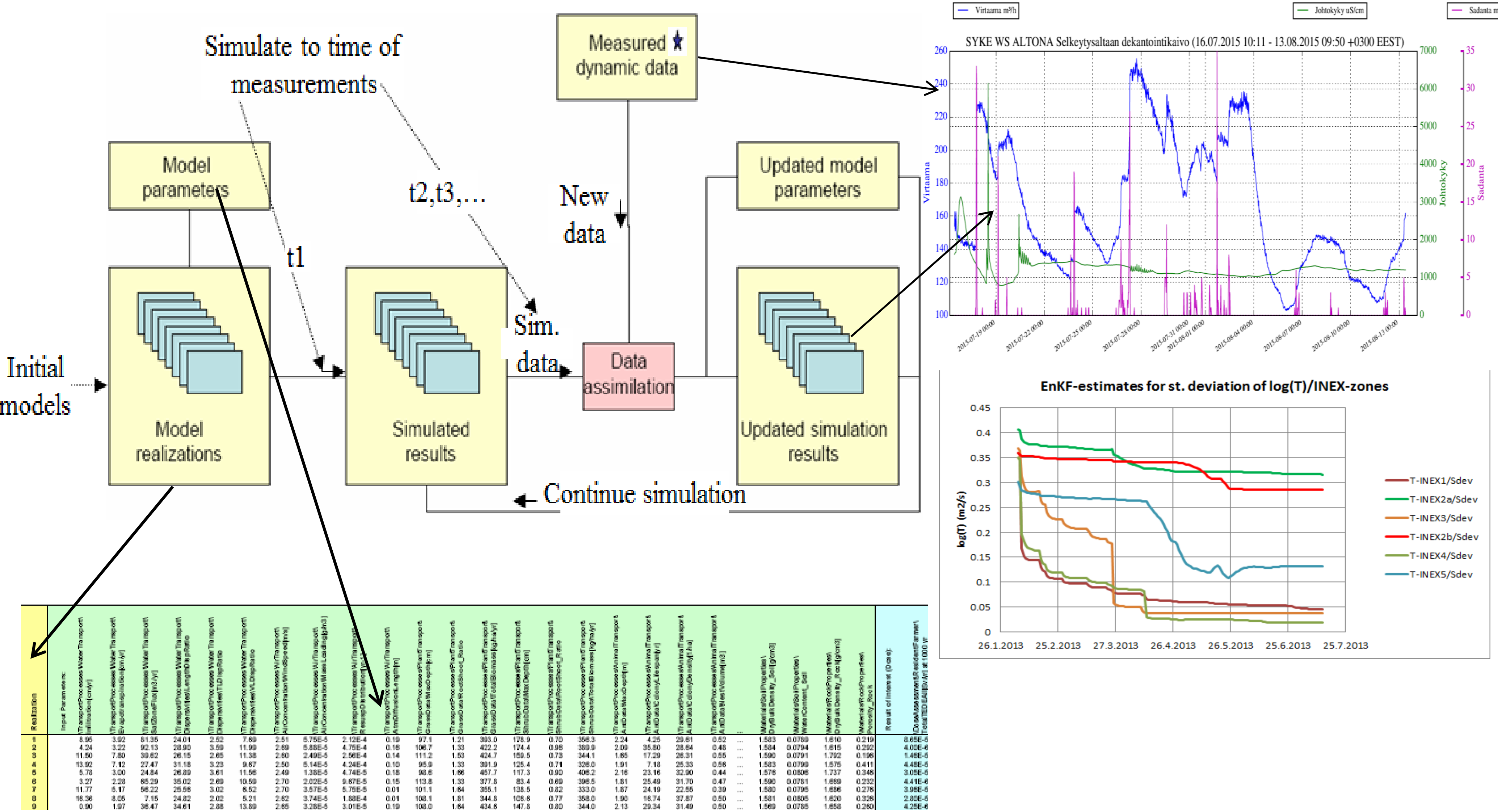
Mineral	Vol. Fraction	Grain Radius	Surface A
calcite	0,0	n/a	
chlorite	0,08	5,0E-5	
cordierite hydr	0,0	5,0E-5	
goethite-2	0,0	5,0E-5	
illite	0,16	5,0E-5	
k-feldspar	0,171	5,0E-5	
kaolinite	0,0	5,0E-5	
pargasite	0,014	5,0E-5	
pyrite-2	0,0	5,0E-5	
quartz	0,232	5,0E-5	
sio2(am)	0,0	5,0E-5	



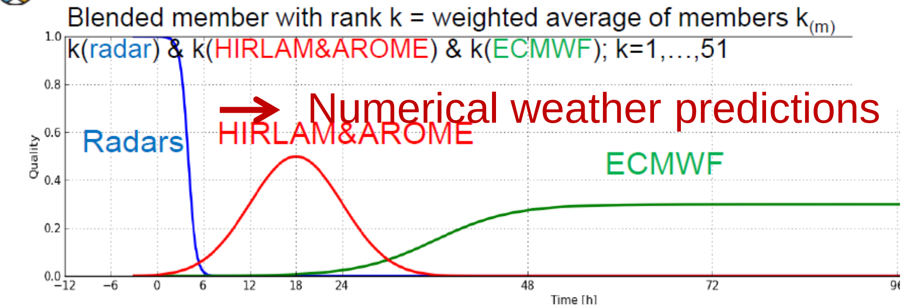
Monitoring + Modelling (dynamic calibration, optimization, ensemble forecasting)

- Data-assimilation is an optimal approach to combine observations into water balance calculations
- ”Data Driven” modelling is carried out using the Ensemble Kalman Filter (EnKF) – method and stochastic simulation of predictive realizations (dynamic calibration for time-series results in a set of parameter values that is time dependent)
- EnKF can produce continuous updating of model predictions and parameters always when new measurements are available. The deviation between the model output and the measured data is reduced over the monitoring period.
- EnKF is integrated into Goldsim platform using its stochastic tools
- EnKF process produces automatically also uncertainty and sensitivity information

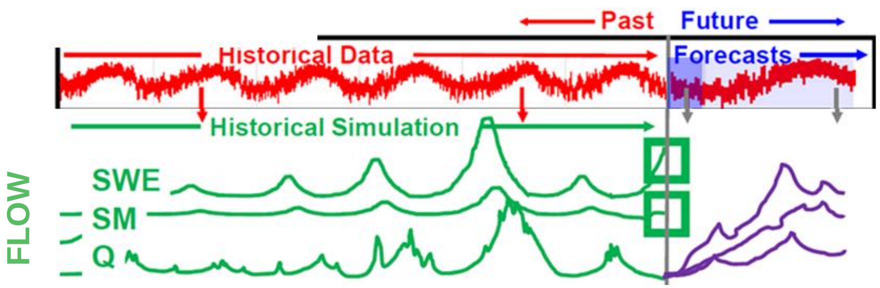
Updating predictions, calibration as well as uncertainty and sensitivity analysis - Ensemble Kalman Filter process



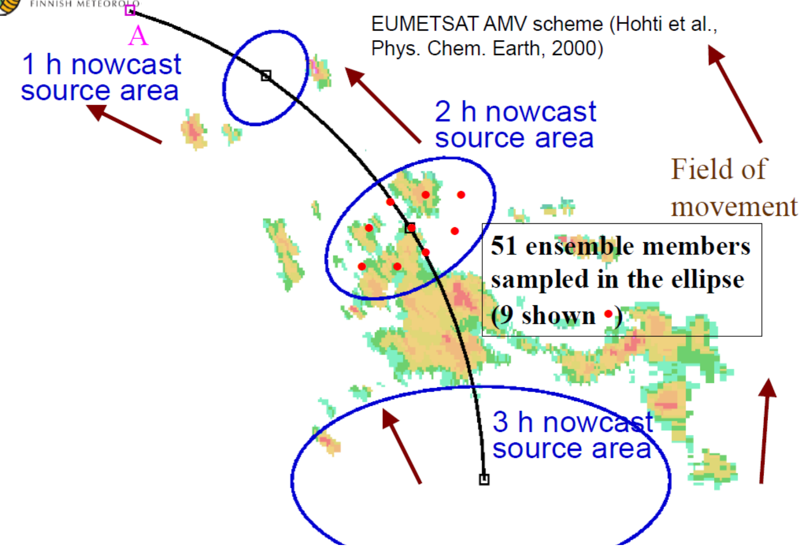
Seamless blending of precipitation ensembles



Rainfall ensembles (from open FMI data) and then water flow ensembles

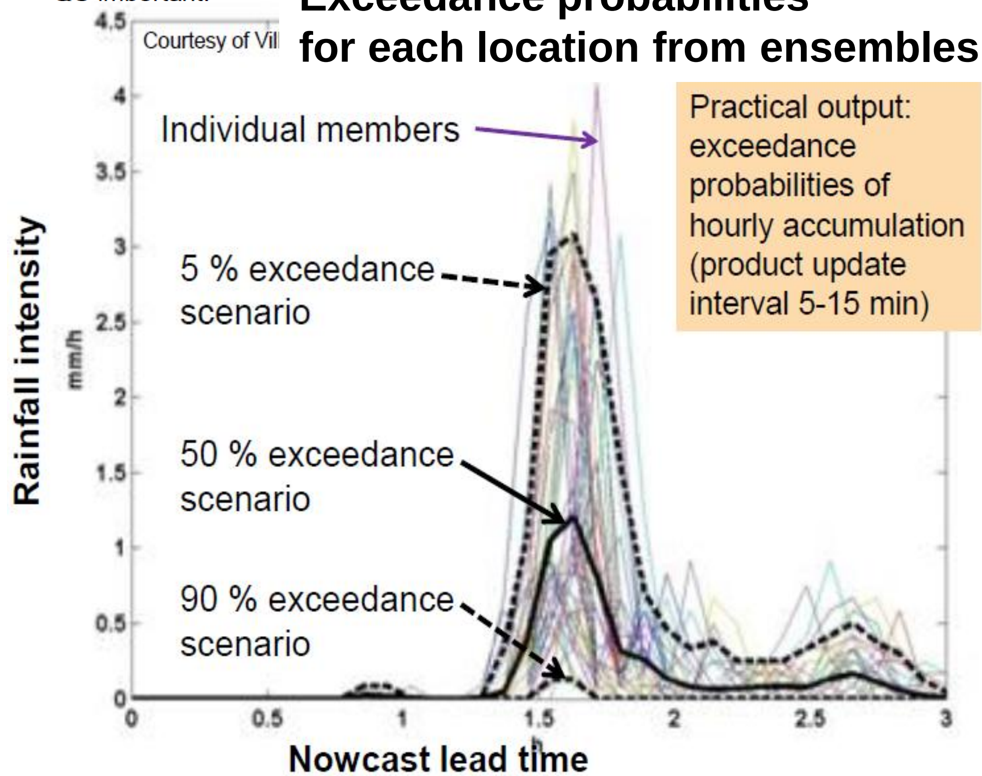


Radar-based ensembles

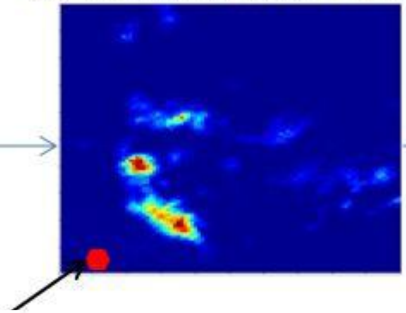


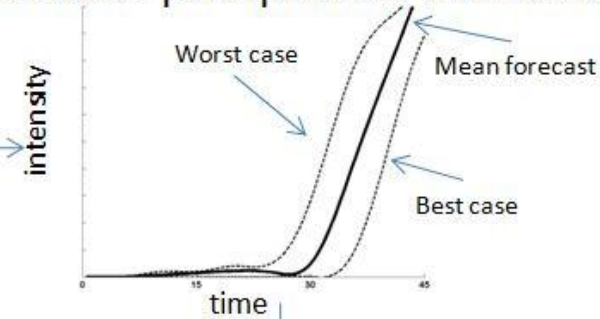
- QC important!

Exceedance probabilities for each location from ensembles



From radar observations … to rainfall intensities … and ensemble precipitation forecasts





This cycle is updated in real time for each radar scan (5 min intervals)

Predicted water levels trigger different warnings depending on the location

Water levels in three selected locations with different forecasts

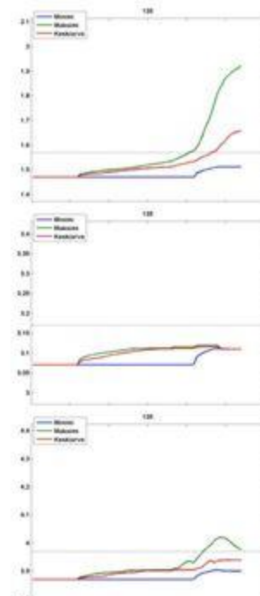
Water levels on the ground are simulated using different forecast scenarios

Flood action needed

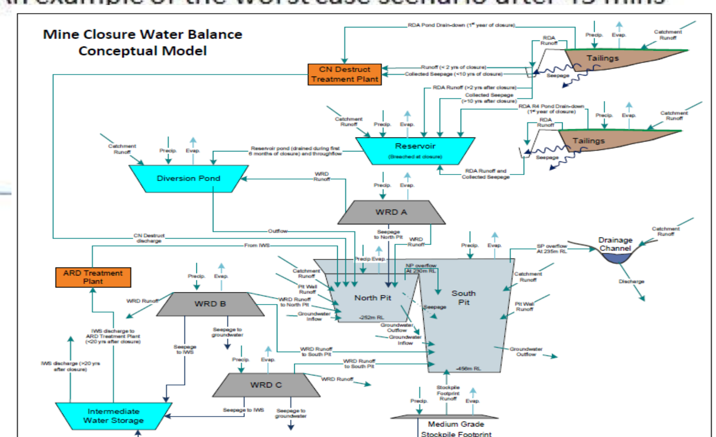
No danger

Potential flood

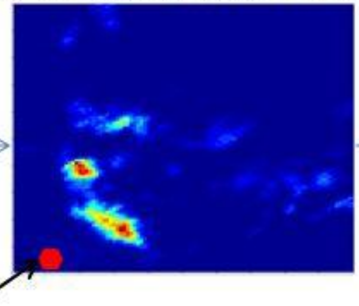
No danger

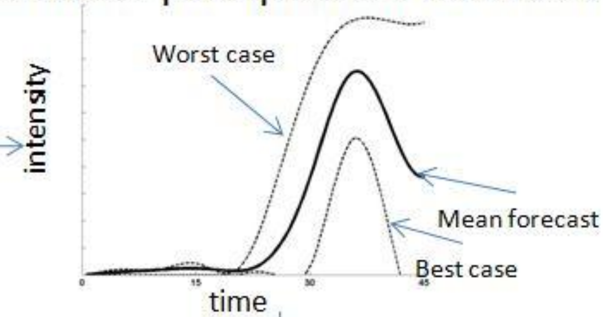


An example of the worst case scenario after 45 mins



From radar observations ... to rainfall intensities ... and ensemble precipitation forecasts





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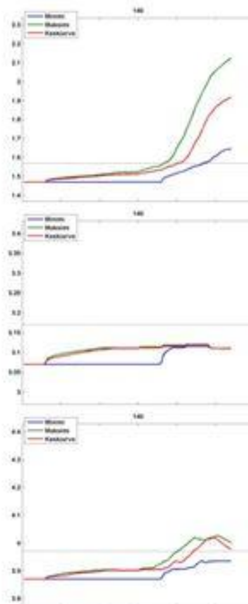

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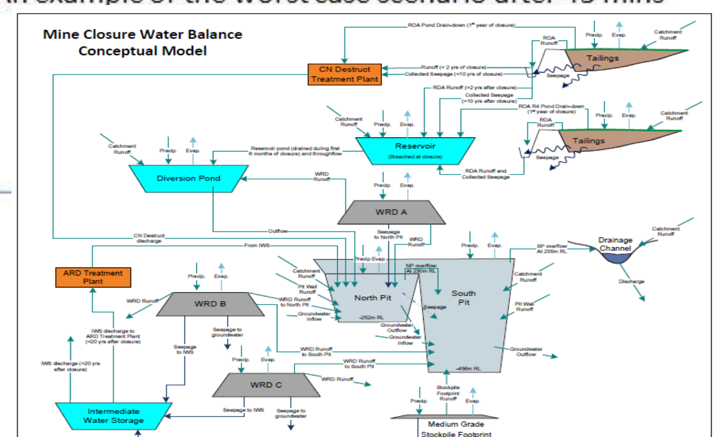
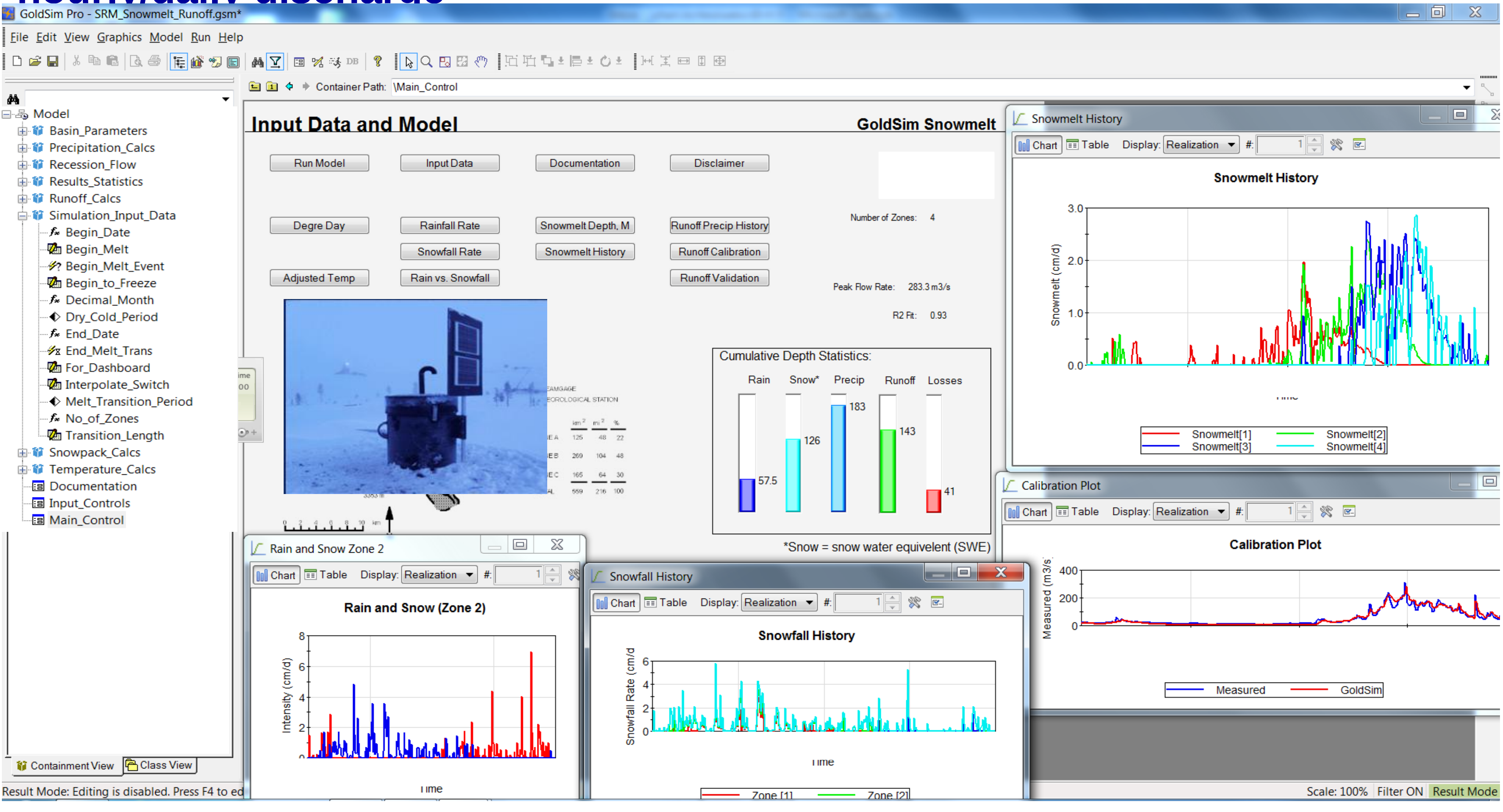
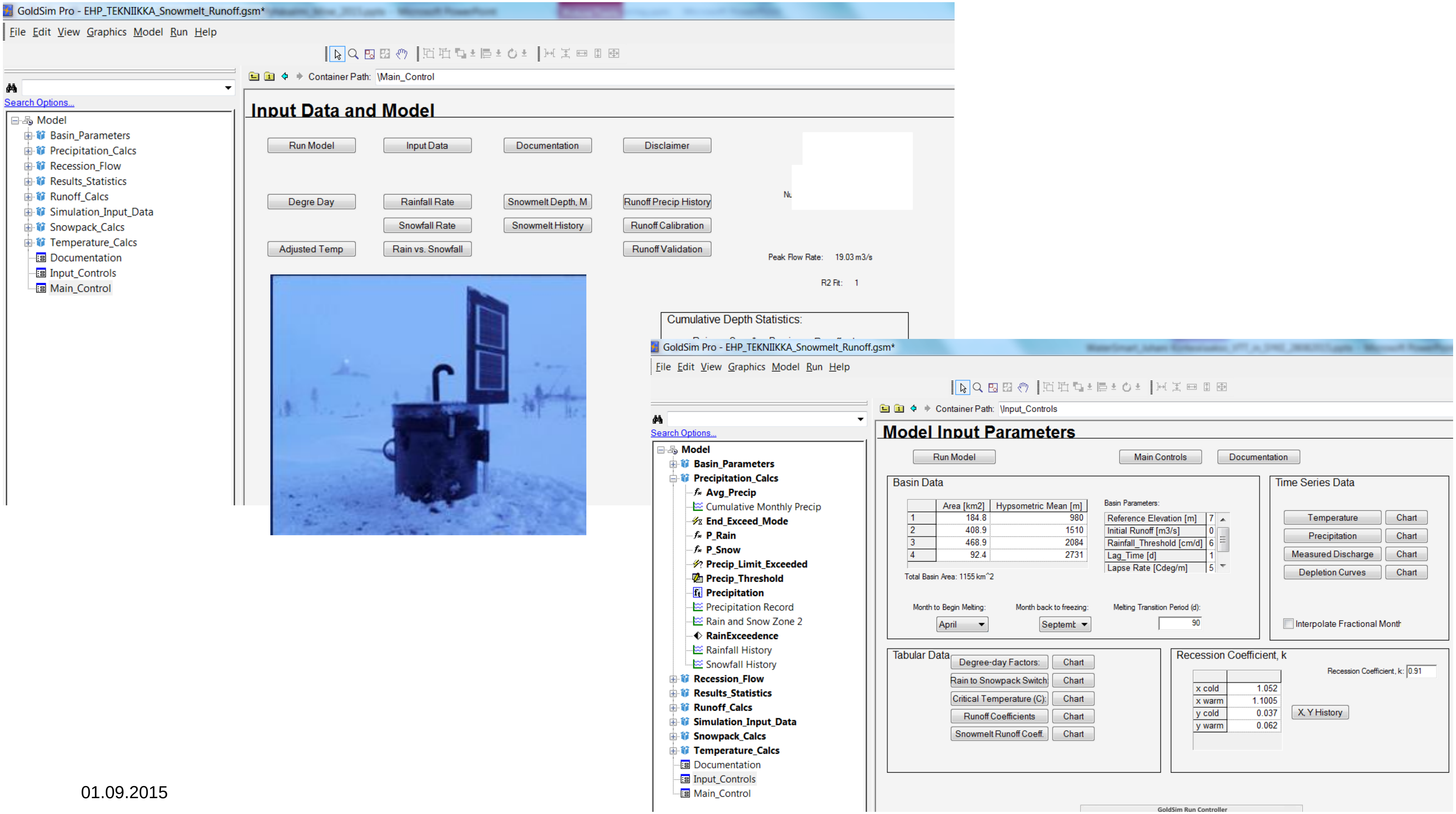


Process-specific user interface for mine-specific water balance calculations –

Hourly/daily timestep, the water produced from rainfall and from snowmelt is computed, superimposed on the calculated recession flow and transformed into hourly/daily discharge

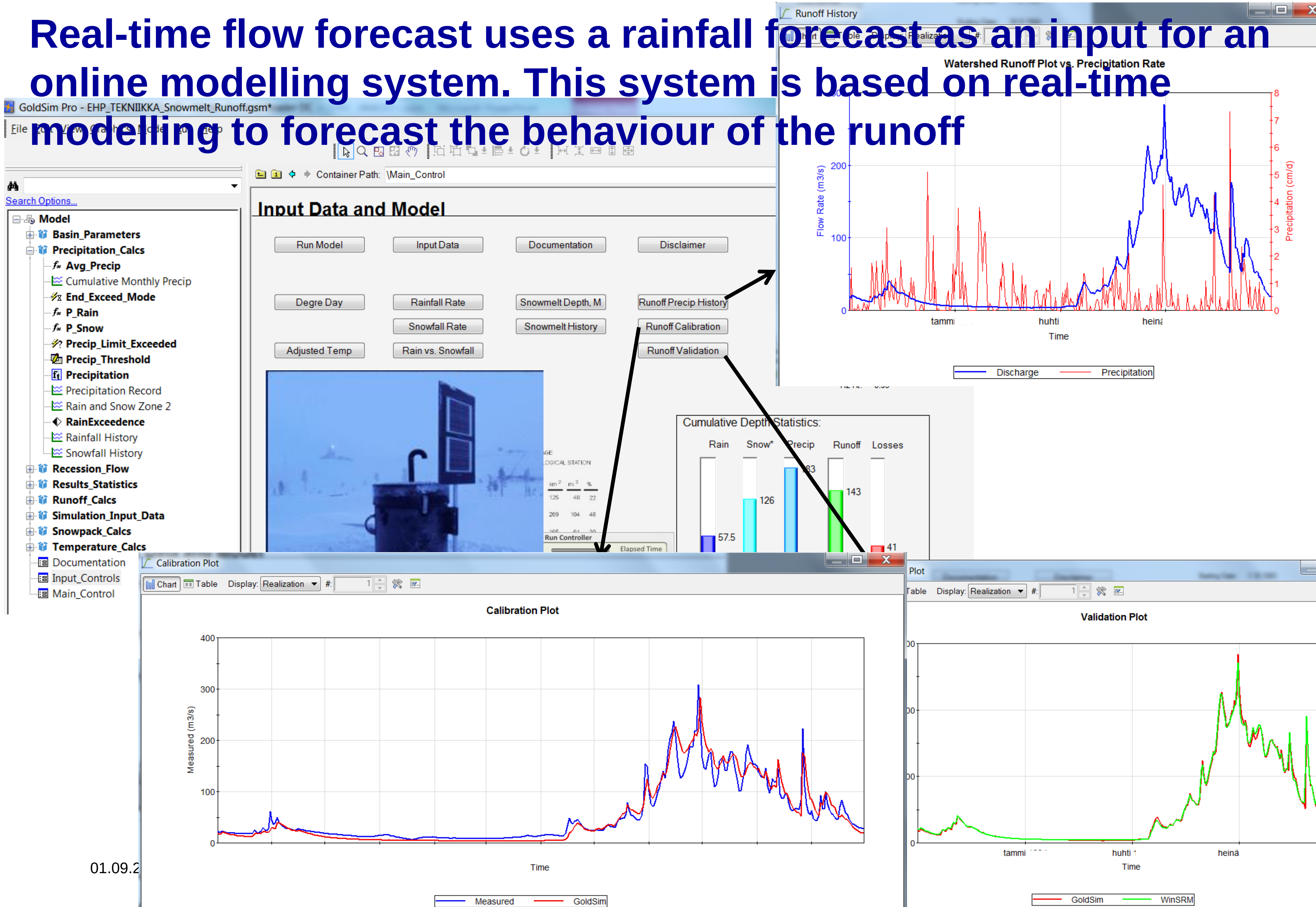


Together with EHP-tekniikka, Oulu we have innovated ways to integrate on-line flow measurements into updating model predictions and parameters as well as to produce flow forecasts

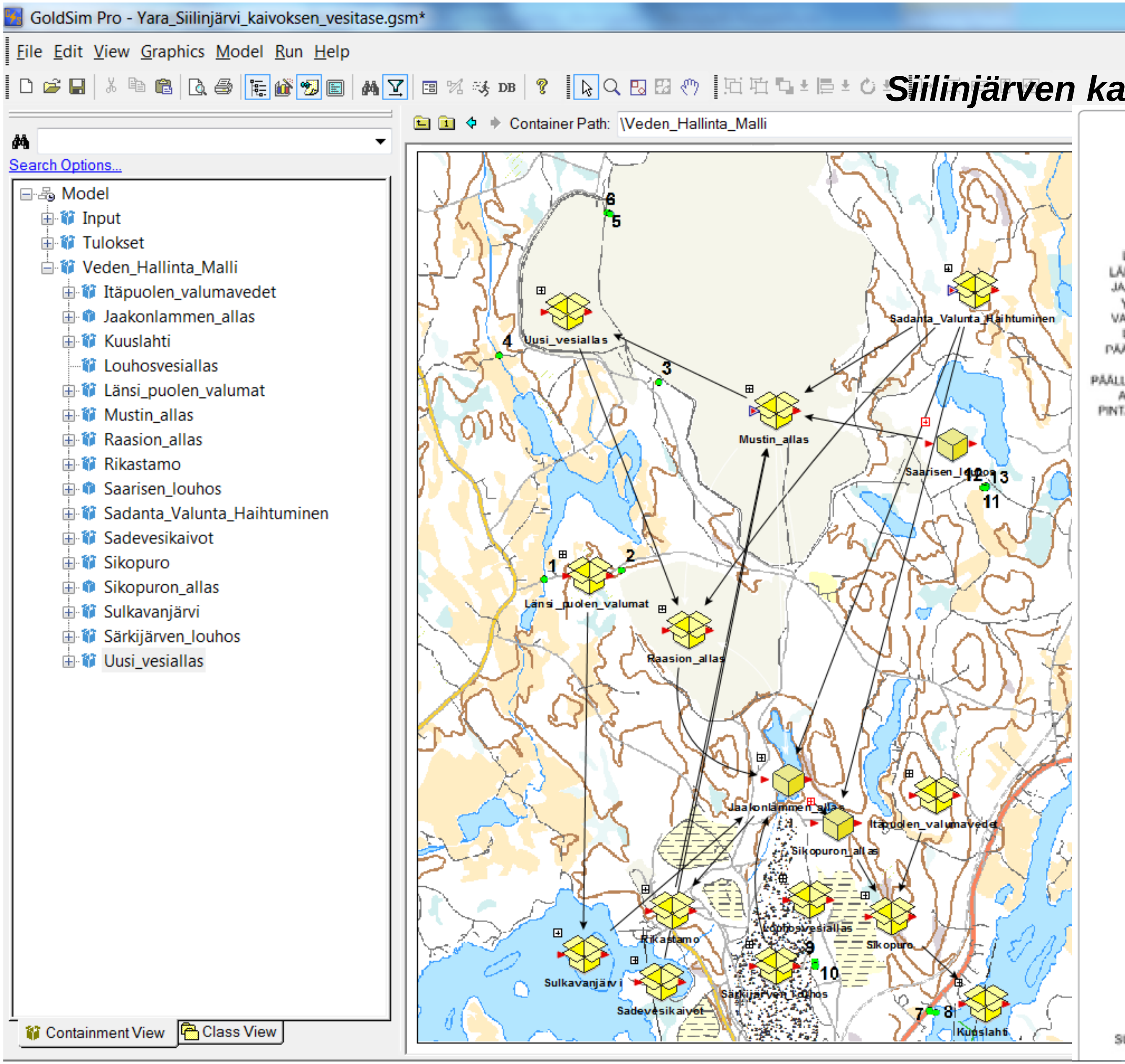


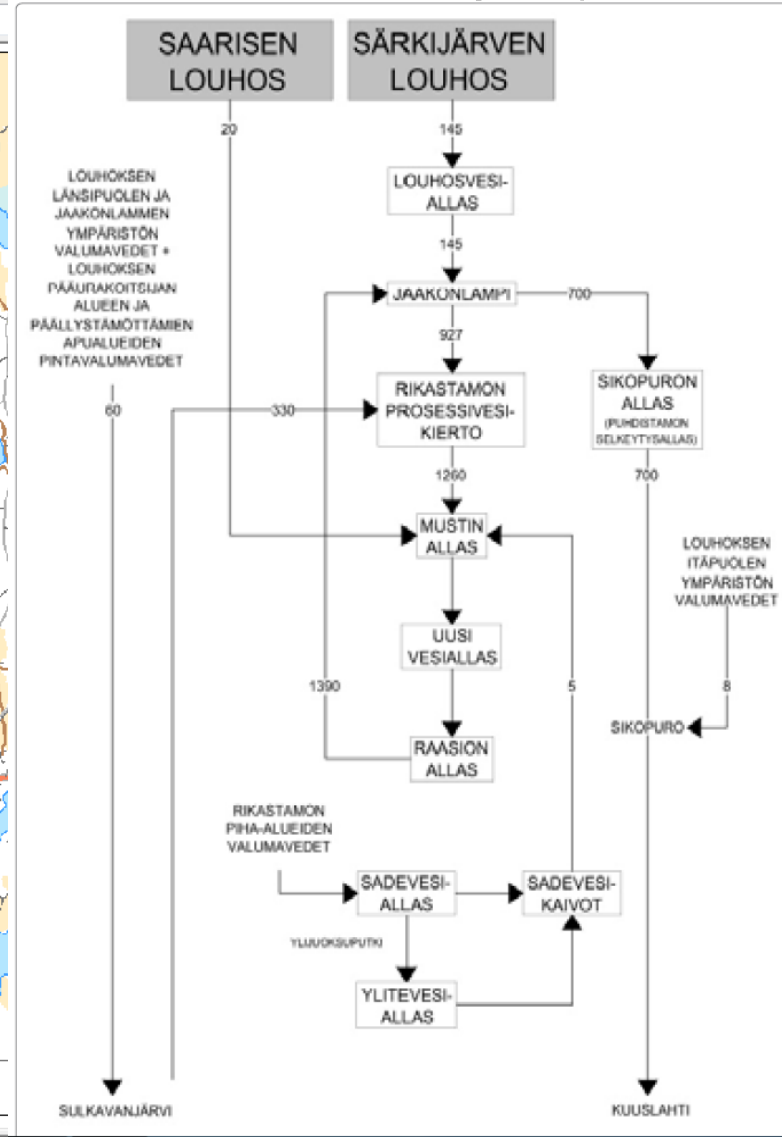
01.09.2015

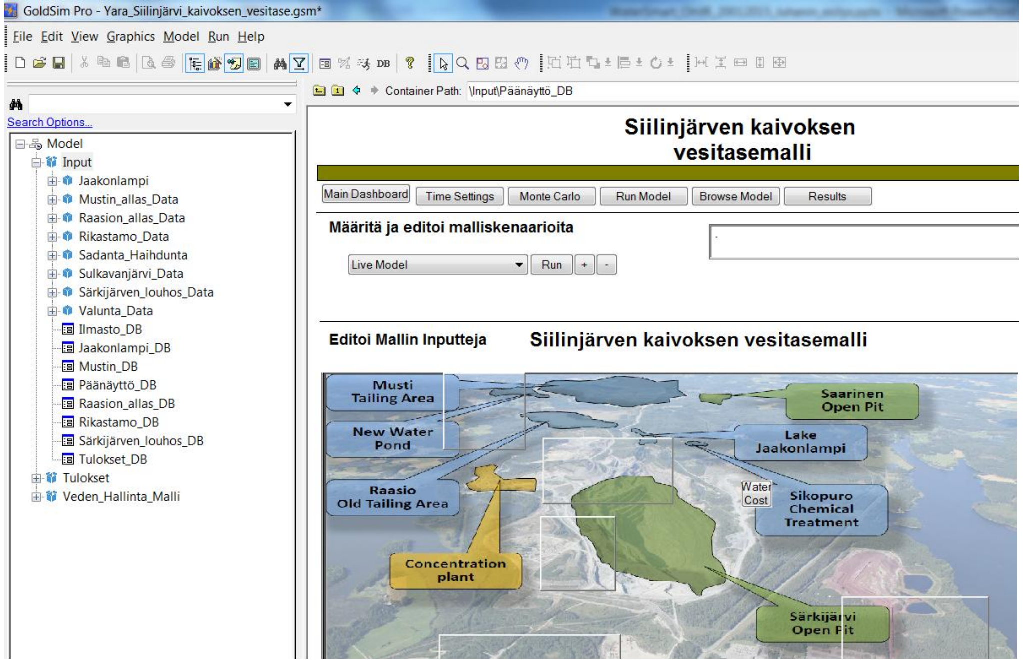
Real-time flow forecast uses a rainfall forecast as an input for an online modelling system. This system is based on real-time modelling to forecast the behaviour of the runoff

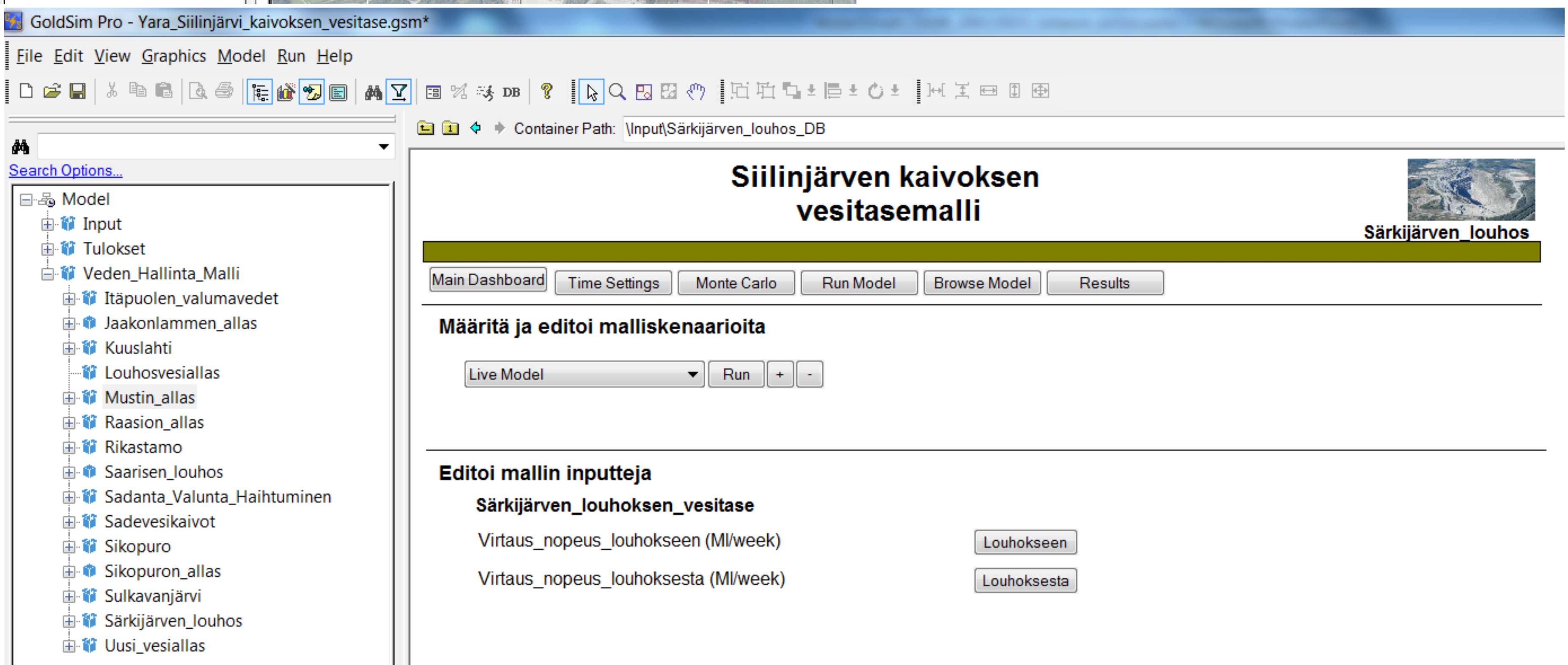


Siilinjärven kaivoksen vesikaavio (m3/h)






GoldSim Pro - Yara_Siilinjärvi_kaivoksen_vesitase.gsm*
File Edit View Graphics Model Run Help
Container Path: \Input\Päänäyttö_DB
Search Options...
Model
Input
Jaakonlampi
Mustin_allas_Data
Raasion_allas_Data
Rikastamo_Data
Sadanta_Haihdunta
Sulkavanjärvi_Data
Särkijärven_louhos_Data
Valunta_Data
Ilmasto_DB
Jaakonlampi_DB
Mustin_DB
Päänäyttö_DB
Raasion_allas_DB
Rikastamo_DB
Särkijärven_louhos_DB
Tulokset_DB
Tulokset
Veden_Hallinta_Malli
Siilinjärven kaivoksen vesitasemalli
Main Dashboard
Time Settings
Monte Carlo
Run Model
Browse Model
Results
Määritä ja editoi malliskenaarioita
Live Model
Run
Editoi Mallin Inputteja
Siilinjärven kaivoksen vesitasemalli
Musti Tailing Area
New Water Pond
Raasio Old Tailing Area
Concentration plant
Saarinen Open Pit
Lake Jaakonlampi
Water Cost
Sikopuro Chemical Treatment
Särkijärvi Open Pit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Search Options...
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Kuuslahti
Louhosvesiallas
Mustin_allas
Raasion_allas
Rikastamo
Saarisen_louhos
Sadanta_Valunta_Haihtuminen
Sadevesikaivot
Sikopuro
Sikopuron_allas
Sulkavanjärvi
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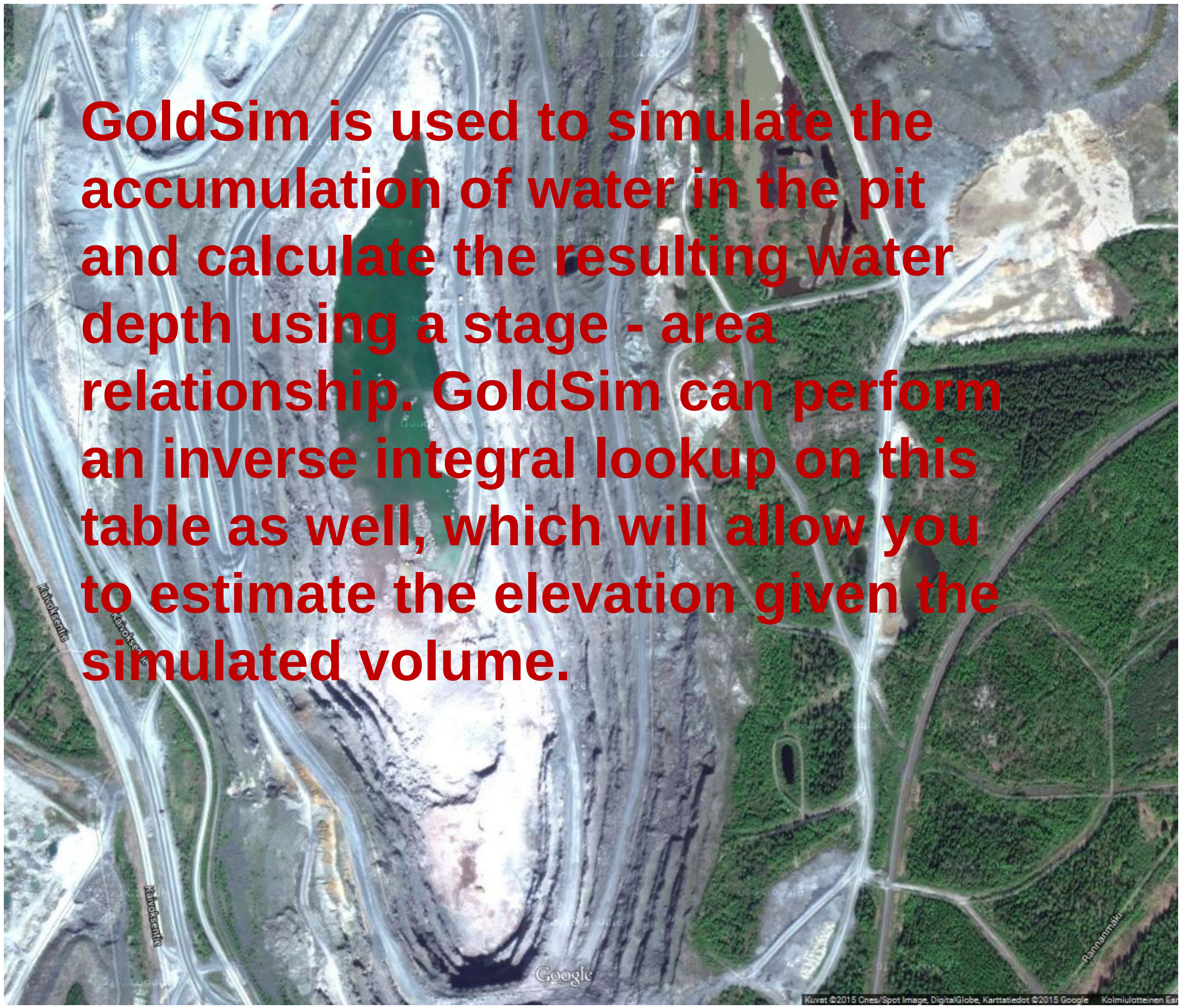
Live Model
Run
Editoi mallin inputteja
Särkijärven_louhoksen_vesitase
Virtaus_nopeus_louhokseen (Ml/week)
Louhokseen
Virtaus_nopeus_louhoksesta (Ml/week)
Louhoksesta

Yara Siilinjärvi Site: Strategic Planning (”what if”) Example -> estimations of needed pumping changes due to the expansion of the open pit area/volume



GoldSim is used to simulate the accumulation of water in the pit and calculate the resulting water depth using a stage - area relationship. GoldSim can perform an inverse integral lookup on this table as well, which will allow you to estimate the elevation given the simulated volume.

System Dynamics Approach
– the integration of all needed water balance components into the common modelling and monitoring environment…

- Quantitative tool to evaluate the performance of the system and to test the logic of each mining subactivity – calculations should include all those processes of the mine site components where the water quantity and/or quality can change during different life cycle phases of the mining project
- Databases and spreadsheets can be integrated dynamically into the overall simulations – the effects of input-changes can be simulated on the fly
- it is possible to predict future behaviour, identify which factors have the greatest influence, answer "What-if?" questions, and evaluate alternatives (also through an optimization process)
- It is possible to link and integrate external process simulators, reactive, hydrothermochemical transport models, 3D surface, seepage and groundwater flow models etc. into the system platform and into the overall dynamic calculations
- Traceability and transparency (player/exe-versio for end-users without the Goldsim licence requirement; client-specific user interfaces and control panels
- Uncertainty and sensitivity analysis using the Monte Carlo tools
- Data assimilation: Execution of the updating of model parameters and predictions always when new measurements are available.