Hydrological forecasting and real time monitoring in Finland:
The watershed simulation and forecasting system (WSFS)

Bertel Vehviläinen, Markus Huttunen, Inese Huttunen and Noora Veijalainen

Finnish Environment Institute
WSFS:

- Operational forecasts for over 20 years
- Covers about 390,000 km²
- Forecasts for over 1300 lakes and rivers
- Forecasts on public www-pages
- Forecasts updated approximately every 3-5 hours
Components of WSFS

- Semi-distributed watershed model over Finland
  - catchment division, elevation model, land use
- Data collection: real time, registers, satellite, radar
- Data assimilation
- Meteorological forecast (EPS):
  - European Centre for Medium-Range Weather Forecasts (ECMWF) and Finnish Meteorological Institute (FMI)
- WWW user-interface: operational regulation
- Forecasts: www.environmet.fi/waterforecast
Watershed simulation and forecasting system (WSFS)

- A conceptual hydrological model which simulates runoff using precipitation, potential evaporation and temperature as input
- Includes models for: precipitation, snow, soil moisture, subsurface and ground water
- Operates for 6200 drainage basins covering 390 000 km²
- Simulates 2400 lakes (>1 km²)
- Test version with 59 000 lakes (>1 ha) and water quality simulation
Based on the conceptual HBV-model:
Forecasts for

- Flood risk evaluation and warning
- Monitoring of water resources
- Operational lake regulation
- Information to media ... local people
- www.environment.fi/waterforecast
Forecasts provide predictions on hydrological phenomena for the needs of hydropower industry, flood forecasts, and tourism.
Daily WSFS operation

- Meteorological observations transferred from FMI
- Hydrological data transferred from registers and automatic observation stations
- Automatic model updating
- Meteorological forecasts from FMI
- Hydrological forecast run in SYKE
- Distribution of forecasts through the internet
www.environment.fi/waterforecast
Available forecasts:

- Discharges and water levels
- Almost all other simulated variables
- MAPS:
  - Areal precipitation
  - Soil and lake evaporation
  - Snow: water equivalent and coverage
  - Soil moisture
  - Ground water changes
  - Runoff
Water level forecast

- Shows also uncertainty of the forecast
- 50 simulations with different EPS forecasts and historical weather data
Three sources of uncertainty in the hydrological forecasts:

1. Uncertainty in the weather forecast
   • Use of 50 EPS forecasts

2. Uncertainty in the state of the model in the beginning of the forecast (snow, soil moisture, etc.)
   • Data assimilation is used to find the best estimate of the state
   • Uncertainty of the estimate is not known

3. Inaccuracy of the hydrological model
   • Not taken into account
ECMWF EPS-forecasts
Total precipitation, EPS number 1
240 hours, mean 35 mm
Reference time 2004/06/20 12 h

Total precipitation, EPS number 45
240 hours, mean 29 mm
Reference time 2004/06/20 12 h
Aim of the data assimilation:
- To estimate the state of the hydrological system today

Assimilation observations of:
- Discharge and water levels (427 stations)
- Snow water equivalent (158 stations)
- Snow cover area (SCA) satellite data
- Flood cover area (experimental)
- Soil moisture and Snow water equivalent (experimental)
Data assimilation algorithm 2/2

- Corrects inputs of the model (daily precipitation and temperature)
- Simulation is corrected to agree with observations on a 1-2 year long period backward
- Expected result of the data assimilation:
  - Hydrological storages (snow, soil moisture, etc.) are more correct
Observation networks:

- Synoptic weather stations, 50 daily measurements
- Snow courses, 161 monthly measurements
- Other weather stations, 200 daily measurements
- Discharge station, 200 daily measurements
Remote sensing data in WSFS:

- Snow cover area (SCA) satellite data in operational use since 2002 (EnviSnow)
- Weather radar precipitation in use since 2004
- Water cover area satellite data in pre-operational use in 2005 (FloodMan)
- Soil moisture satellite data (FloodMan) under development
Snow monitoring using EO-data from year 2000

- Employs daily NOAA/AVHRR-images
- TERRA/MODIS-data in test use
- ENVISAT/MERIS data currently collected
- Snow map: areal fraction of snow covered area within 6200 small drainage basins
Remote sensing of snow in SYKE

- **Reflectance model**
  - standard reflectances:
    - wet snow
    - snow-free ground
    - forest
  - cloud detection
  - image corrections

Snow covered Area (SCA)
  - numerical values for hydrological model
  - Snow maps into SYKE’s WWW-pages

- forest transmissivities
AVHRR SCA maps spring 2004
Snow cover area, %
Porvoo drainage basin: example of assimilation
The effect of updating on volume forecasts
WEATHER RADAR precipitation

- Radar data: hourly, 1x1 km grid, one hour delay
- Hourly precipitation is estimated from gauge and radar measurements.
- Radar and gauge measurements are weighted based on the reliability estimate.
- Daily precipitation as sum of hourly values
- Radar: more realistic rainfall distribution
Precipitation summer 2000

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Use of flood area information:

- In the spring 2005 we received flood area images from Norut for Kemijoki basin
- The flood cover data was shown on detailed maps in the www-interface of the SYKE-WSFS system
- The flood cover data was used in the hydrological model for improving the forecasts
- An improved method for using the flood cover data was implemented
An example of the flood cover area maps:
Improved method for using the flood cover data

- Simulation of flood extent
- Simulation is based on DEM and runoff data from the hydrological model
- Result: we can show flooded areas on the map and compare to the satellite data
- DEM is corrected to make the simulated flood extent agree with satellite observations
An example of the simulated and observed flood extent:

SYKE-WSFS flood area simulation, basin 65.994

Red: Satellite observations, Green: Simulated, Blue: observed and simulated. Map © Maanmittauslaitos, lupa nro 07/12/Y/04.
Flood area simulation model

- Input of the simulation: runoff and discharge data from the hydrological model
- DEM for routing the surface water
- Simulation resolution: 2-50 m
- When there is available satellite images:
  - DEM is corrected so that the simulation agrees with observed flood extent
  - higher and lower floods are then interpolated/extrapolated from observed flood areas using DEM
Procedure in using the flood cover area data in the hydrological model

1. Runoff and discharge is simulated with the hydrological model
2. Flood extent is simulated with the flood area simulation model
3. Flood area simulation is corrected to agree with observed flood area by correcting runoff
4. Hydrological model simulation is updated to agree with the corrected runoff
Conclusions in the use of water cover area data

- We can show the satellite observations of flood cover areas on detailed maps (within hours)
- We can simulate and animate the flood extent
- We have procedure to use the data in the hydrological model
- We don’t have an example of a case when the flood cover data improves the hydrological forecast
Steps:
1. Order data
2. Download product flood extent
3. Produce maps
4. Public (Internet/extranet)
5. Inform customer

FloodMAN DEMO (Apr.-Aug. 2005)

a) ordering system
b) present data in near real time
c) services (extranet, Internet)
d) collocate feedback

Jari Silander & Mikko Sane
Floods in northern Lapland (cities Kittilä and Ivalo, May 2005):
10 days prior to flood regional defense org. contacts SYKE
4 days prior to flood image ordering

Situation:
Flood map available from Ivalo year 1981 and expected dike failure > 900 m³/s.
Predicted discharge 1200 m³/s.
Population few thousands.
Available image 1 day after flood peak.
Weather cloudy (no optical scenes available)
River width 30 meters.
LESSONS LEARNED

- resolution at least 1/3 x river width
- over 80% of the water can be detected
- analyzed flood extent should be combined with other GIS-data (land use, water mask)
- more classes are needed (water, snow, ice, moisture)
- reference data should be available to improve water detection accuracy
- difficult to detect water in forests, flat areas, bushes or plowed fields
- remote sensing helpful when flood maps ‘useless’ (sea level and ice impact, construction, land uplift)
- end-users should be trained

**major barrier** still image price (compare air-photos)
Conclusions in the use of remote sensing data

- Weather radar data essential for forecasting fast rainfall floods
- SCA data useful in spring flood forecasts
- Flood cover data useful, but:
  - Availability and price of the data
- Soil moisture and snow water equivalent data:
  - No experiences in the operational forecasts, but good potential
Large scale phosphorus load modelling in Finland

Inese Huttunen, Markus Huttunen, Sirkka Tattari, Bertel Vehviläinen,
SYKE
Finnish Environment Institute
Watershed Simulation and Forecasting System (WSFS)
www.environment.fi/waterforecast
Description of phosphorus load model

- **phosphorus transport from land areas** has straight relation with runoff from the subcatchment, it is divided into two land use classes – agriculture and non-agriculture, also load from scattered settlement and point load is included.

- **phosphorus transport in rivers** is simulated in similar way as simple hydraulic river routing,

- **phosphorus balance in lakes** takes into account balance between inflow loading, out flowing load and phosphorus net sedimentation.
Schematic presentation of distributed hydrological and phosphorus transport model

- $c_2 = f(Q_2)$
- $L_2 = c_2 Q_2$

- $L_4 = c_4 Q_4$
- $c_4 = f(Q_4)$

Flow routing model
Phosphorus transport in river bed

Lake phosphorus balance model
- $c_{in} = f(Q_{in})$
- $L_{in} = c_{in} Q_{in}$

- $c_3 = f(Q_3)$
- $L_3 = c_3 Q_3$

- $c_1 = f(Q_1)$
- $L_1 = c_1 Q_1$
Relationships between Ptot concentration and runoff

1. Operational version
   - Runoff r (= r1+r2+r3+r4+r5) is divided into 5 classes r_x, each class has Ptot concentration c_{x,x} which is calibrated
     - r1: runoff in runoff class 1, 0-1 mm/day
     - r2 runoff in runoff class 2, 1-3 mm/day
     - r3 runoff in runoff class 3, 3-6 mm/day
     - r4 runoff in runoff class 4, 6-10 mm/day
     - r5 runoff (unlimited) in runoff class 5, > 10 mm/day
   - Concentration relationship with runoff

2. Development version
   - Runoff divided in baseflow and fast flow
   \[ C_x = \frac{r_1 \times c_1 + r_2 \times c_2 + r_3 \times c_3 + r_4 \times c_4 + r_5 \times c_5}{r} \]
   - fast flow’s concentration relationship with fast flow (mm)
   \[ C = \frac{c_{\text{fastflow}} \times r_{\text{fastflow}} + c_{\text{baseflow}} \times r_{\text{baseflow}}}{r} \]
   \[ c_{\text{fastflow}} = x_{\text{SCA}} \times x_{\text{plough}} \times \frac{r_{\text{fastflow}}}{r_{\text{max,sim}}} \times c_{\text{max}} \]

Example of concentration runoff relationship for one out of four seasons

- \( c_x \) – daily total phosphorus concentration (µg/l)
- \( x_{\text{SCA}}, x_{\text{plough}}, c_{\text{max}}, c_{\text{min}}, d \) – calibrated parameters
- \( r_{\text{sim}} \) – simulated daily runoff, mm
- \( r_{\text{max,sim}} \) – Simulated mean maximum runoff of 1990-2007
Phosphorus balance in lakes

\[ \frac{dm}{dt} = I(t) - Q_{out} c - \sigma V_c \]

- **Inflow loading**
- **Outflowing inflow**
- **Net sedimentation**

\[ \text{Net sedimentation} \]

Water balance components for each lake are simulated in hydrological model.

Daily sedimentation rate is a calibrated parameter and it does not vary in time and is the same within one 3rd level subcatchment (limits for \( \sigma_{day} \) is from 0.002 to 0.003)

Future development would be to make daily sedimentation rate changing in time depending on the inflowing discharge and load.

\[ \frac{dm}{dt} = I(t) - Q_{out} c - \partial_{sett} V_c + rA \]

- **Internal load**

Where A – is the surface area of the lake and r – release rate of phosphorus from sediment (M L^{-2} T^{-1}), calibrated parameter, for Karhijärvi internal load is 1 mg/m²/day.
Calibration

Calibration is the process of modifying the parameters to a model until the difference between output from the model and observed data sets is minimum.

Optimization criteria is:

\[ OC = w_1 \sum_{i=1}^{n_{\text{eq}}} (\text{conc}_{\text{obs}}(i) - \text{conc}_{\text{sim}}(i))^2 + w_2 \sum_{i=1}^{n_{\text{eq}}} (\text{load}_{\text{obs}}(i) - \text{load}_{\text{sim}}(i))^2 \]

- all observation points located at the same calibration area are taken into calibration:
  - + there is a need to use all available observations in the calibration even if the are very infrequent (few times per year),
  - − more frequently observed points gets more weight in the calibration procedure.

- appropriate weights for each type of observations are found and tested to reach the best possible calibration result.

- Water quality observations are not daily
GIS data in water quality simulation

- Drainage basins (and land use) for:
  - 58 000 lakes
  - 14 000 river water quality observation points
- Potential places for wetlands
  - 850 000 potential wetlands in Finland
- Data for fields:
  - In Finland 1 100 000 fields (2 300 000 ha), for each:
    - Slope
    - Soil texture
    - Plant
Mean annual riverine phosphorus load from Finland
(3750 t / year)
Annual riverine phosphorus load from Finland

- Point sources directly to the Baltic Sea are not included
- Unmonitored catchments are not in the comparison (right graph)
- Mean monthly method calculations provided by A. Räike, SYKE
Retention in different parts of Baltic Sea catchment

**Gulf of Finland**, specific load 15 kg/year/km²

- Load entering water bodies, t/year: 1005
- Load leaving watershed, t/year: 593
- Retention, t/year: 411

**Archipelago Sea**, specific load 37 kg/year/km²

- Load entering water bodies, t/year: 361
- Load leaving watershed, t/year: 346
- Retention, t/year: 15

**Bothnian Sea**, specific load 18 kg/year/km²

- Load entering water bodies, t/year: 855
- Load leaving watershed, t/year: 606
- Retention, t/year: 249

**Bothnian Bay**, specific load 11 kg/year/km²

- Load entering water bodies, t/year: 2035
- Load leaving watershed, t/year: 1886
- Retention, t/year: 149

**Ladoga**, specific load 8 kg/year/km²

- Load entering water bodies, t/year: 807
- Load leaving watershed, t/year: 228
- Retention, t/year: 579
Source apportionment for parts of Baltic Sea catchment

Note: point load includes atmospheric deposition to lake surface

- **Catchment of Gulf of Finland**: 1007 t/year formed in catchment
  - Agricultural areas: 46%
  - Non-agricultural areas: 21%
  - Scattered settlement: 14%
  - Point source: 19%

- **Catchment of Archipelago Sea**: 360 t/year formed in catchment
  - Agricultural areas: 79%
  - Non-agricultural areas: 10%
  - Scattered settlement: 9%
  - Point source: 2%

- **Catchment of Bothian Sea**: 856 t/year formed in catchment
  - Agricultural areas: 55%
  - Non-agricultural areas: 22%
  - Scattered settlement: 11%
  - Point source: 12%

- **Catchment of Bothnian Bay**: 2034 t/year formed in catchment
  - Agricultural areas: 64%
  - Non-agricultural areas: 28%
  - Scattered settlement: 6%
  - Point source: 10%
Results from agricultural clayey soil Aurajoki catchment (870 km²)
2. Simulated concentration for Säkkijoki (48 km²)
3. Simulated concentration in the lake Karvianjärvi (153 km²)
Causes of high phosphorus concentrations during low flow periods

- For river reaches with point source outlets and scattered settlement the ratio of effluent flow to river flow is higher during low flow periods;
- It might be that geochemical processes in the soil saturated zone itself, possibly in brook sediments, cause release of dissolved reactive phosphorus (Lazzarotto, 2004);
- Increased concentrations during low flows are especially to be noted in the peat land drainage areas and peat mining areas (Sallantaus, 1985, Kløve, 2001).
Results for peat dominated catchment with lakes - Karvianjoki (3438 km²)
Phosphorus load under changing climate
Conclusions

- Developed phosphorus load model can be used for quantifying phosphorus load to the Baltic Sea from territory of Finland;
- Phosphorus concentration sampling frequency is typically quite poor. Automatic measurement techniques would improve the model calibration efficiency and also model process description;
- This study clearly demonstrates that different geographical regions require different aspects into model. Separation between fast flow and base flow is necessary in simulation phosphorus transport in peat soil catchments;
- Phosphorus retention in inland lakes has big role on the phosphorus balance on county-wide scale, phosphorus retention is 30% in total in inland lakes in Finland.
Thank You!

www.environment.fi/waterforecast