# Introducing WSFS-P, Process-based Version of the Watershed Simulation and Forecasting System (WSFS) in Finland

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## 1. Abstract

This study introduces the WSFS-P model, an evolution of the well-established national WSFS (Watershed Simulation and Forecasting System) hydrological model. This new model represents a significant shift, moving from a conceptual WSFS hydrological model framework to a more physically based, and process-oriented approach (WSFS-P). WSFS-P is a two-layer semi-distributed hydrological model developed at the Finnish Environment Institute (Syke) to offer more detailed physical representations in hydrological forecasting and research. This hydrological model incorporates several sub-models that cover a wide range of hydrologic processes, including precipitation, snow dynamics, evapotranspiration, lake evaporation, soil moisture, groundwater, river routing, and ice thickness. The WSFS-P aims to enhance the accuracy and effectiveness of hydrological forecasting and research in Finland by leveraging spatially distributed data, such as CORINE Land cover, altitude, and Finnish soil database. This model covers the entire Finnish mainland and transboundary catchments. This study assesses the WSFS-P model in 58 different catchments in Finland that were selected to cover diverse hydrological characteristics, reliable data, and minimal influence from lake regulation. The preliminary results demonstrate the model's capabilities in predicting water availability, contributing to efficient water resource management and enhanced flood and drought prediction in Finland. This study aims not only to introduce the WSFS-P model but also to validate its operational readiness for diverse hydrological conditions.

## 2. Introduction to the WSFS-P Hydrological Model Use Cases

At the Finnish Environment Institute, Syke, Finland, The WSFS-P hydrological model is used as the main hydrological tool for water resource management, environmental planning, and research, and serves a wide spectrum of applications, addressing the needs of various stakeholders. Some of its key applications are:

- **Operational Forecasting:** The WSFS-P produces daily hydrological forecasts along with monthly-to-seasonal drought forecasts with updated observations and weather forecasts. This critical data empowers authorities, hydropower companies and lake regulators, facilitating informed decision-making and efficient resource management (Fig. 1, Fig. 2).
- **Flood Risk Management**: Advanced flood simulations and the mapping of potential flood zones contribute to proactive disaster preparedness and mitigation.
- **Water Regulation Analysis**: Analysis of inflow, outflow and water levels in regulated lakes facilitate effective water management and conservation strategies (Users: ELY-Centers, Hydropower companies).
- **Scientific and Technical Simulations**: Beyond its utility in forecasting and water management, the WSFS-P hydrological model is instrumental in research, notably for evaluating **climate change** impacts.

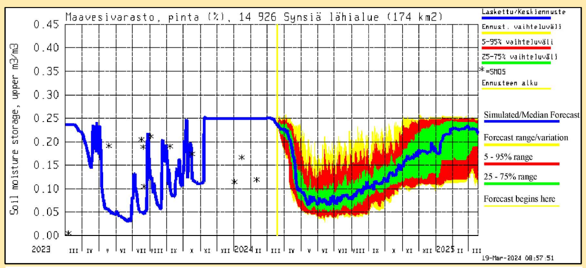


Fig. 1. Upper soil layer soil moisture long-term forecast. Note: *SMOS soil moisture observations in winter are unreliable.

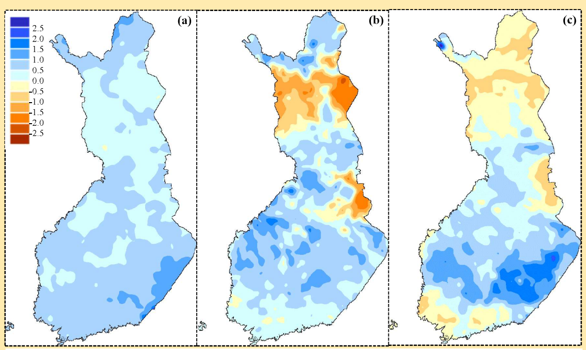


Fig. 2. Drought average forecast maps for April-2024 in Finland: (a) The Standardized Precipitation Index (SPI), (b) The Soil Moisture Anomaly (SMA), and (c) The Standardized Runoff Index (SRI). Note: 2.00 and more extremely wet, 1.50 to 1.99 very wet, 1.00 to 1.49 moderately wet, -0.99 to 0.99 near normal, -1.00 to -1.49 moderately dry, -1.50 to -1.99 severely dry, -2.00 and less extremely dry.

## 3. Exploring the Main Processes of the WSFS-P Hydrological Model

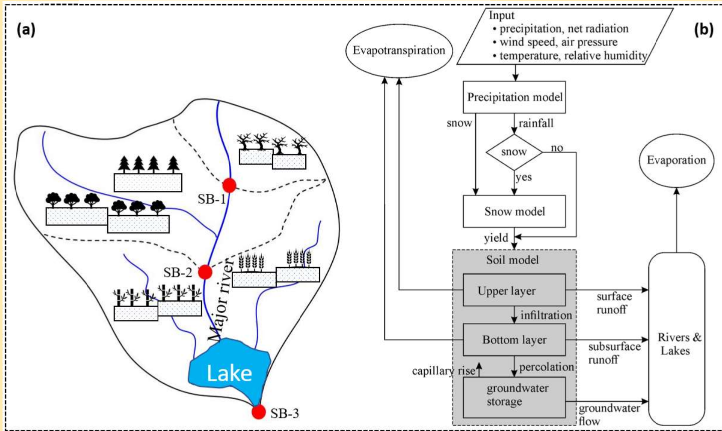


Fig 3. (a) Schematics demonstrating the watershed delineation for the WSFS-P model, its subbasins (SB-1, SB-2, SB-3) and the grid-cell discretization by soil type, vegetation, and elevation, (b) a two-layer soil moisture model with the major hydrologic processes for each soil-land-use class.

The **WSFS-P** hydrological model consists of several sub-models (Fig. 3), each based on physical principles. Together, these sub-models contribute to a detailed and integrated understanding of the hydrological processes, enabling better water resource management, flood, and drought forecasting, and climate change impact assessments. The key sub-models included in the **WSFS-P** hydrological model are:

### Precipitation model

We use corrected point precipitation data from Finnish Meteorological Institute and nearby countries, adjusting for gauging errors based on air-temperature and wind. Areal precipitation for subbasins is then calculated using the three closest stations, applying an **inverse distance weighting** method that considers altitude differences between stations and subbasins.

### Snow Model

Our snow model simulates snow accumulation and melt using inputs of areal precipitation and daily temperature. The simulation of snow melt is conducted through the utilization of snow energy balance, which accounts for factors such as snow compaction and the temperature-dependent formation of new snow. The simulation of energy balance incorporates various factors, including short and long wave radiation, precipitation, latent and sensible heat, and the cold content of snow. The process of compaction is influenced by both temperature and the snow water equivalent of the snow cover. We separately simulate snowmelt for **open and forest areas**, critical for accurate long melt period simulations with variable temperatures and ensuring an accurate areal snow cover distribution. This sub-model has several parameters which are calibrated against observed data (snow water equivalent, thickness and density are measured in 4 km long courses in different land use classes).

### Evapotranspiration and Lake Evaporation Model

This sub-model estimates reference crop evapotranspiration for each land use class using the **Penman-Monteith** formula, incorporating the impact of soil moisture and vegetation on daily evaporation. Total sub-basin evaporation is the weighted average from various land use classes. **The lake evaporation rate** is calculated using the aerodynamic formula for latent heat flux, which quantifies the energy associated with the phase change of water from liquid to vapor.

### Soil Moisture Model

The simulation of soil moisture is based on a two-layer soil moisture model (Upper-layer ~10 cm & Bottom-layer ~80 cm soil thickness). The soil properties of different soil types, such as porosity, field capacity, wilting point and hydraulic conductivity, have a significant impact on soil moisture, infiltration, percolation, and runoff. Water infiltration from the surface to the sub-surface layer occurs when soil moisture exceeds field capacity. Runoff from the surface layer occurs solely during ground freeze conditions. The subsurface layer contributes primarily to runoff for river routing and lake models, along with percolation into groundwater storage.

### Groundwater Model

In this sub-model, **percolation** from various soil types in the subsurface layer, calculated in the soil-moisture-model, is the main input to groundwater storage. Water leaves a groundwater storage via capillary pressure, which is only measured at groundwater monitoring stations, and groundwater flow (or baseflow) to nearby rivers.

### Lake and River Routing Model

In WSFS-P model, every sub-basin is either a river or lake area. For rivers, we calculate their length and width based on the sizes of the current and upper sub-basins, then divide the river into segments. Local runoff is distributed equally across these segments, with upstream discharge added to the first segment. Water flow (Qout) through each segment is then calculated, and river parameters are calibrated using discharge observations. **Lake water balance** in the model accounts for inflows from precipitation, local runoff, upstream discharge, and evaporation. Lakes are categorized as either unregulated (natural) or regulated. Outflows, through one or more outlets, are calculated using methods such as rating curves, equations based on calibrated parameters or defined regulation rules.

### Soil Frost Model

In WSFS-P, the impact of soil frost on hydrological dynamics are evaluated, focusing on its influence on surface-to-sub-surface water infiltration, subsurface runoff, and percolation to groundwater storage. Soil frost related model parameters are calibrated against soil frost observations. Forested, open, and swamp areas are considered separately and have their own set of calibrated parameters.

## References

Vehviläinen, B. (1992). Snow cover models in operational watershed forecasting: National Board of Waters and the Environment. Vesi-ja ympäristöhallitus.
Jakkila, J., Vento, T., Rousi, T., & Vehviläinen, B. (2013). SMOS soil moisture data validation in the Aurajoki watershed, Finland. Hydrology Research, 45(4-5), 684-702. doi:10.2166/nh.2013.234

## 4. Model Calibration and Validation Results

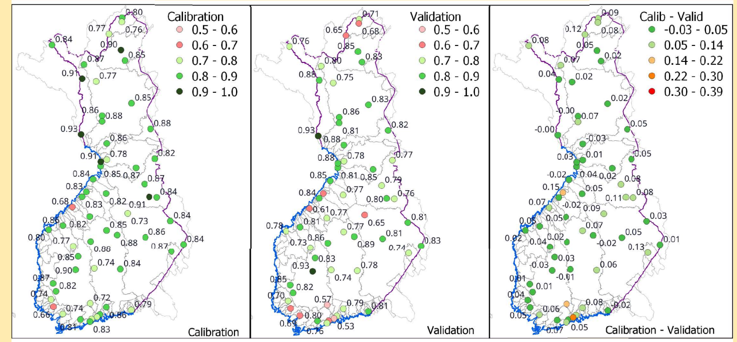


Fig 4. Nash-Sutcliffe efficiency (R²) across Finland: calibration period (1991-2015, left), validation (1981-1991 and 2015-2021, middle), and their differences (right).

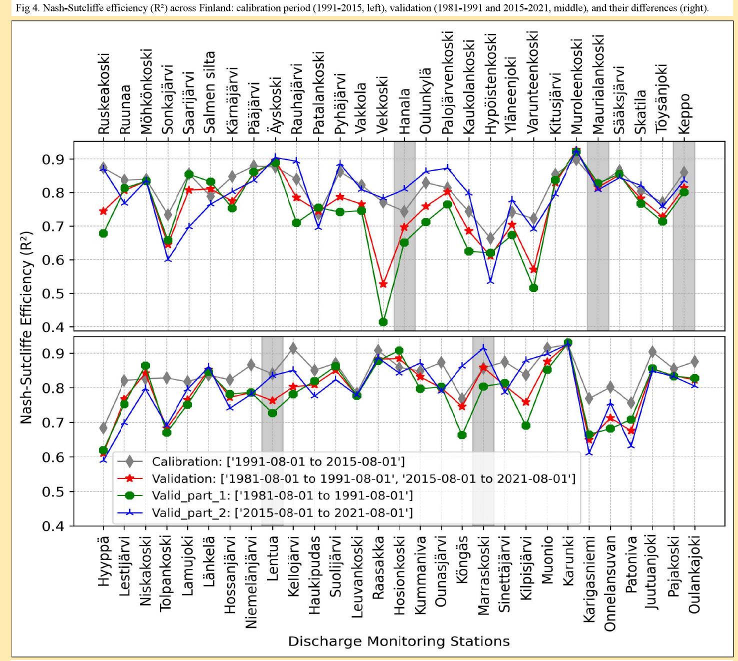


Fig 5. Nash-Sutcliffe efficiency (R²) for discharge stations in Finland, covering calibration, validation, and subdivided validation (Valid_part_1 and Valid_part_2) periods.

## 5. Conclusions and Future Developments

The WSFS-P hydrological model has undergone extensive calibration and validation procedures, consistently delivering satisfactory results (Fig. 4, Fig. 5), and is now ready for **operational deployment**. However, the groundwater component within the WSFS-P hydrological model still requires significant refinement due to its oversimplified representation of complex phenomena, especially regarding inter-subbasin flows and regional flows. To address this, we have initiated an integration effort with MODFLOW (USGS: Fully physical three-dimensional groundwater flow model), where it receives simulated percolation (recharge) data from WSFS-P. Subsequently, MODFLOW undertakes the simulation of groundwater flow and levels. This integration process is currently in the testing phase.

## Acknowledgement & References

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