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## INTRODUCTION

- **Groundwater flow** is the primary control on radionuclide transport in deep geological disposal systems, governing both transport pathways and travel times over long timescales.
- **Hydrogeological conditions**, including hydraulic properties and boundary conditions, play a key role in determining the behavior and evolution of subsurface flow systems.
- Long-term safety assessment requires reliable monitoring data to support model development, validation, and reduction of uncertainties over geological timescales.
- A **multi-scale monitoring framework** is essential to integrate regional boundary conditions with site-specific hydrogeological processes and improve predictive confidence.

## HYDROGEOLOGICAL FACTORS

### ① Meteorological Data

Key parameters	Characteristics
<ul style="list-style-type: none"> <li>✓ Precipitation</li> <li>✓ Temperature</li> <li>✓ Evapotranspiration</li> <li>✓ Atmospheric pressure</li> <li>✓ Wind speed and direction</li> <li>✓ Solar radiation</li> </ul>	<ul style="list-style-type: none"> <li>• Defines upper boundary conditions of the hydrogeological system</li> <li>• Controls groundwater recharge and water balance</li> <li>• Drives long-term climate variability and system evolution</li> <li>• Provides essential input for future scenario modeling</li> </ul>

### ② Groundwater Data

Key parameters	Characteristics
<ul style="list-style-type: none"> <li>✓ Groundwater level / Hydraulic head</li> <li>✓ Hydraulic conductivity(K)</li> <li>✓ Groundwater flow velocity</li> <li>✓ Pore pressure</li> <li>✓ Fracture connectivity</li> <li>✓ Inflow / leakage rates</li> <li>✓ EDZ(Excavation Damaged Zone) properties</li> </ul>	<ul style="list-style-type: none"> <li>• Directly controls flow pathways and transport processes</li> <li>• Governs radionuclide migration and travel time</li> <li>• Sensitive to excavation and repository-induced disturbances</li> <li>• Requires high-resolution, site-specific monitoring</li> </ul>

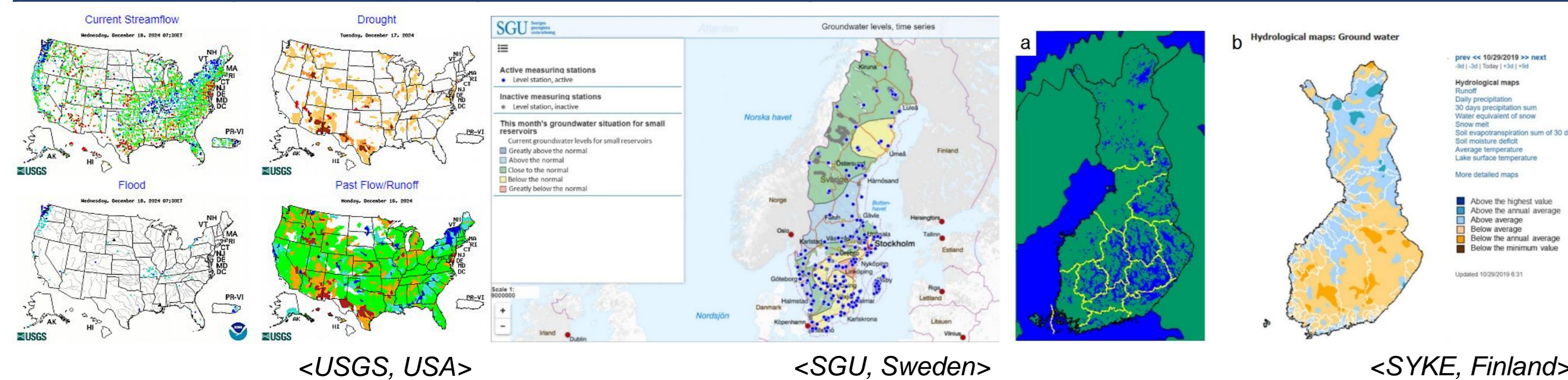
### ③ Surface Water Data

Key parameters	Characteristics
<ul style="list-style-type: none"> <li>✓ Surface water level</li> <li>✓ Surface water discharge</li> <li>✓ Infiltration / recharge rate</li> <li>✓ Sea level (coastal sites)</li> </ul>	<ul style="list-style-type: none"> <li>• Defines hydraulic boundary conditions</li> <li>• Controls groundwater discharge and recharge zones</li> <li>• Represents surface-subsurface interactions</li> <li>• Essential for basin-scale water balance analysis</li> </ul>

## INTERNATIONAL MONITORING CASES

### I. National-Scale Hydrogeological Monitoring

Country	Organization	Key Parameters	Key Characteristics
USA*	USGS	Stream flow, runoff, drought/flood indicators	Real-time monitoring with high temporal resolution; open-access data system
Canada	WSC (ECCC)	Water level, discharge	Standardized national hydrometric network with real-time data
Sweden*	SGU	Groundwater level, chemistry	High-frequency groundwater monitoring(4-6 times/day); spatial-temporal analysis
Finland*	SYKE	Groundwater level, quality	Long-term datasets (~40 years); integrated monitoring + prediction
Switzerland	FOEN (NAQUA)	Groundwater level, quality, discharge	Combined quantity and quality monitoring; long-term statistical datasets



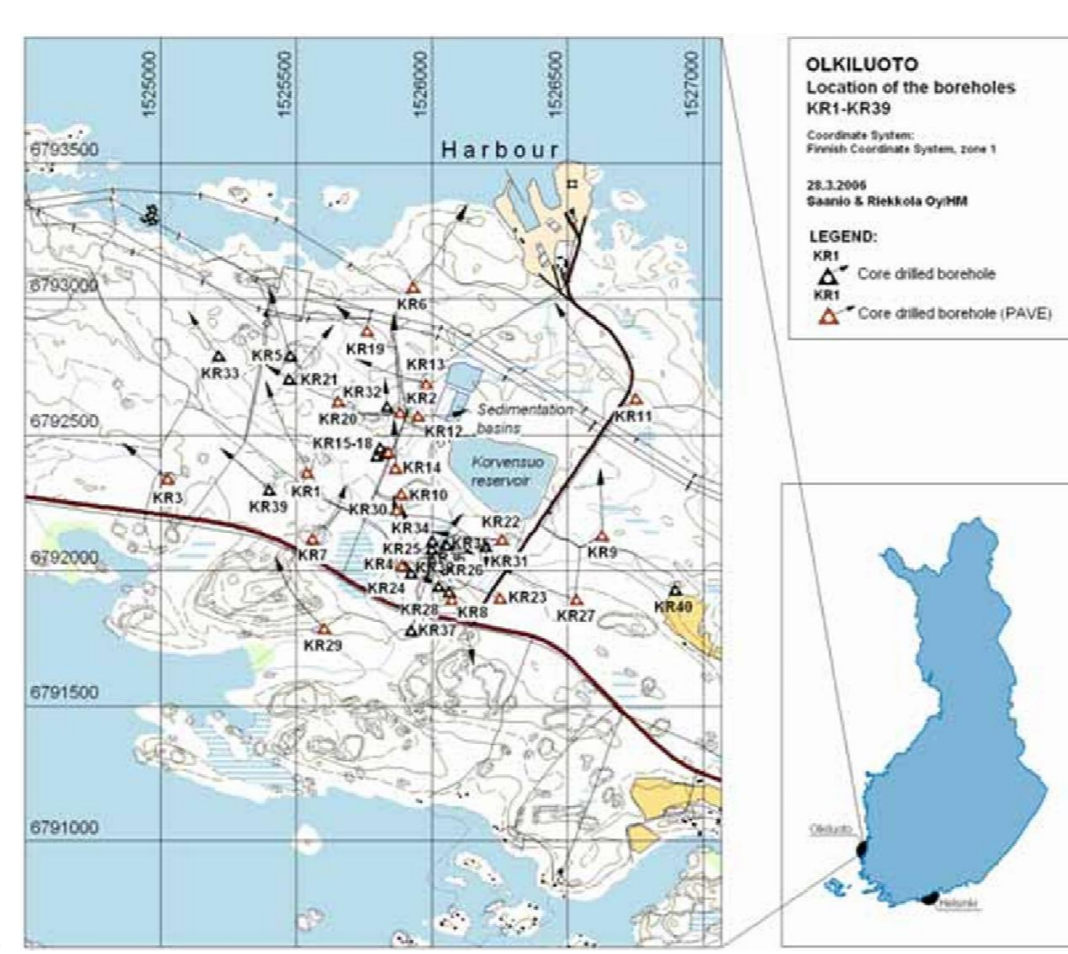
### II. Site-Scale Hydrogeological Monitoring

#### ① Forsmark, Sweden

- **Meteorological monitoring**: Temperature, precipitation, and wind conditions  
→ Evaluation of long-term climate variability and recharge processes
- **Surface water monitoring**: Water levels and flow rates in lakes, streams, and coastal systems  
→ Assessment of surface-groundwater interaction
- **Near-surface hydrogeological monitoring**: Shallow groundwater levels and seasonal variations  
→ Recharge and discharge processes
- **Deep bedrock hydrogeological monitoring**: Hydraulic head and groundwater flow in fractured rock  
→ Long-term stability of deep groundwater systems

#### ② Olkiluoto, Finland

- **Meteorological monitoring**: Temperature, precipitation, wind, and snow cover  
→ Evaluation of climate effects on groundwater system
- **Surface hydrology monitoring**: Surface water flow patterns and discharge pathway  
→ Analysis of recharge-runoff relationships and water balance
- **Hydrogeological monitoring**: Hydraulic head measurements across different depths  
→ Determination of groundwater flow patterns in fractured rock

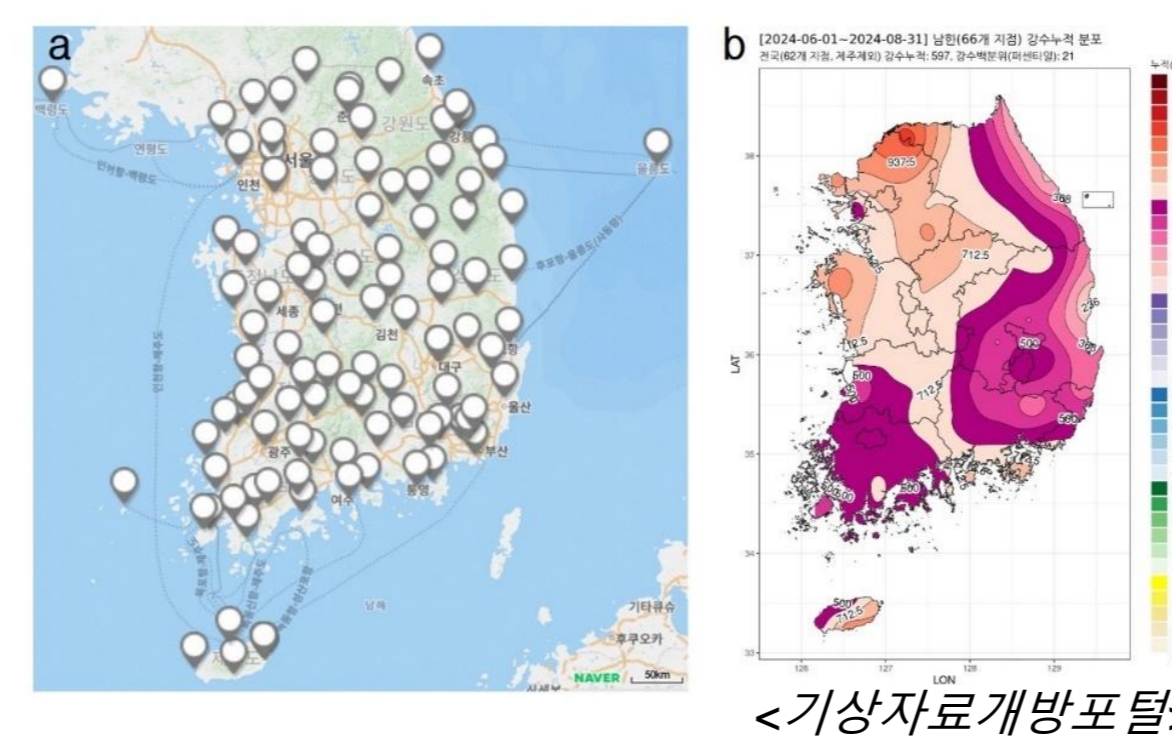


## HYDROGEOLOGICAL MONITORING IN KOREA

### I. National-Scale Monitoring

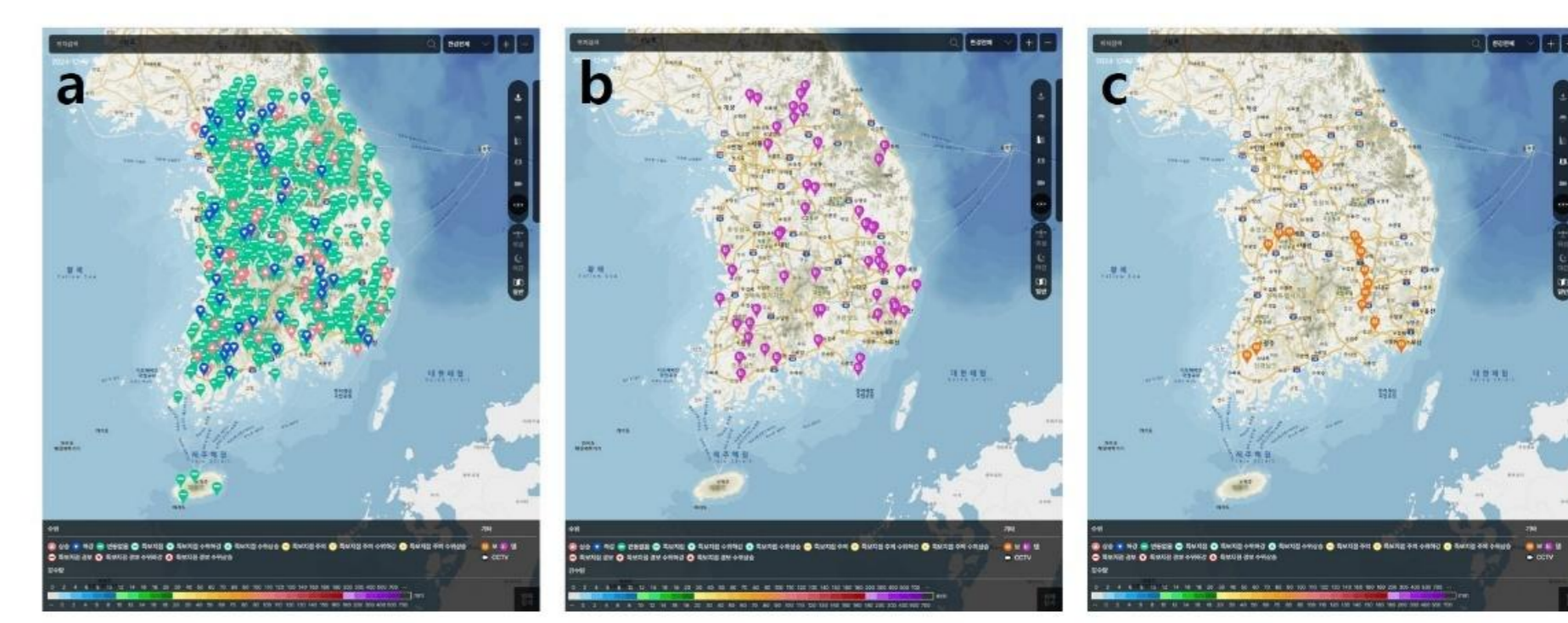
#### • Meteorological monitoring

: Nationwide meteorological stations operated by Korea Meteorological Administration(KMA)  
*Precipitation, temperature, humidity, wind speed & direction*  
High temporal resolution (minute-scale observations)



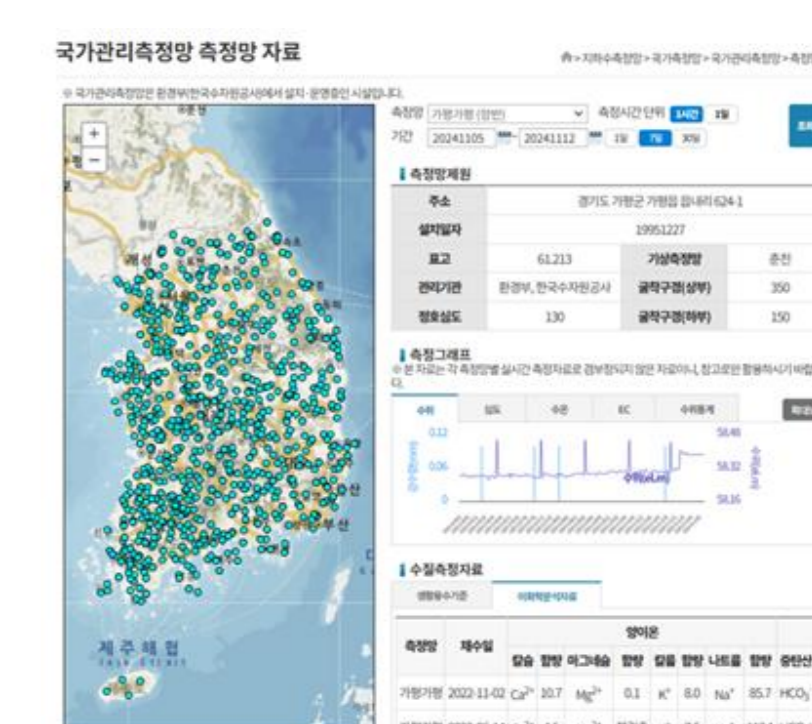
#### • Surface water monitoring

Nationwide monitoring networks operated by multiple agencies  
Real-time observation of *river stage and discharge data* used for water resource management and hydrological analysis



#### • Groundwater monitoring

: National groundwater monitoring network (~6000 wells)  
*Groundwater level, groundwater temperature, electrical conductivity*  
Data accessible through centralized database system



### II. Strategy for Site-Scale Monitoring

#### ◆ Hydrogeological Monitoring Parameters and Purposes

Category	Monitoring Parameter	Purpose
Meteorological	Precipitation	- Estimation of recharge and water balance
	Rainfall intensity	- Analysis of rainfall-head response
	Temperature / Humidity	- Estimation of potential evapotranspiration (PET)
	Atmospheric pressure	- Correction of hydraulic head data
	Wind speed / direction	- Input for evapotranspiration estimation
	Solar radiation	- Energy balance and PET estimation
	Evapotranspiration	- Estimation of actual ET
Hydrogeological	Groundwater level / head	- Determination of hydraulic gradients
	Multi-depth head	- Identification of fracture-specific head
	Hydraulic conductivity (K)	- Quantification of permeability
		- Small-scale K estimation
	Groundwater velocity	- Estimation of bulk aquifer properties
	Groundwater discharge	- Measurement of actual flow velocity
Surface Water	Flow pathways	- Quantification of fracture flow rate
	EDZ (Excavation Damaged Zone)	- Identification of flow paths and travel time
	Rock structure	- Evaluation of excavation-induced changes
	River stage	- Fracture orientation and connectivity
	River discharge	- Stage recording and boundary condition
	Temperature / exchange	- Discharge estimation
Sea level	- Groundwater-surface water interaction	
	- Evaluation of tidal influence and density flow	

#### ◆ Recommended Monitoring Frequency

**Continuous (5~10 min)**: Meteorological data and groundwater level (hydraulic head)

**Event-based**: Rainfall response, pressure response, tracer tests

**Periodic/Long-term**: Hydraulic properties (K), EDZ monitoring, trend analysis