KIOS
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Interconnected Digital Twins for Water Contamination Management

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KIOS Research and Innovation Center of Excellence

University of Cyprus

EGU2025: Session HS5.4.4 Digital water and interconnected urban infrastructure

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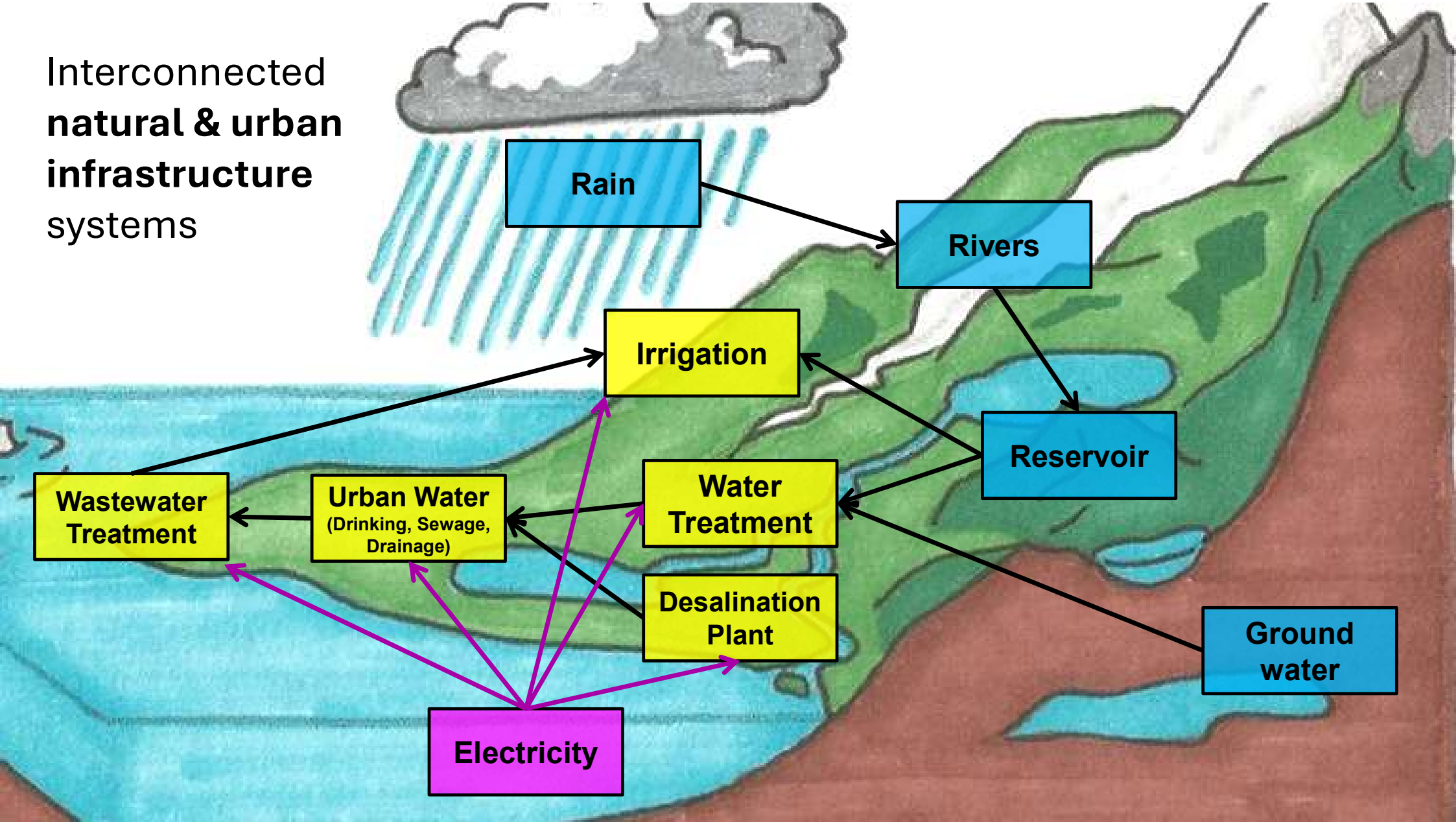
Interconnected **natural & urban infrastructure** systems



Pathogen Contamination Risk

- **Floods increase the risk of water contamination** from sewage overflows, and decomposing organic matter
- **Waterborne pathogens**: E. Coli, Campylobacter, Norovirus, enterovirus, etc.
- **Health risks**: Gastrointestinal & respiratory infections, long-term health effects, death
- **Cascading risks due to digital breakdown**: power outage affecting pumping/treatment, automations not working

NEWS

The risk that a massive blackout represents for water supply in Spain

Although backup systems allow for gaining a few hours or days of time, their inevitable depletion leads to the collapse of the entire water cycle. Capture, purification, distribution, and sanitation depend deeply on electricity

Challenging the status quo

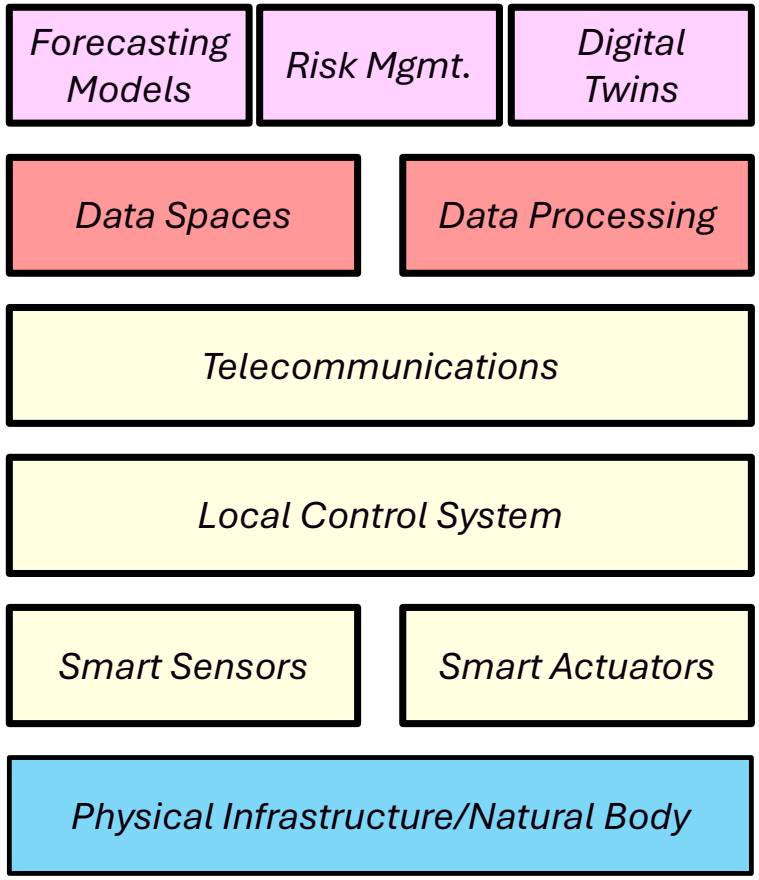
- Typically, each (smart) water, power, and transport system is managed **separately** by a different agency.
- Each agency follows different **regulations** and **responsibilities**.
- There is limited **data sharing** between systems and agencies.
- Scientific **specializations** limited to a subset of these system.
- **Boundary conditions** for **models** (and Digital Twins) are assumed "known".

Moving towards interconnected digital twins, implies using **digital tools** to monitor, simulate and manage smart systems in a **holistic**, **distributed** way.

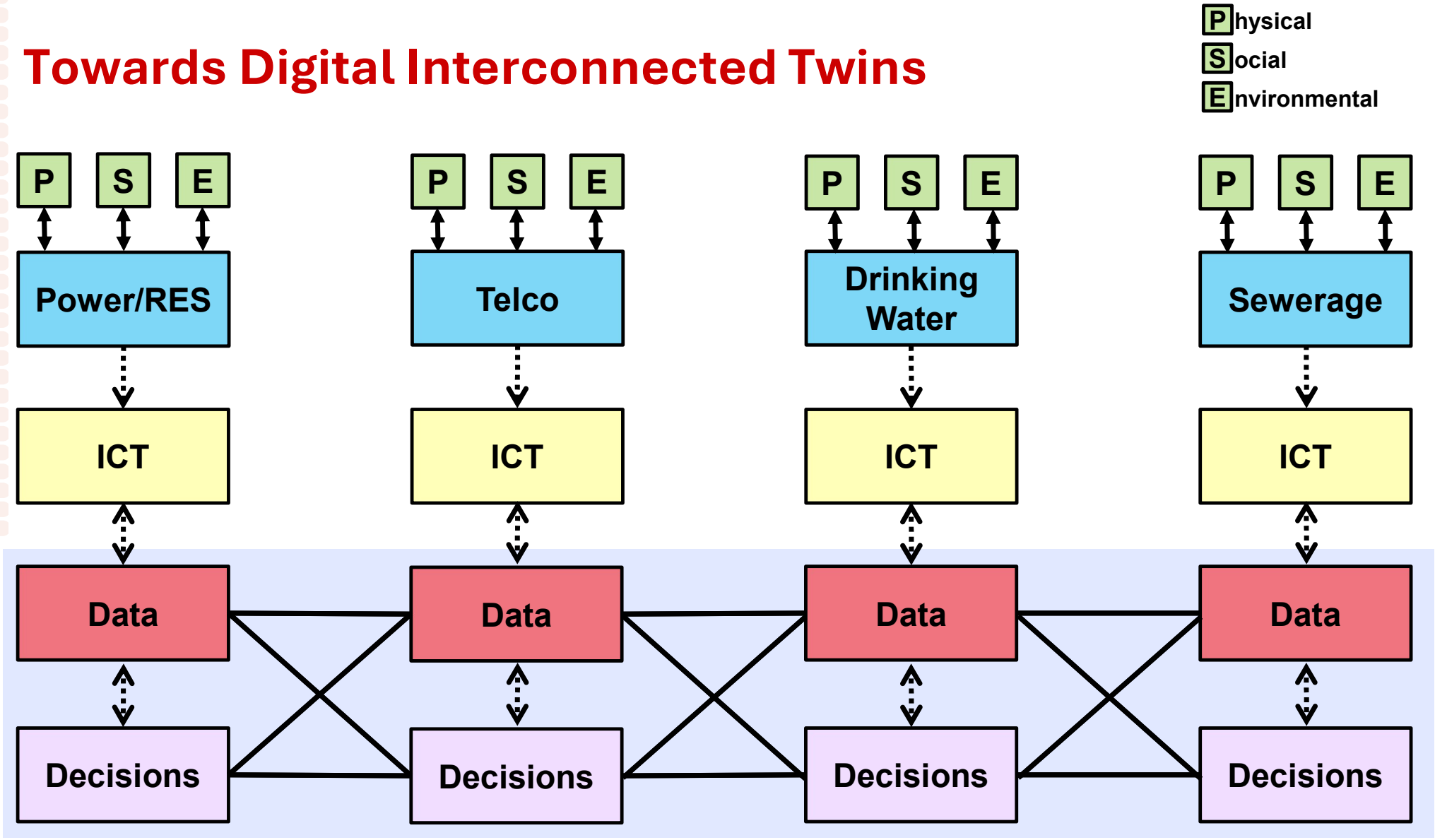
- ✓ Internet of Things/EO
- ✓ Digital Twins
- ✓ Data Spaces
- ✓ Artificial Intelligence

What is a Smart Water System?

- Integration of **smart sensors** and **smart actuators** into water systems using **information technology**, **communications**, and **data spaces**.
- Tools for short-term and long-term **decision-making**, optimization, and control through **digital twins** and **artificial intelligence**.
- Enhancement of **efficiency** and improvement of the **safety**, **reliability**, **resilience**, **quality**, and **robustness** of water supply systems.
- **Minimization of risks** due to uncertainties, extreme events, and climate change.

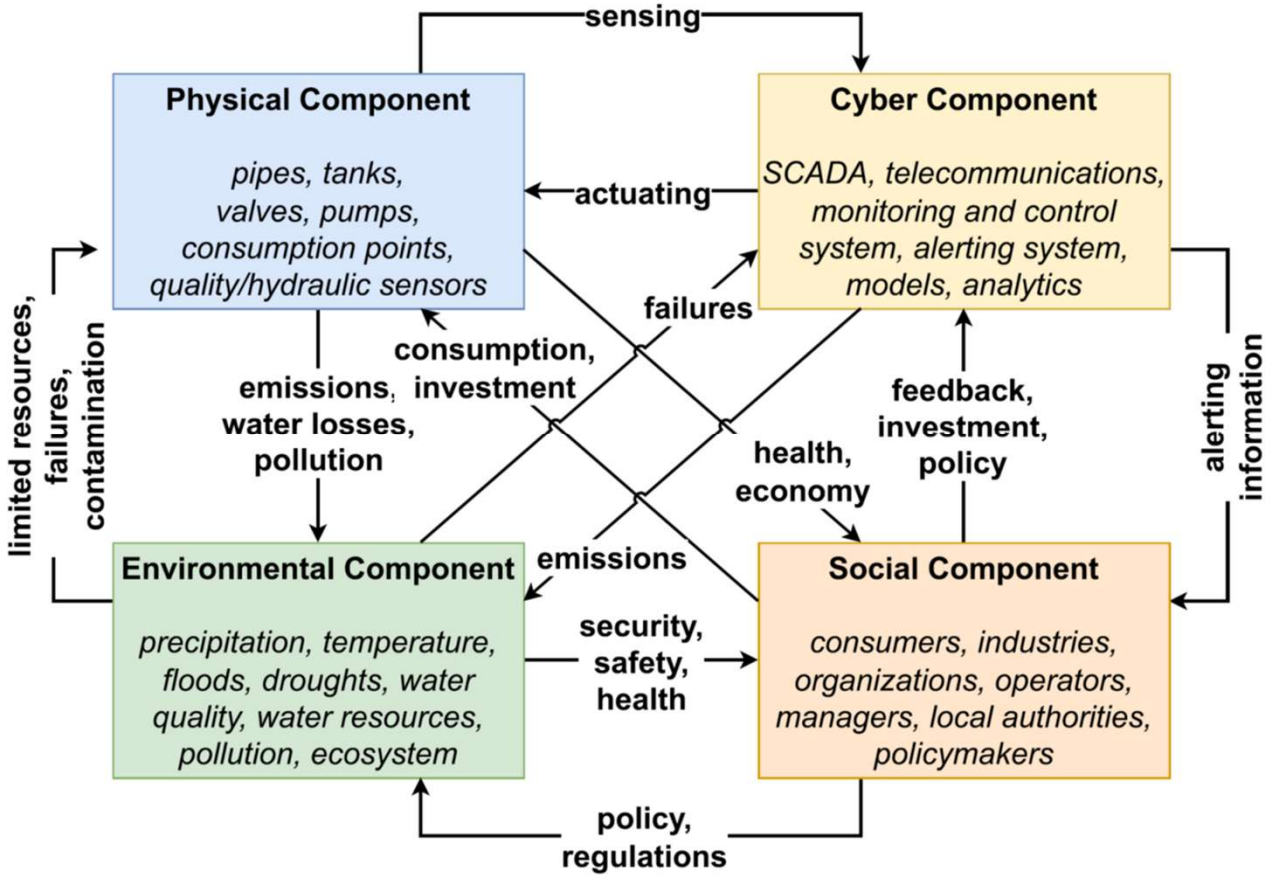


Towards Digital Interconnected Twins



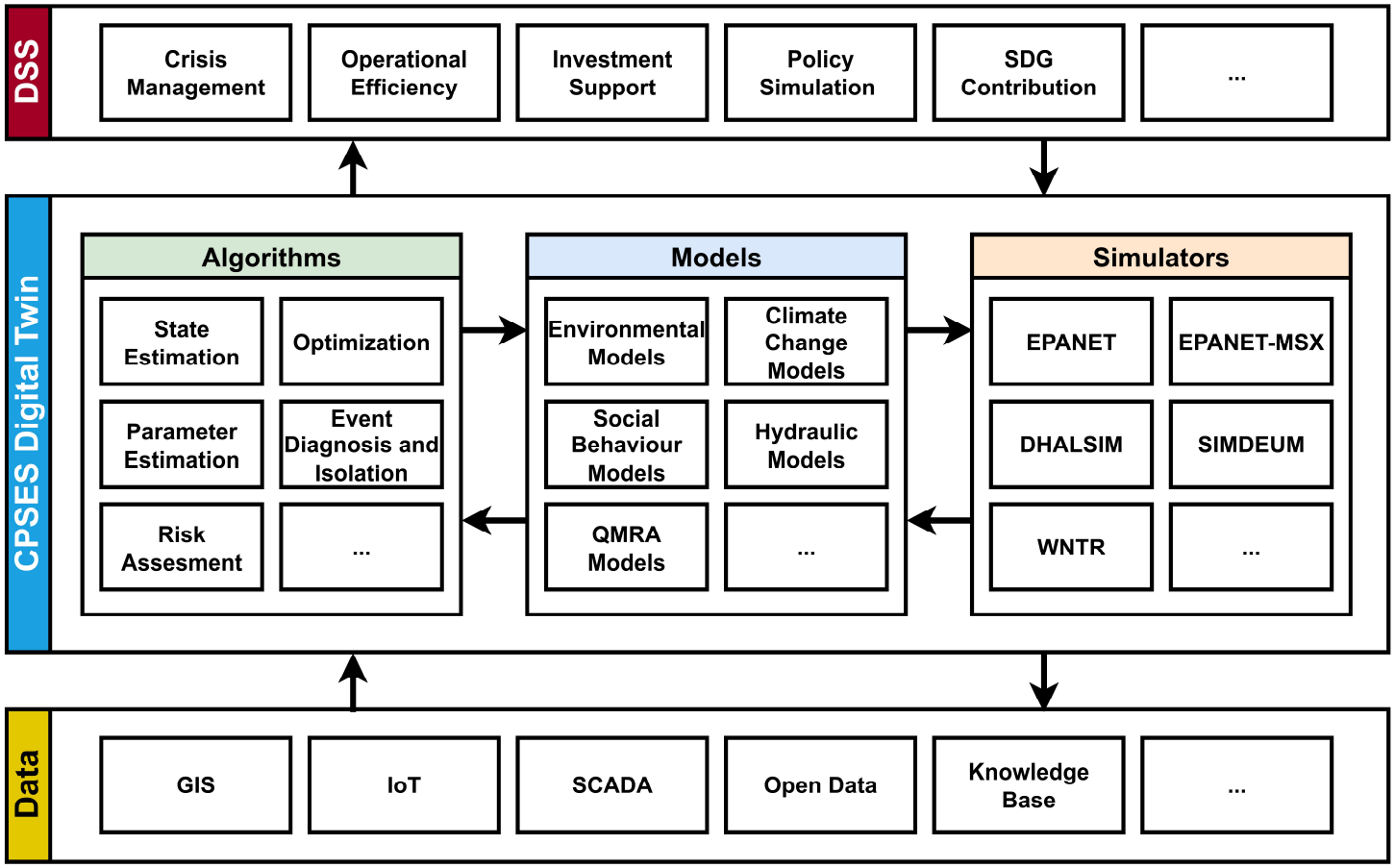
Cyber-Physical-Socio-Environmental System (CPSES)

- Water systems have multiple interdependencies with cyber, physical, social, and environmental components.
- Their interdependencies need to be mapped.
- Digital Twins could model some of these.



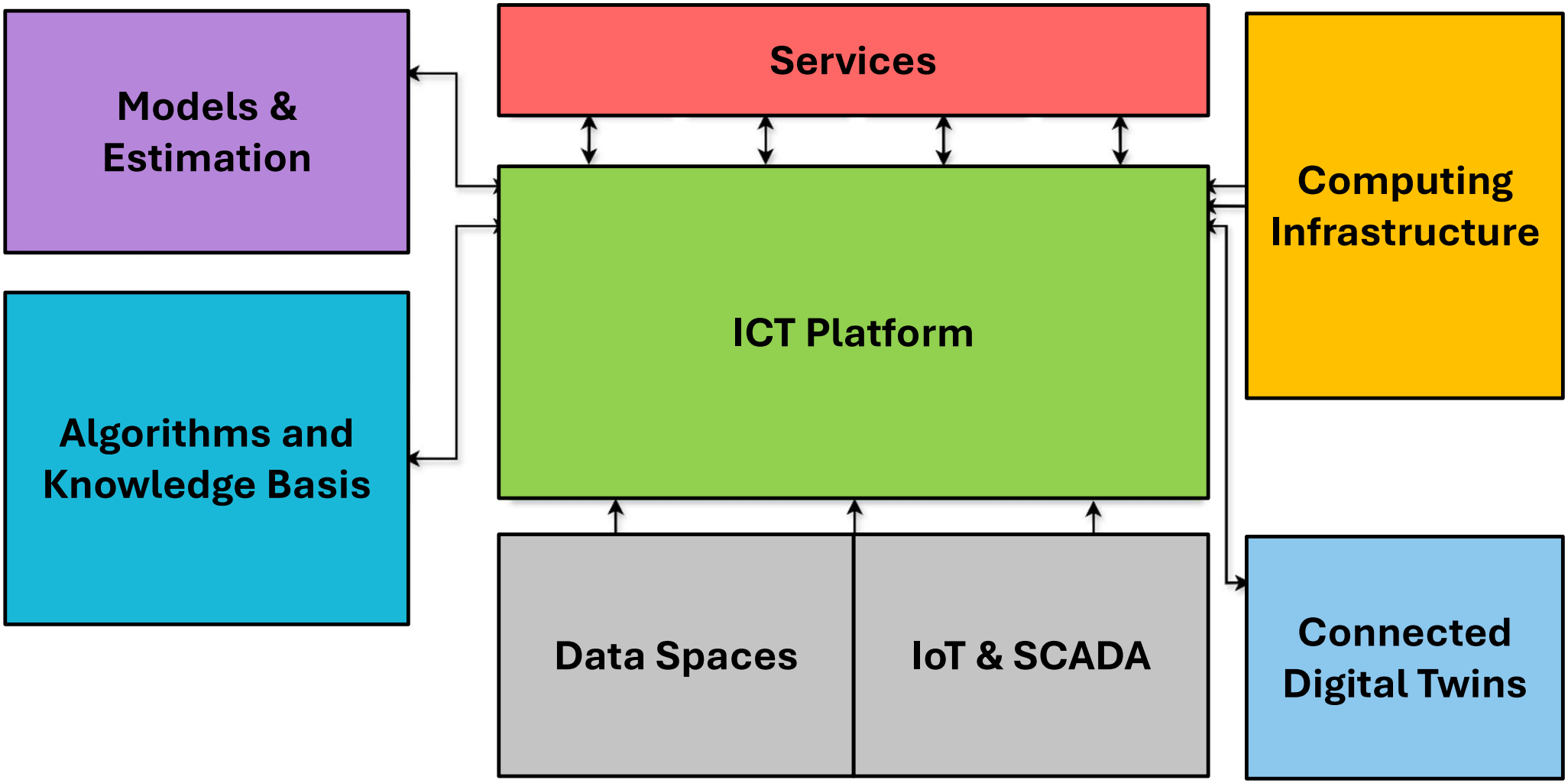
Eliades, D.G., Malialis, K., Vrachimis, S. and Polycarpou, M.M., 2024. Smart Water Networks as Cyber-Physical-Socio-Environmental Systems. *IEEE Transactions on Industrial Cyber-Physical Systems*.

Cyber-Physical-Socio-Environmental System (CPSES)

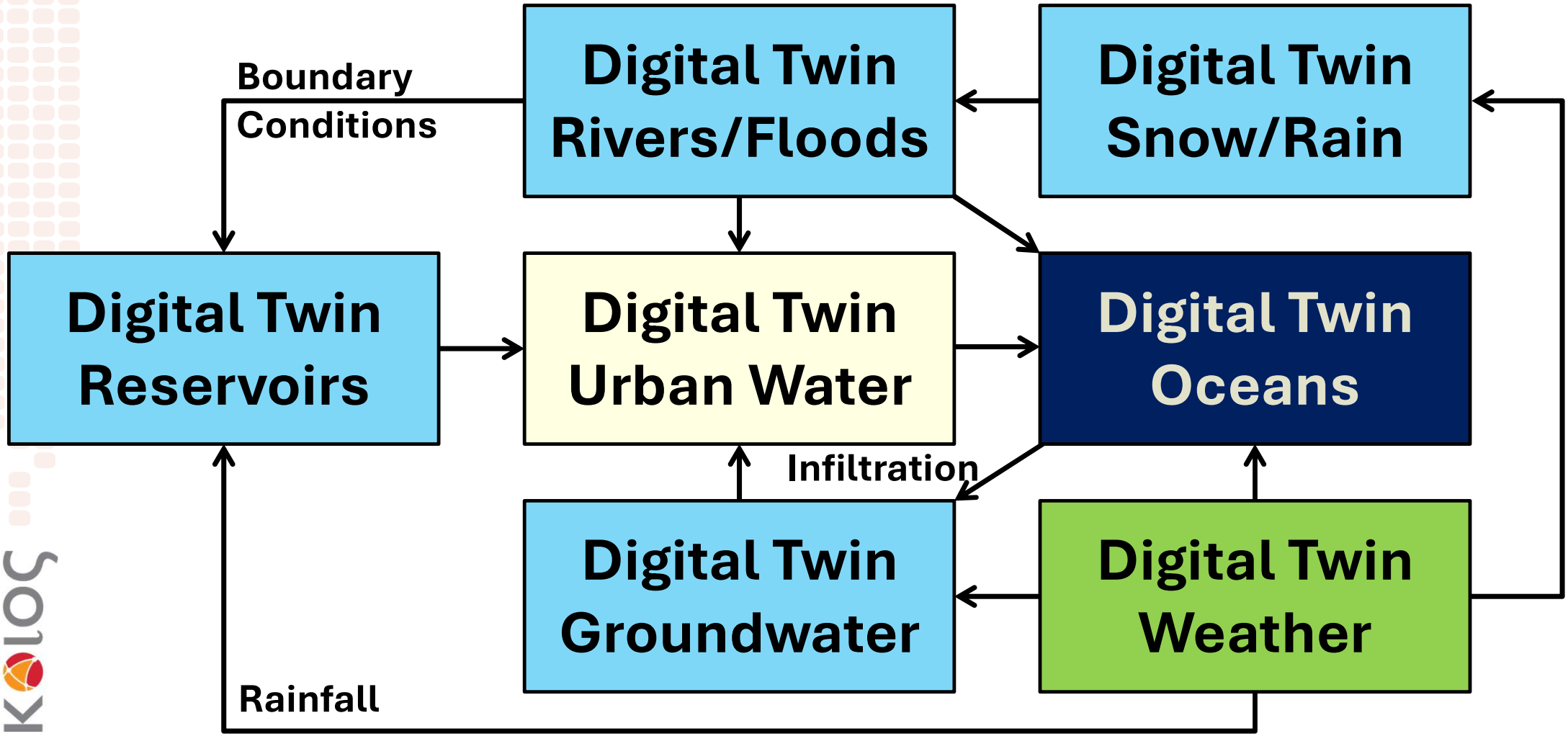


Eliades, D.G., Malialis, K., Vrachimis, S. and Polycarpou, M.M., 2024. Smart Water Networks as Cyber-Physical-Socio-Environmental Systems. *IEEE Transactions on Industrial Cyber-Physical Systems*.

Under the hood of a Digital Twin

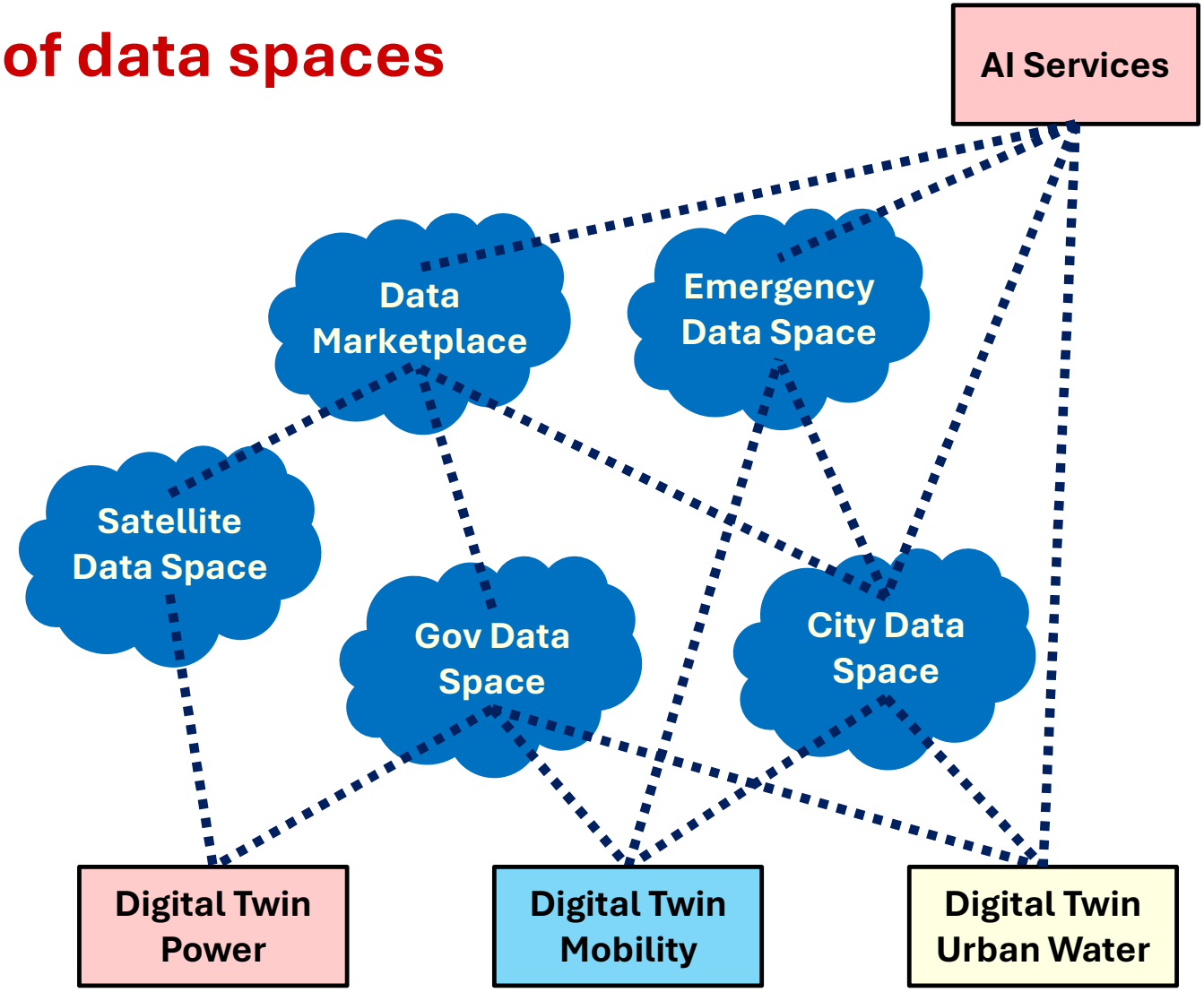


Interconnected Digital Twins



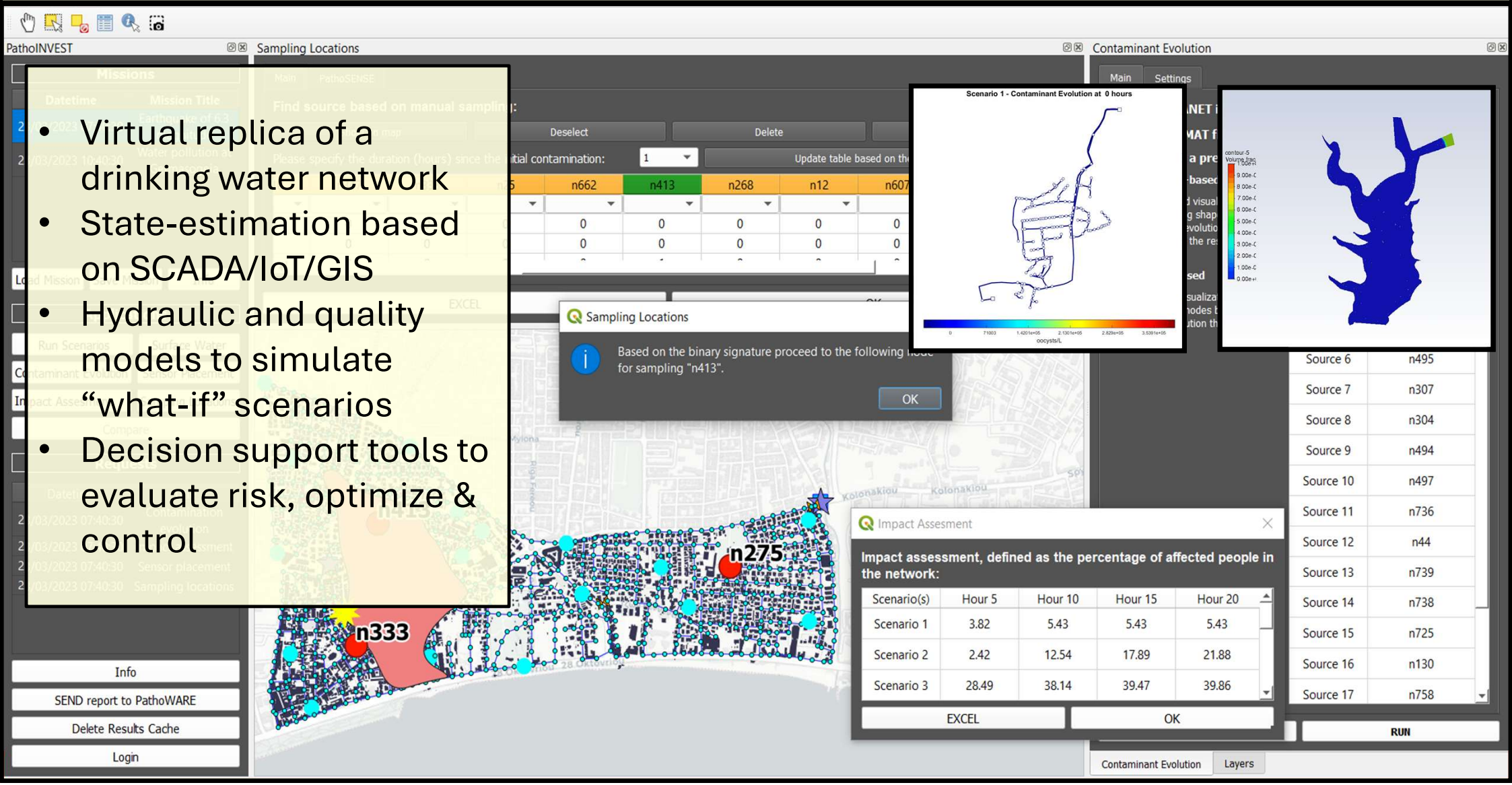
A federated network of data spaces

- The concept of data spaces was introduced in the **European Data Strategy** to support the idea of a single market for data (EU Data Act).
- It goes beyond data sharing by introducing data governance.
- A federated, secure, trustworthy, and interoperable network of data spaces enables AI services.



Example: Digital Twin for Urban Water Quality

- Virtual replica of a drinking water network
- State-estimation based on SCADA/IoT/GIS
- Hydraulic and quality models to simulate “what-if” scenarios
- Decision support tools to evaluate risk, optimize & control



CYPRUS DIGITAL TWIN (CYDT)

CyDT Overview

Power Networks

Water and waste-water networks

Telecom

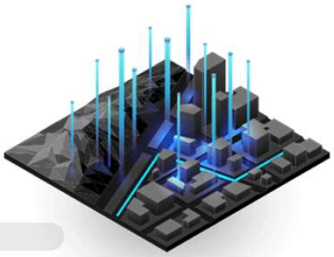
Intelligent Transportation Systems

Emergency Response

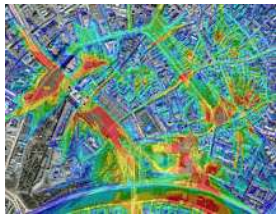
Cyprus Digital Twin

Include simulators for the dynamical behavior of each **individual** infrastructure and simulate the **cascading effects** of an event in **multiple** infrastructures

Decision support



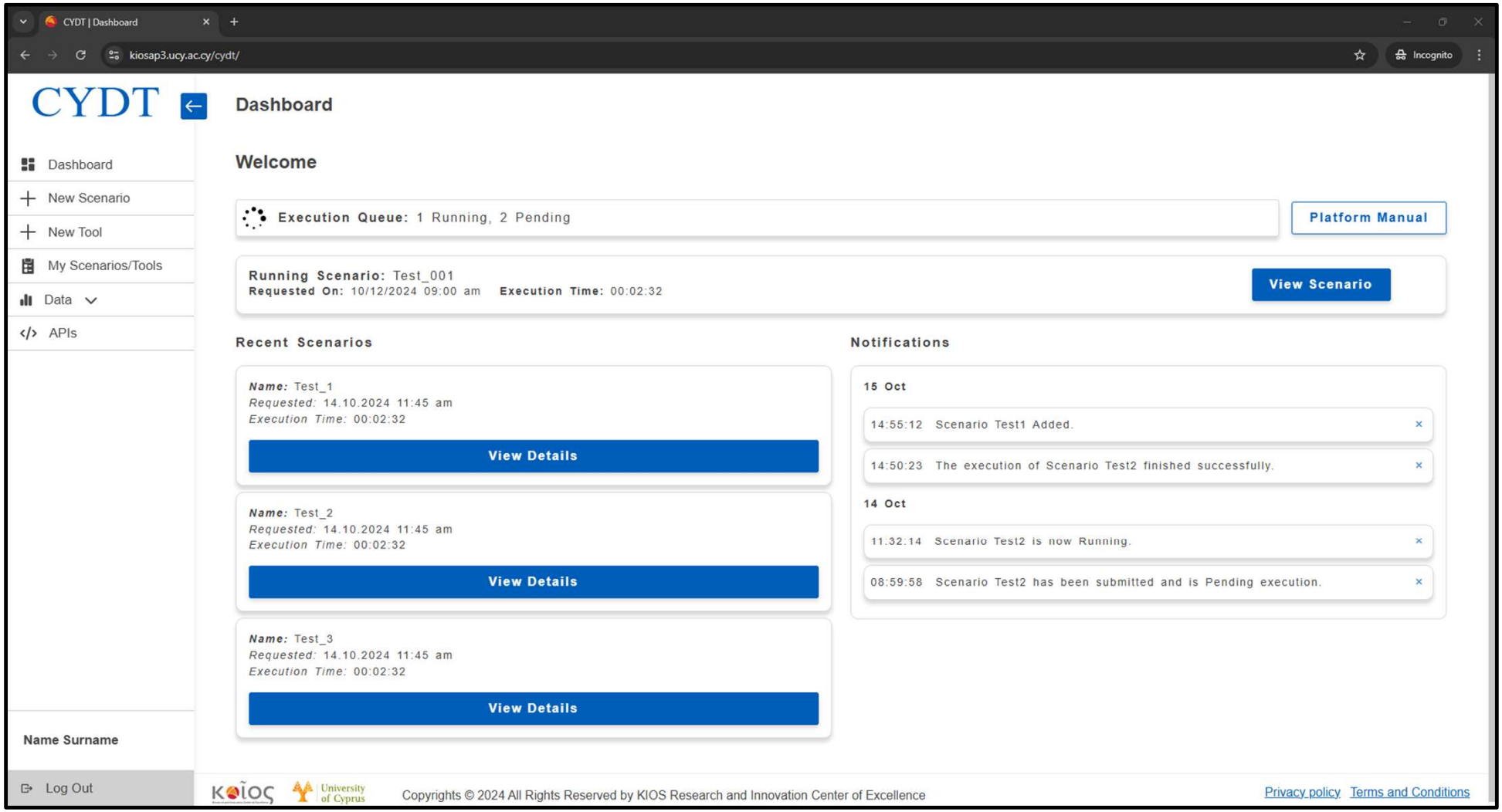
Impact assessment



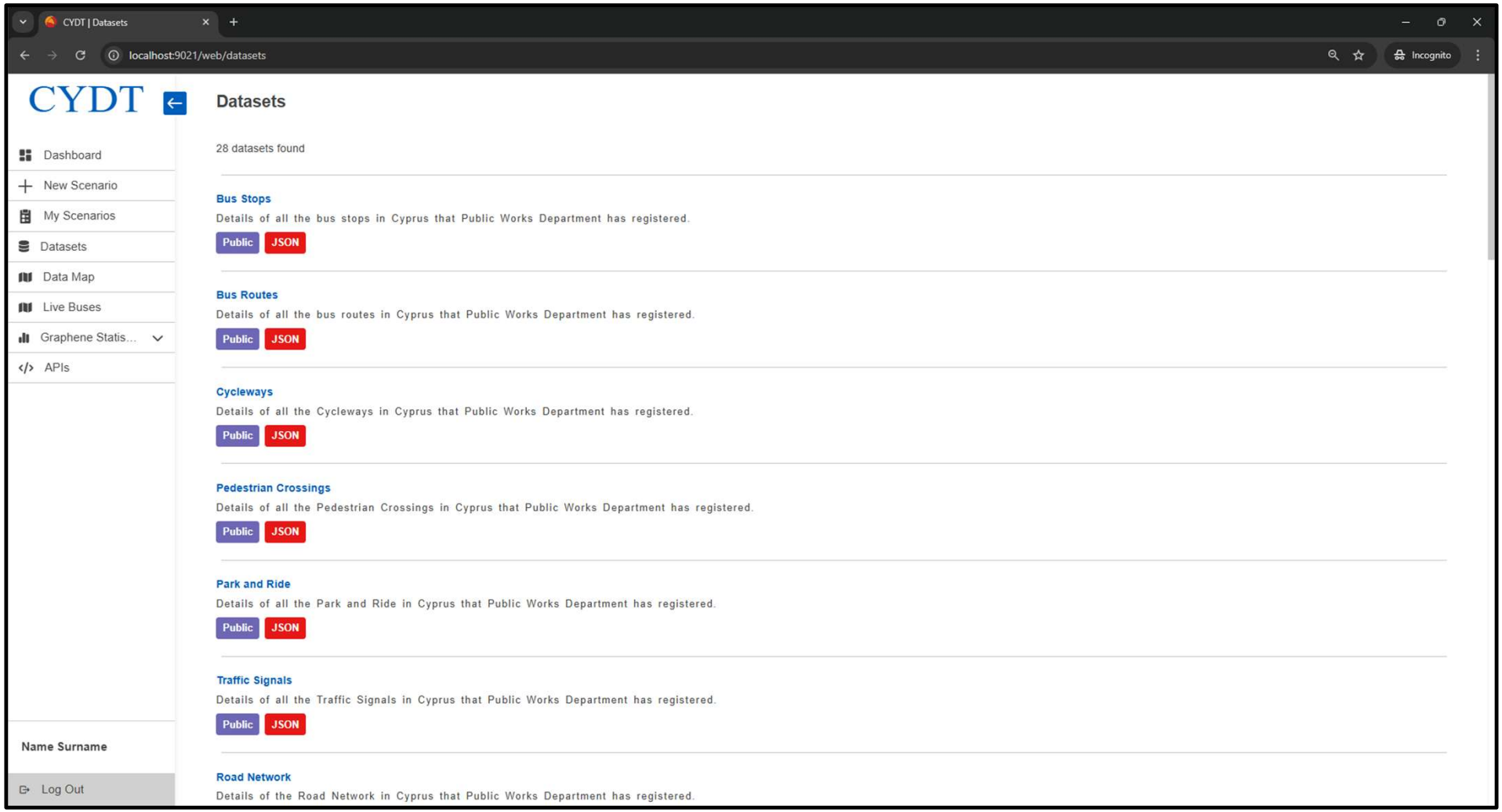
Risk estimation

'What-if' scenarios

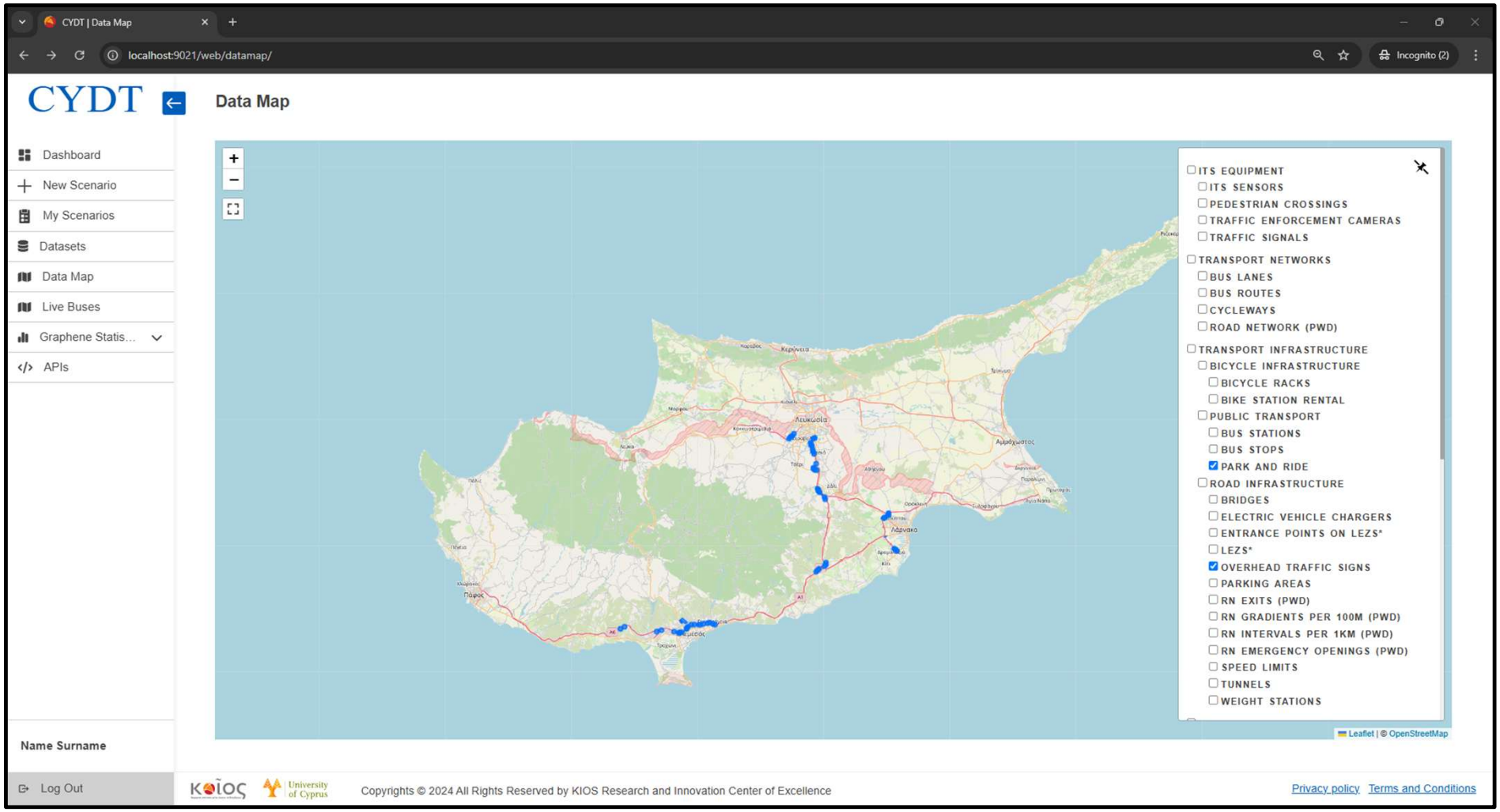
Web-based HMI – User Dashboard



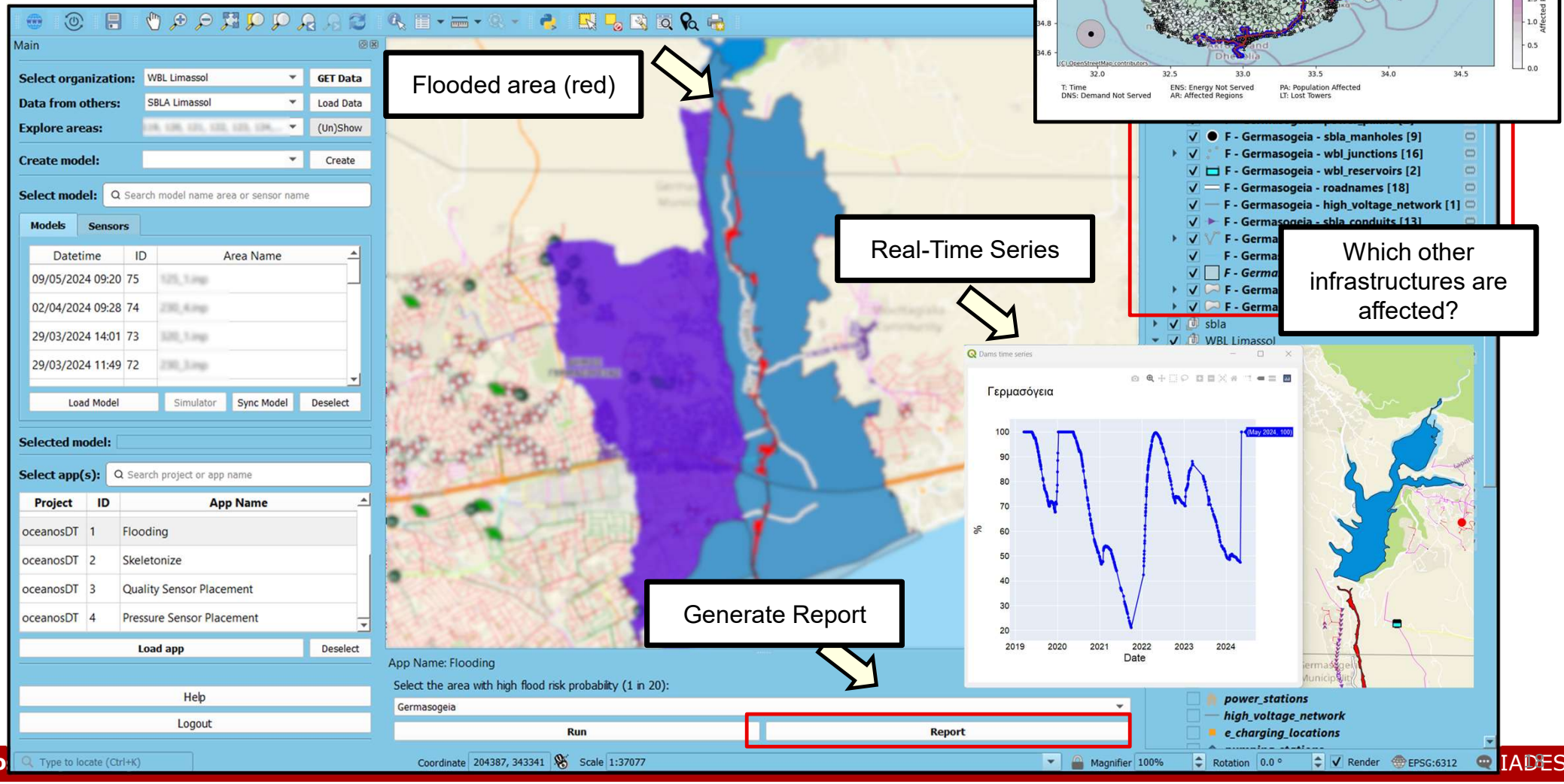
Static/Real-time Data – Datasets

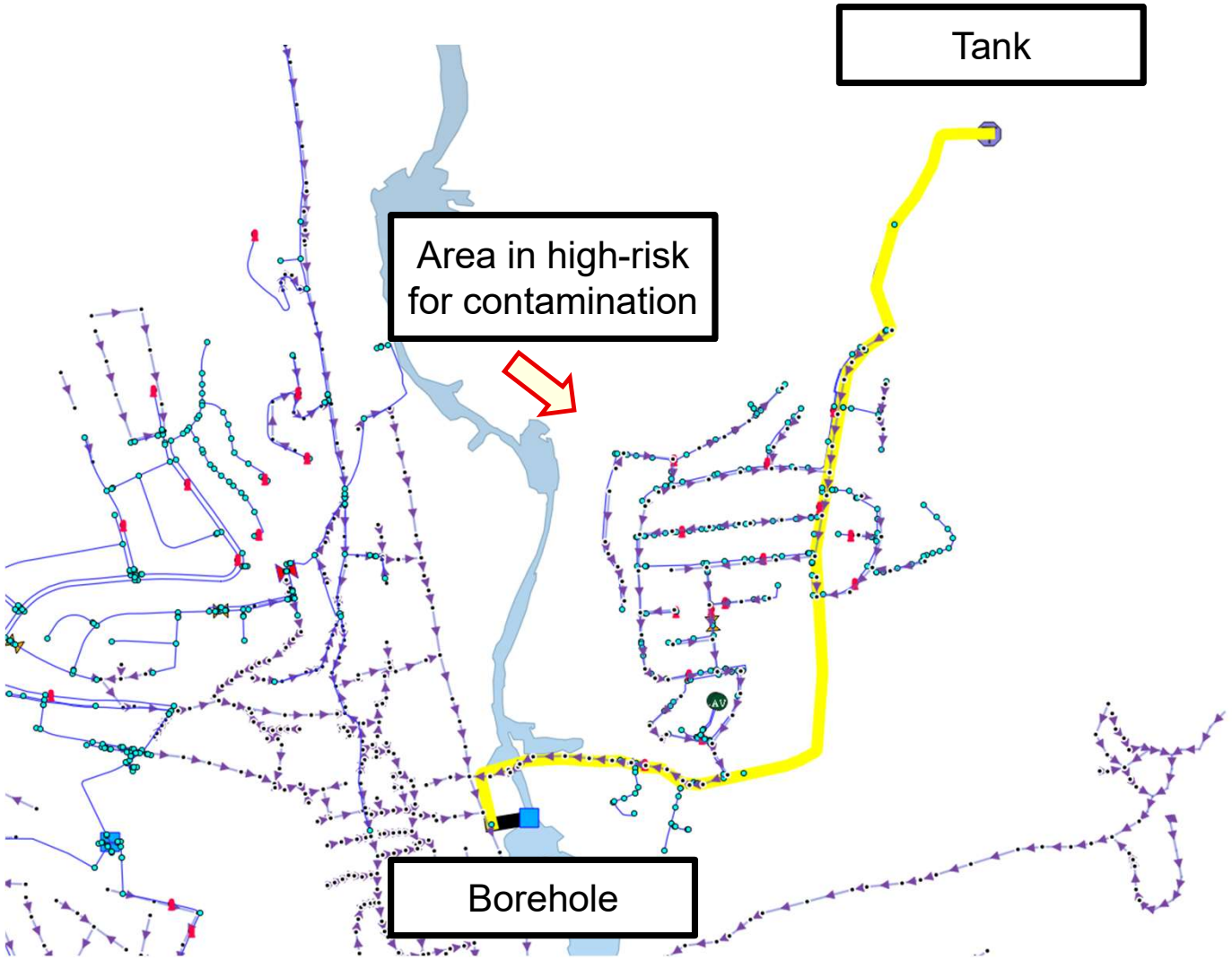


Static/Real-time Data – Data Layers

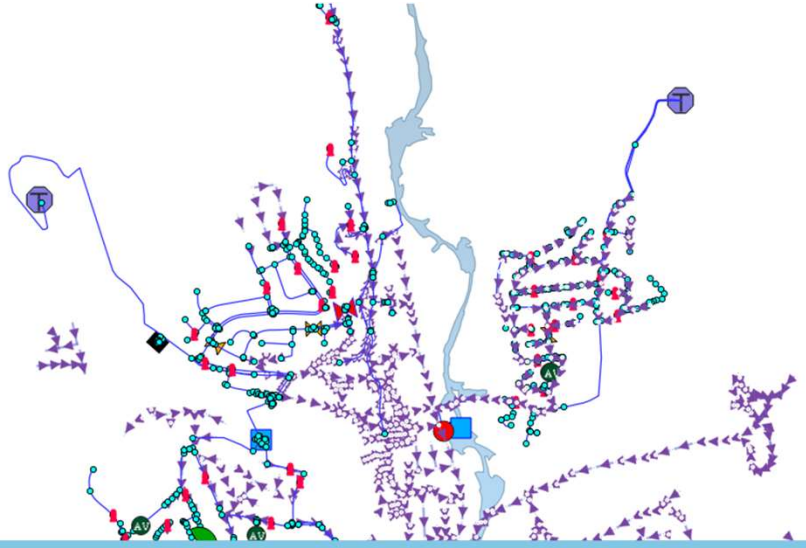


Cascade failures due to flooding




Tank
Area in high-risk for contamination
Borehole

Estimate Contamination Risk



Run Scenarios

Main | Settings | Response

Please select contaminant type: Cryptosporidium | Concentration (oocysts/L): 1000000 | TOC (mg/L): 140 | Injection start time: 5:30 П.М. | Duration (hrs): 24,0

Please select RESERVOIR to set the TOC and Chlorine: Y15 | TOC (mg/L): 1,00 | Chlorine (mg/L): 0,00 | Contamination day 1

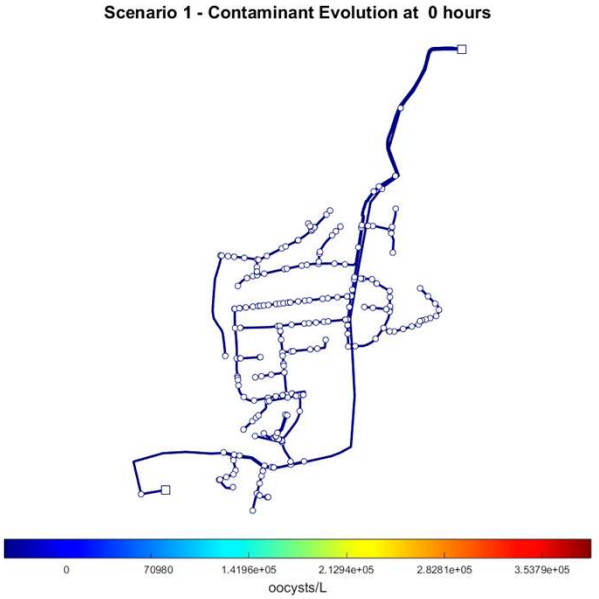
Please select TANK to set the TOC and Chlorine: T_Kefalokremos | TOC (mg/L): 1,00 | Chlorine (mg/L): 0,80 | SAVE | Simulation Time (days) 1

Please select a link to change status based on the template of control: LINK linkID status IF NODE nodeID ABOVE-BELOW value

Select from map | Import selected | Show on map | Deselect all | Delete

	Link(s)	Status/Setting	IF node	Action
1	Y15_pump	OPEN	T_Kefalokremos	BELOW
2	Y15_pump	CLOSED	T_Kefalokremos	ABOVE

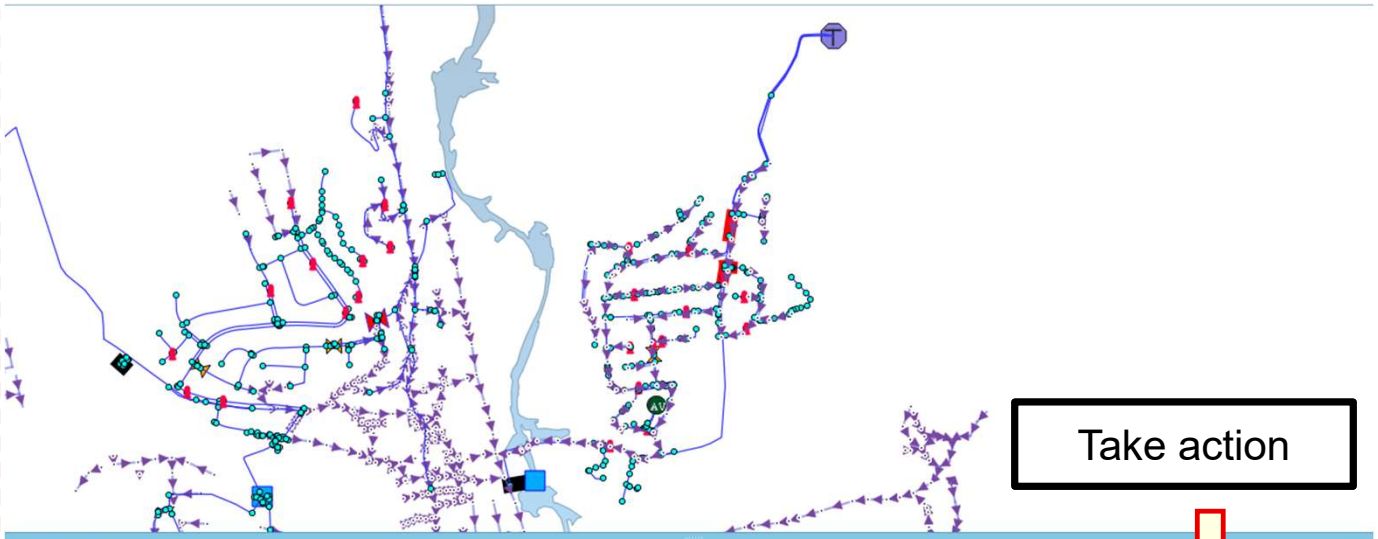
Cancel | RUN



Impact assessment, defined as the percentage of affected people in the network:

Scenario(s)	Hour 5	Hour 10	Hour 15	Hour 20
Scenario 1	0	35.87	78.19	94.6

Evaluation impact of decision



Take action

Run Scenarios

Main | Settings | Response

Please select contaminant type: Cryptosporidium | Concentration (oocysts/L): 1000000 | TOC (mg/L): 140 | Injection start time: 6:30 П.М. | Duration (days): 24,0

Please select RESERVOIR to set the TOC and Chlorine: Y15 | TOC (mg/L): 1,00 | Chlorine (mg/L): 0,00 | Contamination day 1

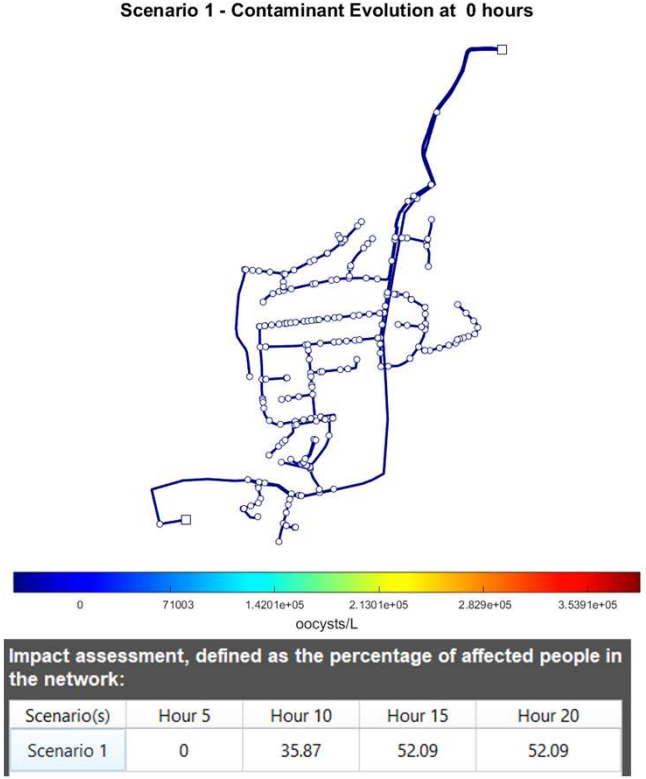
Please select TANK to set the TOC and Chlorine: T_Kefalokremos | TOC (mg/L): 1,00 | Chlorine (mg/L): 0,80 | SAVE | Simulation Time (days) 1

Please select a link to change status based on the template of control: LINK linkID status AT TIME time

Select from map | Import selected | Show on map | Deselect all | Delete

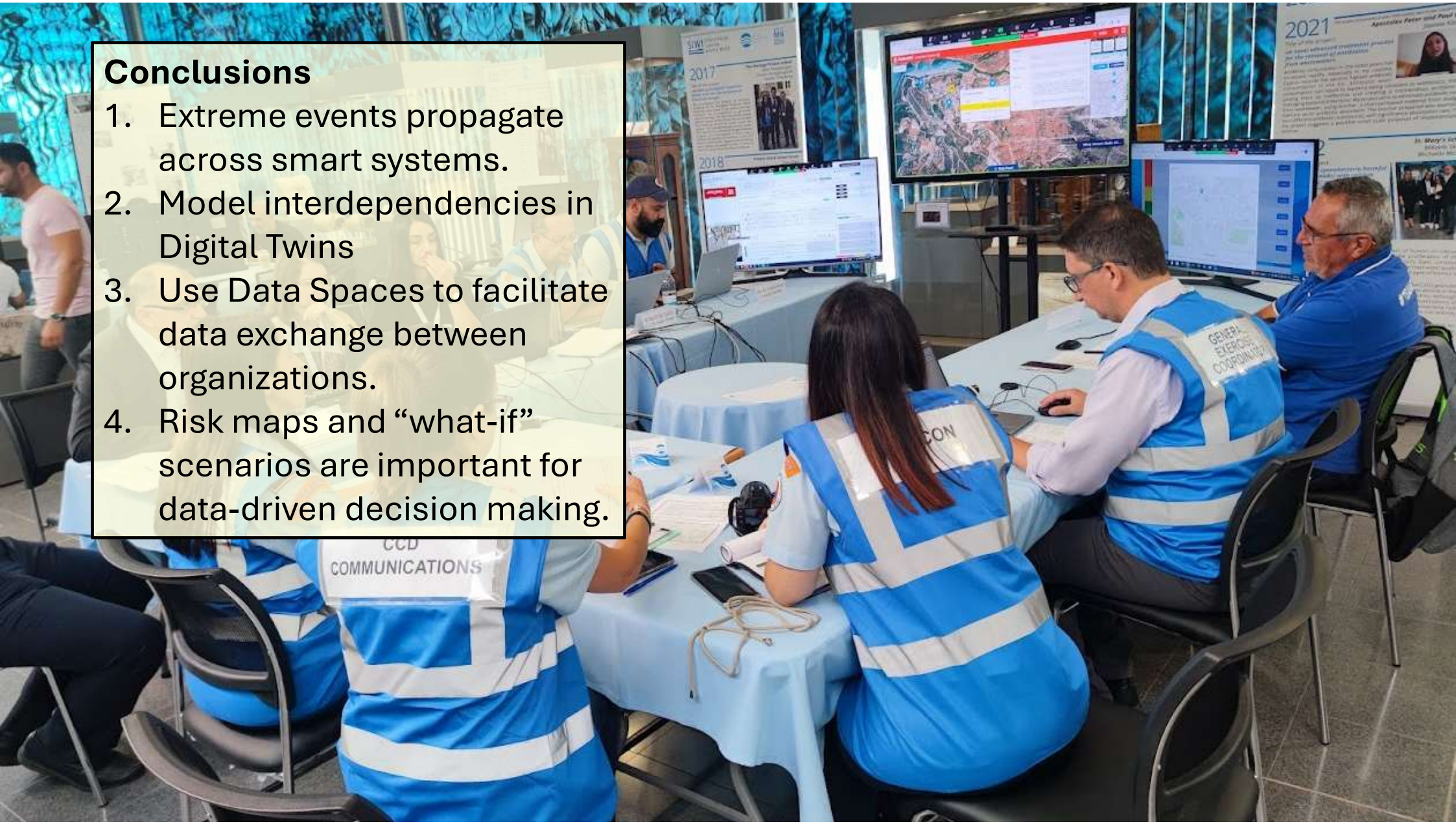
	Link(s)	Status/Setting	At time
1	237	CLOSED	9:00 П.М.
2	4	CLOSED	9:00 П.М.
3	79	CLOSED	9:00 П.М.

Cancel | RUN



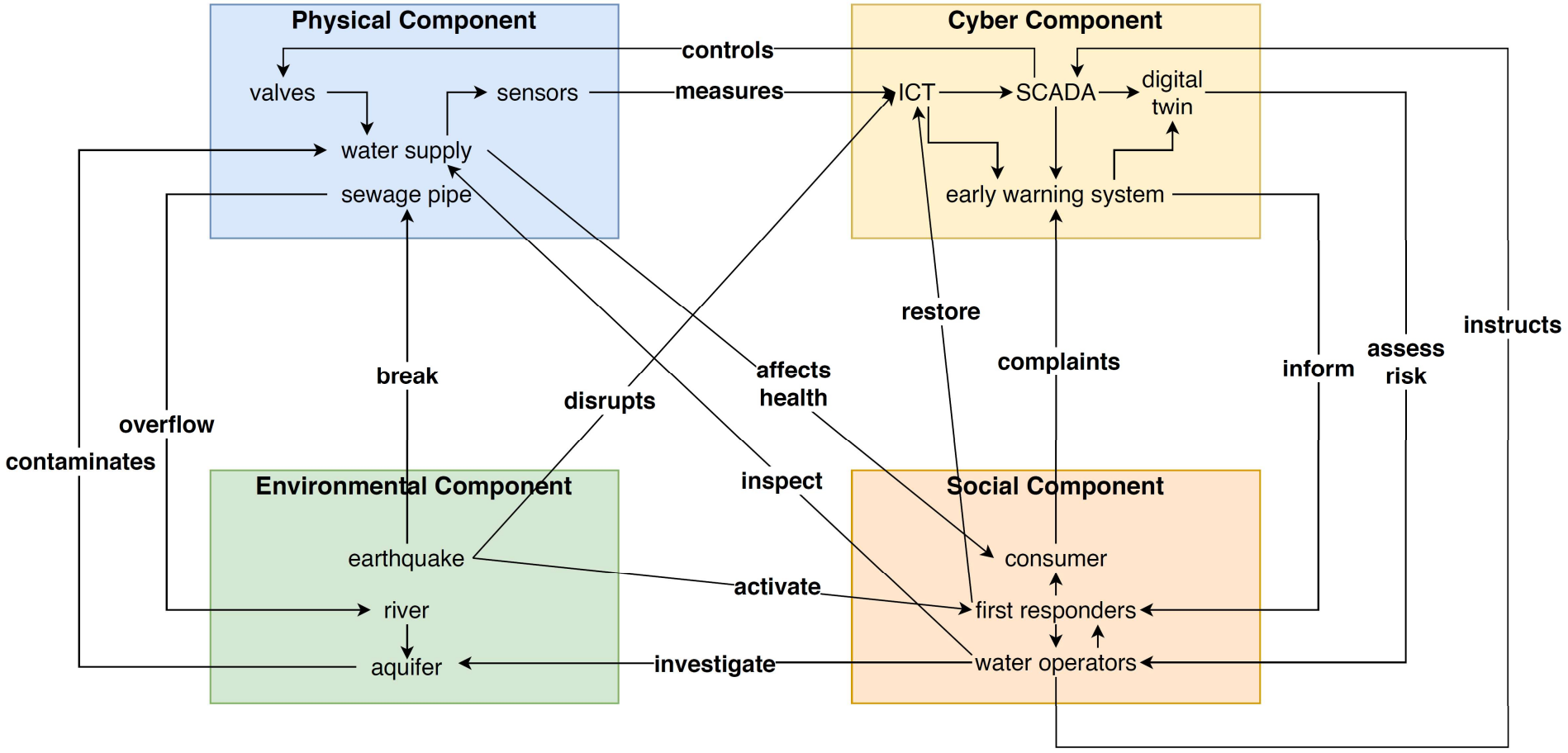
Impact assessment, defined as the percentage of affected people in the network:

Scenario(s)	Hour 5	Hour 10	Hour 15	Hour 20
Scenario 1	0	35.87	52.09	52.09



Conclusions

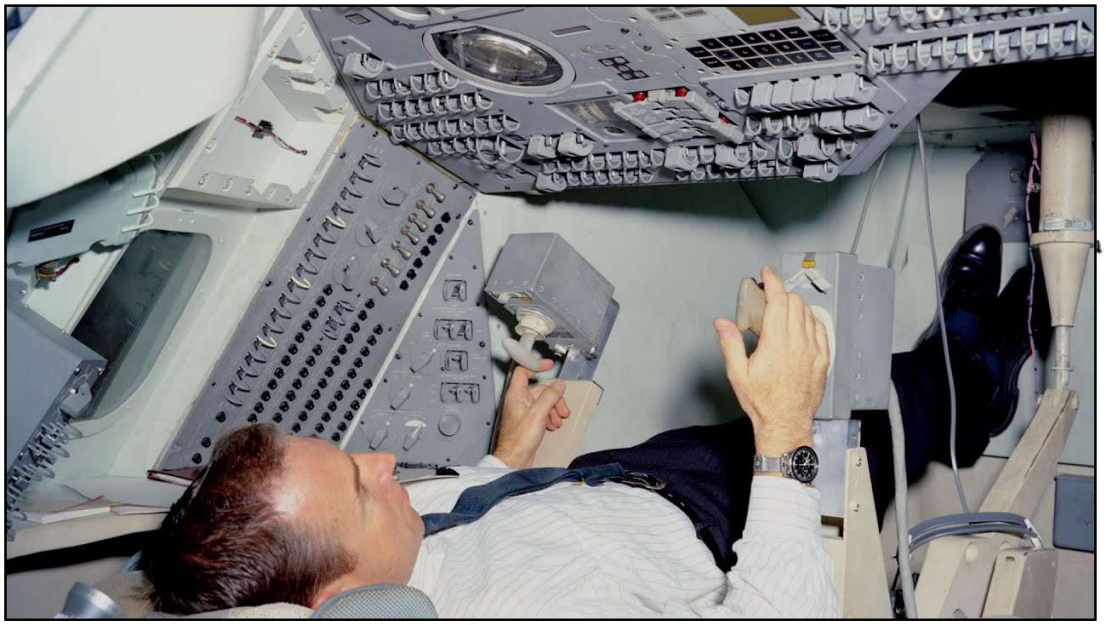
1. Extreme events propagate across smart systems.
2. Model interdependencies in Digital Twins
3. Use Data Spaces to facilitate data exchange between organizations.
4. Risk maps and “what-if” scenarios are important for data-driven decision making.


Physical Component
valves
sensors
water supply
sewage pipe
Cyber Component
ICT
SCADA
digital twin
early warning system
Environmental Component
earthquake
river
aquifer
Social Component
consumer
first responders
water operators
controls
measures
restore
complaints
inform
assess risk
instructs
break
disrupts
affects health
overflow
contaminates
inspect
activate
investigate

Apollo 13: “Houston, we’ve had a problem”

April 13, 1970

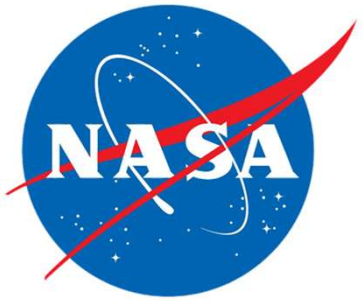
- An **explosion changed the physical dynamics** of Apollo 13. Trajectory changed; astronauts' lives were at risk.
- NASA created a “**living model**”. Data from telemetry were continuously ingested in models to analyze situation.
- Multiple simulators were reprogrammed with new models to find the best way to resolve the situation.
- Apollo 13 safely returned to earth a few days later.



02 07 55 20	CDR	I believe we've had a problem here.
02 07 55 28	CC	This is Houston. Say again, please.
02 07 55 35	CDR	Houston, we've had a problem. We've had a MAIN B BUS UNDERVOLT.
02 07 55 42	CC	Roger. MAIN B UNDERVOLT.
02 07 55 58	CC	Okay, stand by, 13. We're looking at it.

What is a Digital Twin?

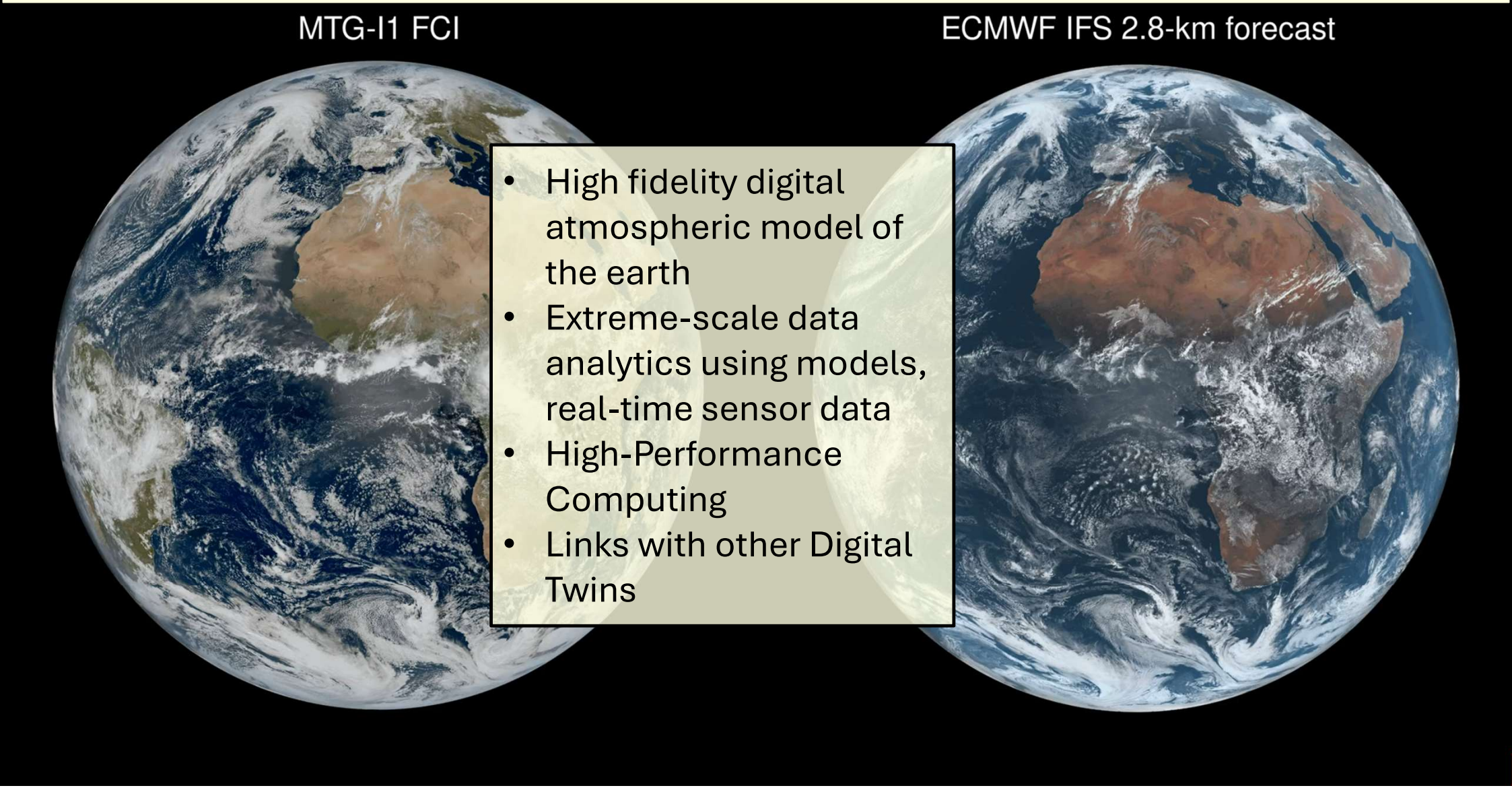
- **Computational "living" model** of a real system
- Integrates physical, mathematical or machine learning **models**
- Integrates **operational data** (sensors, actuators), and historical data
- Updates **dynamically,** considers changes
- Evaluate **"what-if" scenarios**
- Operates on **various time scales**
- Enables analytics, optimization, risk management and control
- Used as a **virtual certification/validation** (testing before applying a new system)



*"The **digital twin** concept… enable[s] a suite of comprehensive multidisciplinary **physics-based models**… incorporating these capabilities in the **production** and **operation** of spacecraft."*

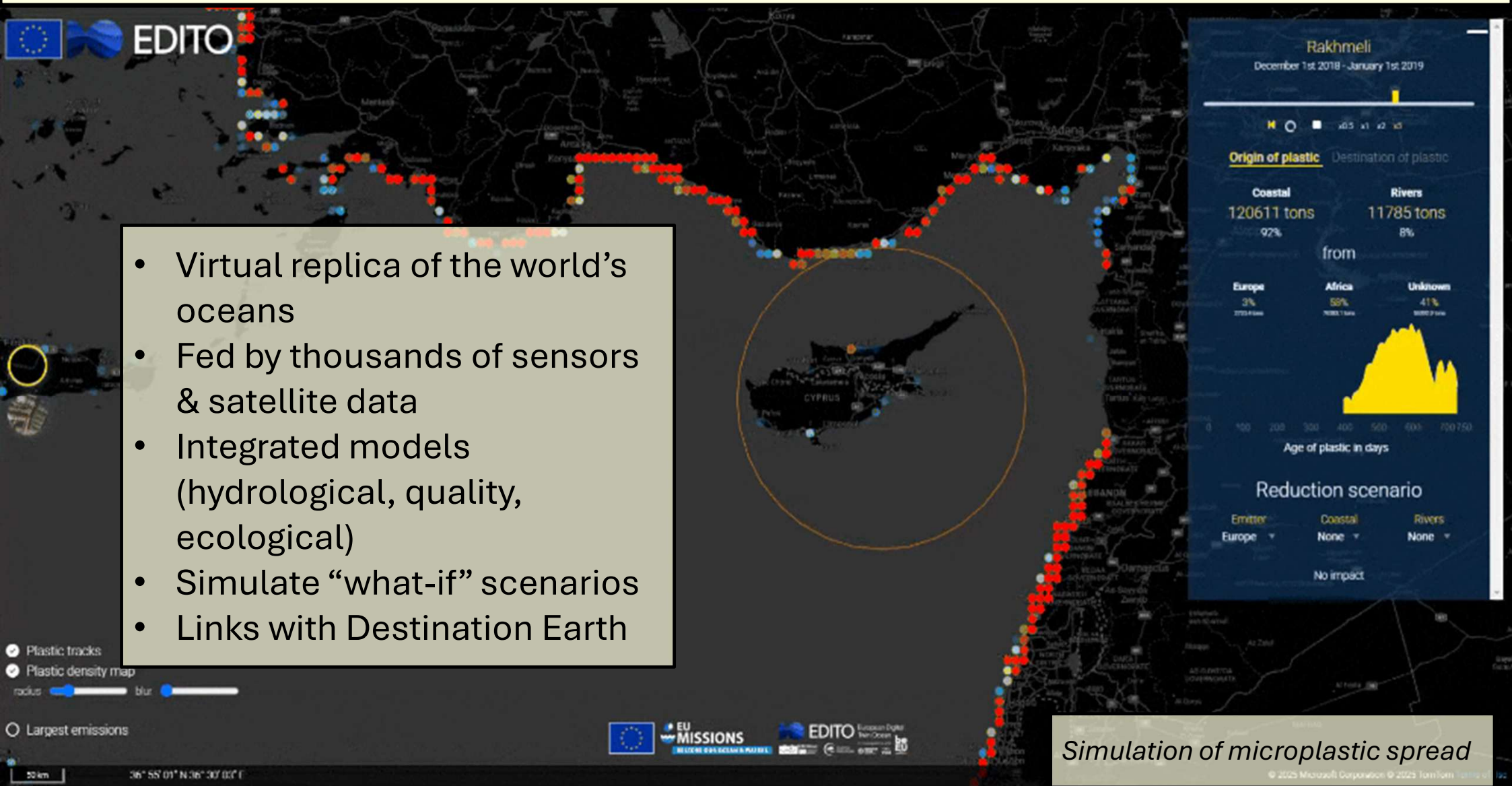
Glaessgen, E., & Stargel, D. (2012, April). The digital twin paradigm for future NASA and US Air Force vehicles. In *53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA* (p. 1818).

Destination Earth (DestinE)



- High fidelity digital atmospheric model of the earth
- Extreme-scale data analytics using models, real-time sensor data
- High-Performance Computing
- Links with other Digital Twins

Digital Twin Oceans (DTO)



- Virtual replica of the world's oceans
- Fed by thousands of sensors & satellite data
- Integrated models (hydrological, quality, ecological)
- Simulate "what-if" scenarios
- Links with Destination Earth

Simulation of microplastic spread

Digital Twin for Contaminations