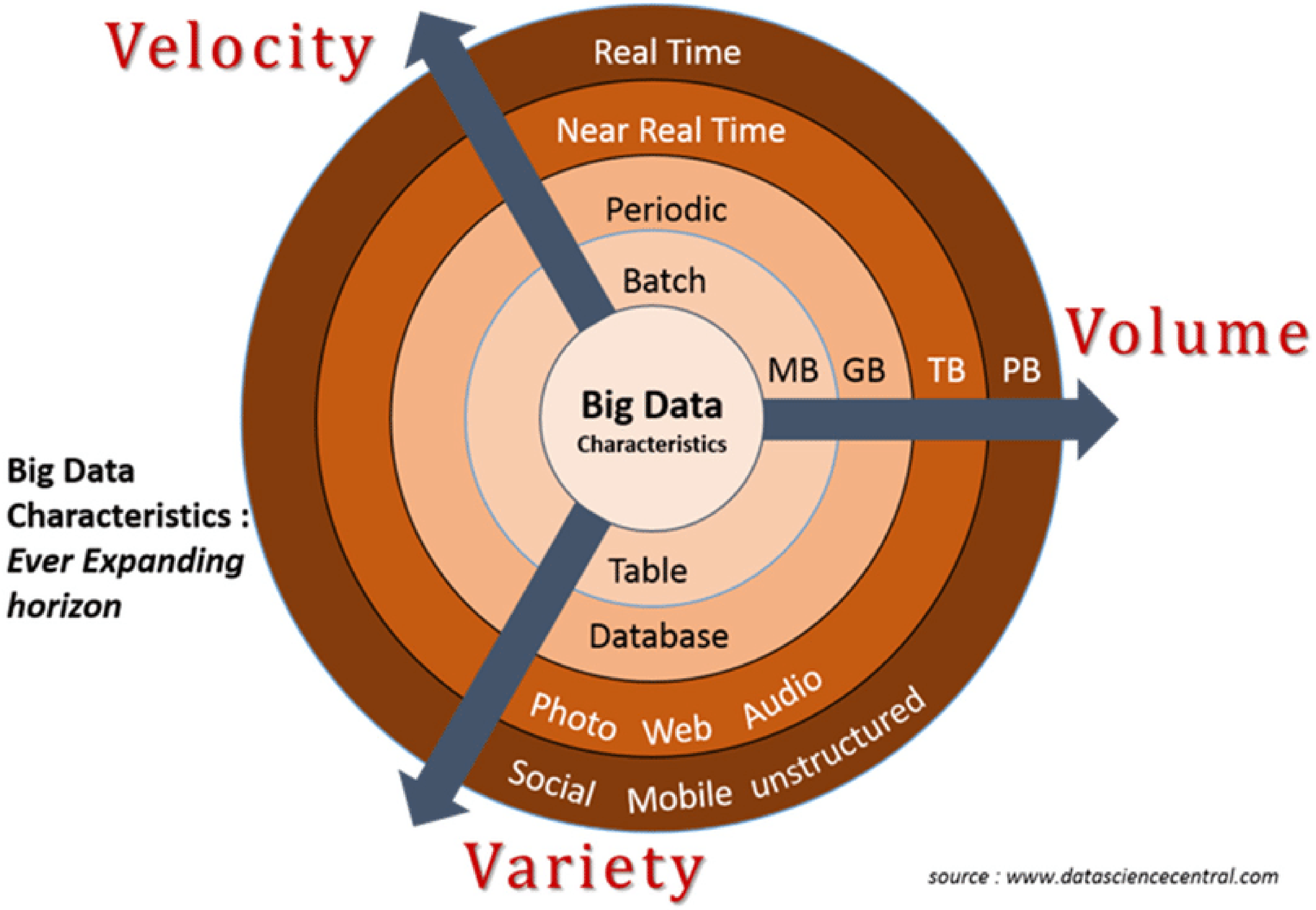
Digitalization and Sustainability in Environmental Monitoring

ACM Europe Digital Humanism Summer School | Atakan Aral and Katrin Attermeyer | Sep 3, 2024

Refresher

- Big Data: “A revolution in environmental decision-making”
  - Predictive models
  - Informed decisions



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Big Data Challenges in Environmental Monitoring

- Volume and storage
- Data scarcity
- Variety and integration
- Velocity
- Data Governance and Provenance
- Cost management

Infrastructural Challenges

- Long-term storage vs real-time decision-making
- Access to electricity
- Access to network
- Cost and ecological footprint
- Intermittent, unreliable, and limited local computing resources

Agenda

1. Introduction to / Examples of Digitalization in Environmental Monitoring
2. Key technologies
3. Case Study: SWAIN
4. Bridging the Gap Between Environmental and Computer Science

Digitalization of Environmental Monitoring

“Integration of digital technologies, such as IoT sensors, remote sensing, big data analytics, and AI, to enhance the collection, analysis, and management of environmental data, particularly in real-time, leading to more accurate, efficient, and responsive environmental protection and management.”

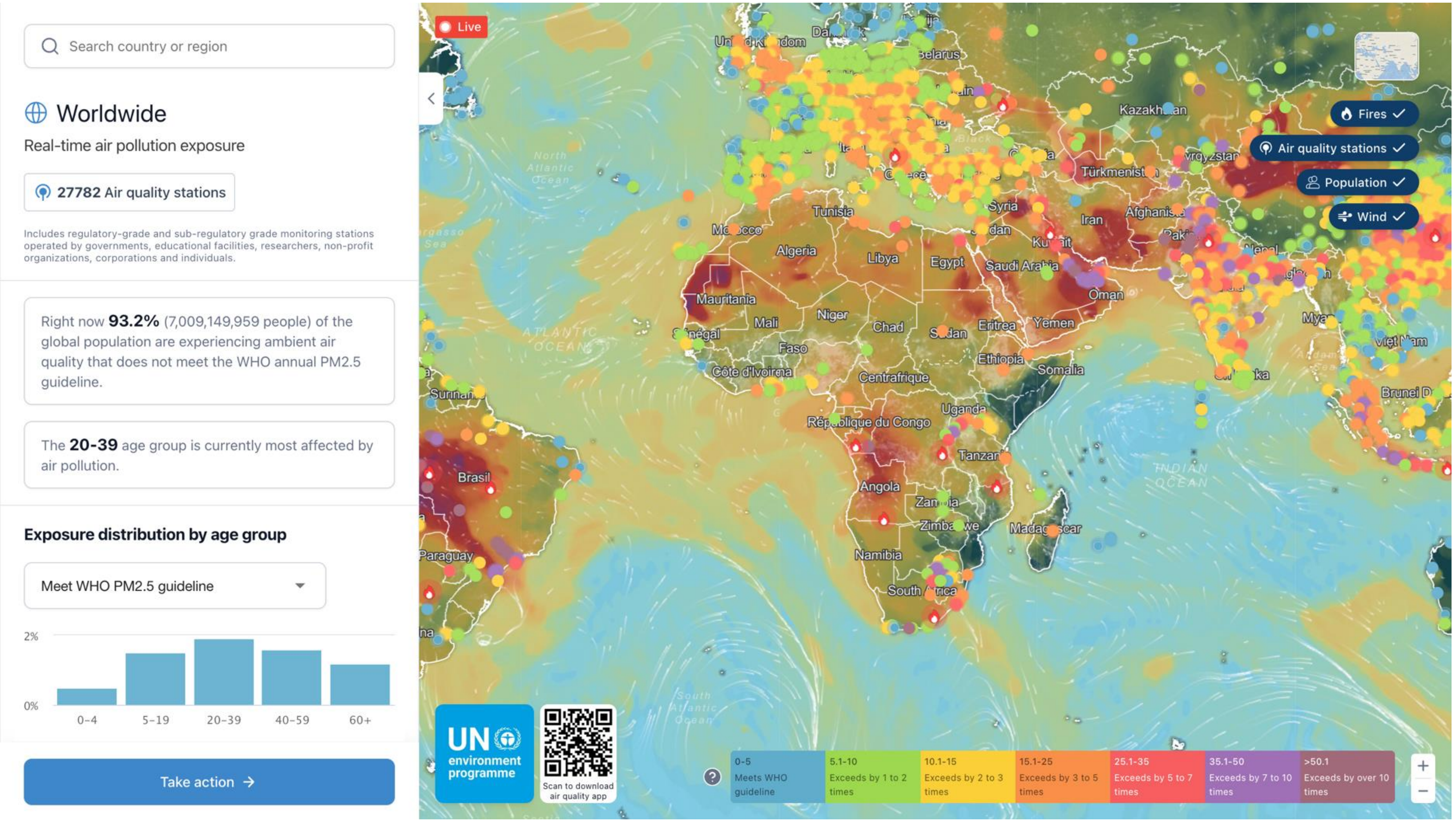
Rural Environmental Monitoring Systems

- Pollution Monitoring
  - Air Quality
  - Water Quality
- Disaster Warning
  - Seismic Activity
  - Avalanche
  - Nuclear Explosion
- Industrial IoT
  - Agriculture
  - Oil and Gas Well

GEMS/Air

- Part of UNEP
- 27 782 air quality stations
- Hourly measurements

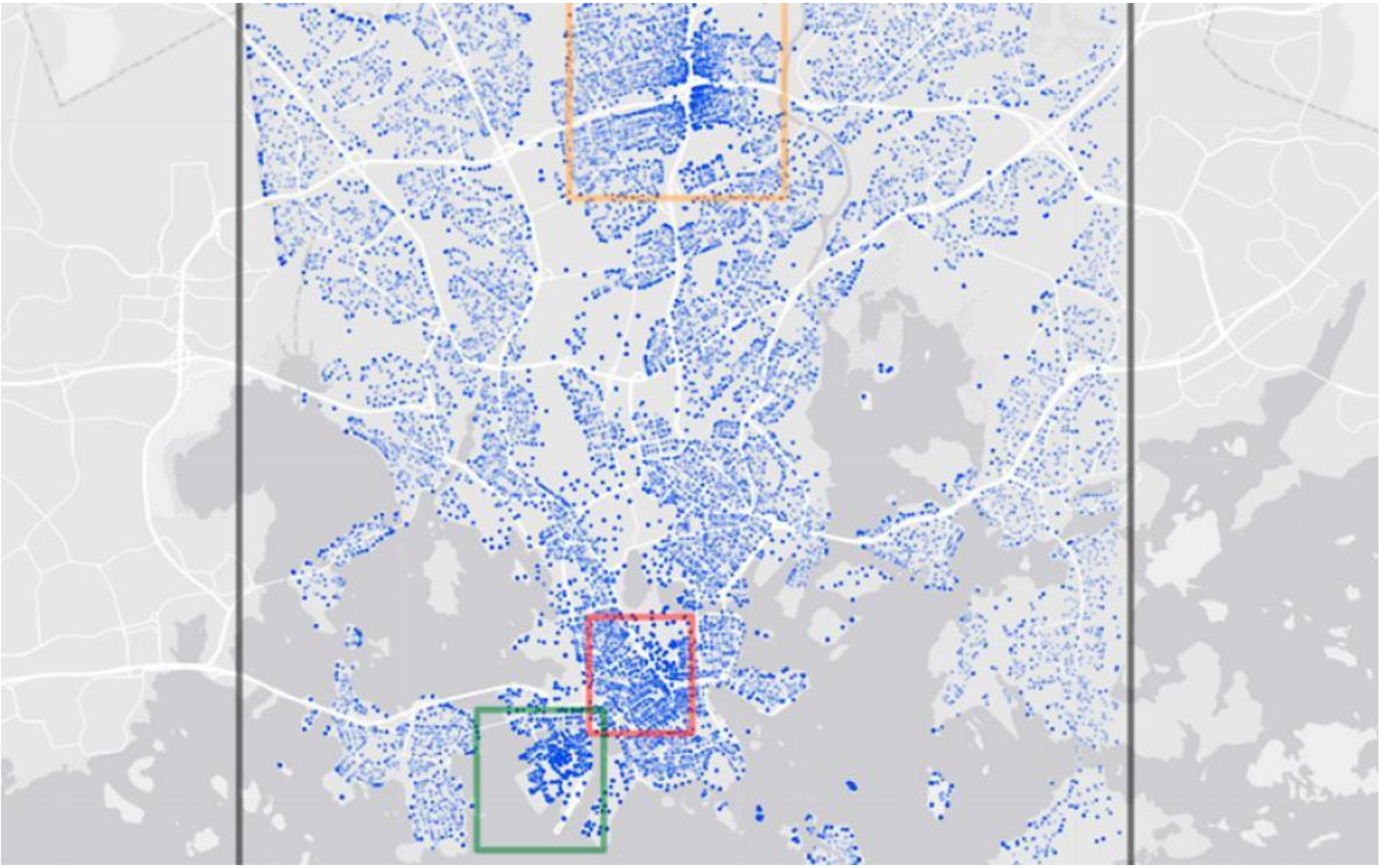
- https://www.iqair.com/unep



MEGASENSE

- Scalable real-time 5G air pollution sensing as a service for megacities
- Use ML to calibrate many low-cost sensors (e.g., wearables) with a few highly accurate measurement stations.

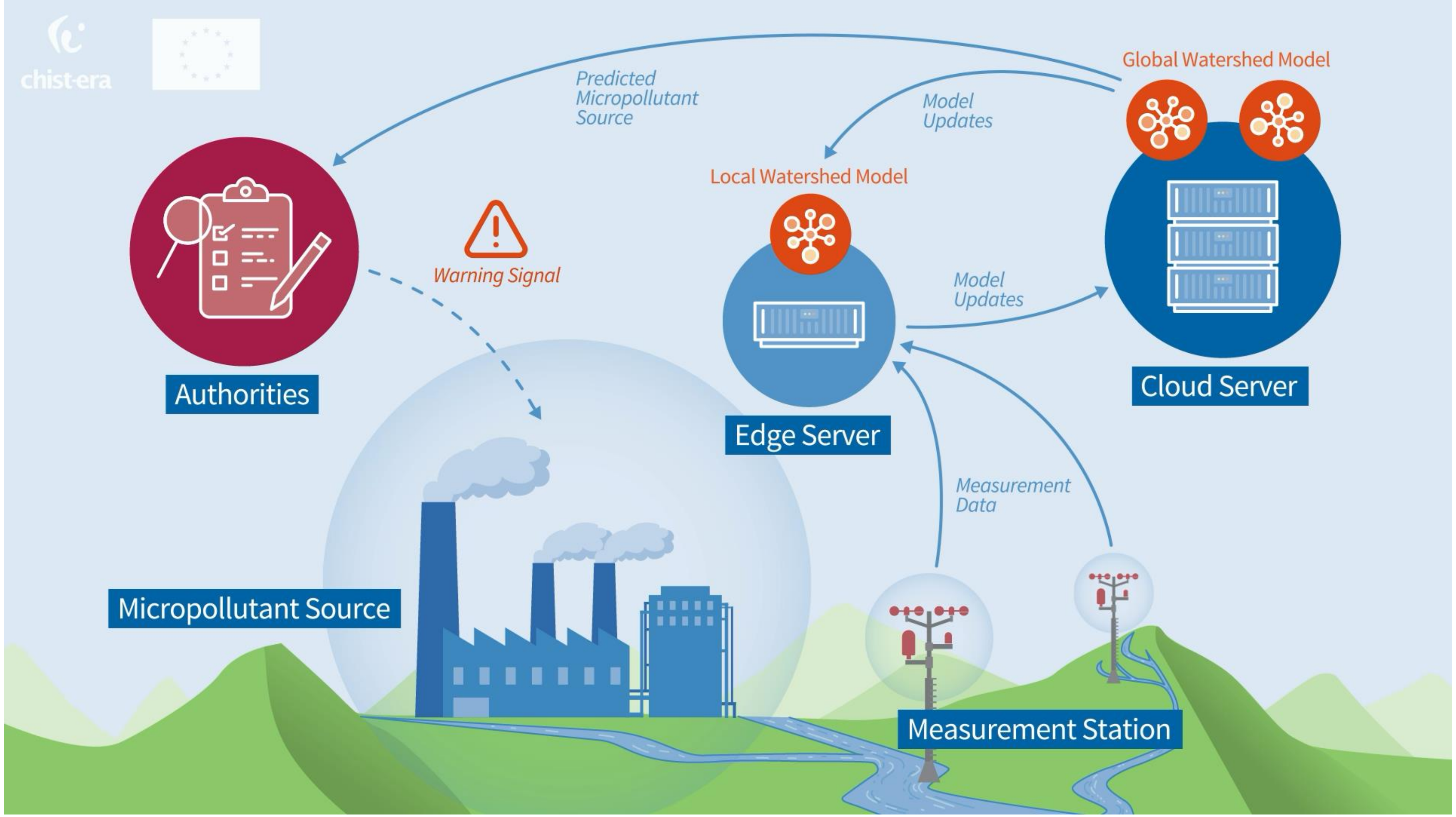
- https://helsinki.fi/en/researchgroups/sensing-and-analytics-of-air-quality



SWAIN

- Up to 100 sensors
- Two prototype deployments
- Sub-minute measurements
- Feedback loop

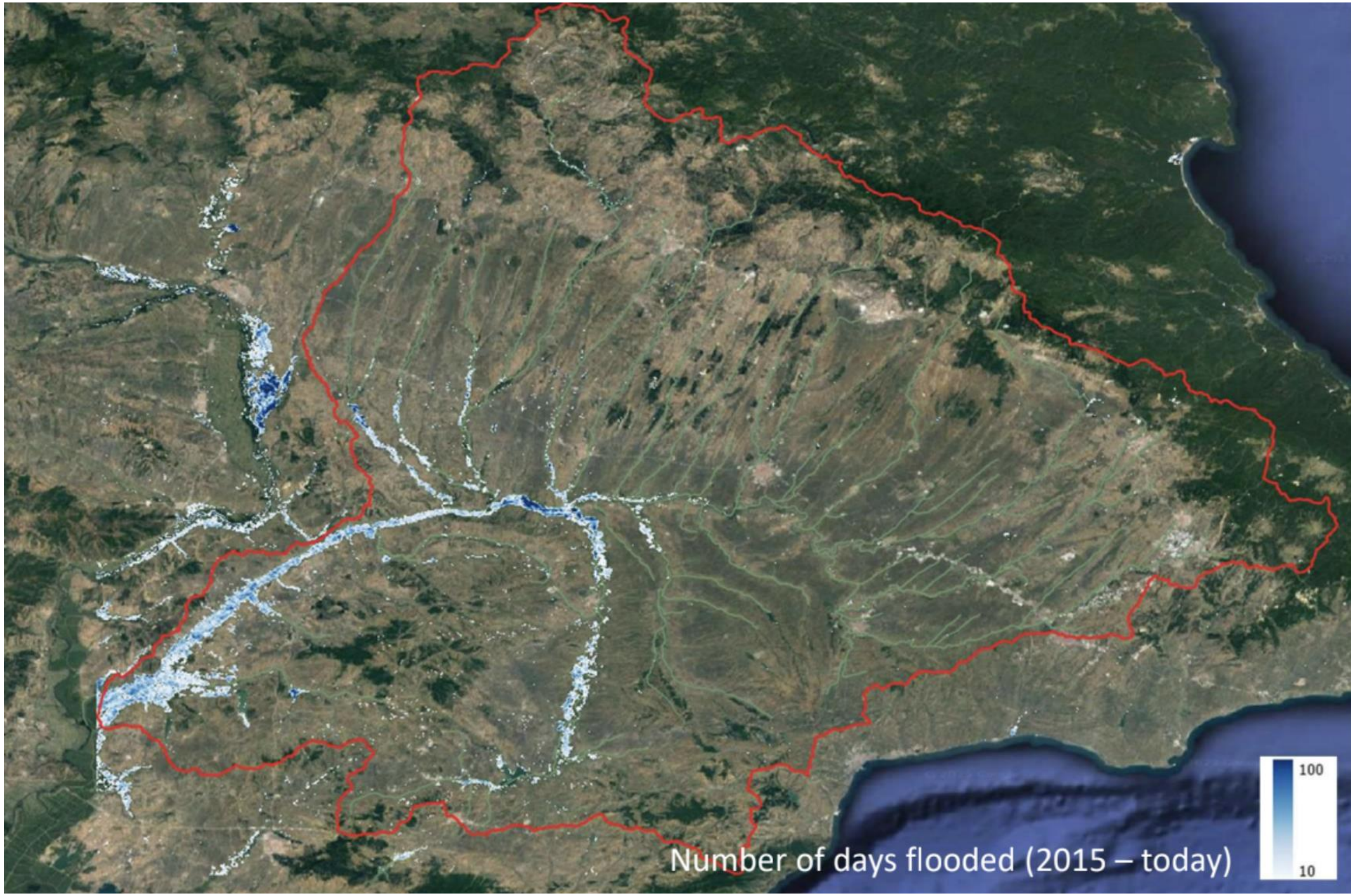
- https://swain-project.eu/



WATERLINE

- Remote sensed data
- Historical data
- In-situ data
- Crowdsourced data

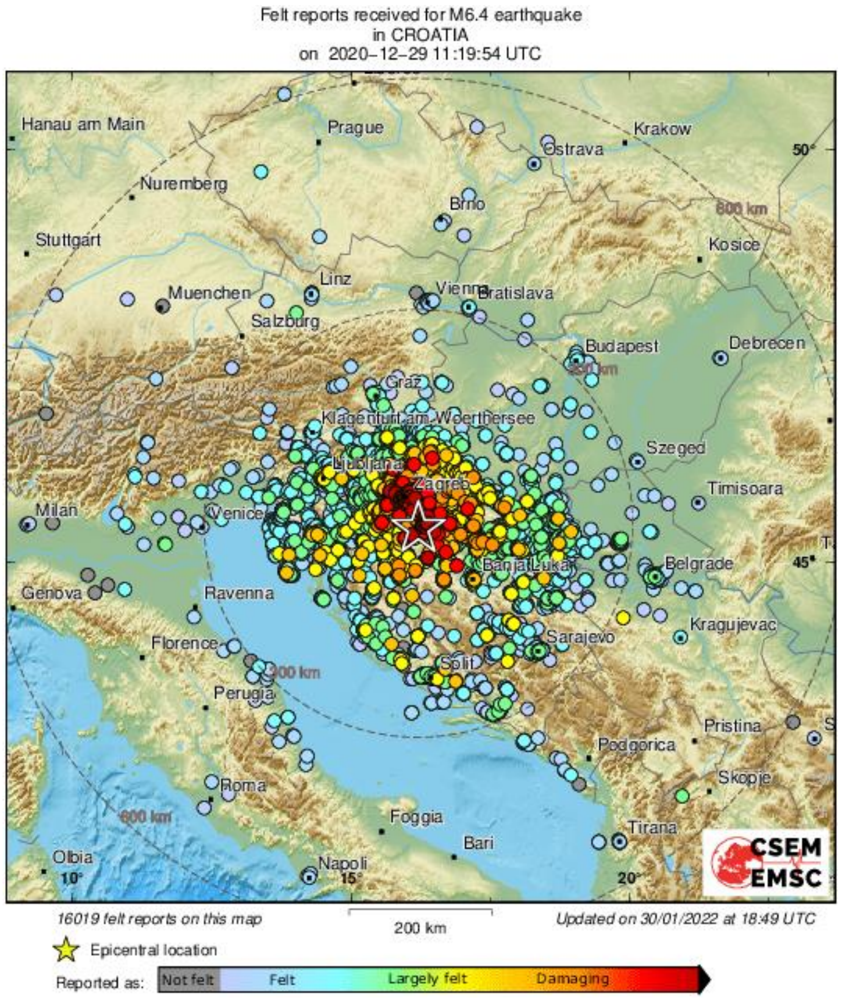
- https://waterlineproject.eu/

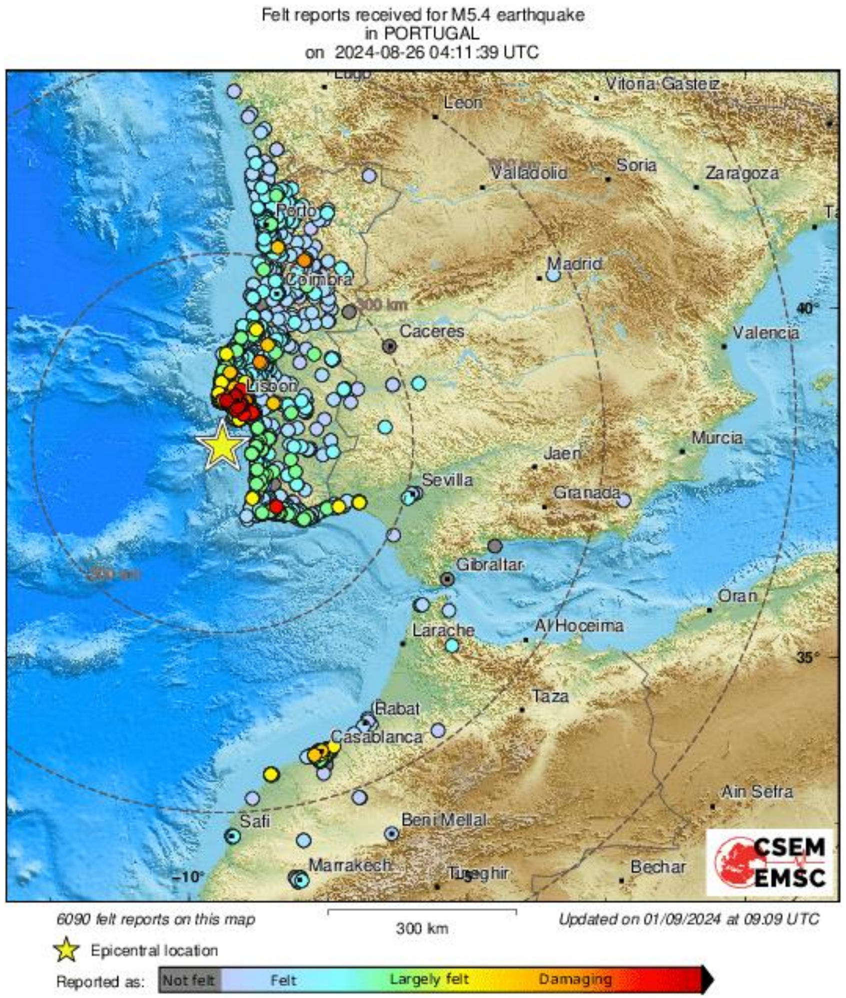


EMSC

- More than 2500 sensors
- Sub-minute measurements
- Sensors deployed in urban areas

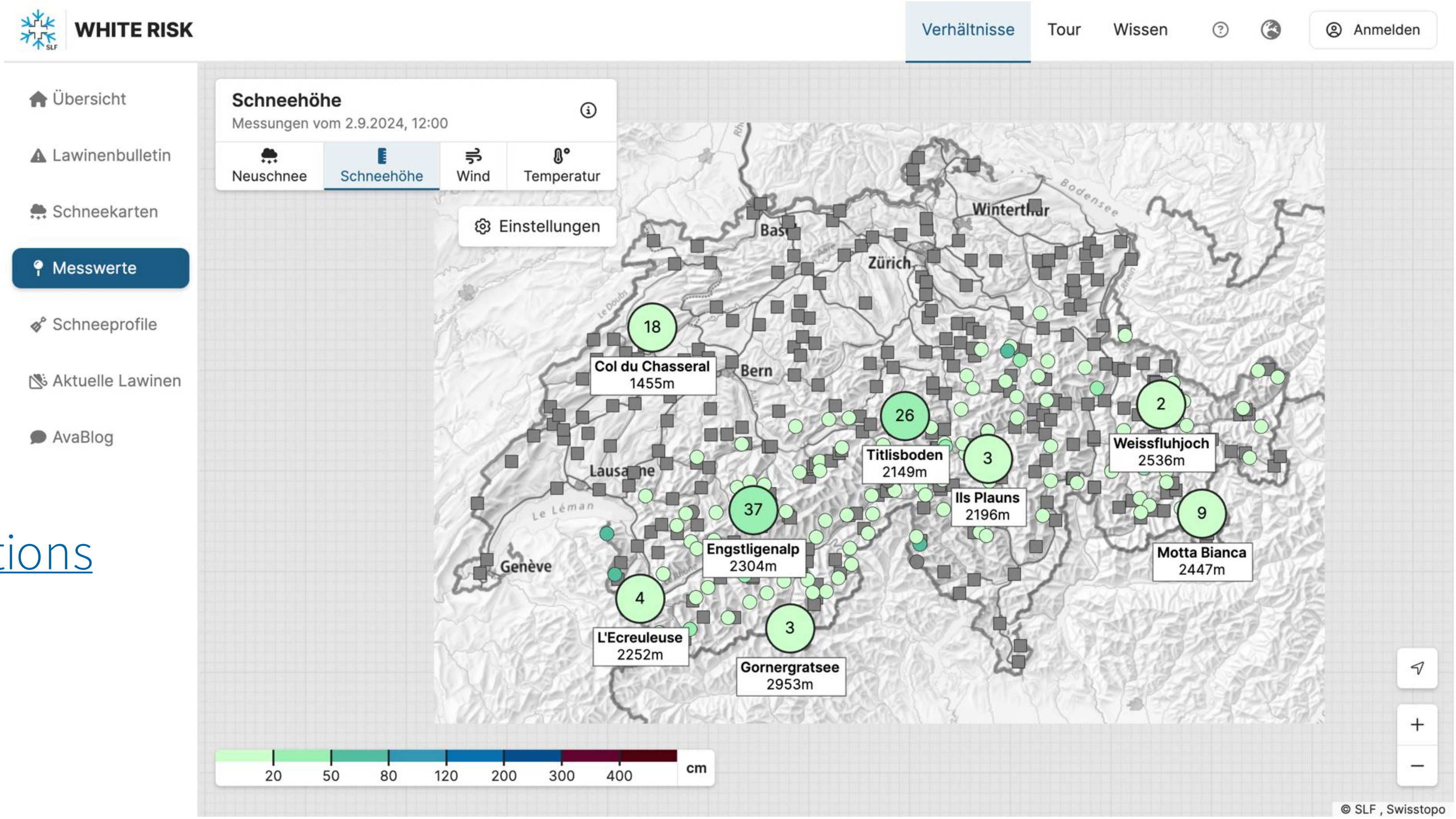
- https://emsc.eu/





SLF IMIS

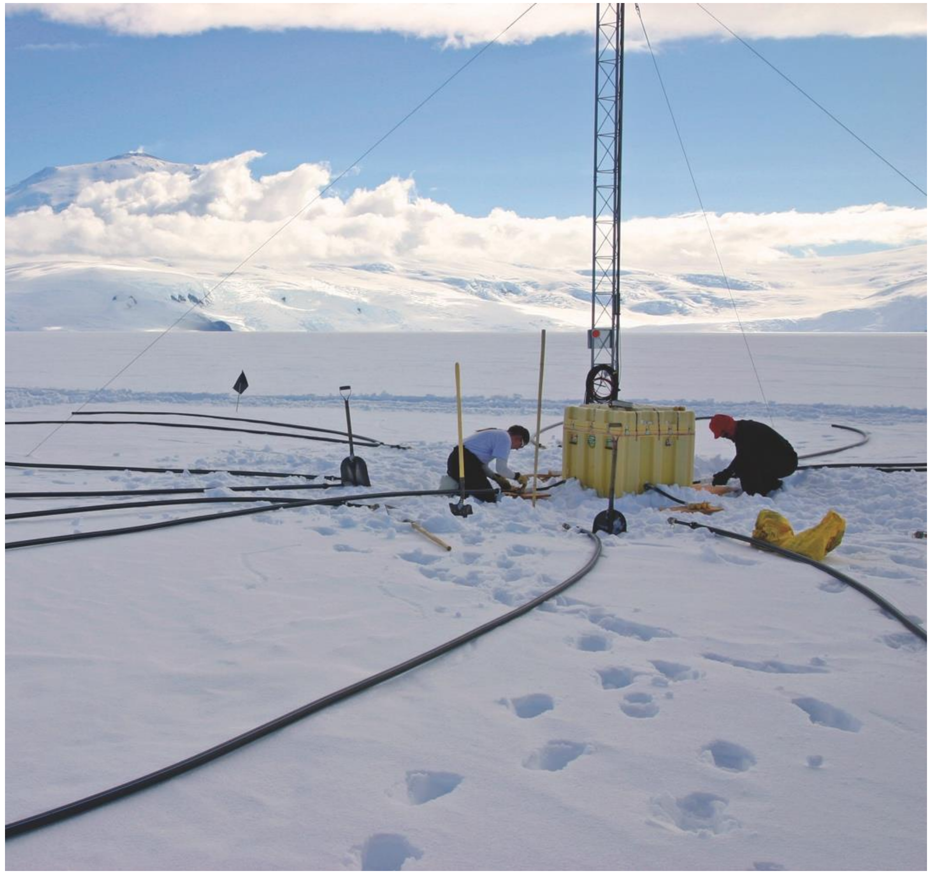
- 189 stations in the Swiss Alps and Jura Canton
- Highly remote areas
- Every 30 minutes
- https://whiterisk.ch/en/conditions



CTBTO

- 337 facilities worldwide
- Hourly measurements
- Homogenously distributed around the earth

- https://ctbto.org/



The boundaries and presentation of material on this map do not imply the expression of any opinion on the part of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) Preparatory Commission concerning the legal status of any country, territory, city or area or its authorities, or concerning the delimitation of its frontiers or boundaries.

Revised August 2021 | CTBTO.ORG

Summary

Rural Environmental Monitoring Use Case	Number of Stations	Dispersion	Real-Time Constraint	Proximity to Urban Areas	Potential for Electricity Access	Potential for Internet Access	Safety Risk	Data Sensitivity
Air Quality (GEMS/Air)	10s of 1000s	Global	Hour	Any	Moderate	Moderate	Moderate	Low
Water Quality (SWAIN)	30 to 75	Regional	Minute	Any	Low	Low	High	Low
Seismic Activity (EMSC)	$\geq$ 2500	Continental	Minute	Any	High	Moderate	High	Low
Avalanche (SLF IMIS)	186	Regional	Hour	Mid to Far	Low	Low	High	Low
Nuclear Explosion (CTBTO)	337	Global	Hour	Mid to Far	Low	Low	High	High
Agriculture	$\approx$ 1 per 2 ha	Local	Hour	Near to Mid	Low	Low	Moderate	Low
Oil and Gas Well	$\approx$ 1 per well	Local	Minute	Mid to Far	High	Low	High	High

Aral, A. 2024. The Promise of Neuromorphic Edge AI for Rural Environmental Monitoring. Environmental Data Science. Cambridge University Press. (to appear)

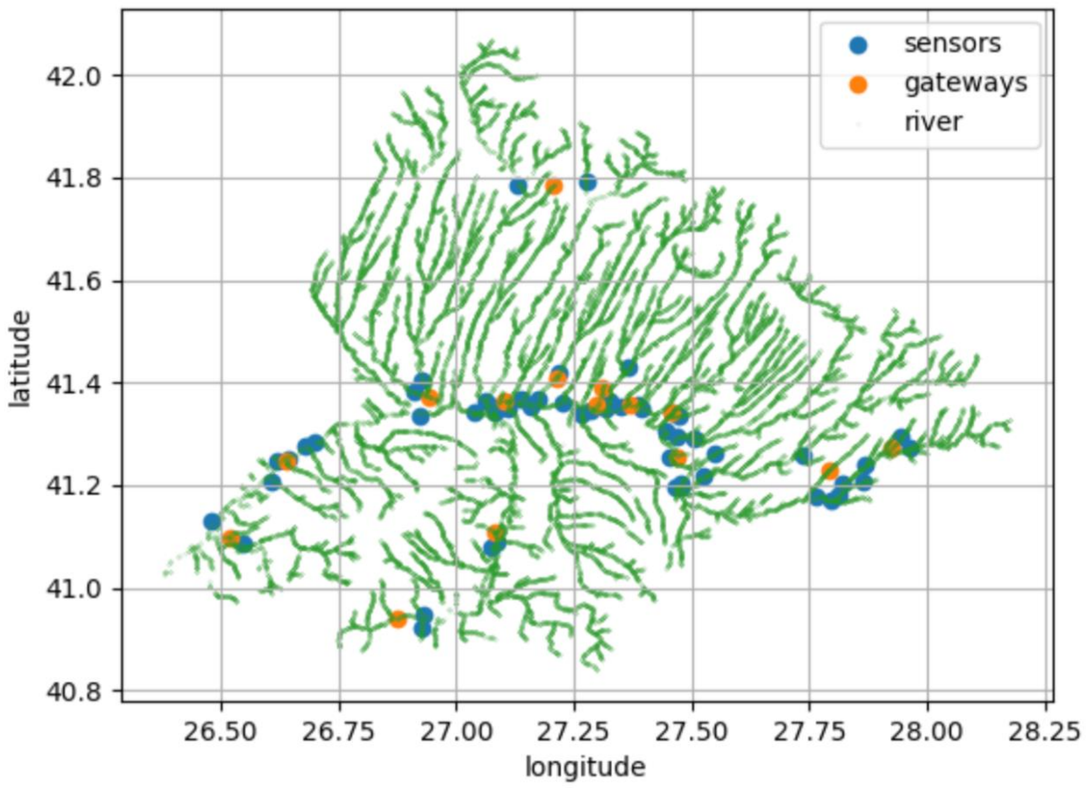
Key Technologies

Integration of Digital Technologies at Different Stages

- Spatial Planning and Sensor Placement
- Sensor Technologies
- Data Communication
- Data Processing
- Data Storage
- Data Analysis and Modeling
- Decision Making

Spatial Planning and Sensor Placement

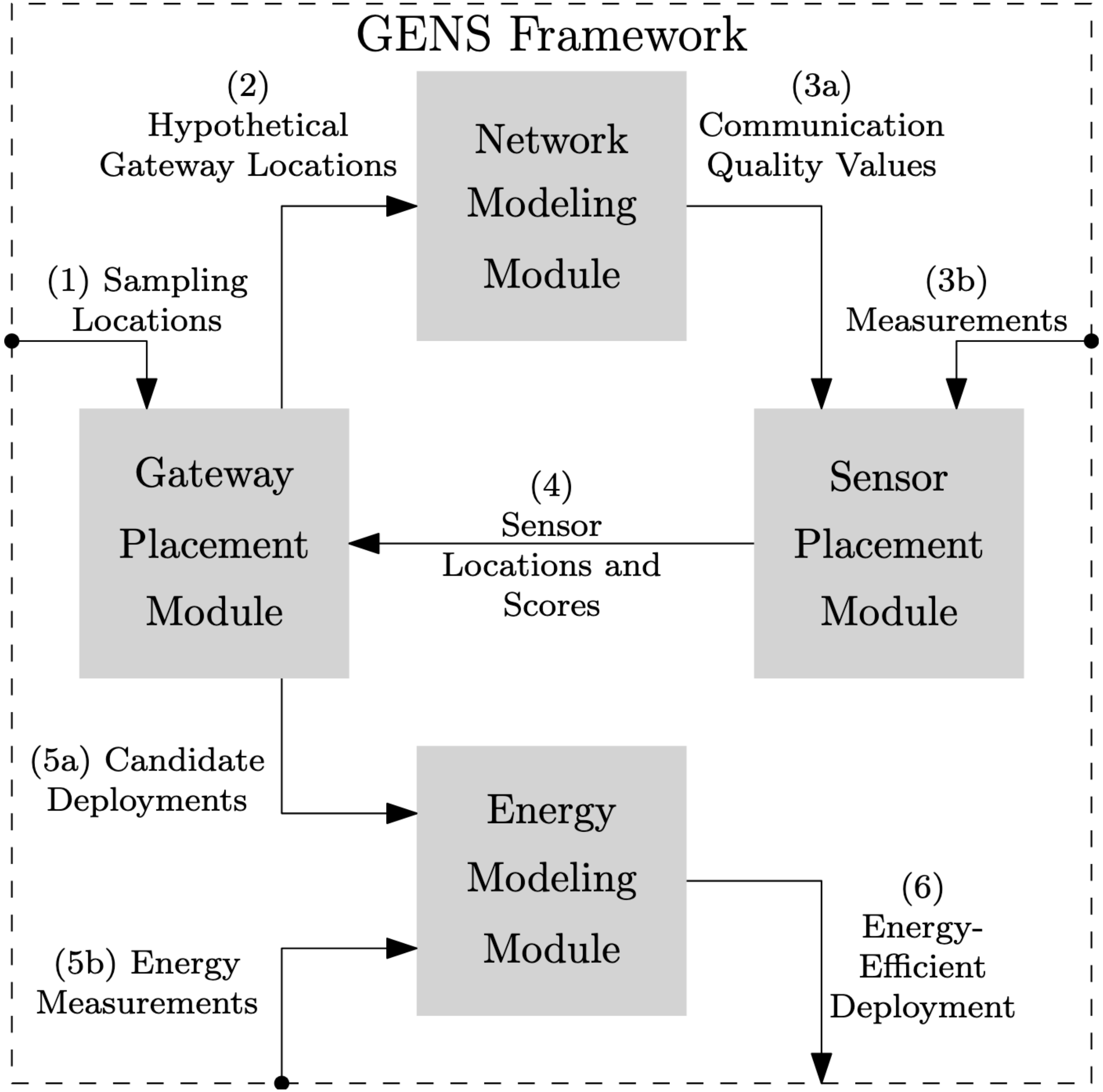
- Data quality / informativeness
- Reliability
- Maintainability
- Accessibility to electricity / network
- Cost
- Sustainability / Ecological footprint



GENS Framework

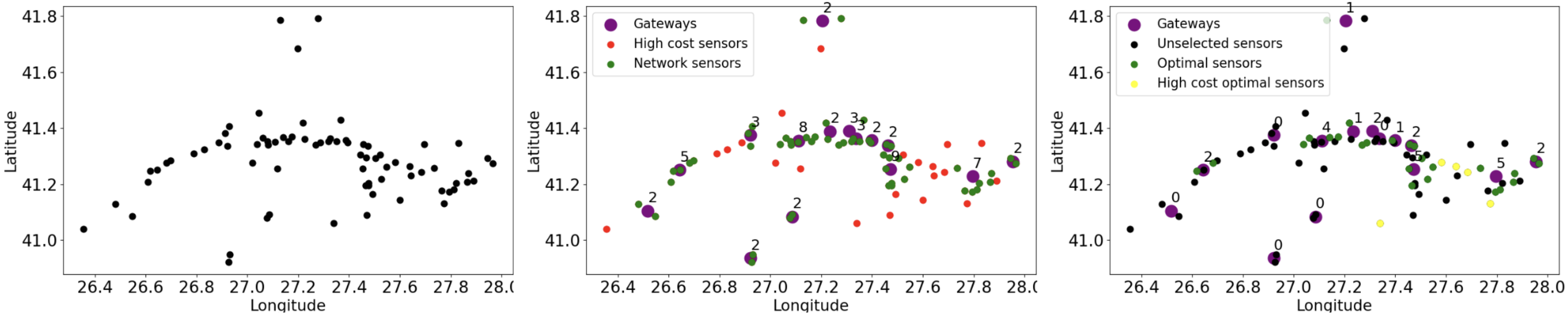
- Data quality / informativeness
- Network accessibility
  - Also decides gateway locations
- Ecological footprint and cost
- Energy efficiency

- Starts from an initial placement!



Ahmad, S., Uyanık, H., Ovatman, T., Sandıkkaya, M.T., De Maio, V., Brandić, I. and Aral, A., 2023. Sustainable environmental monitoring via energy and information efficient multi-node placement. IEEE Internet of Things Journal.

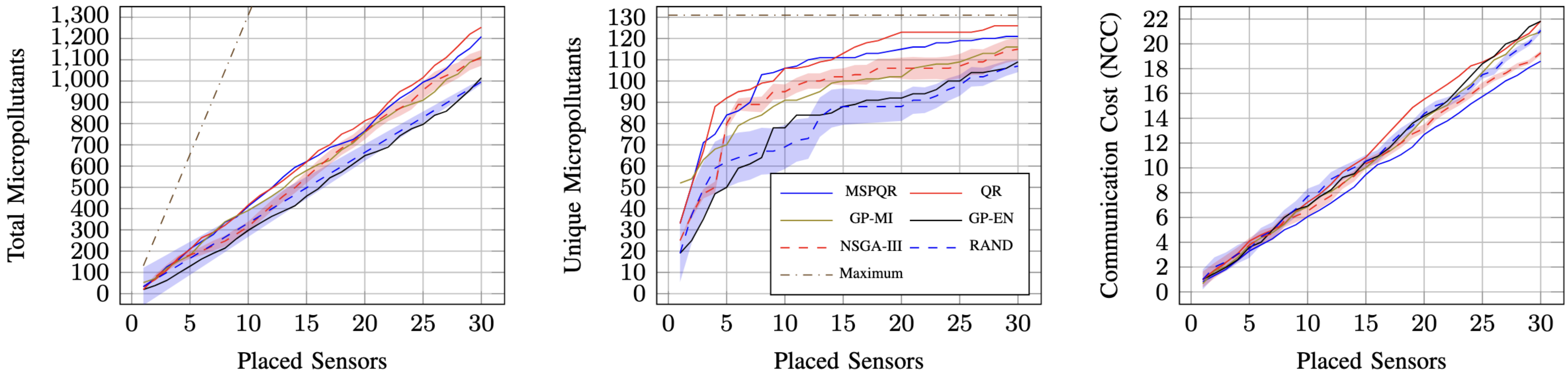
GENS Framework



(a) Sample Measurement Locations (b) Gateway Placement (15 GWs, 54 sensors) (c) Sensor Placement (Optimal locations)

Ahmad, S., Uyanık, H., Ovatman, T., Sandıkkaya, M.T., De Maio, V., Brandić, I. and Aral, A., 2023. Sustainable environmental monitoring via energy and information efficient multi-node placement. IEEE Internet of Things Journal.

GENS Framework



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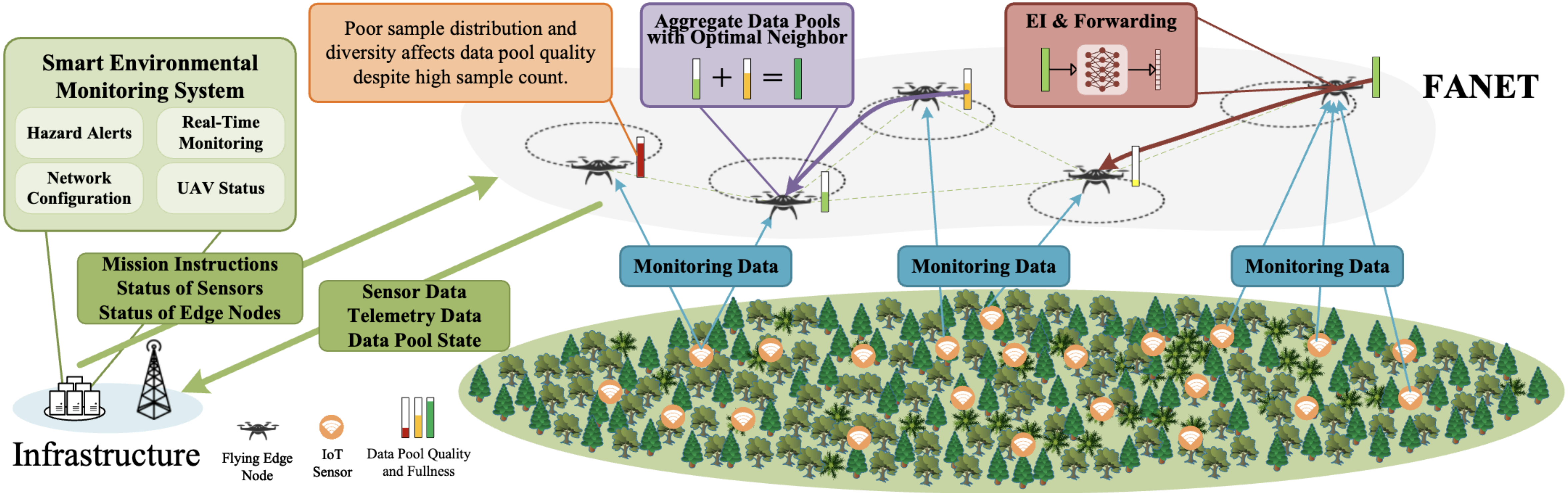
Sari, T.T., Ahmad, S., Aral, A. and Seçinti, G., 2023. Collaborative Smart Environmental Monitoring Using Flying Edge Intelligence. In GLOBECOM 2023-2023 IEEE Global Communications Conference (pp. 5336-5341).

UAV-based Monitoring

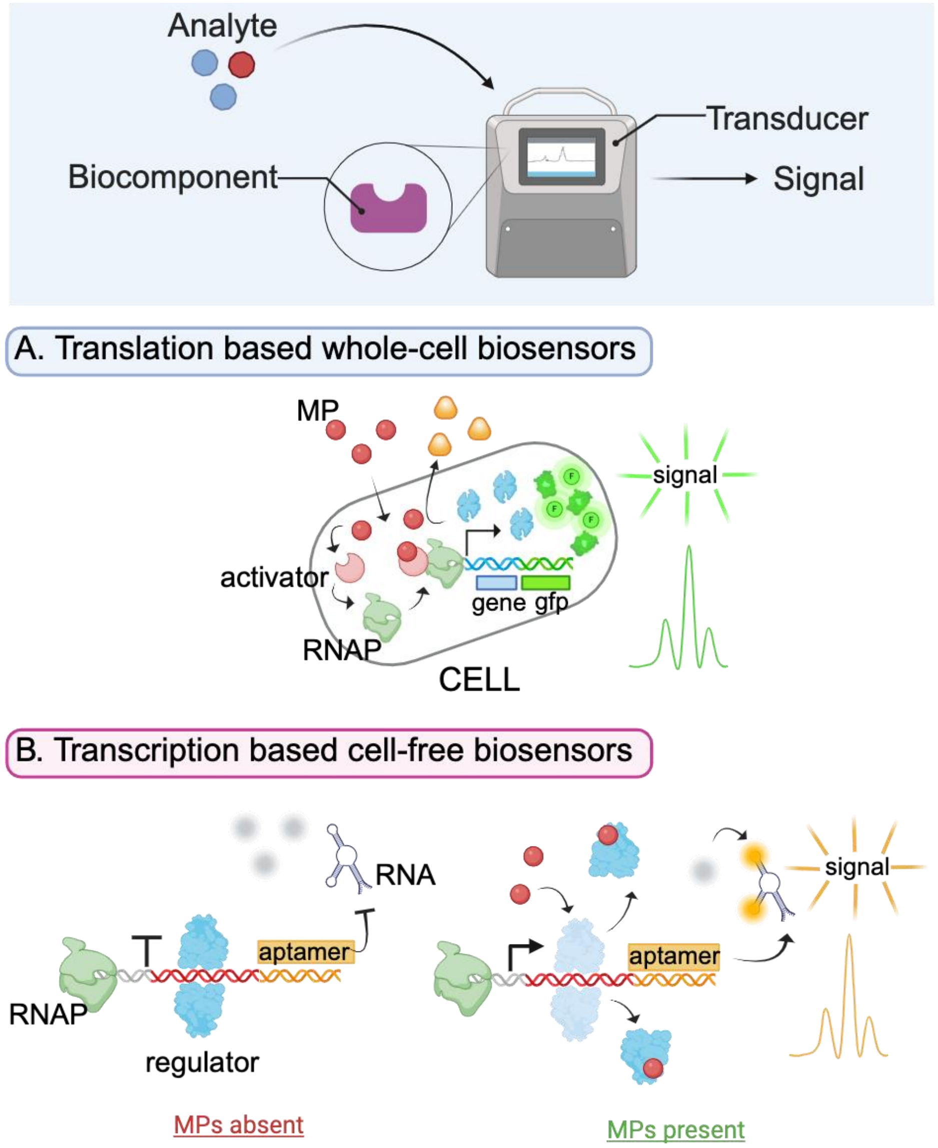


Integration of Digital Technologies at Different Stages

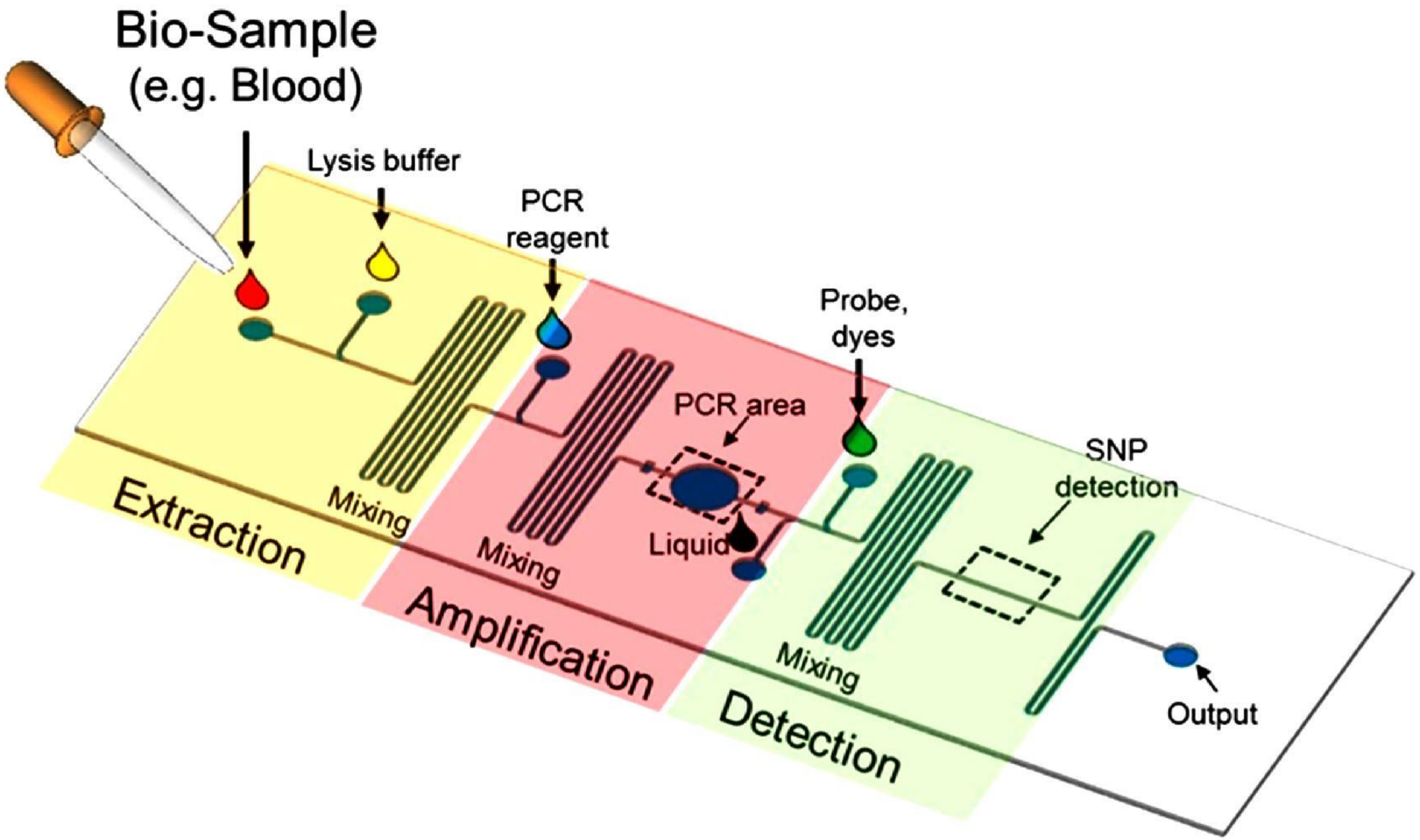
- Spatial Planning and Sensor Placement
- Sensor Technologies
- Data Communication
- Data Processing
- Data Storage
- Data Analysis and Modeling
- Decision Making

Biosensors

- Pollutants exert stress on bacterial communities
- Bacteria activate various response mechanisms
  - Biodegradation
  - Resistance
- Regulated at the genetic level
- Transcription and translation of reporter genes generate a detectable signal



Laboratory on a chip (LOC)



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Remote Sensing

Applications:

- Deforestation monitoring
- Water quality assessment
- Air quality monitoring
- Climate change monitoring
- Disaster management (e.g., floods, wildfires)

Challenges:

- Data storage and management
- High computational requirements
- Sensor calibration and accuracy
- Data integration and interoperability
- Privacy and ethical concerns

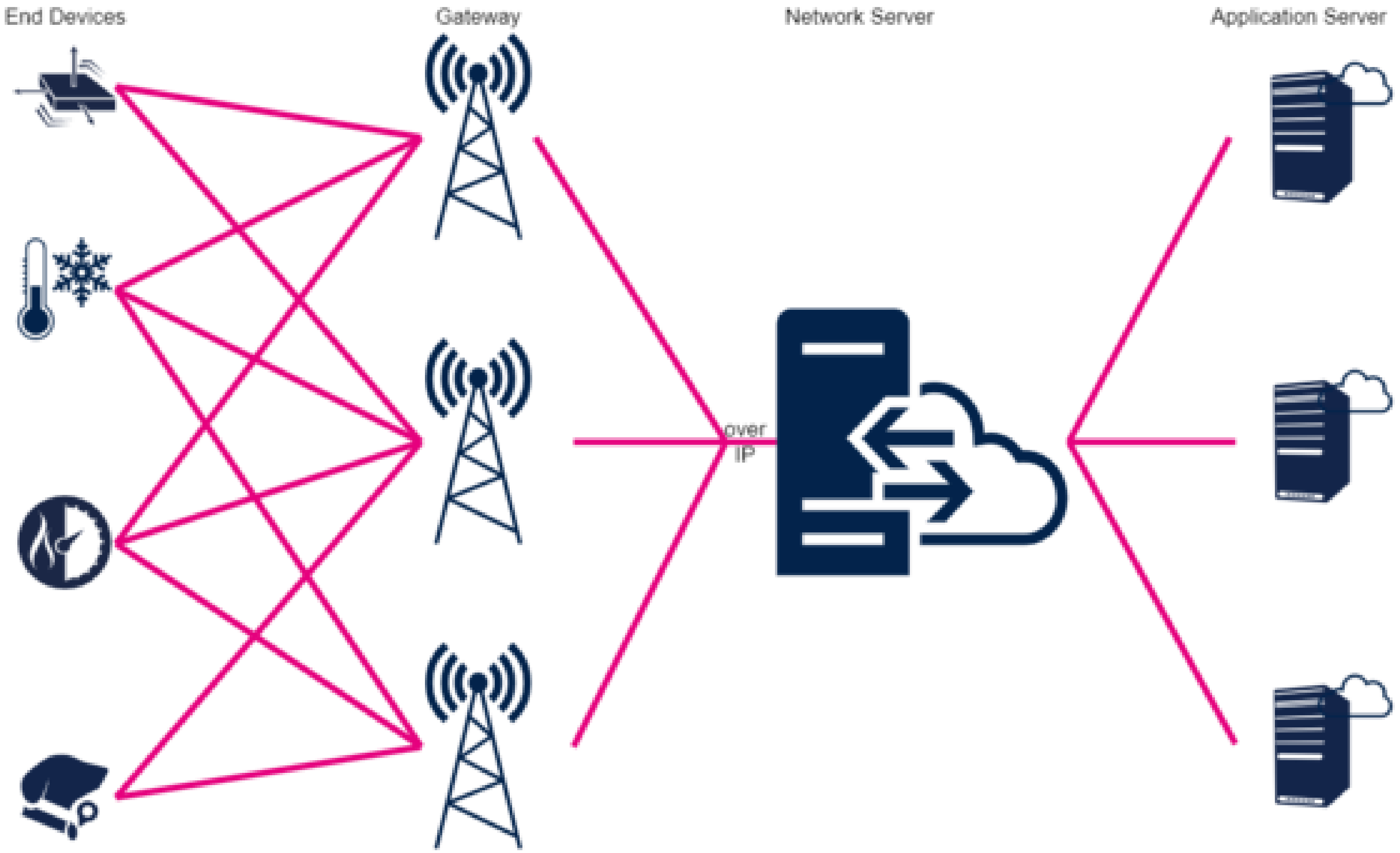
Integration of Digital Technologies at Different Stages

- Spatial Planning and Sensor Placement
- Sensor Technologies
- Data Communication
- Data Processing
- Data Storage
- Data Analysis and Modeling
- Decision Making

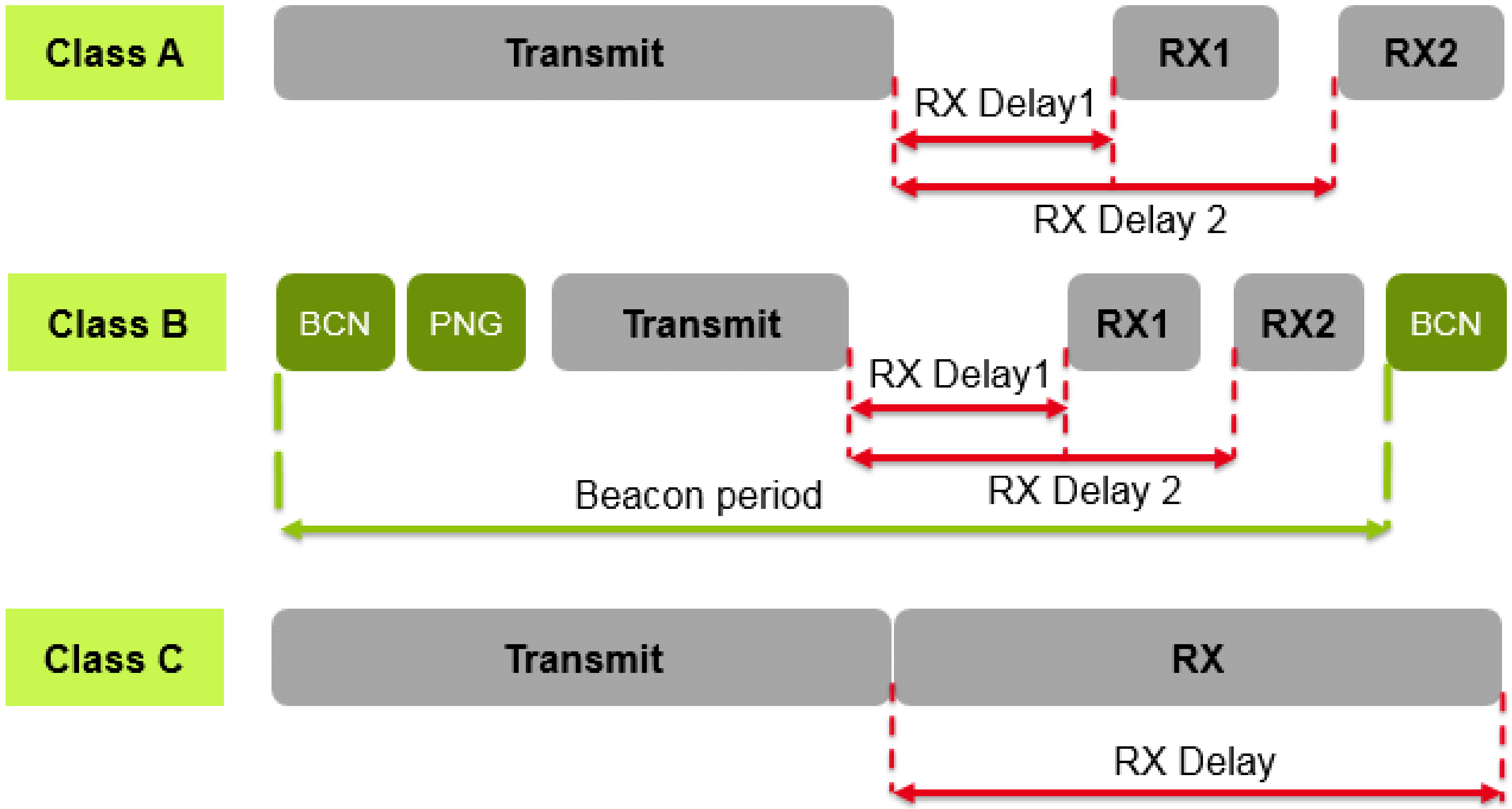
LoRaWAN

- Very energy efficient
- Very low bandwidth
- Configurable spreading factor
- Different device types

- Range: 2 to 20 kms
- Data rate: 0.3 to 50 kbps



LoRaWAN



Class A
Transmit
RX1
RX2
RX Delay1
RX Delay 2
Class B
BCN
PNG
Transmit
RX1
RX2
BCN
RX Delay1
RX Delay 2
Beacon period
Class C
Transmit
RX
RX Delay

Integration of Digital Technologies at Different Stages

- Spatial Planning and Sensor Placement
- Sensor Technologies
- Data Communication
- Data Processing (soon)
- Data Storage
- Data Analysis and Modeling
- Decision Making

The SWAIN Project: An Overview

- Sustainable Watershed Management Through IoT-Driven Artificial Intelligence
  - Funded EUR 1.2M from 2021 to 2024

  - University of Vienna, Vienna University of Technology
  - Università della Svizzera italiana
  - Finish Environmental Institute
  - Istanbul Technical University, Bogazici University

https://swain-project.eu/ @SWAIN_Project

Industrial Facilities in Watersheds

- Fabrication
- Processing
- Washing
- Dilution
- Cooling
- Transportation

Water Treatment Plants

Water Pollution Disasters

- Kokemäki, Finland, 2014
  - 66 tons of nickel
  - 30 hours

UUTISET > **NEWS**

News 13.7.2014 7:00 | updated 13.7.2014 11:50

Dead mussels found in Kokemäki river after nearby nickel leak

Experts first insisted that no link could be proven between the dead shellfish and last week's release of cooling fluids from the Norilsk Nickel mine in Harjavalta, southwest Finland. Pori environmental director Matti Lankiniemi now says that the link is highly likely.

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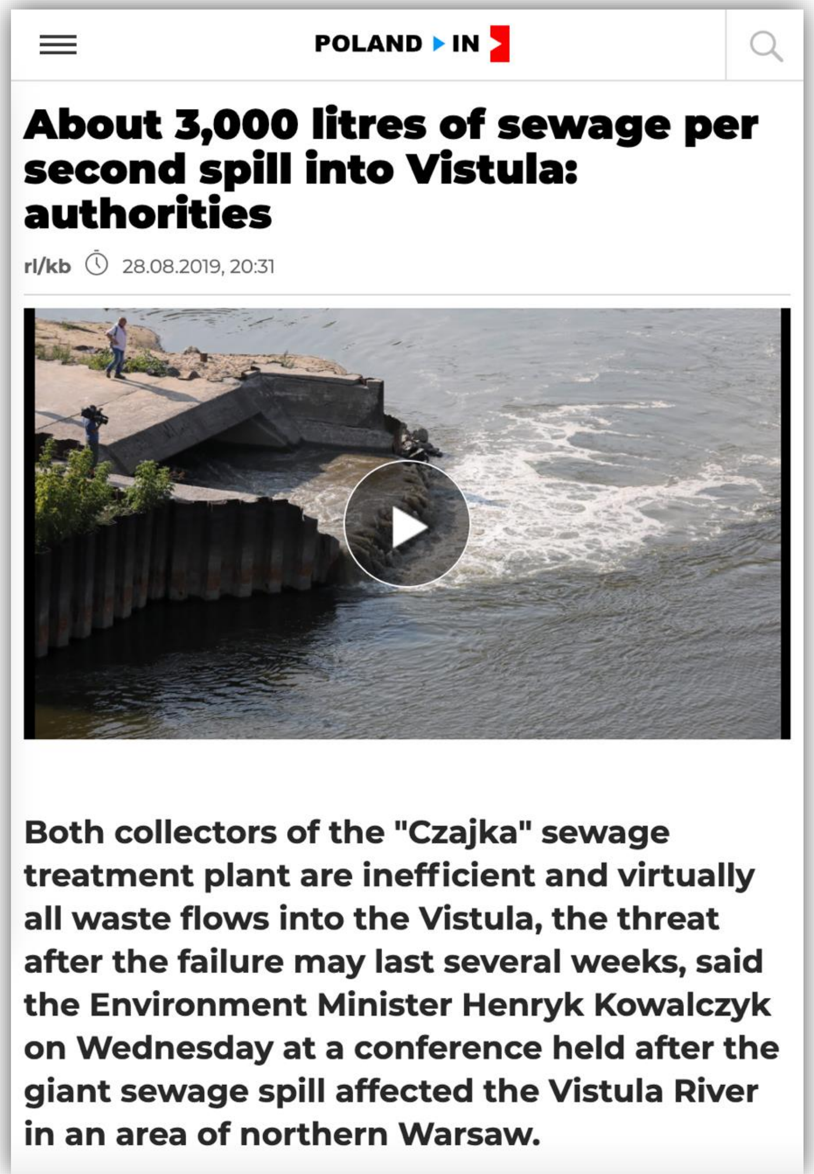
Water Pollution Disasters

- Vistula, Poland, 2019
  - 300 tons of nitrogen
  - 30 tons of phosphorus
  - Five days
- Oder River, Germany, 2022


POLAND IN

About 3,000 litres of sewage per second spill into Vistula: authorities

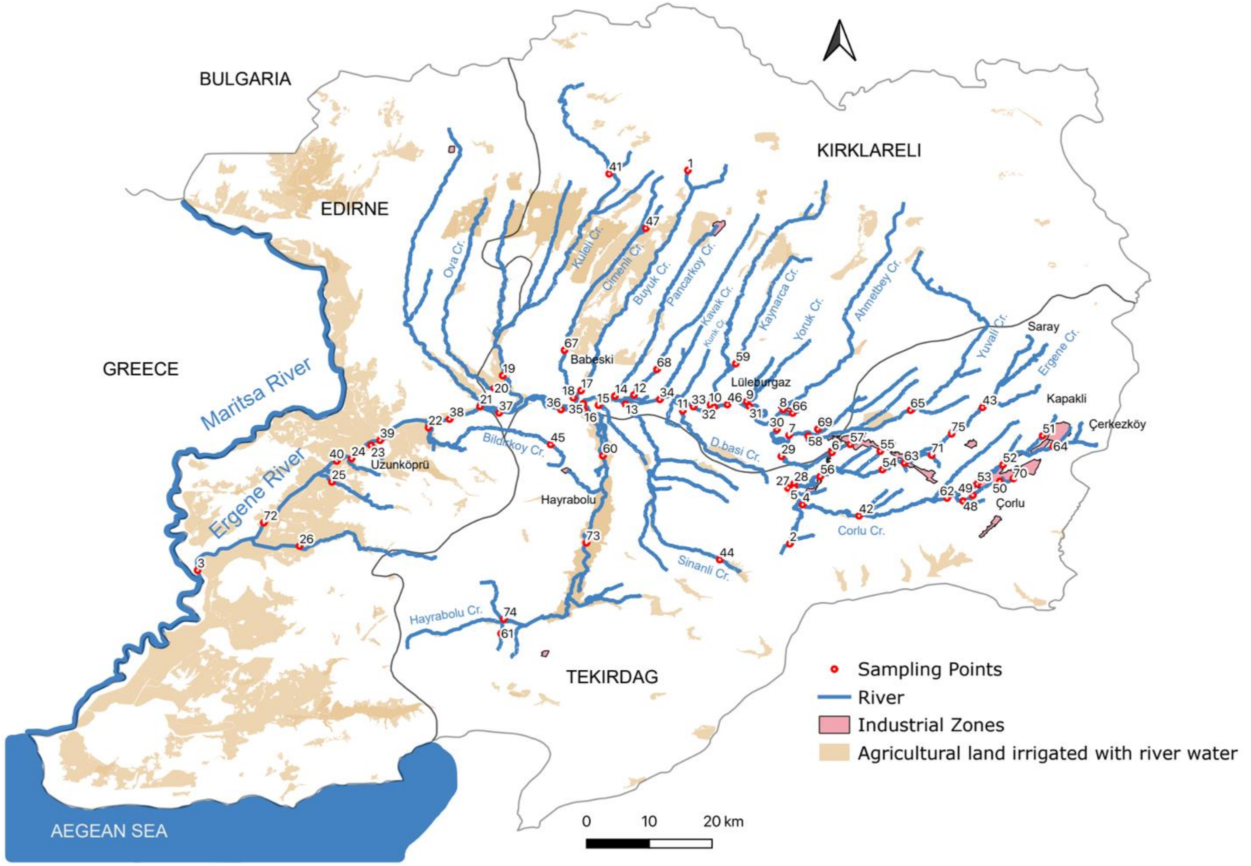
rl/kb 28.08.2019, 20:31

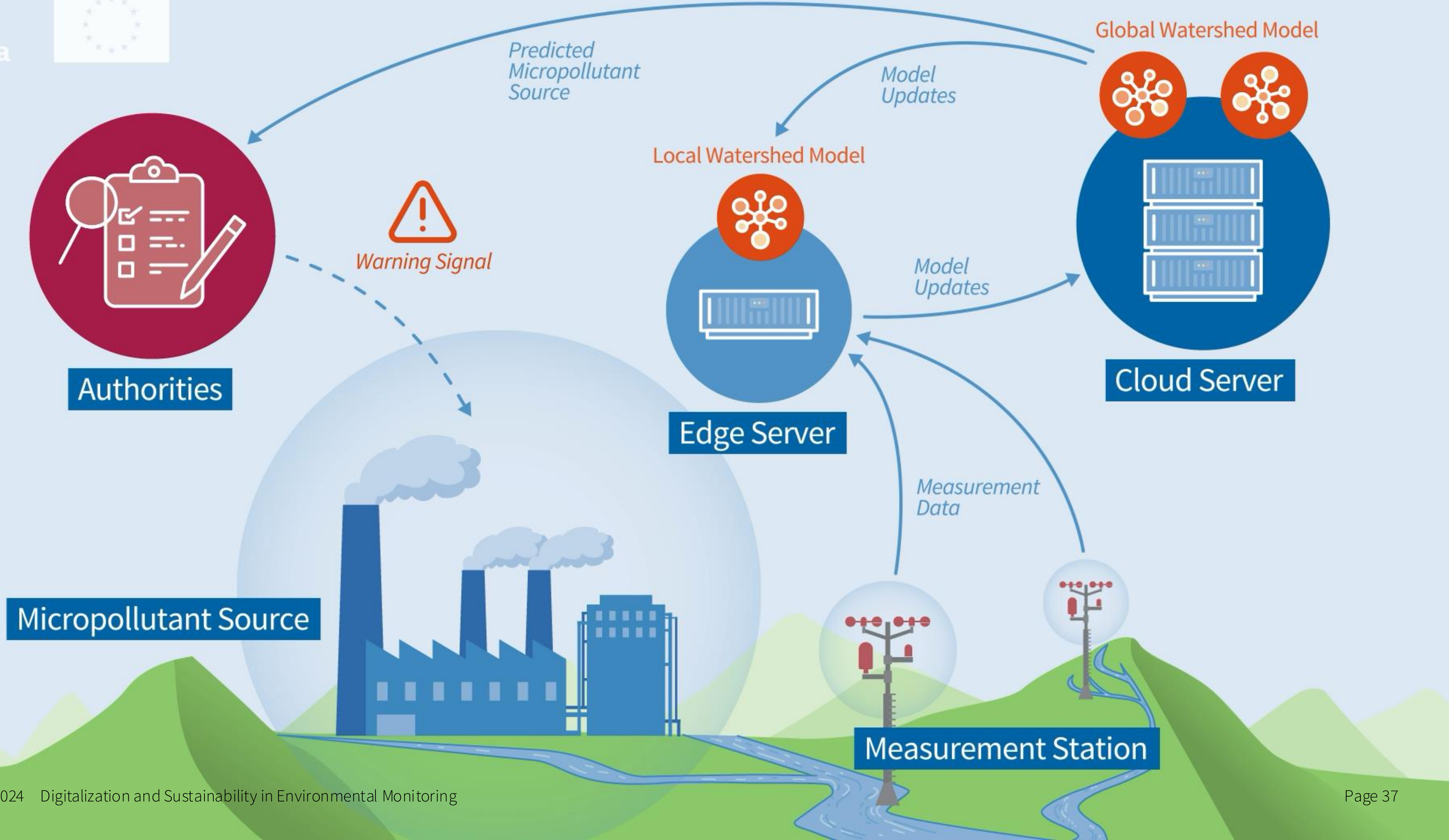
Both collectors of the "Czajka" sewage treatment plant are inefficient and virtually all waste flows into the Vistula, the threat after the failure may last several weeks, said the Environment Minister Henryk Kowalczyk on Wednesday at a conference held after the giant sewage spill affected the Vistula River in an area of northern Warsaw.

Use Cases

- Use Case 1
  - Ergene River in Northwestern Turkey

- Use Case 2
  - Kokemäki River in Southwestern Finland




Global Watershed Model
Predicted Micropollutant Source
Model Updates
Local Watershed Model
Warning Signal
Authorities
Model Updates
Cloud Server
Edge Server
Measurement Data
Micropollutant Source
Measurement Station

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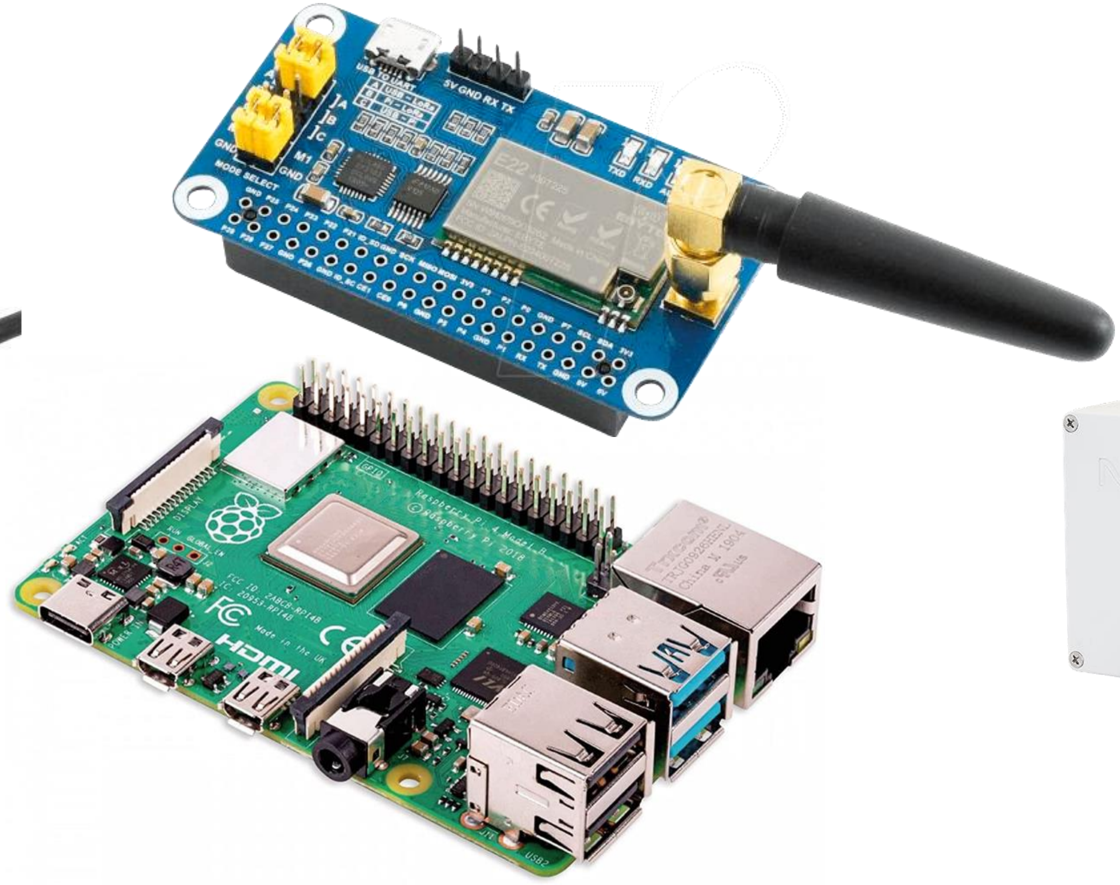

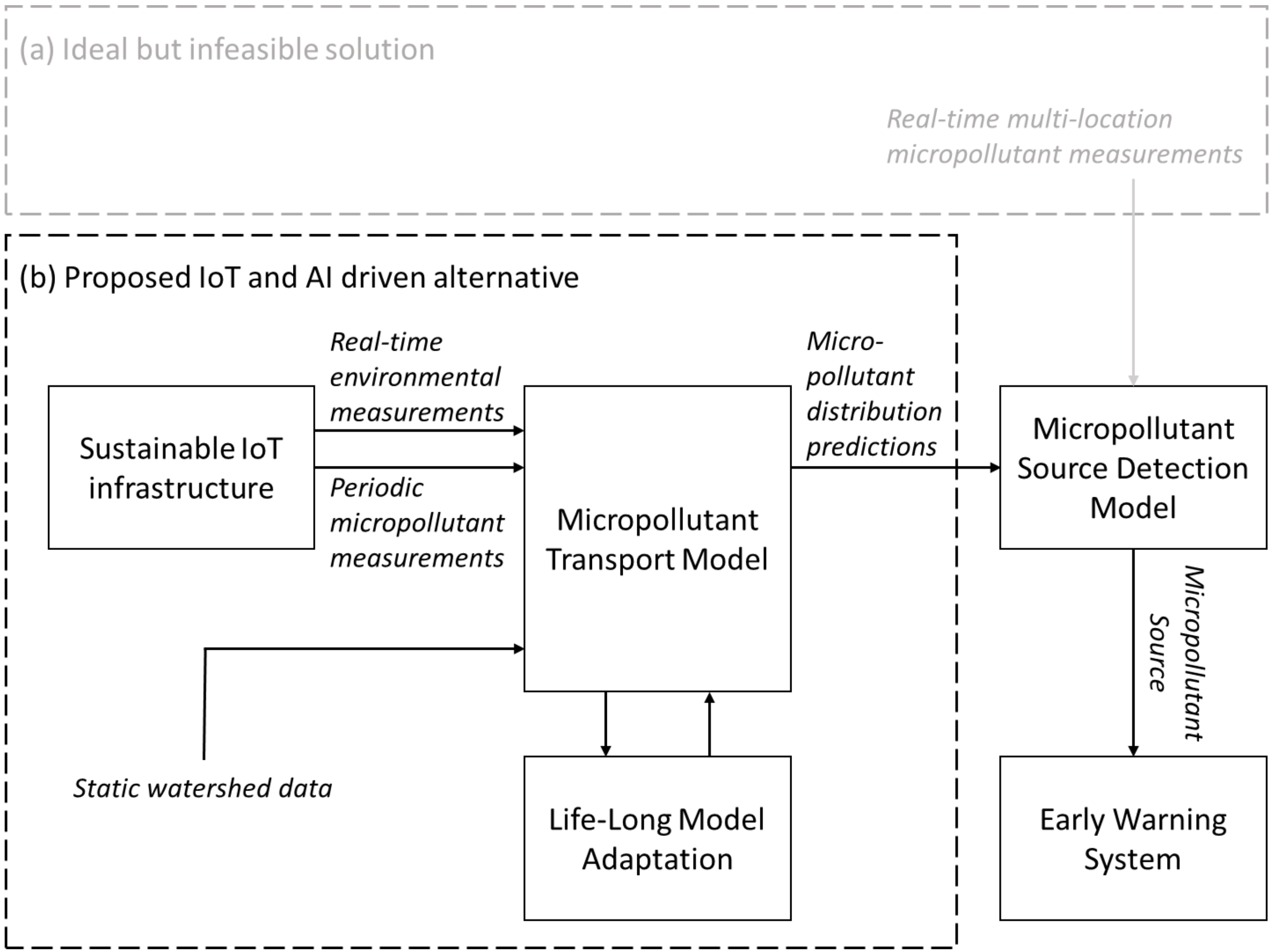
(a) Ideal but infeasible solution
Real-time multi-location micropollutant measurements
(b) Proposed IoT and AI driven alternative
Sustainable IoT infrastructure
Real-time environmental measurements
Periodic micropollutant measurements
Micropollutant Transport Model
Micro-pollutant distribution predictions
Micropollutant Source Detection Model
Micropollutant Source
Static watershed data
Life-Long Model Adaptation
Early Warning System

Integration of Digital Technologies at Different Stages

- Spatial Planning and Sensor Placement
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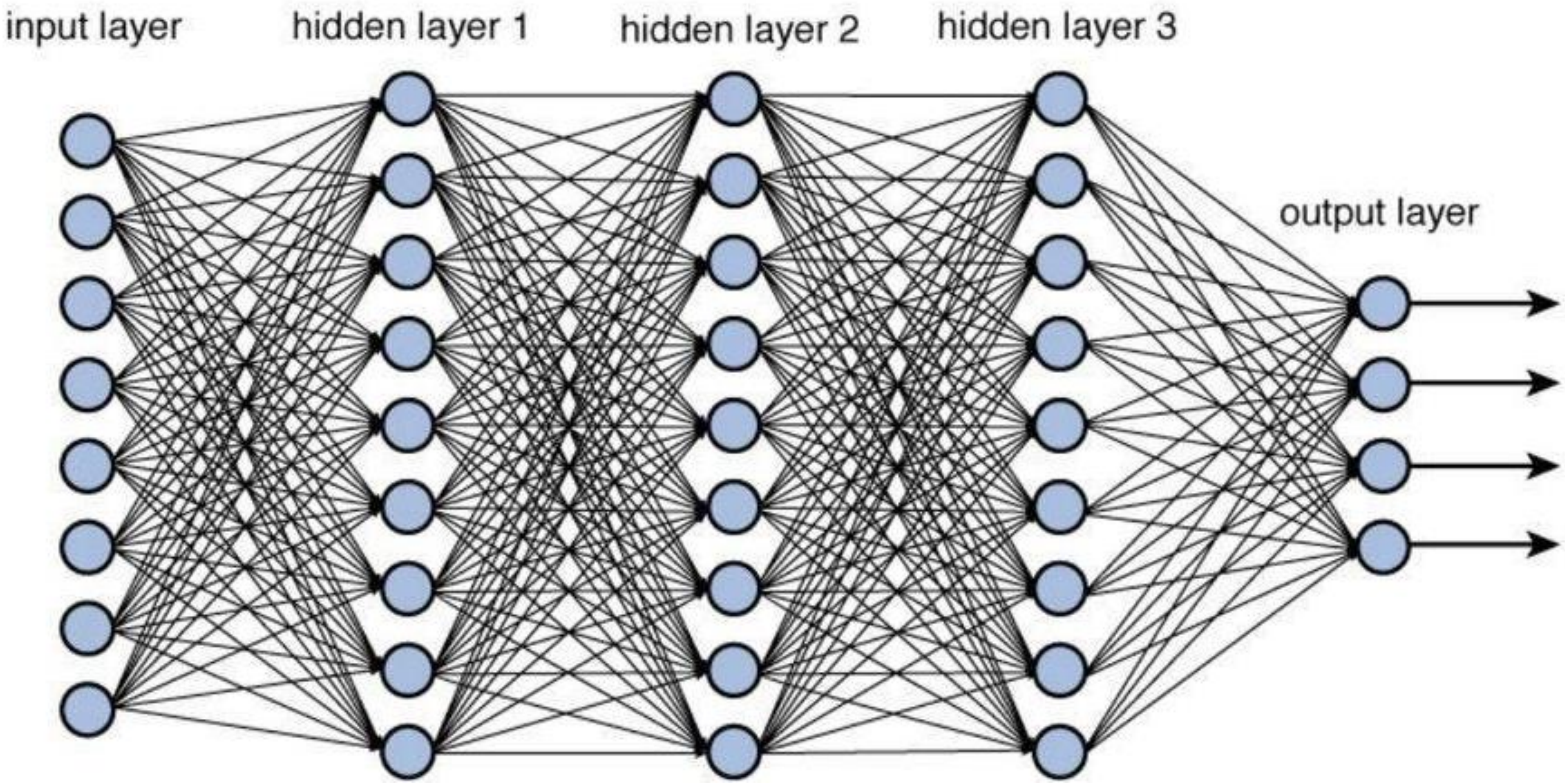
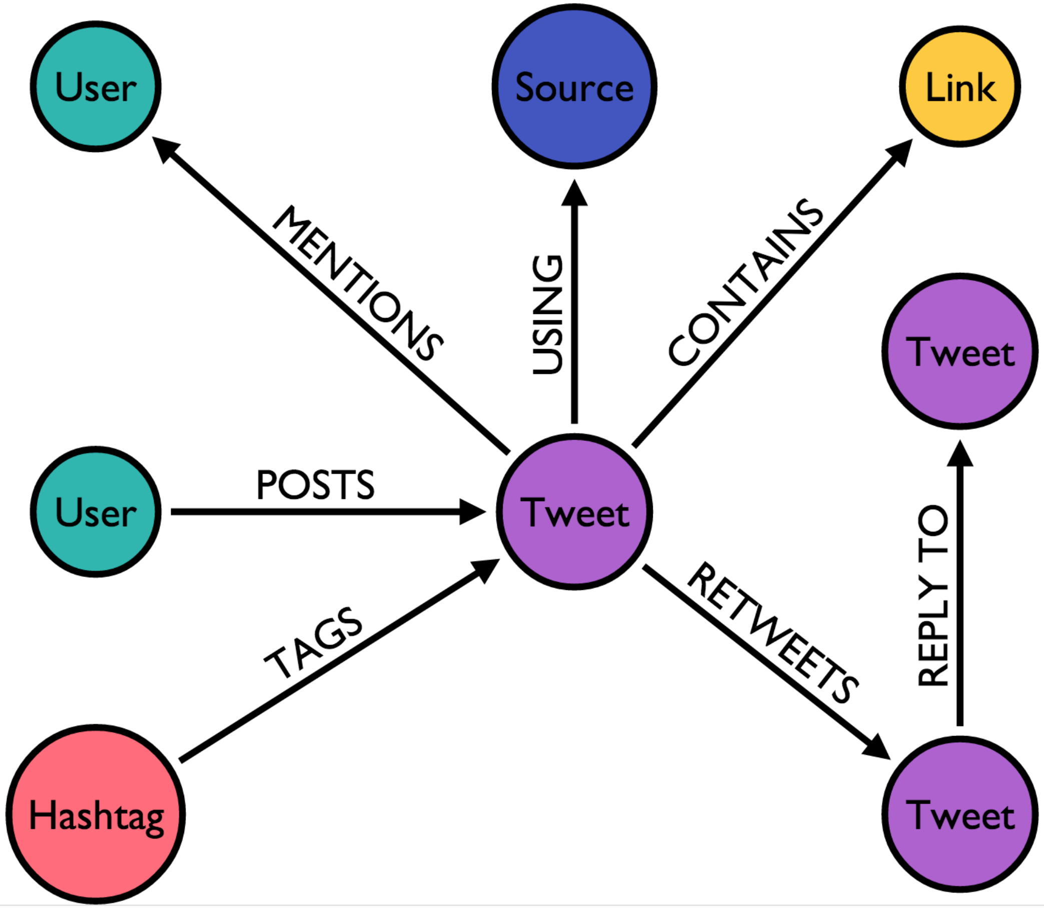
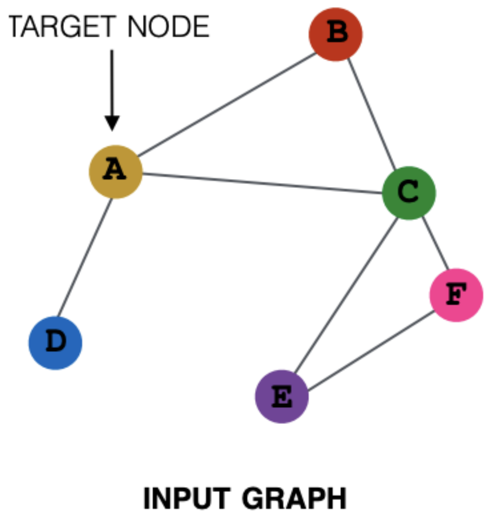

input layer
hidden layer 1
hidden layer 2
hidden layer 3
output layer

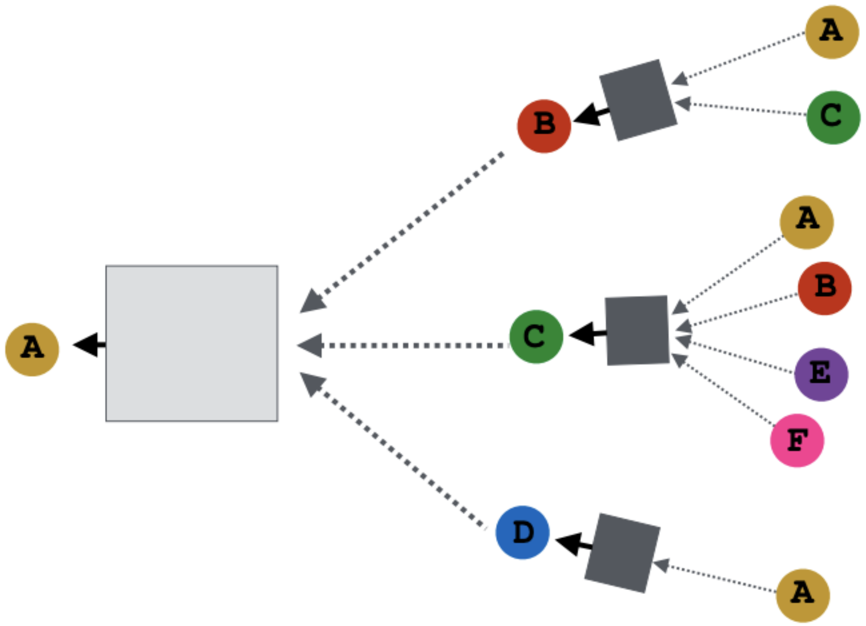
Graph Convolutional Networks

- Use case: Fake tweet detection
- Classify each tweet individually
  - Lose link information
- Label propagation
  - Lose content information
- Solution: Neighbor averaging



Neighbor Averaging

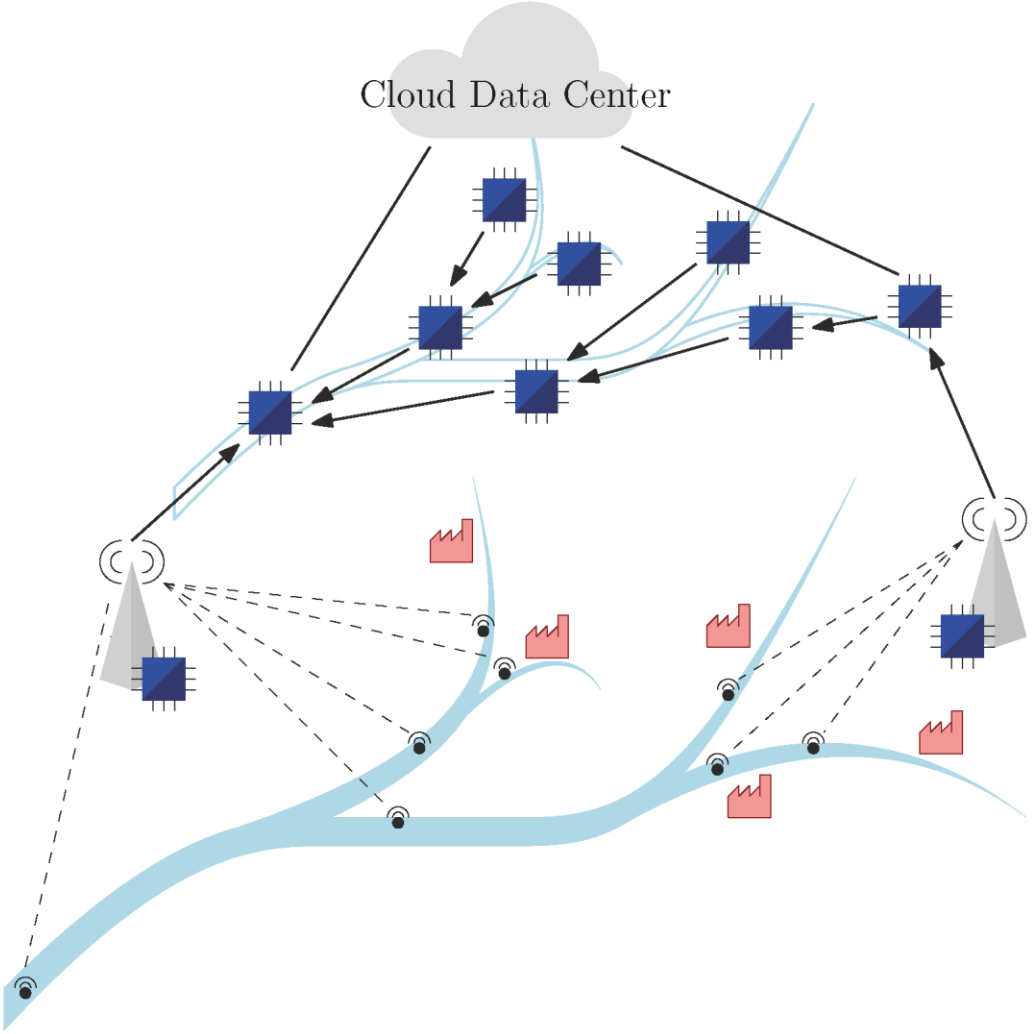




Graph Attention Networks

- GCN: $$\mathbf{h}_{\mathcal{N}(v)} = \sum_{u \in \mathcal{N}(v)} w_{u,v} \mathbf{h}_u$$

- GAT: $$\mathbf{h}_{\mathcal{N}(v)} = \sum_{u \in \mathcal{N}(v)} a(\mathbf{h}_u, \mathbf{h}_v) \mathbf{h}_u$$



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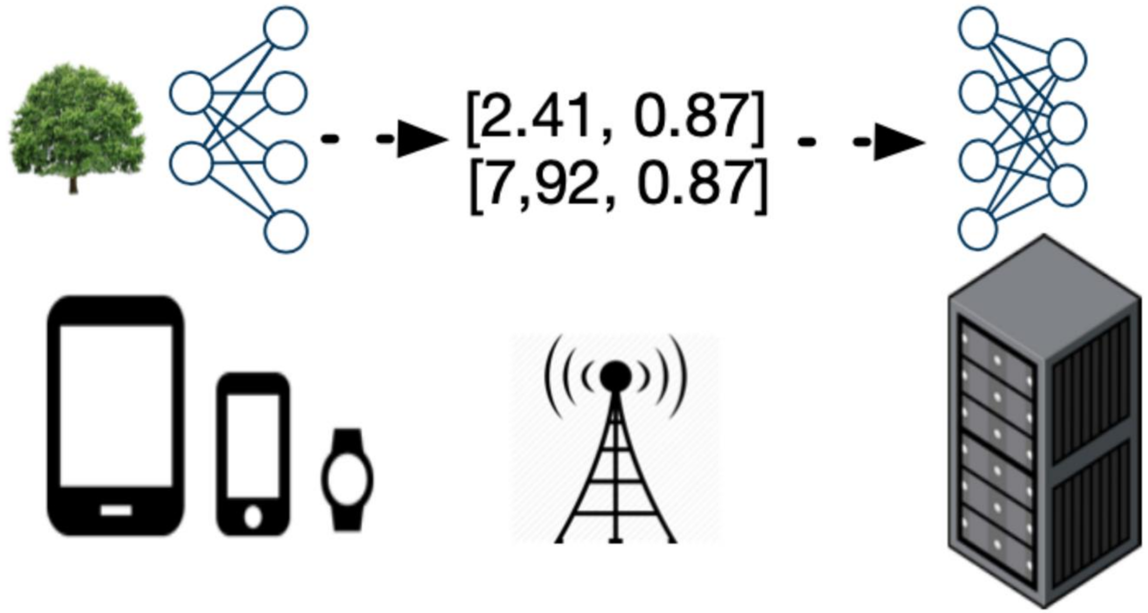
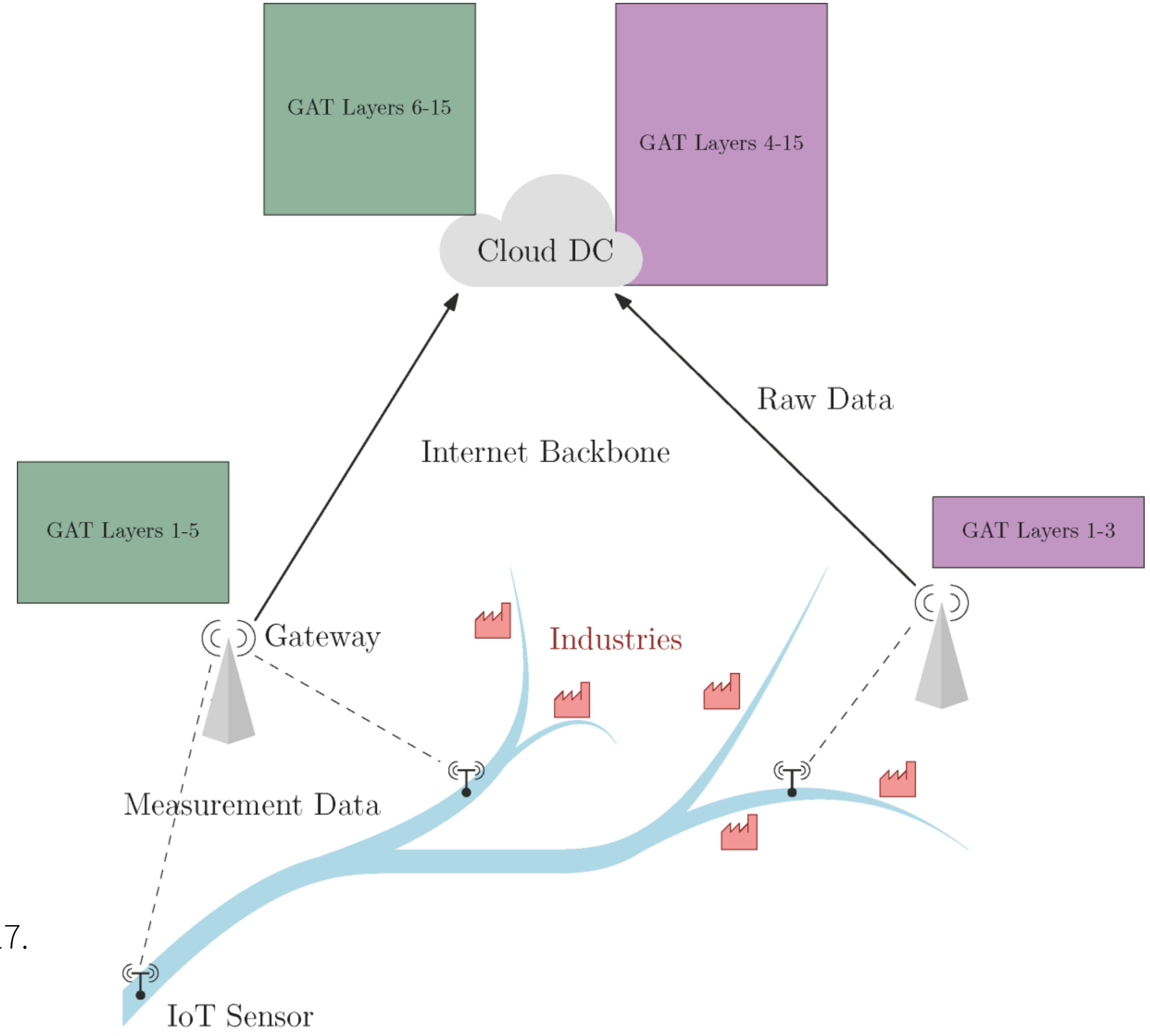
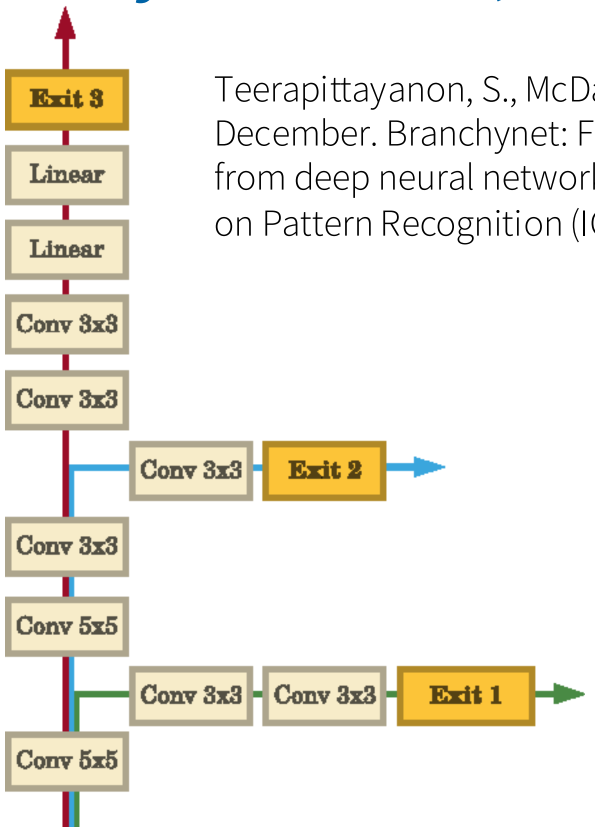
DNN Partitioning (NeuroSurgeon)



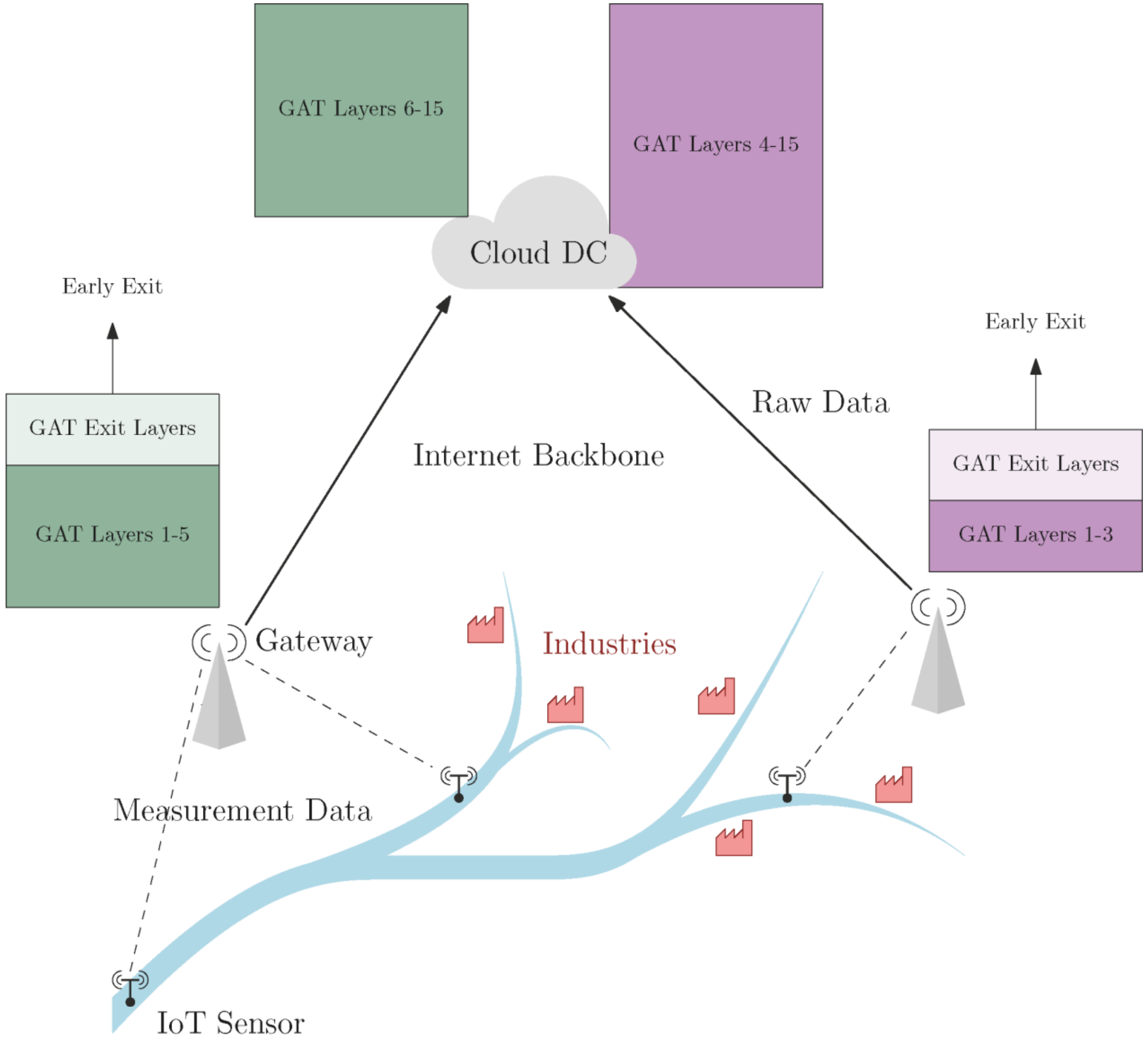
Kang, Y., Hauswald, J., Gao, C., Rovinski, A., Mudge, T., Mars, J. and Tang, L., 2017. Neurosurgeon: Collaborative intelligence between the cloud and mobile edge. ACM SIGARCH Computer Architecture News, 45(1), pp.615-629.



Early Exit DNN (BranchyNet)



Teerapittayanon, S., McDanel, B. and Kung, H.T., 2016, December. Branchynet: Fast inference via early exiting from deep neural networks. In International Conference on Pattern Recognition (ICPR) (pp. 2464-2469).



Questions?

Bridging the Gap Between Computer and Environmental Science

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Challenges in Interdisciplinary Collaboration on Environmental Monitoring

- Differences in Terminology and Language
- Divergent Research Goals / Cultures
  - Understanding vs. novel techniques
  - Long-term vs. short-term goals
- Technical Skill Gaps
- Need for shared platforms and tools in facilitating cooperation
  - What platforms do you know about?

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Center for AI and ML (CAIML)

- Special Interest Group on Climate (2022—2024)
  - Coordinator: Atakan Aral

- Special Interest Group on Sustainability (2024—now)
  - Coordinators: Ezio Bartocci and Ivona Brandic

ECH

- Bridges faculties and scientific disciplines at the University of Vienna and beyond to better understand the triple crisis of climate change, biodiversity loss, and pollution.

Environment and Climate Research Hub

- 65 researchers across 14 faculties of the University of Vienna.
- from climate science and ecology to sociology, economics, and philosophy.

Next Event: 12. Umwelt im Gespräch: Schnee war gestern – Klimawandel in den Alpen, 08.10.2024, Naturhistorisches Museum Wien (in German)

Climate Change AI

https://www.climatechange.ai/

Climate Informatics

https://www.climateinformatics.org/

Open Floor for Discussion

1. How does environmental monitoring relate to your field of study or profession?
2. Can you identify any environmental issues that intersects with your personal values or ethics?
3. How might you apply digital environmental monitoring tools in your future career or studies?

Key Takeaways and the Summary of Discussion

- Environmental monitoring is crucial for science because it provides critical data that informs research, advances our understanding of ecological processes, and supports evidence-based decision-making in environmental management.
- It is also crucial for society because it helps to prevent environmental threats, protect public health, and ensure sustainable use of natural resources. It also provides an objective basis for informing the public, modeling, and decision-making.
- Integration of digital technologies can enhance the collection, analysis, and management of environmental data and lead to more accurate, efficient, and responsive environmental protection and management.

Key Takeaways and the Summary of Discussion

- Environmental monitoring networks such as ILTER and GLEON and collaboration networks such as ECH and Climate Change AI for fostering inter- and transdisciplinarity are essential to make sufficient and appropriate use of the collected data.