The art of monitoring

Monitoring for IWRM – ground-based network design and sensor technology, in-stream

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INWRDAM

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Need for measurements

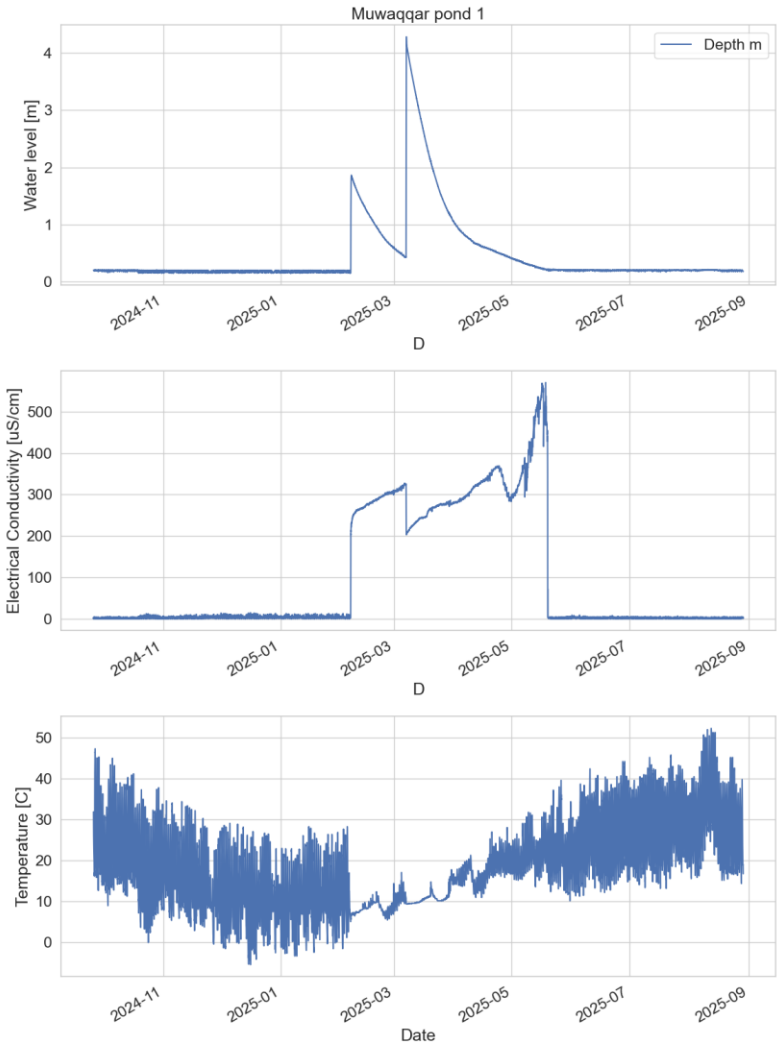
Measured ground and space observations play a crucial role in our daily life:

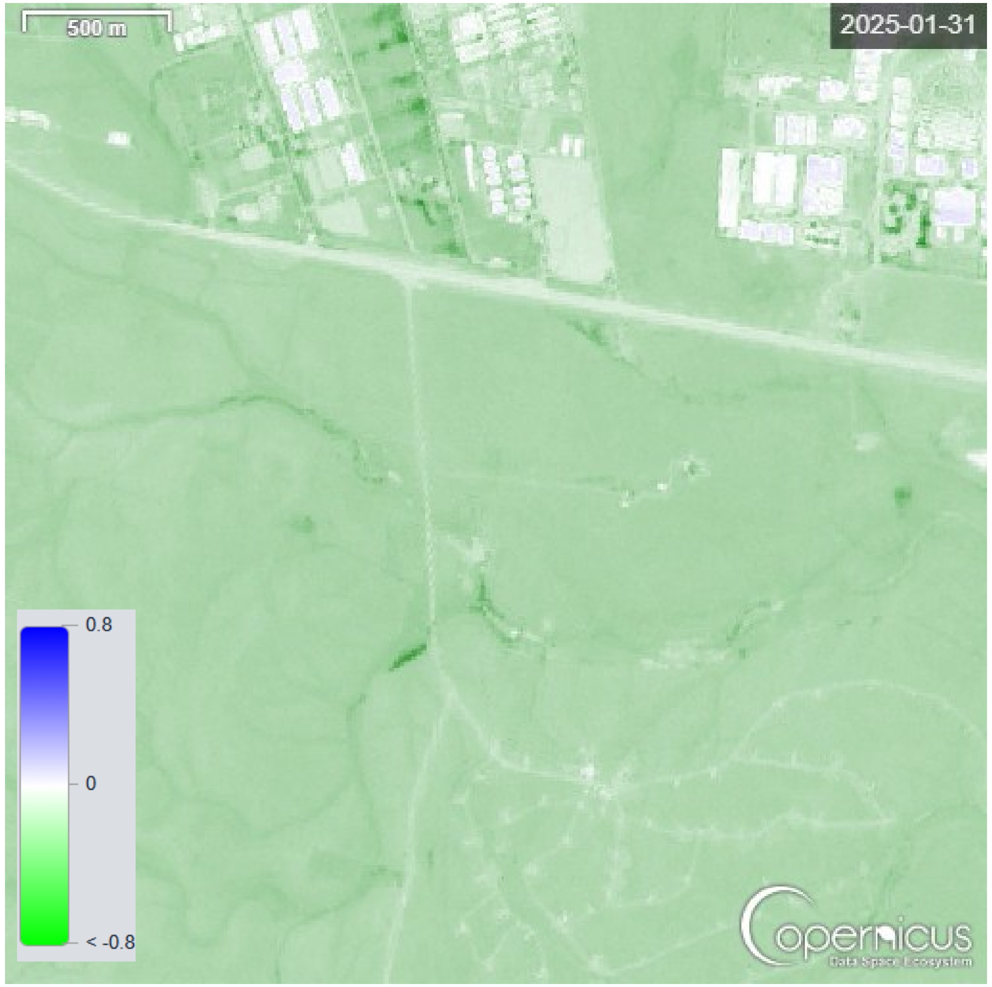
- Meteorology for weather prediction and providing alarms
- Flood warning through meteorology and water level measurement networks
- Earthquake monitoring through seismic measurement network
- Carbon monoxide and smoke monitoring devices in your home
- Thermostat for switching on/of heating systems
- Water quality measurements in drinking water supply
- Medical monitoring in hospitals, etc.
- IWRM requires data for developing strategies and monitoring impacts

Need for measurements to evaluate RWH

- Different objectives for RWH application at different scales require different observations to assess efficiency
  - We have just discussed the impacts on upland, in-stream and artificial groundwater replenishment systems
  - Comparison between control and intervention observations
- Common observations
  - Plot-scale - Soil moisture status or tension
  - Small-scale - Surface runoff
  - Sediment loss and deposition
  - Larger scale - River runoff (total discharge, peak discharge, dry season flow)
  - Agricultural production
  - Greenness of area, biodiversity
  - Land surface temperature
  - Extend of flooding
  - Change in community perception of RWH
  - Change in livestock
  - Change in groundwater

Example: physical measurements vs RS





Measurement needs related to use objectives

1. Important to properly define questions that need answers for management
2. Define data needs related to the questions - yesterday's exercise
3. Select appropriate monitoring techniques, measurement intervals and study periods

- What are the criteria, data and monitoring needs for assessing
  - Rainwater harvesting interventions?
  - Field-scale irrigation water use?
  - Water supply resilience?
  - Biodiversity status?

Measurement interval selection

- Depend on rate of change of measured parameter
  - Slow changing large river system ➔ could be once a day
  - Fast changing small river system ➔ 5-minute intervals may be required to capture variation
  - Precipitation: at least daily for long-term monitoring, 5-minute intervals for kinetic rainfall intensity impact to soil erosion, or event-based (record date/time of each tip)
  - Eddy covariance method for determining turbulent thermal, H_2O, CO_2, CH_4, NO_x fluxes from land surface, measured through turbulent exchange: measurements at >10 Hz
  - Satellite land surface monitoring – about weekly/twice monthly for Modis / Landsat / Sentinel
- If data are stored there used to be a trade-off with available memory for storage on measurement device: Eddy covariance daily 12 MB data files

Biophysical monitoring system block schematic

Desired parameters

Sensor

- Signal type
- Range
- Sensitivity
- Response time
- Data transmission (cable)
- Reliability
- Maintenance needs
- Power supply needs

Data collecting unit

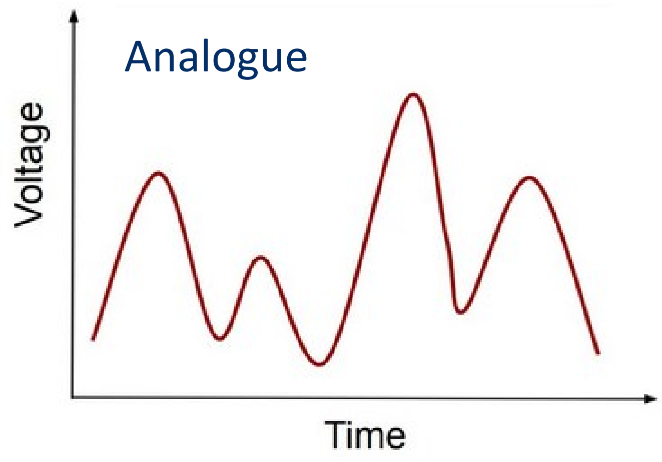
- Signal type interface / resolution
- Range and sensitivity
- Data conversion and processing (e.g. averaging)
- Reliability
- Storage size, telemetry
- Maintenance needs
- Power supply needs

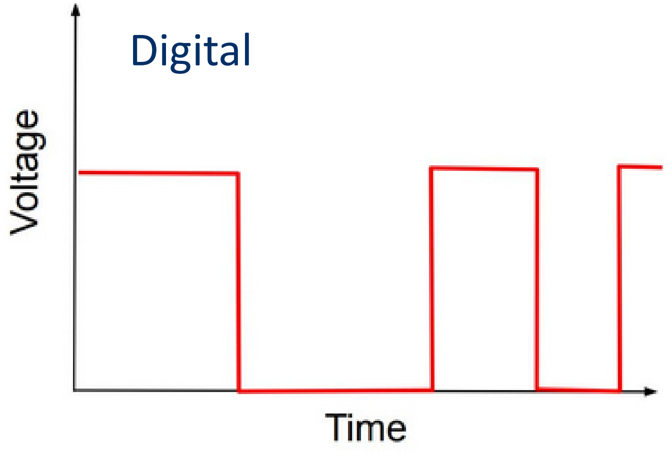
Retrieval-user interface

- Telemetry data receiver
- Storage facility / backup
- Data processing / quality checks
- Security
- User interface
- Maintenance needs
- Power supply needs

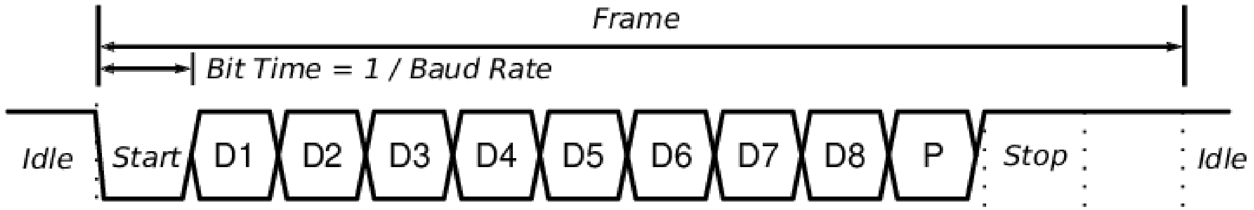
Sensor signal types

- Visual output (observer), e.g. water level staff gauge)
- Analogue (voltage, current 4-20 mA, resistance), e.g. thermocouple, pressure transducer
- Digital (voltage pulse, switch closure), e.g. tipping bucket rain gauge, water flow meter
- Serial data transfer protocol (digital data transfer between sensor and reading interface: I2C, SDI-12, One-wire, RS232, RS485, Modbus protocols), e.g. Meter group CTD sensor, UV-Vis nitrate probe





Serial Universal Asynchronous Receiver – Transmitter (UART)



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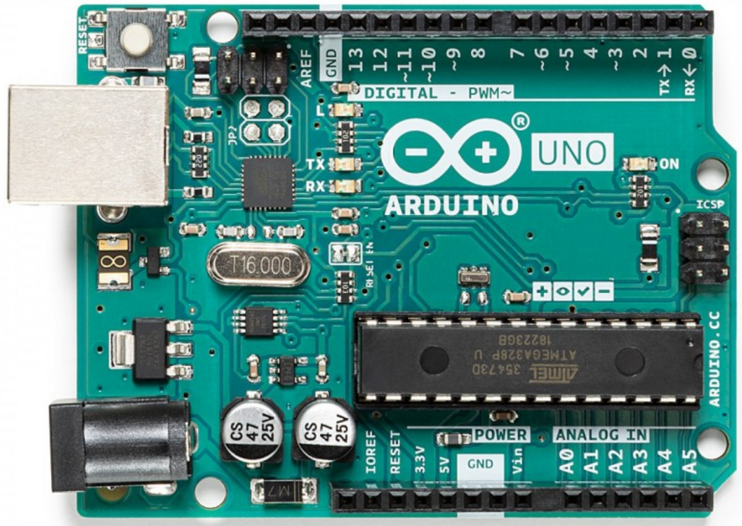
Datalogger language

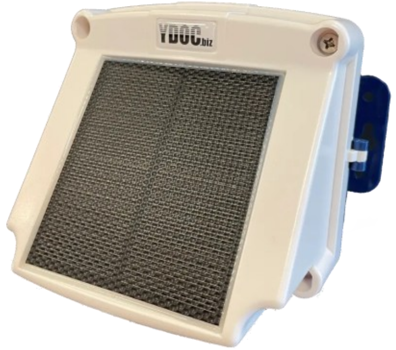
- Sensors are connected to ports or channels
  - Measurement ports
  - Excitation ports
  - Control ports
- Analogue ports
  - Single ended or differential measurement
  - Importance of bits (10, 12 , 16 bits) – divide voltage range by 2^{bits} to get resolution, for instance 10 V on 12 bits has a resolution of 2.4 mV
  - Thermocouple response 68 µV/°C, 13 bits ADC at 2.5 mV range is 0.33 µV = 0.004 °C resolution (CR1000)

Arduino Uno, 30 euro



Lilygo Wifi/Bluetooth/Lora
15 euro

Campbell scientific, many channels, needs external modem >1000 euro



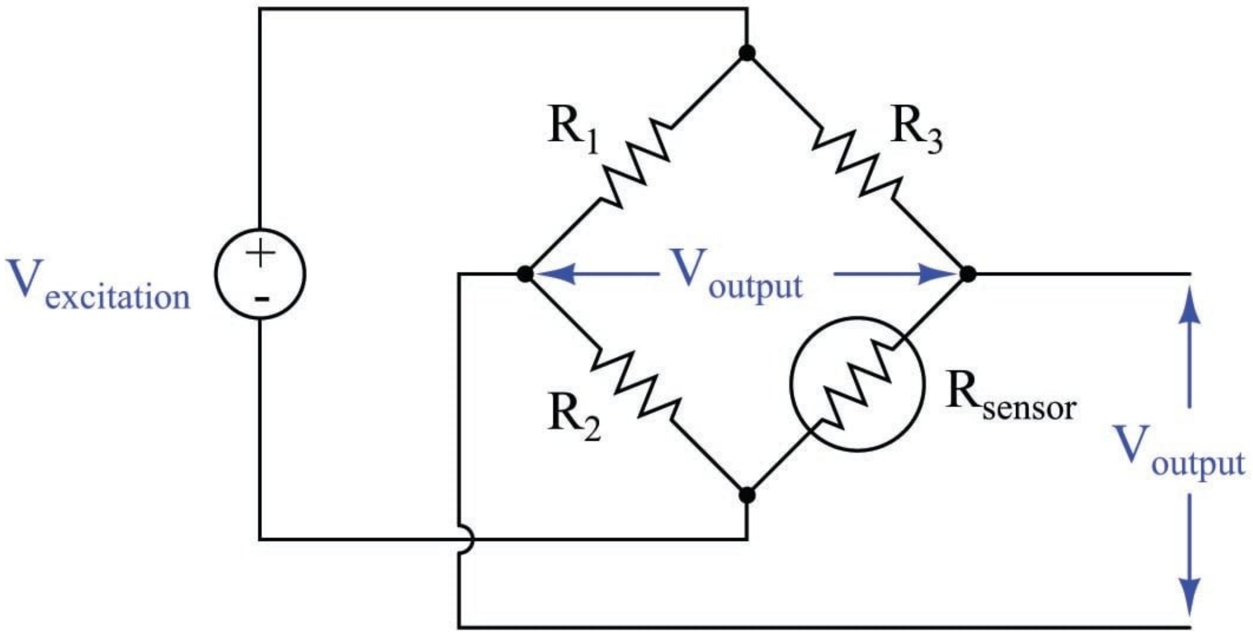
YDOC telemetric solar powered logger, 700 euro

Serial communication

- Universal asynchronous receiver-transmitter (UART) RS-232, RS-485, Modbus and SDI12, SPI, I2C, one-wire protocols most common
- Sensor with one (one-wire, SDI-12) to two wires (RS-485) data transmission (+ power, ground wires)
- Many sensors can be connected to the same port
- Excitation port should be able to supply power to combined sensors (watch mA specification of logger), apply power only during measurement to save power
- Each sensor needs to have a different address (0-9, A-Z, a-z)
- Datalogger sends measurement request to sensor with a certain address, hexadecimal code
- Sensor makes measurement (sensor response time important can be a few seconds), then sends response. Datalogger waits a set time for response of sensor
- Datalogger receives measurement values from sensor (e.g. pressure, temperature, EC) and stores these

Pressure sensor mechanism (water levels)

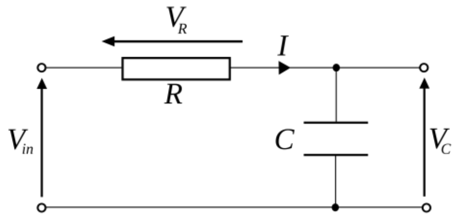
- Bridge of Wheatstone principle (pressure transducer)
- Stable excitation voltage needed, R_1, R_2, R_3 are fixed resistances. If R_{sensor} changes, V_{output} changes

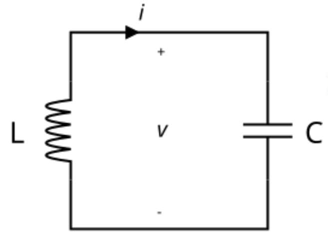


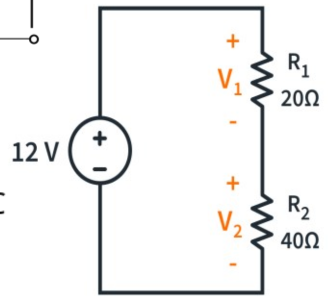
Ohm's / Kirchhof's laws

Sensor – logger impedance match

- Impedance *Z* is measure of the "total opposition" that a circuit presents to an electric current (combination of resistor and capacitor/inductor). Phase shift occurs between voltage / current. Cables act as inductor / capacitor
- Impacts distribution of voltage over sensor and datalogger port impedances. *Z* changes with frequency of alternating current (AC)
- You want all voltage measured on the datalogger port!
- Datalogger port impedance (YDOC = 32 k Ω , CR1000 = 20 GΩ) needs to be much higher than sensor impedance, otherwise only partial voltage on datalogger port
- pH and other ion-selective electrode (ISE) impedance is very high (MΩ), so only small part of sensor voltage appears on YDOC analogue port, but CR1000 can handle ISE probes
- High impedance ISE interface boards available







Ohm's / Kirchhof's laws
Maxwell / Faraday laws

Powering sensors

- Passive sensors (e.g. thermocouple, rain gauge, solar radiation, water meters) do not need power
- Active sensors need power to function (e.g. relative humidity, pressure transducer) or to transmit serial data (SDI-12, RS-485)
  - Hydros21 SDI-12 CTD sensor: 8 mA
  - Teros 12 SDI-12 soil moisture, temperature and EC sensor: 16 mA
  - Ponsel RS-485 OPTOD dissolved oxygen: 100 mA
- YDOC 12V excitation port can provide max. 200 mA current. If multiple sensors active, use relay board and external power supply (battery), YDOC power functions as trigger
- Only supply power during measurement to save energy!

Datalogger programming and data output

- Datalogger and sensor often integrated in single unit (e.g. Diver water level sensor)
- All dataloggers need programming!
- Most dataloggers provide data storage (SD-card) and file download in the form of ASCII text files (e.g. YDOC, Campbell Scientific, Meter Group loggers)
- SIAP dataloggers (used in FAO, UNICEF projects) provide daily data files in binary format.
  - Cannot be readily imported into Excel or ASCII editors
  - Advantage: smaller file size to be telemetrically transmitted.
  - Python script needed to convert SIAP binary files to ASCII text files

```
'Soil temperatures, 1 depths, 107 NTC probe
'Colour coding:
' Red: signal+ SE7
' Black: excitation Vx1, Vx2;
' Purple: GND
Therm107(Tsoil_10,1,7,1,0,_50Hz,1,0)
'Therm107(Tsoil_20,1,7,1,0,_50Hz,1,0)

'Measure soil moisture content, VWC and PA_uS
'Campbell Scientific (USA) CS616 Water Content Reflectometer
'Colour coding:
'   Green: signal+;
'   Orange: control port 1;
'   Black: signal ground;
'   Red: power;
'   Clear: ground
'SE channels 11,12 and 13
'Control ports 3,4,5,6
If IfTime(0,5,Min) Then
  ' Switch on Power to sensors (NJM2388F10 10.0 V)
  PortSet (1,1)
  Delay (0,500,mSec)
  ' Measure CS616 probes on control ports C3-C6
  CS616 (PA_uS_15,1,11,3,1,1.0,0)
  theta_15 =0.0950+(-0.0211*PA_uS_15)+(0.0010*PA_uS_15^2)
  CS616 (PA_uS_45,1,12,4,1,1.0,0)
  theta_45=0.0950+(-0.0211*PA_uS_45)+(0.0010*PA_uS_45^2)
  CS616 (PA_uS_75,1,13,5,1,1.0,0)
  theta_75=0.0950+(-0.0211*PA_uS_75)+(0.0010*PA_uS_75^2)
  ' Switch off power to sensors (10.0 V)
  PortSet (1,0)
EndIf

'Pulse channels
'Davis Vantage Pro anemometer 6410 wind speed measurement U_ms
'Colour coding:
'   Black: signal;
'   Red: GND
'Pulse channel 1
PulseCount(U_ms,1,1,2,1,1.00584,0.15)
'correct for stalling speed
'If U_ms < 0.15 Then U_ms=0.15
```

Telemetric dataloggers

- Datalogger has hardware to automatically send data to an internet server
  - Iridium satellite network for remote areas where no GPRS signal can be received (Expensive!!!)
  - Satellite IoT through Non-Terrestrial Networks (NTN), still in development, lower costs than Iridium
  - GPRS data transmission over mobile telephone network (2G – 5G)
  - Internet of Things (IoT) LoraWAN radio data transmission to server (low bandwidth, e.g. smart water meters). Needs installation of gateways to transmit data over longer distances. No corrections for data loss

- Data stored on server and imported into temporary database for subsequent quality check and approval and for user interface

Data quality checks

- Quality of observed data always needs validation
  - Errors in manual measurements
  - Sensor drift checks
  - Outlier values checking
  - Sensor malfunctioning checks
  - Interference in observations
- Automatic flagging (range checks, trend checks, statistics, use of AI tools)
- Manual verification nearly always needed (field checking of system operation, remarks of field operator)
- Only reliable quality-checked data to be entered in final database

Data management and display portal

- Collected data needs to be available to users
- Manual or automatic data import into database
- Export of selected time series data
- Statistical computations
- Time series plotting tools for data (graphs)
- Tabulation of data
- Export of tables and graphs
- Automatic report generation

Summary

- Determine what you want/need to measure
- Select intervals, telemetry, sensors, etc.
- Some technical knowledge needed to design a measurement system
- Know how your sensors operate and what its limits and precisions are:
  - Pressure sensor range determines precision (Keller 0.05% full-scale (FS), i.e. 2 cm for a 4,000 hPa pressure range)
- Consider maintenance and operation requirements (e.g. rain gauge, optical sensor cleaning needs, calibration)
- Select appropriate datalogger for making measurements (ports, impedance).
- Think about data collection, transmission, processing, analysis and reporting
- Think about specifications for data management system and user interface

In-stream interventions and data collection

In-stream or reservoir monitoring

- Purpose of monitoring to measure
  1. Water level in stream, lake or reservoir
  2. flow velocity
  3. Discharge
  4. Presence of water
  5. Water quality parameters
     - Physical – temperature, turbidity, sediment concentration, colour
     - Chemical – Electrical conductivity, pH, nitrate, DOC, etc.
- Staff gauge always present for reference height
- Zero level of staff gauge measured with respect to national elevation datum (mean sea level)

Flow measurement site selection I

- Setting up a water level / discharge monitoring site
- Conditions
  - Straight stream course for about 100 m upstream and downstream of gauge site
  - Flow confined to a single channel at all water level heights
  - No subsurface or groundwater flow bypassing the site
  - Streambed in the vicinity of site not subject to changes (scour, fill)
  - Location free of aquatic plants
  - qAt extremely low stages, a pool is present upstream from the site. This ensures recording of extremely low flows and avoids high velocities associated with high stream flows

Flow measurement site selection II

- Conditions continued
  - Gauging site far enough from confluences with other streams, no return flow or backwater effect
  - Site is free of tidal effects to avoid any possible impacts on the measurement of the water level
  - Within the proximity of the measurement site, a river section for the direct measurement of discharge at all stages is available
  - The stream channel has unchanging natural controls. These controls are bedrock outcrops or stable riffle for low flow conditions. During high flows, the controls are channel constrictions or a cascade or falls that is unsubmerged at all stages

In-stream measurement sensor options I

- Most measurements are of water level
  - Pressure sensors (absolute or air pressure compensated)
- Compensated sensor has capillary tube running in the cable transmitting air pressure to sensor, measures only water pressure above sensor
- With a non-pressure compensated sensor air pressure also has to be measured separately
  - Water pressure above the sensor equal to sensor measured pressure – barometric pressure

Compensated sensor

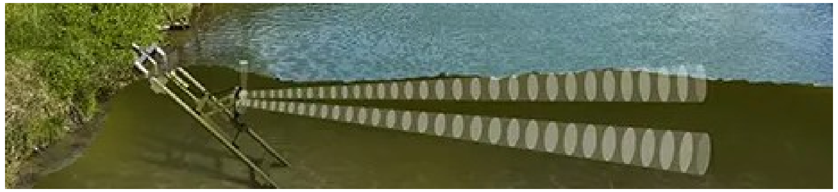
Non-compensated

In-stream measurement options II

- Radar sensor for measuring water level and flow velocity in rivers, lakes, underground pipes, and irrigation canals
  - Radar sensor mounted above the water, usually from a bridge
- Always use in combination with staff gauge serving as a reference for measurement validation
- Reduces risk of damage by debris transported in river

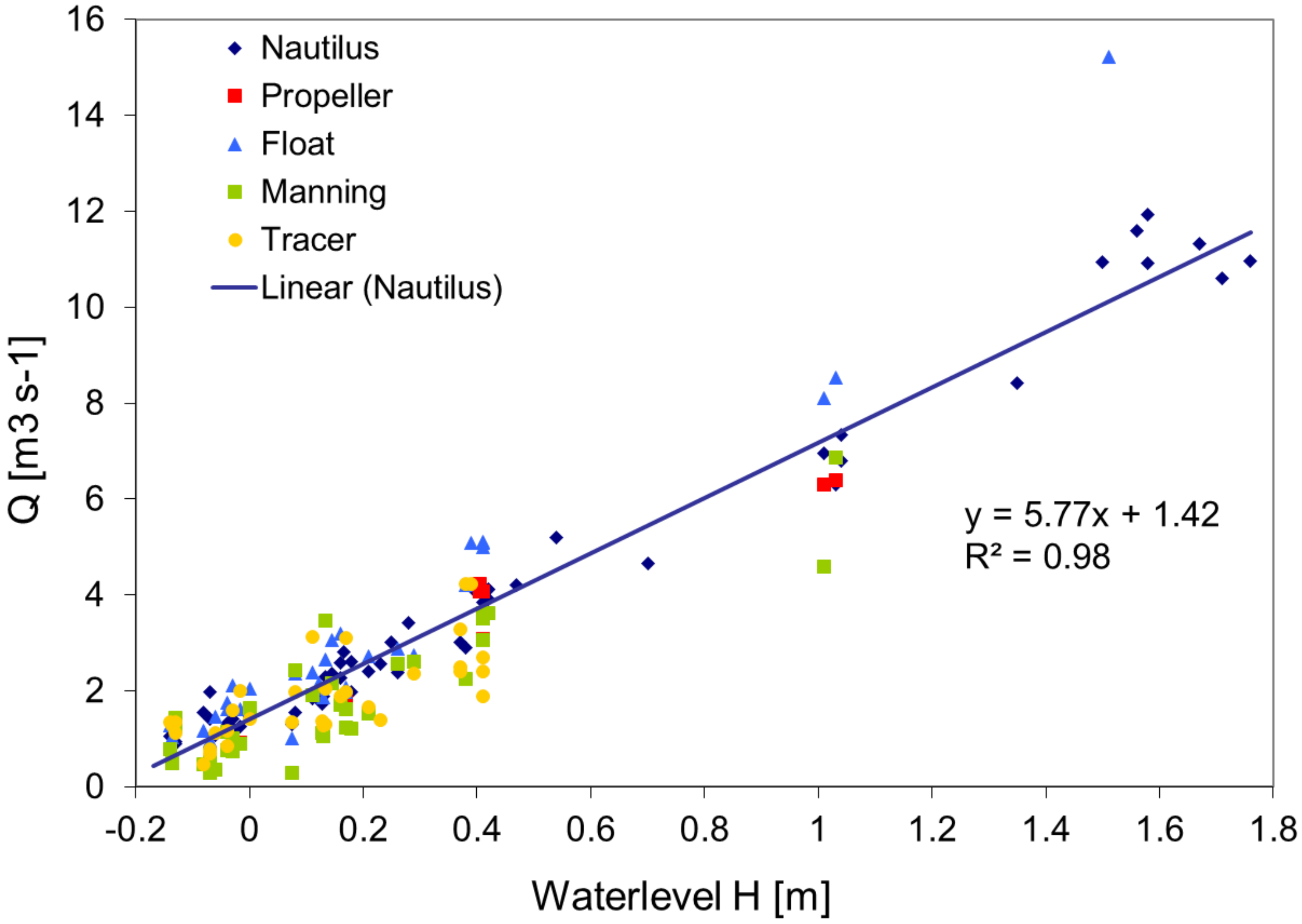
In-stream measurement options III

- Doppler flow sensor measuring velocity and water level in rivers, lakes, underground pipes, and irrigation canals
- Type 1: Side looking, mounted on support in river
- Type 2: Upwards looking mounted on platform placed on riverbed (risk of damage by coarse sediment / rocks)
- Can be used to measure average flow in large rivers



Discharge rating curve

- Water level measurement converted to discharge using a discharge rating curve
- QH-curve made by measuring discharge at different water levels
- Flow measured by propellor, doppler or electromagnetic flow meter – velocity area method



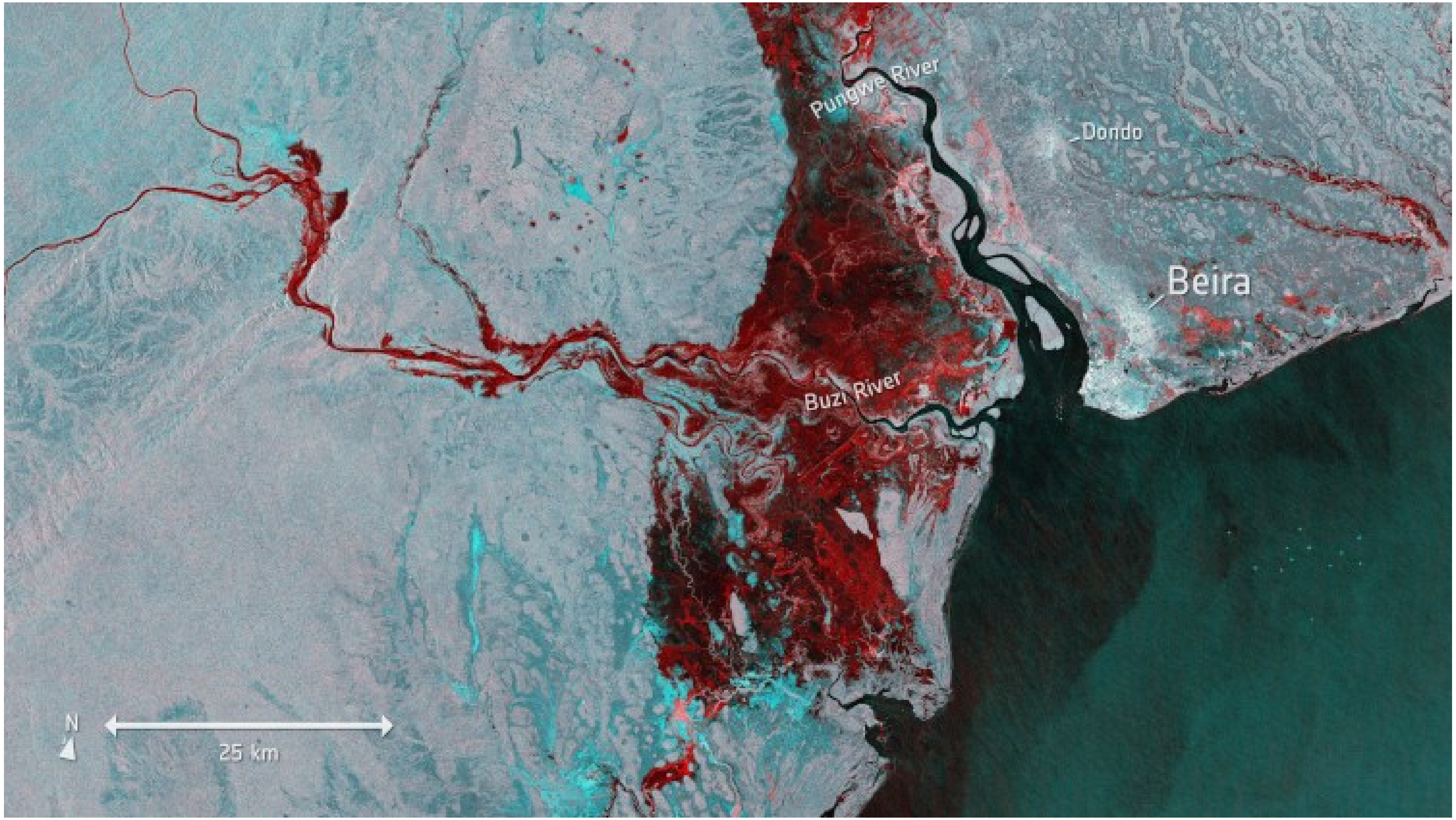
Discharge measurement for rating curve

- Acoustic Doppler Current Profiler (ADCP) flow meter
- Provides a 2D velocity – depth profile for the river
- ADCP flow measurement made and staff gauge water level recorded

Extend of flooding

- Can be obtained by plotting water level time series on elevation map
- Datalogger and sensor can send alarm messages by SMS for flood warning
- Remote sensing imagery can provide extend of flooding, but time resolution of imagery (>5 days) may be such that maximum flood extent is not captured

Sentinel 1 false-colour image of flooding, Mozambique (source: ESA)



Water quality sensors

- Electrical conductivity and temperature sensor often combined with pressure sensor
- UV-Vis sensor can measure suspended sediment / turbidity, nitrate, dissolved organic carbon
- Ion selective electrodes for pH, Cl, NO_3, NH_4, etc.
- Optical sensors for dissolved oxygen, turbidity, etc.
- Connect to datalogger for continuous telemetric measurements

Summary

- Many possibilities to make ground-based measurements of soil moisture, water level, flow and water quality
- Select sensor type, datalogger and measurement location according to objectives
- Take into account temporal resolution of measurements based on objectives for measurements
- Datalogger can be programmed to provide alarms (e.g. for flooding risk, low flow or water quality)
- A good data management system and user interface helps to analyse and display data

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