Applications of Time Domain Reflectometry (TDR) Technologies in Managed Aquifer Recharge Investigations

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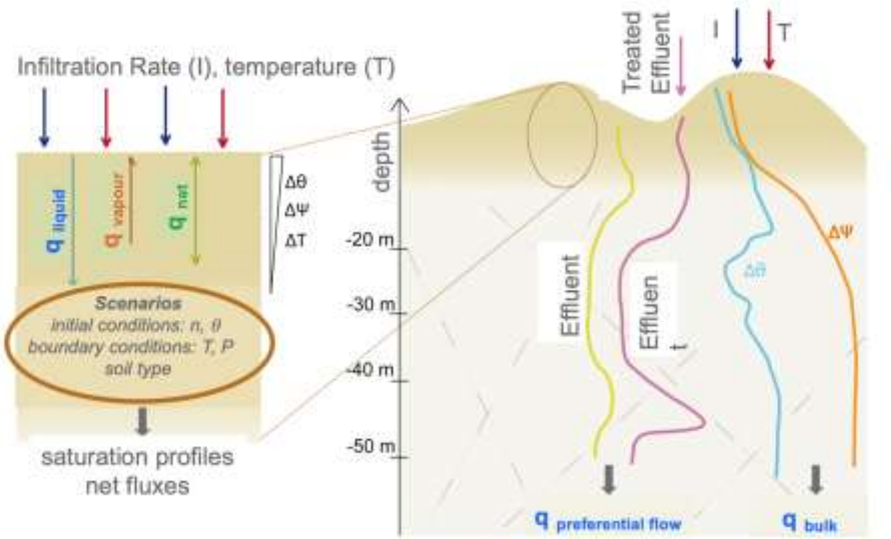
ELECTROMAGNETIC METHODS (EM)

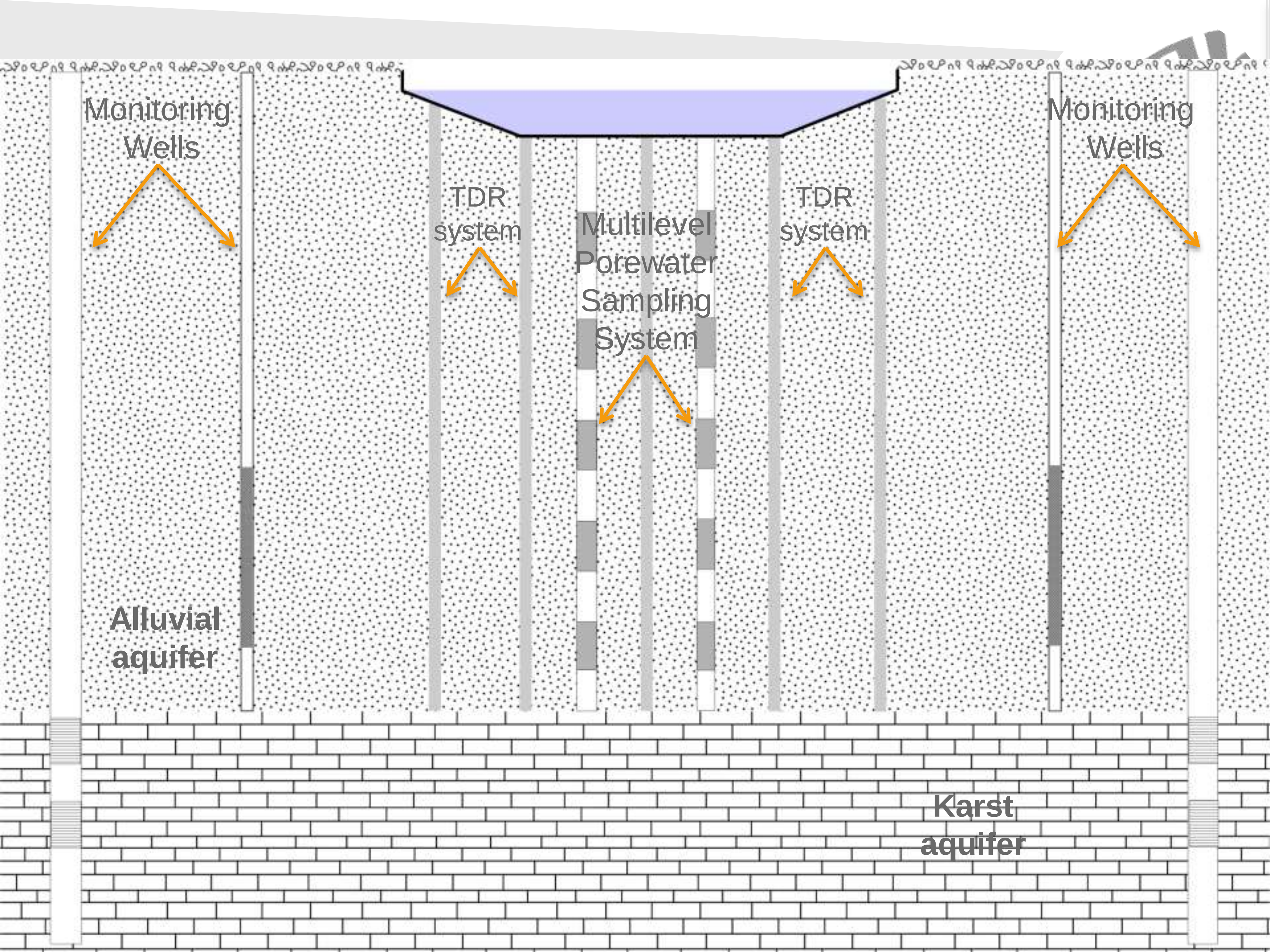
- The wide application of electromagnetic methods (EM) in the collection of water content data have allowed the unsaturated zone to be included quantitatively in numerous hydrological processes
- EM methods and more specifically their application in the investigation of the unsaturated hydrological zone, mainly include:
  - time domain reflectometry (TDR),
  - ground penetrating radar (GPR),
  - capacitance and active microwave remote sensing
- Time-domain reflectometry (TDR) is a complex electronic technology originally used primarily for testing high-speed communication cables.
- TDR estimates the bulk dielectric permittivity, ε_b, of the soil mixture (soil matrix, soil water and air) by measuring the propagation time of an EM pulse, generated by a pulse generator and containing a broad range of different measurement frequencies

Time Domain Reflectometry (TDR)
Applications

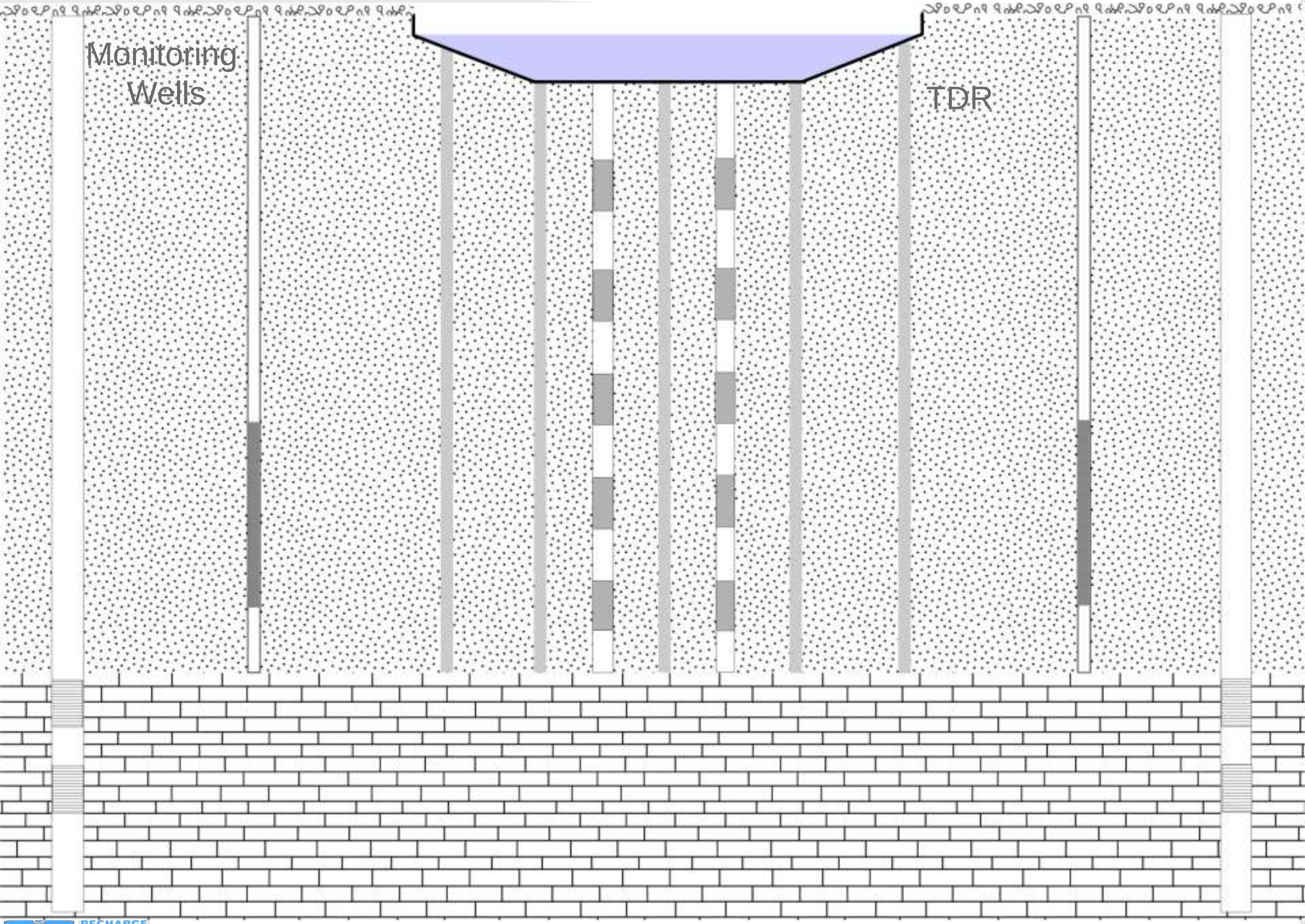
- Investigations in the unsaturated zone, where the hydrological processes play a key role for the understanding of the system
- Some applications regard:
  - Agricultural engineering
  - Arid hydrogeology
  - Soil column experiments
  - Managed aquifer recharge (MAR)



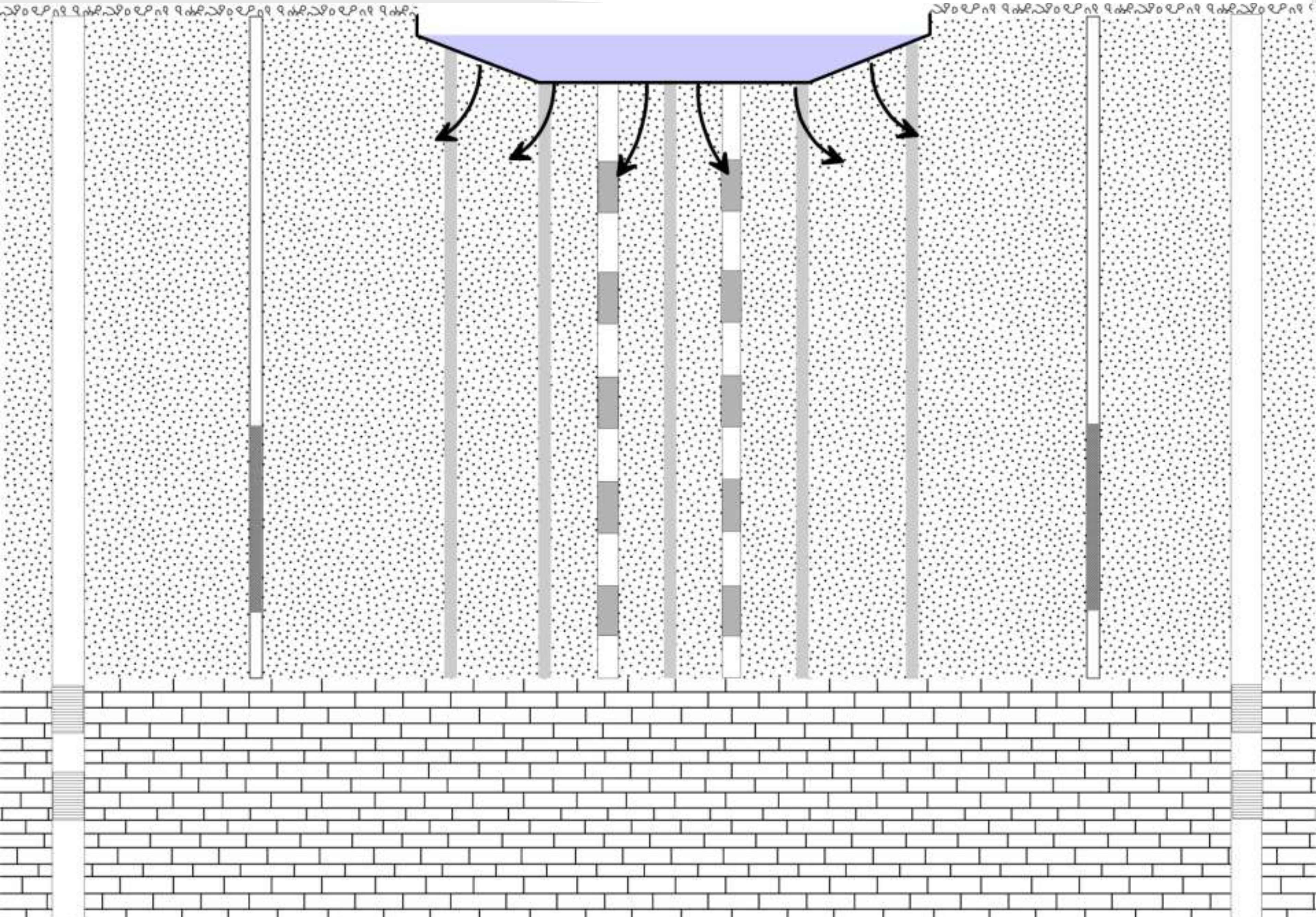
MAR Applications for TDR

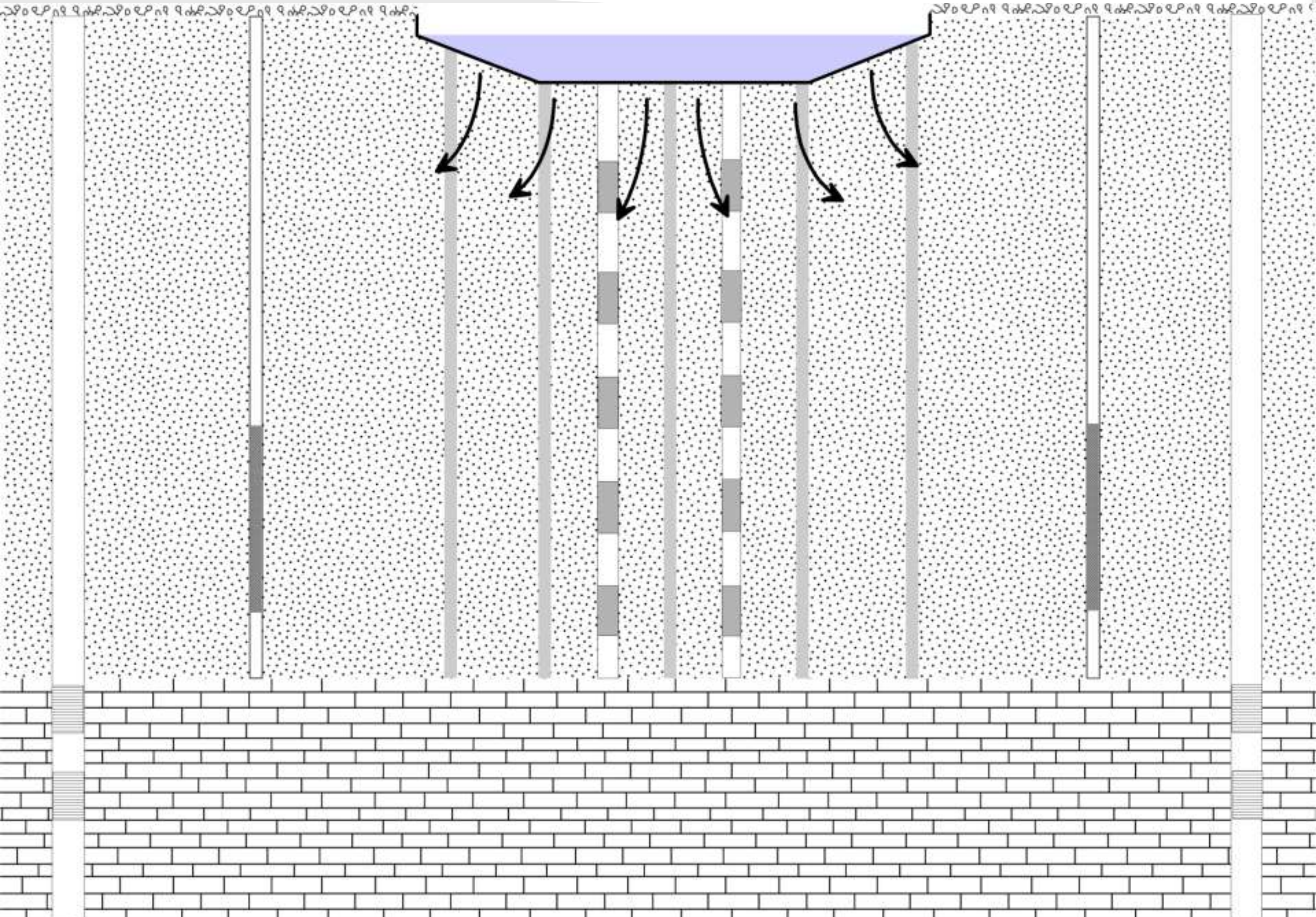


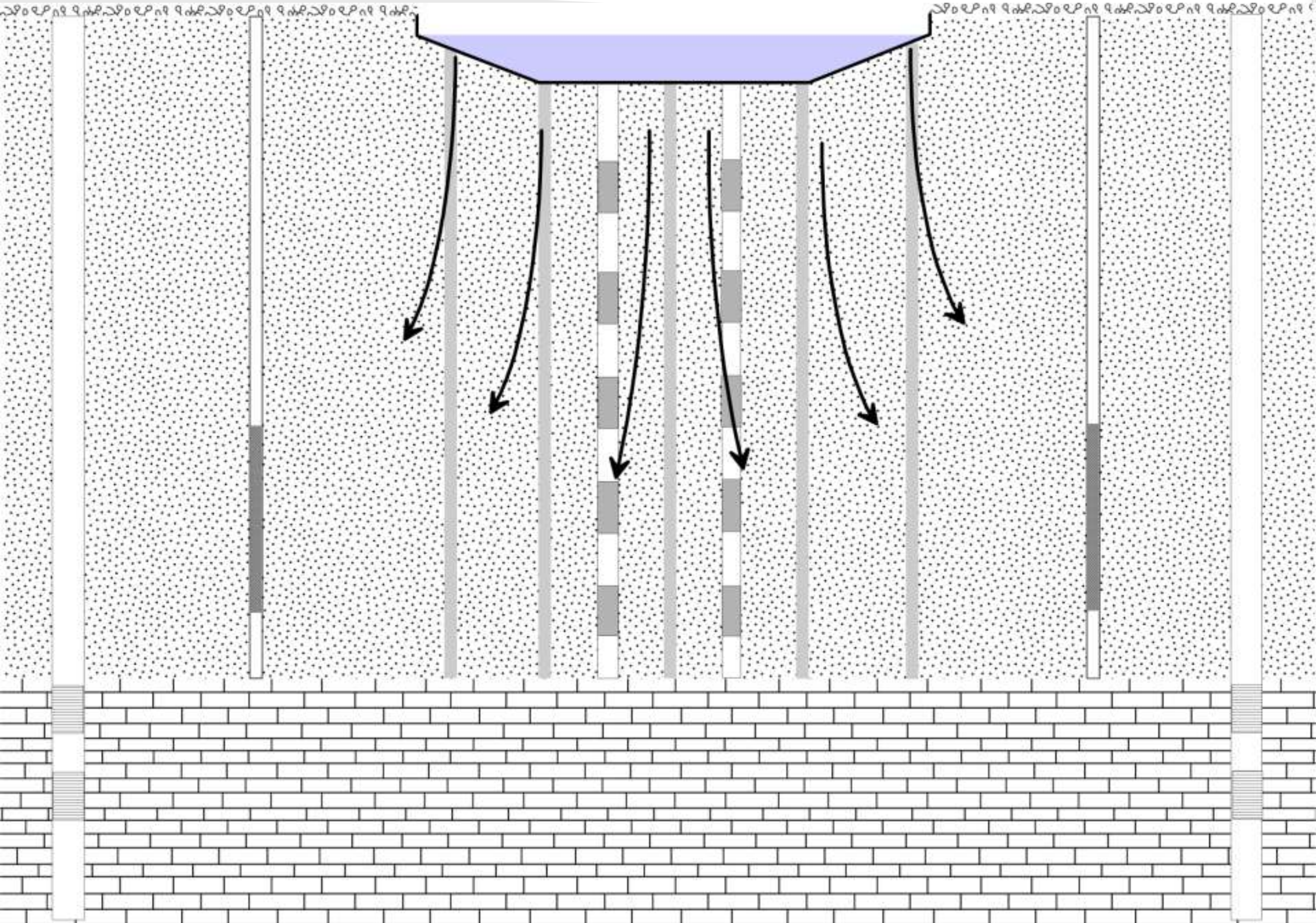
Monitoring Wells
TDR system
Multilevel Porewater Sampling System
TDR system
Monitoring Wells
Alluvial aquifer
Karst aquifer

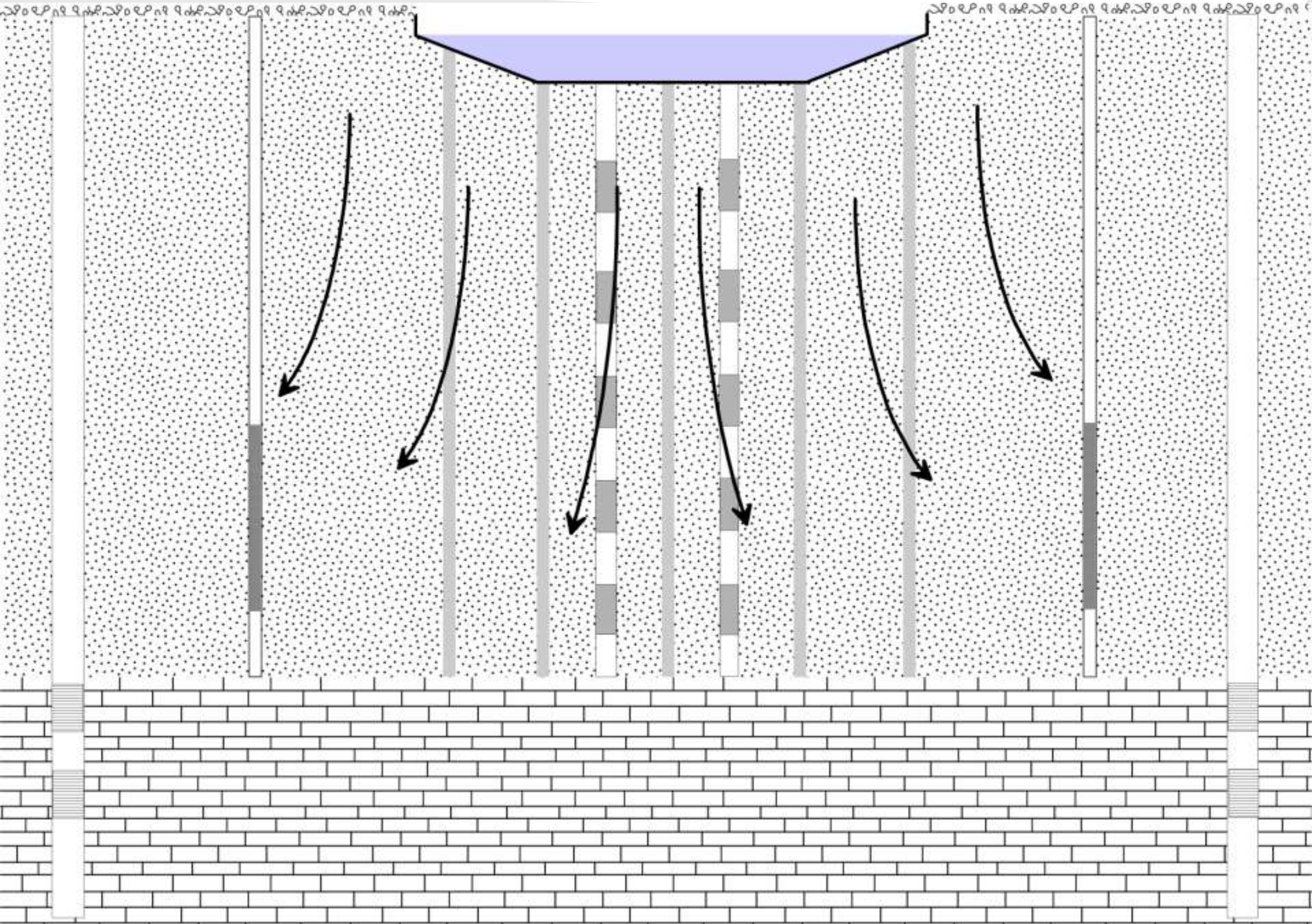


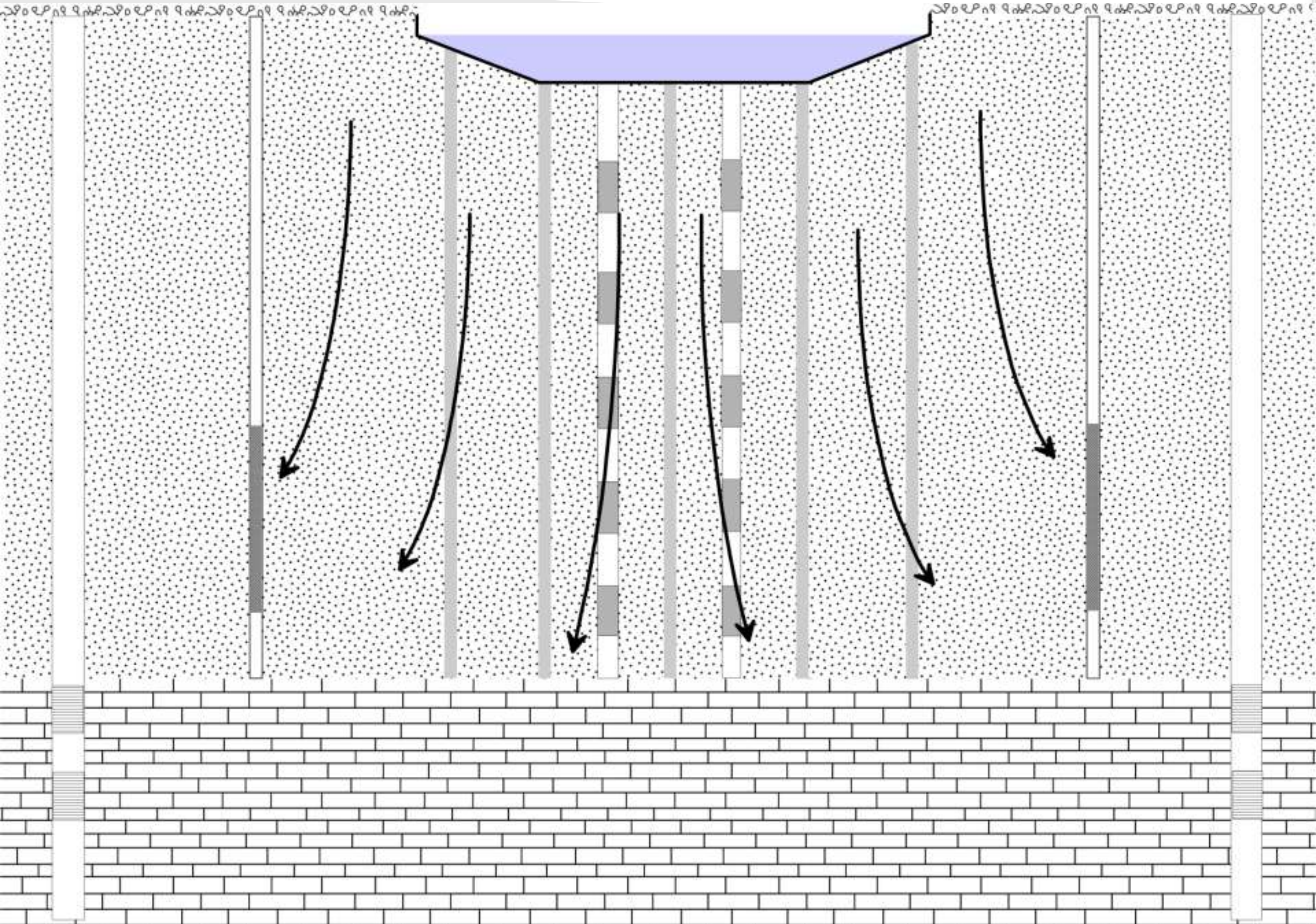
SOL RECHARGE SOLUTIONS

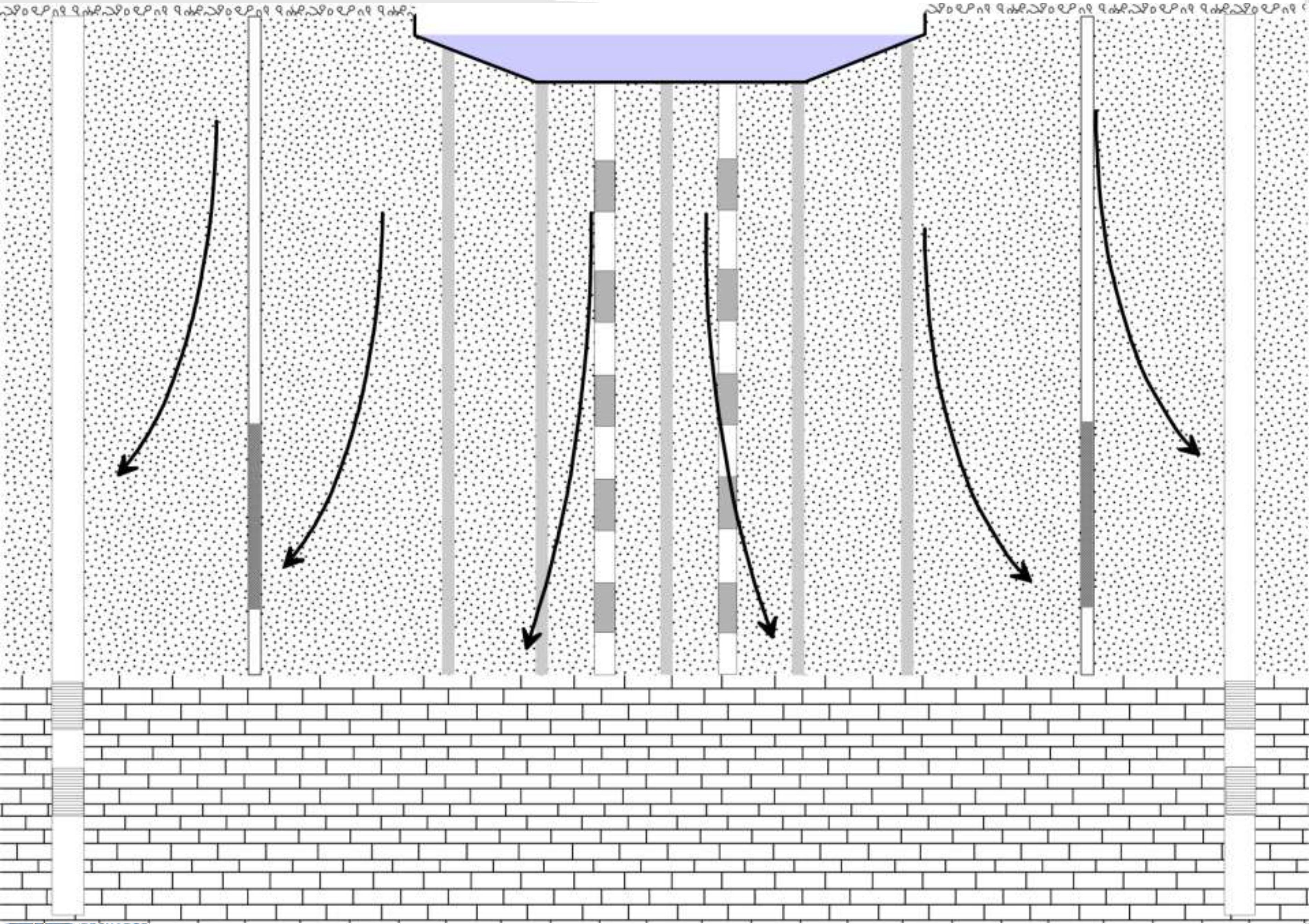


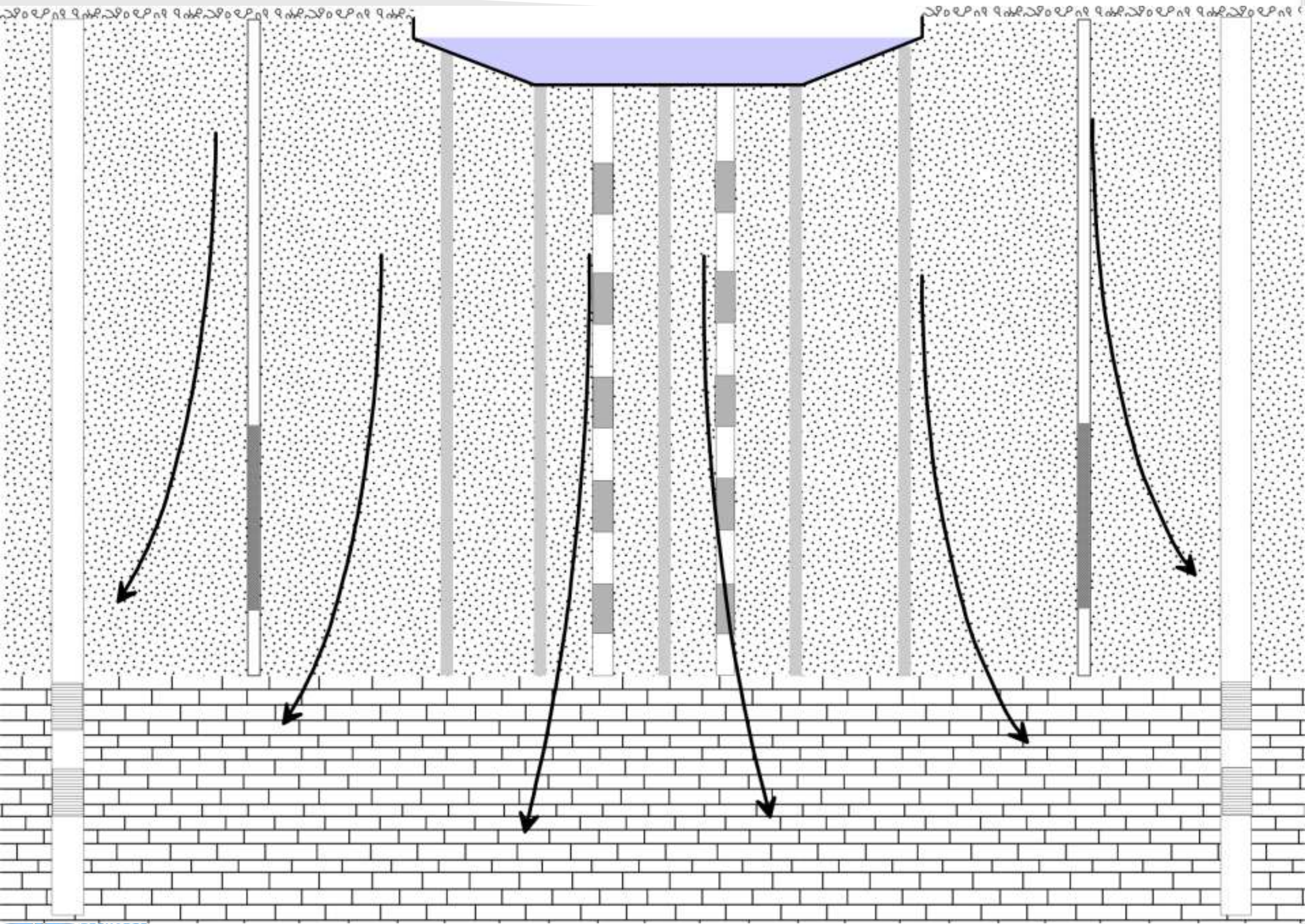


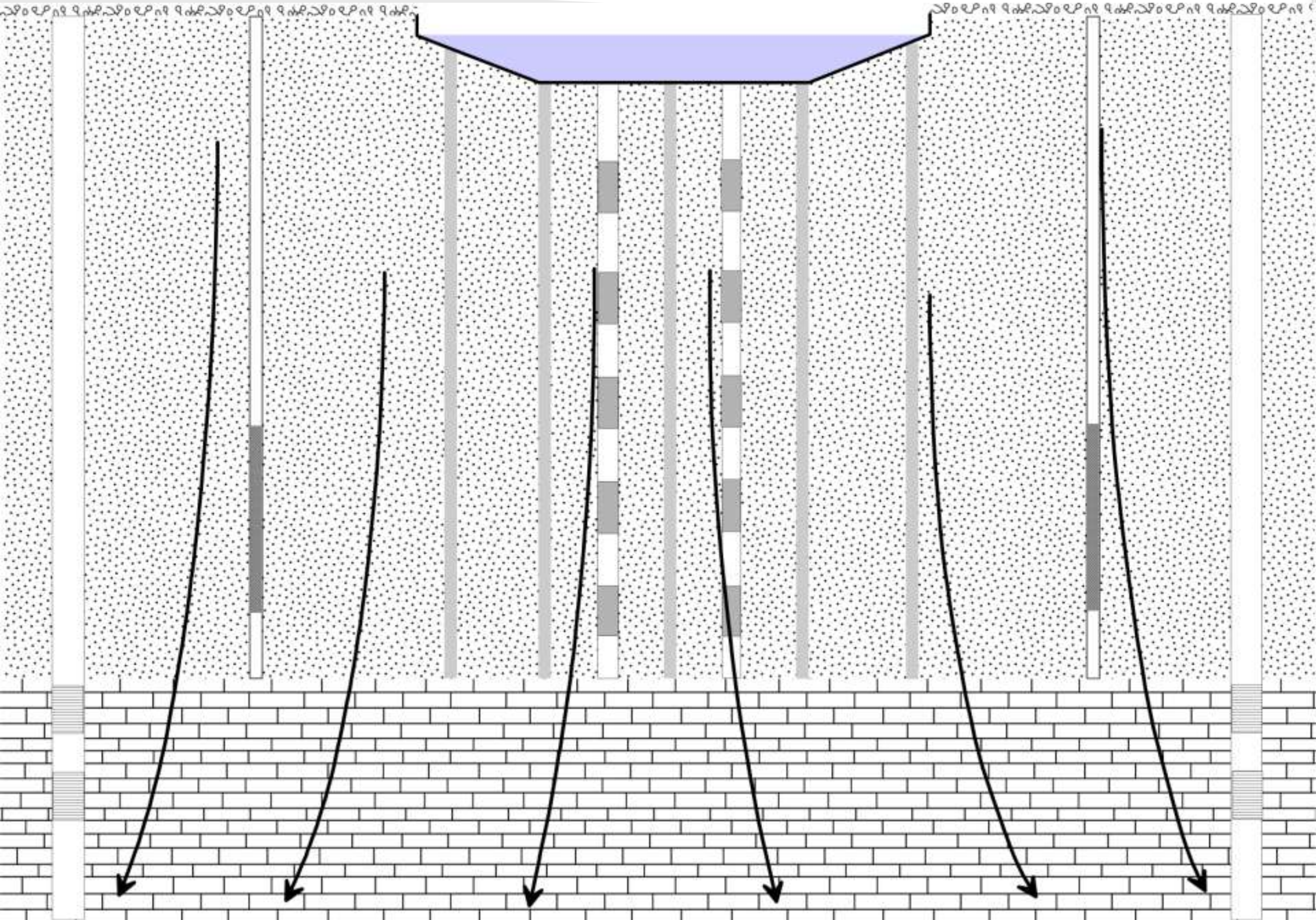






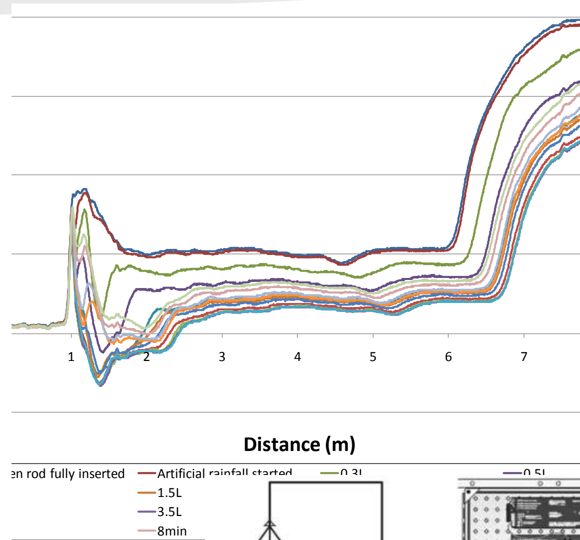


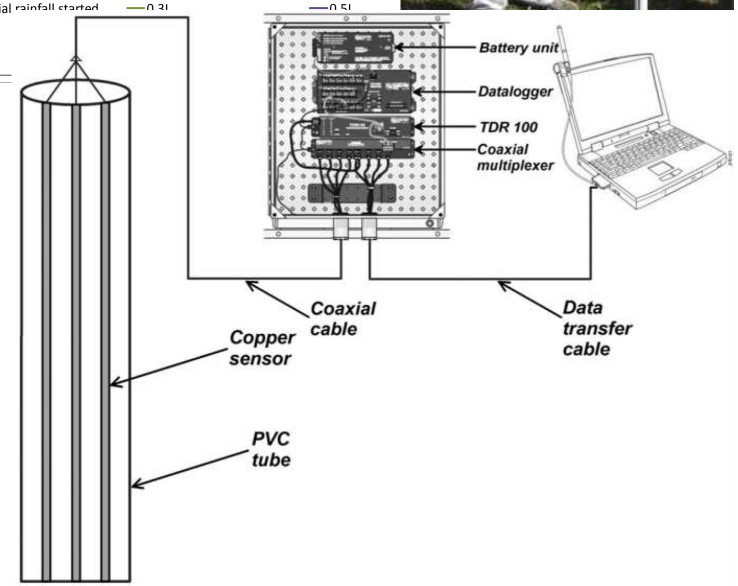




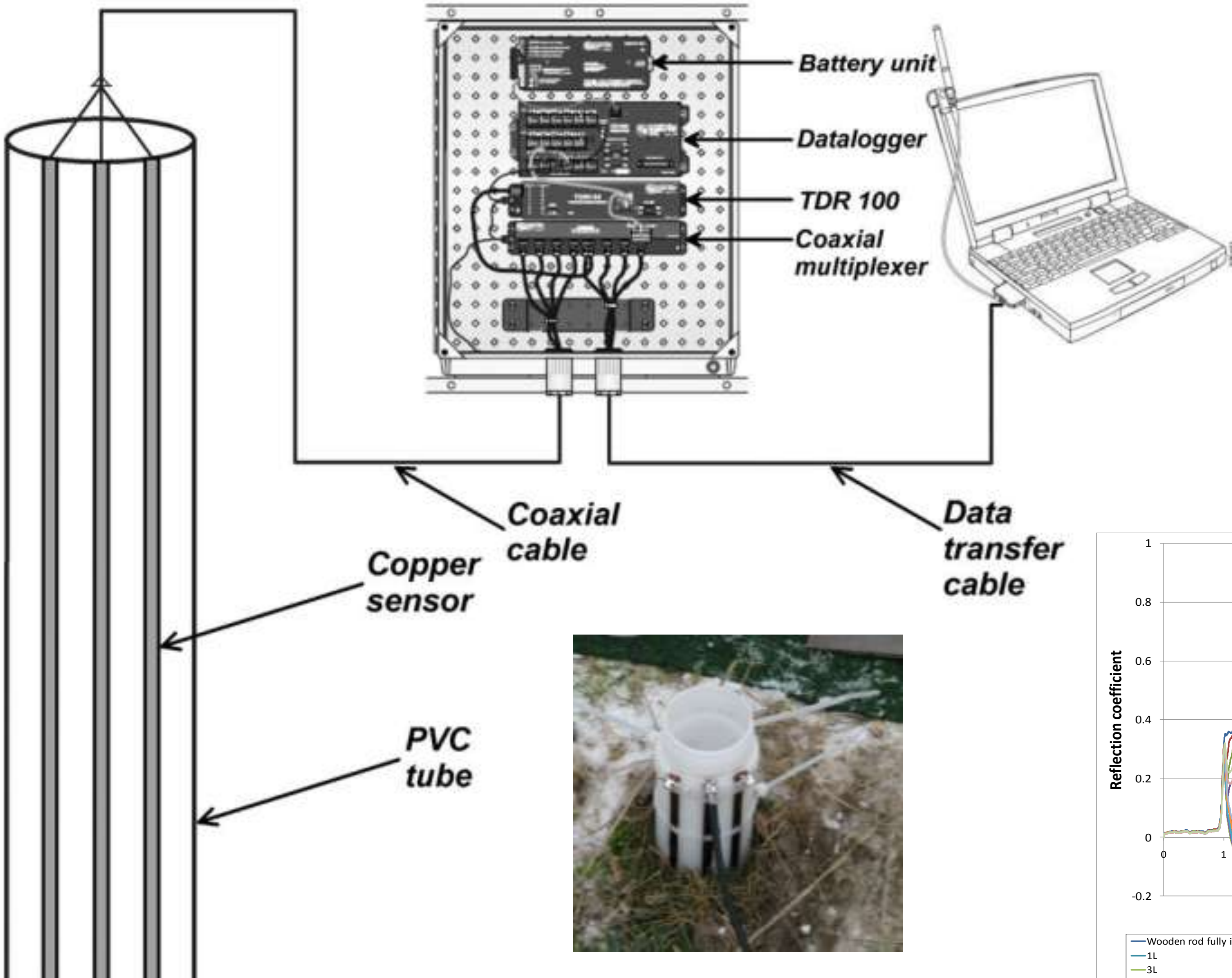
Objective: Get Soil Moisture Profiles

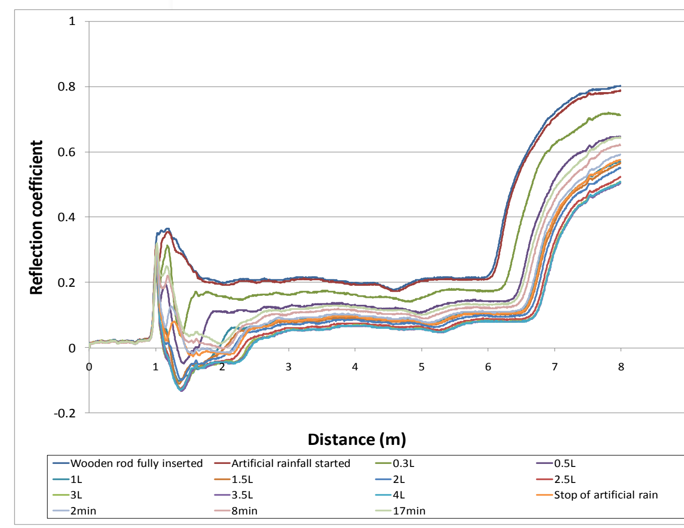
- Moisture content determination
  at significant depths
- Reach significant depths within the unsaturated zone (> 20m)
- Obtain soil water profiles throughout the entire unsaturated zone and monitor soil water content fluctuations
- Get undisturbed soil cores to sample the soil water





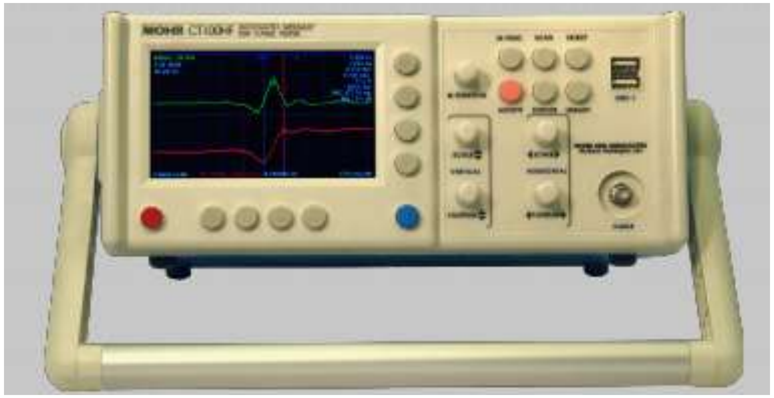
High Resolution TDR System Development





TDR Device (s)

- MOHR CT100 Metallic TDR Cable Tester
  - Rugged, lightweight, portable
  - Bright color screen, long battery life
  - 2+ GB internal memory
  - USB, 10/100 Ethernet PC connectivity
  - USB keyboard, thumbdrive, barcode reader
- TRASE SYSTEM I TDR
  - Measuring range 0 - 100% Volumetric Moisture content
  - High Accuracy (+/- 2% FS or better), 1000 point resolution
  - Largest Pulse on any commercial TDR unit - 1.25V/ 120 ps. risetime give the very best definition of dielectric changes along a waveguide
  - Built-in Datalogger for 200 graphs / 6,300 readings (more with added memory)
  - Remotely Multiplex from 1 up-to 256 measuring points on a daily, weekly or monthly basis
  - Portable, battery operated for field use and use in the lab
  - Wide variety of low cost TDR waveguides (both uncoated and coated) available
  - Easy programmable with One-Key control
  - No calibration required
  - Ready to operate on site or remotely from your computer.



MANAGED AQUIFER RECHARGE SOLUTIONS

TDR device (s)

- Before: Campbell Scientific TDR100 (aka Hyperlabs HL1500) controlled via a serial (RS232) connection.

- Now: HYPERLABS HL1101 Ruggedized Time Domain Reflectometer.
  - **USB** controlled and powered
  - Weighs 453 grams

TDR Acquisition Software

- The acquisition software is rewritten in C++ and ported to the Linux OS.
- The acquisition is **vendor neutral**: The system can communicate and control various TDR instruments.
- We have implemented in C++ a new serial (RS232) interface for the older Campbell Scientific TDR100.
- We are in the process of adapting the drivers for the new Hyperlabs HL1101 (kindly provided by Hyperlabs Inc.) to the Linux OS.

EMBEDDED PROCESSING

- The processing software should be easily be ported to a single board computer that will also act as the TDR network interface

PROCESSING

- Each waveform is automatically processed by the system. The processing steps are:
- Signal Processing: e.g. filtering etc.
- Robust automatic shape analysis of the waveform and calculation of the waveform characteristic feature points (start and end of probe wave guide, extrema) and statistical parameters.

PROCESSING: FEATURE POINTS

The characterization of the feature points and their evolution in time can be used:

- to calibrate accurately the X-axis (depth)
- and correct possible instrument deficiencies (shifting or scaling of the waveform in the X-axis (time) direction).

It can also be used to:

- detect anomalies (peaks or valleys) in the waveforms that are not related to soil electrical conductivity (moisture).

DATABASE

- The waveforms are stored in a database with all the relevant metadata (location, other associated soil measurements, terrain and geophysical data etc).
- The database can be portable (e.g. Access Database file) in the case of standalone analysis,
- or a database server (SQL Server, MySQL) in the case we need centralized and networked data access.

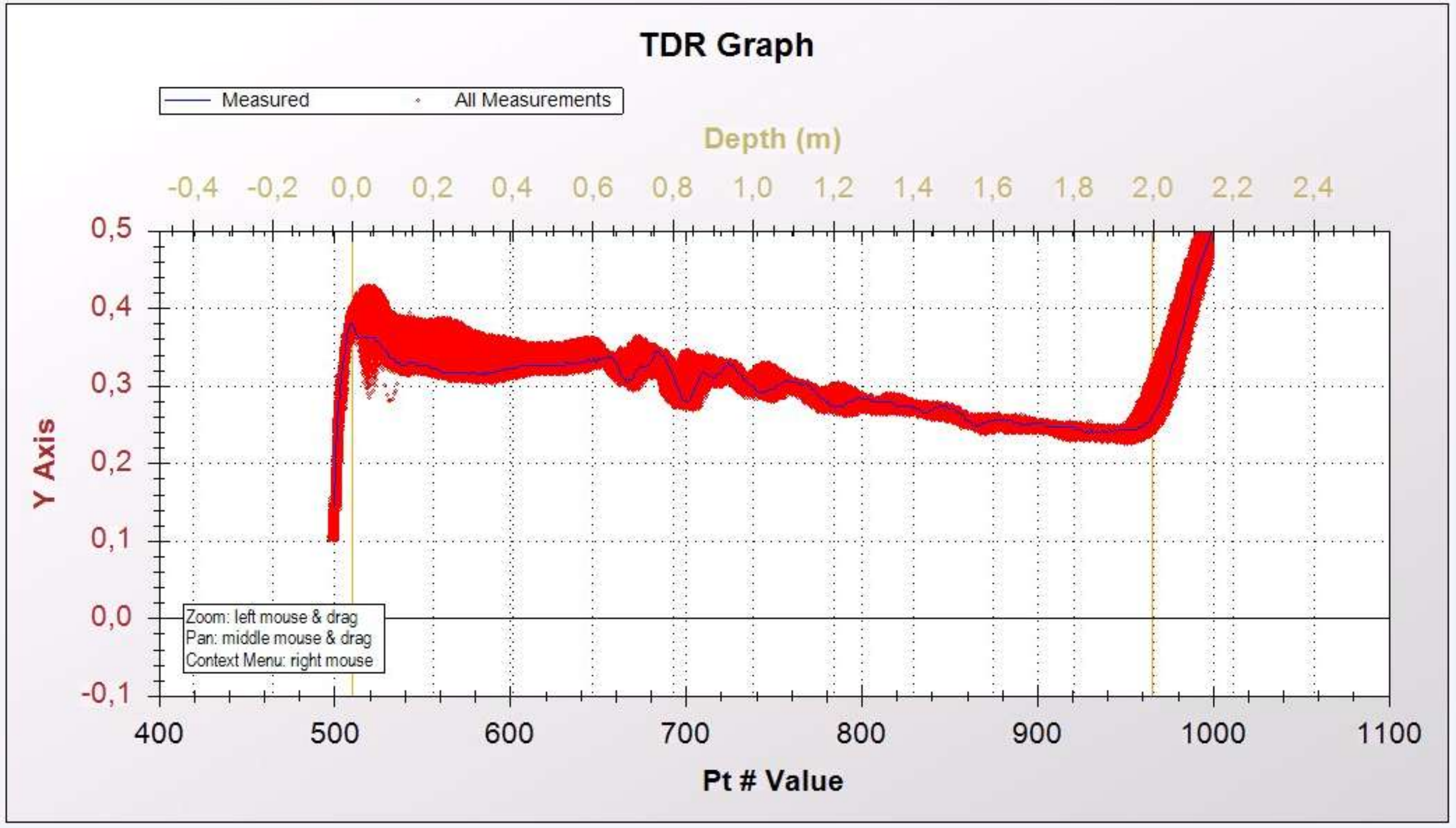
DATA ANALYSIS

The homogenized and extensible storage of waveforms in a database system enables:

- the selection (query)
- the correlation of waveforms and other measurements and meta-data in time and space (sensor grid),
- according to various criteria imposed by the user.

SCREENSHOT

Screenshot showing the raw waveform (blue) and the automatically calculated feature points, superimposed on the scatter plot of all the feature points for a long period.



Database

- The TDR waveforms are stored in a **SQLite** database with all the relevant metadata (location, TDR measurement parameters etc).

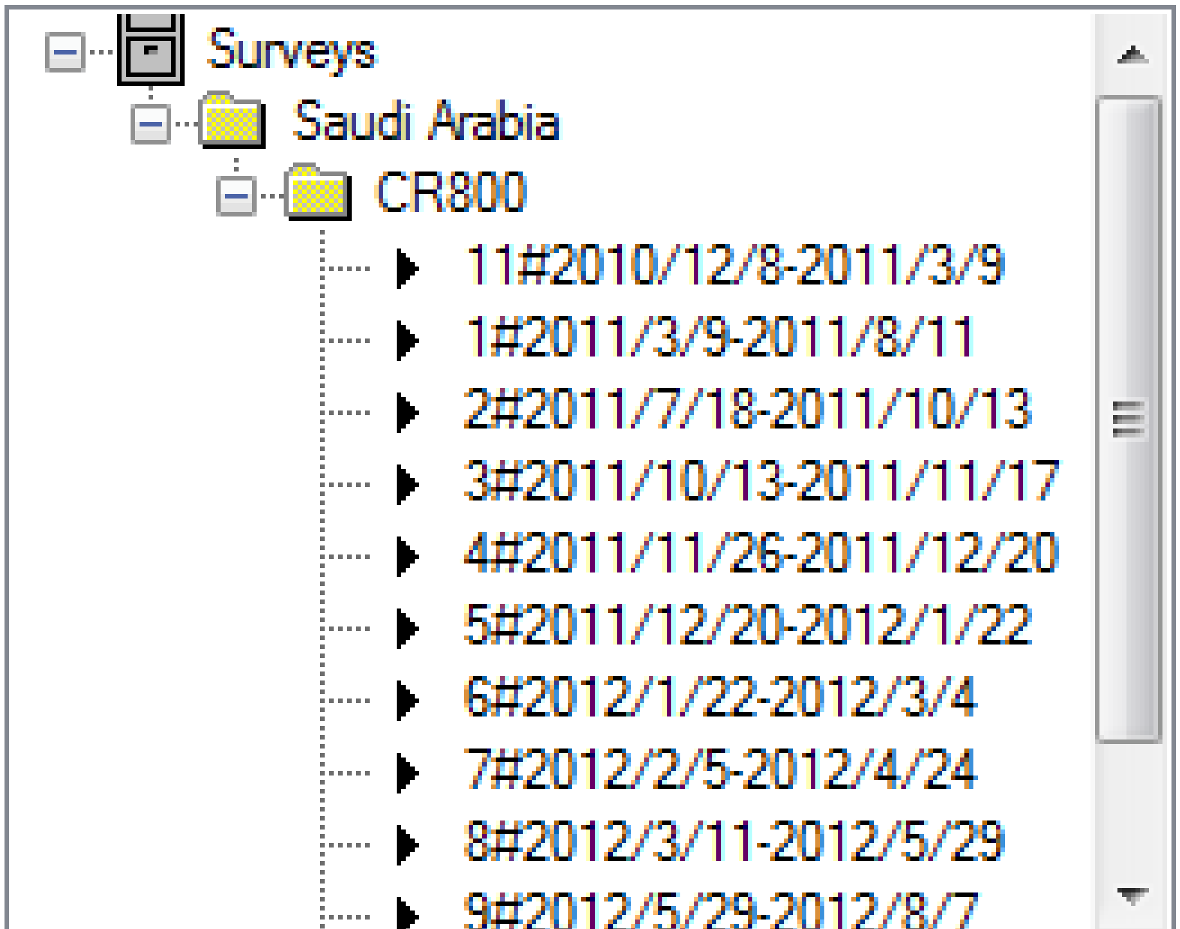
SQLite is the database choice because:

- We need the database to be **portable**, i.e. be able to copy the database (measurements) for further processing or upload to a central repository.
- Other features like intrinsic **security** or **authentication** or **simultaneous queries** available in other database are not an issue in our application.
- **SQLite** implements a self-contained, serverless, zero-configuration, transactional SQL database engine. SQLite is the most widely deployed database engine in the world. The source code for SQLite is in the public domain.

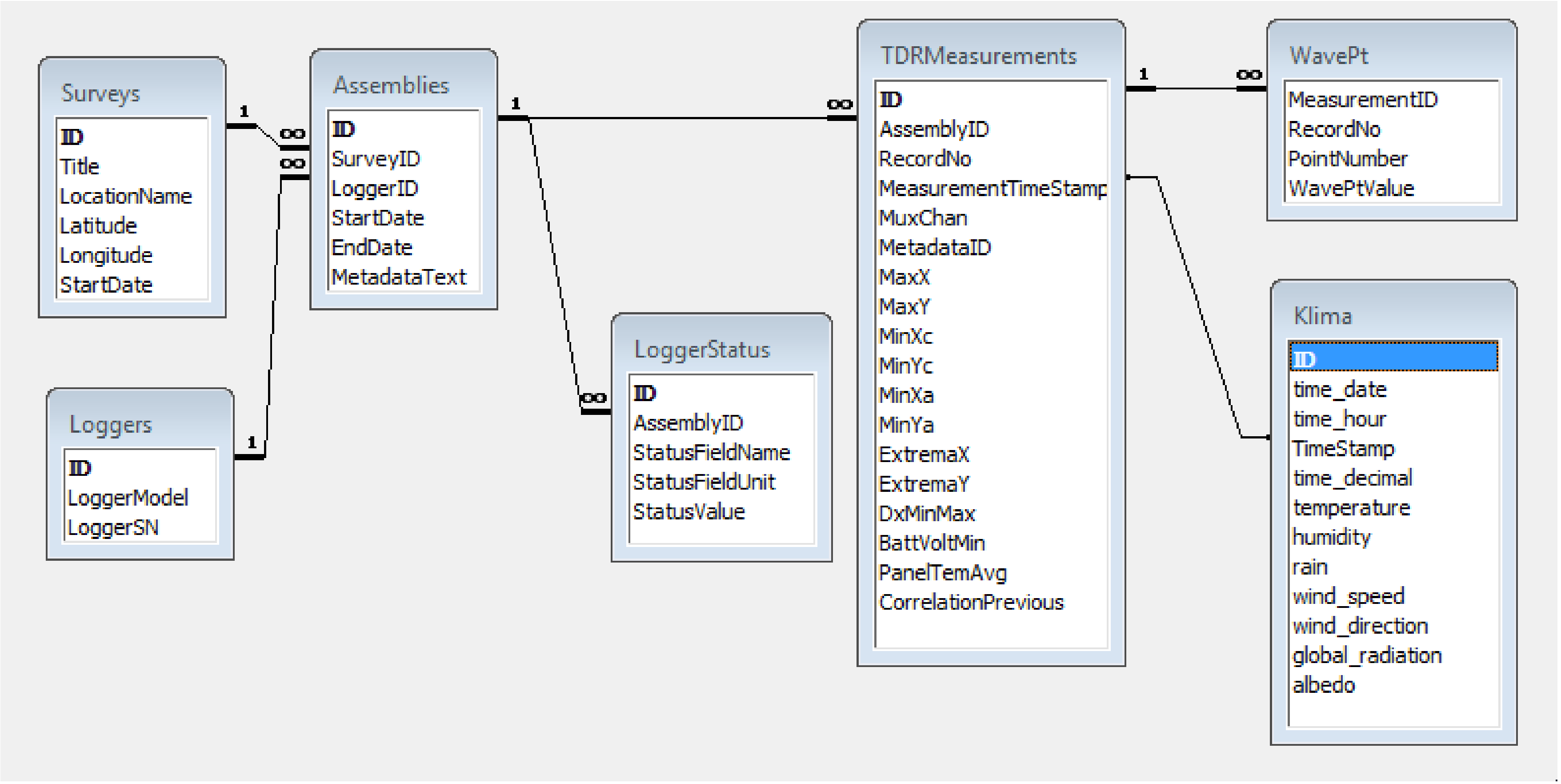
MAR SOL MANAGED AQUIFER RECHARGE SOLUTIONS

DATABASE: HIERARCHICAL ORGANIZATION

- Survey → Logger → Assemblies → Measurements

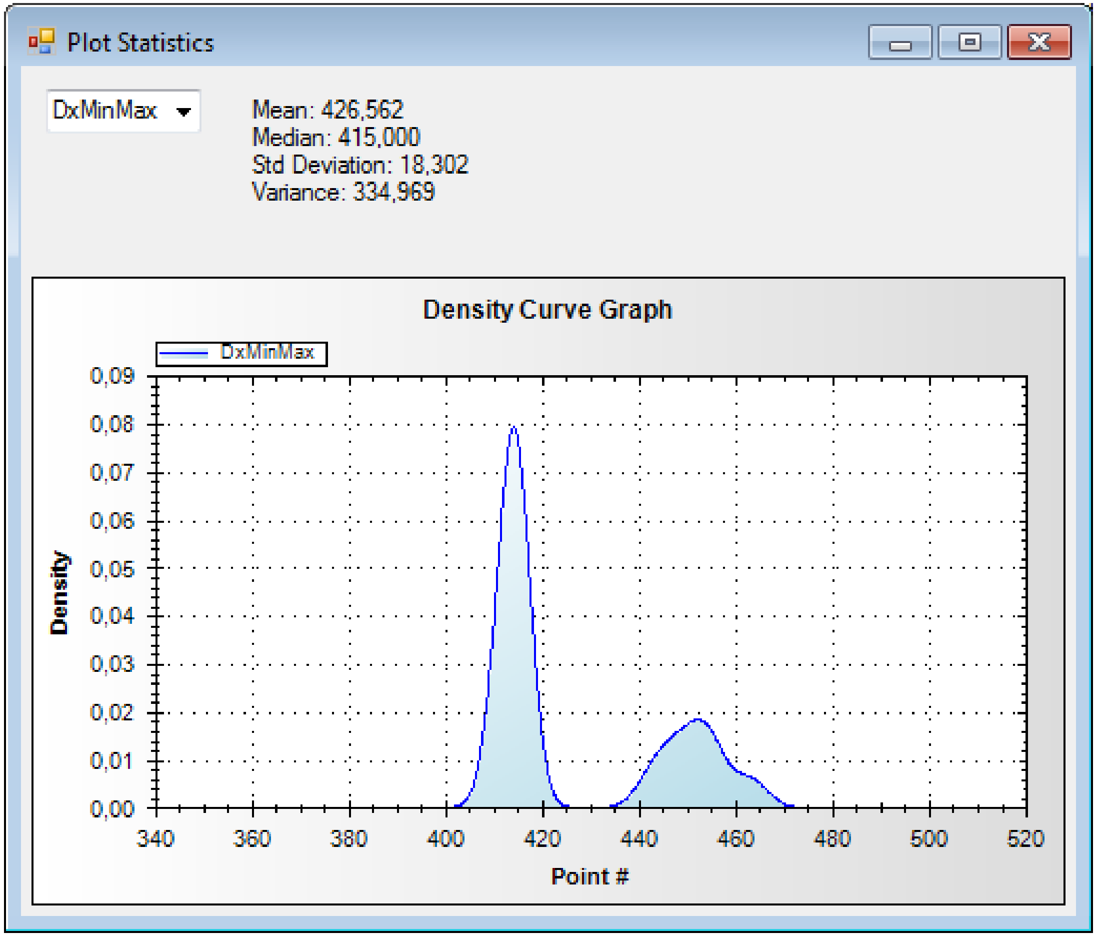


DATABASE: SCHEMA



Integrates also climatic information

STATISTICS


Plot Statistics
DxMinMax
Mean: 426,562
Median: 415,000
Std Deviation: 18,302
Variance: 334,969
Density Curve Graph
DxMinMax
0,09
0,08
0,07
0,06
0,05
0,04
0,03
0,02
0,01
0,00
Density
340
360
380
400
420
440
460
480
500
520
Point #

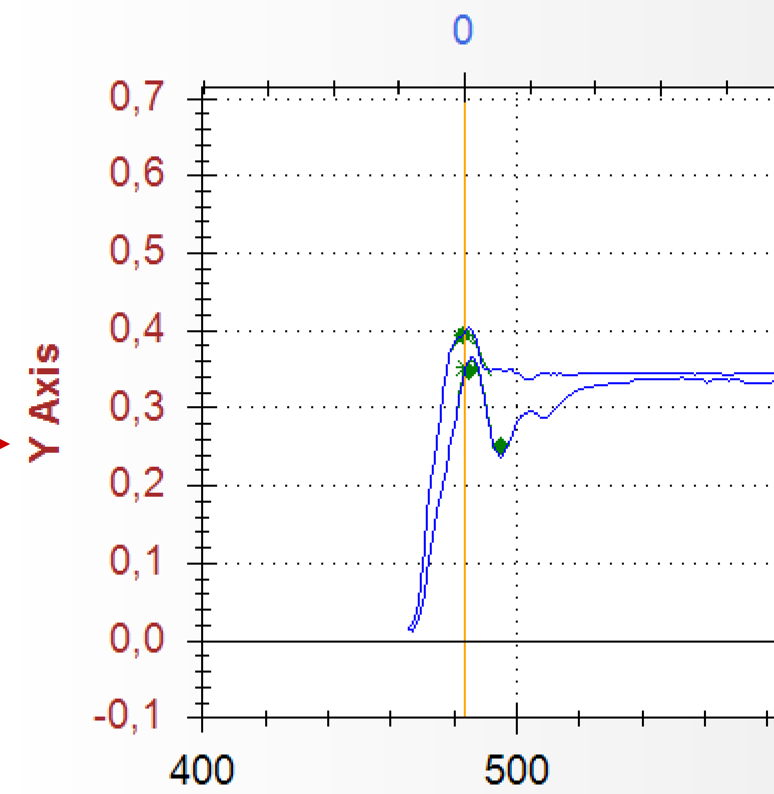
SEQUENCE ANALYSIS

Automatic detection of uncorrelated waveform sequences

→ Water content change

Uncorrelated Waveforms

	Assembly ID	Record No	Time Stamp	Meas ID	View
▸	2	5477	19/9/2011 4:00:...	5045	View
	8	3579	23/4/2012 6:00:...	11765	View
	8	3312	12/4/2012 3:00:...	11498	View
	8	3313	12/4/2012 4:00:...	11499	View
	1	2887	26/5/2011 3:00:...	1875	View
	8	3291	11/4/2012 6:00:...	11477	View
	7	3583	23/4/2012 10:00...	10711	View



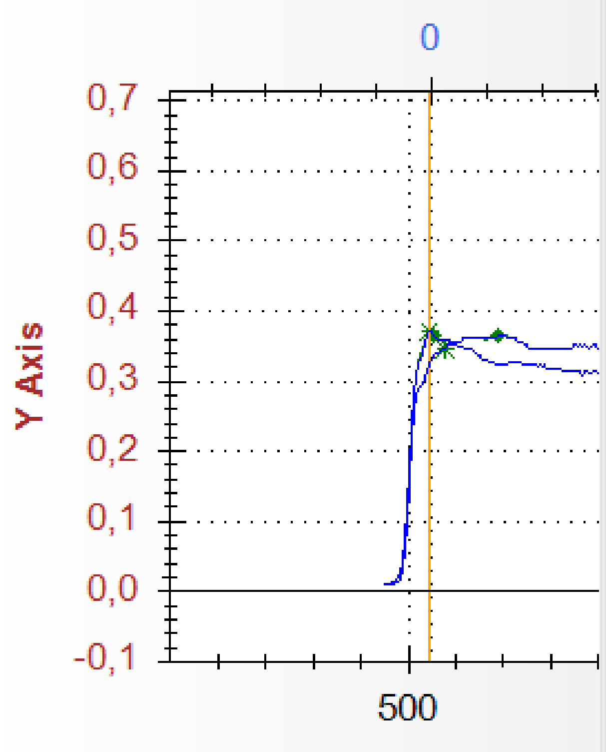
SEQUENCE ANALYSIS

Auto query for rainy days → Water content change evolution

Rainy days

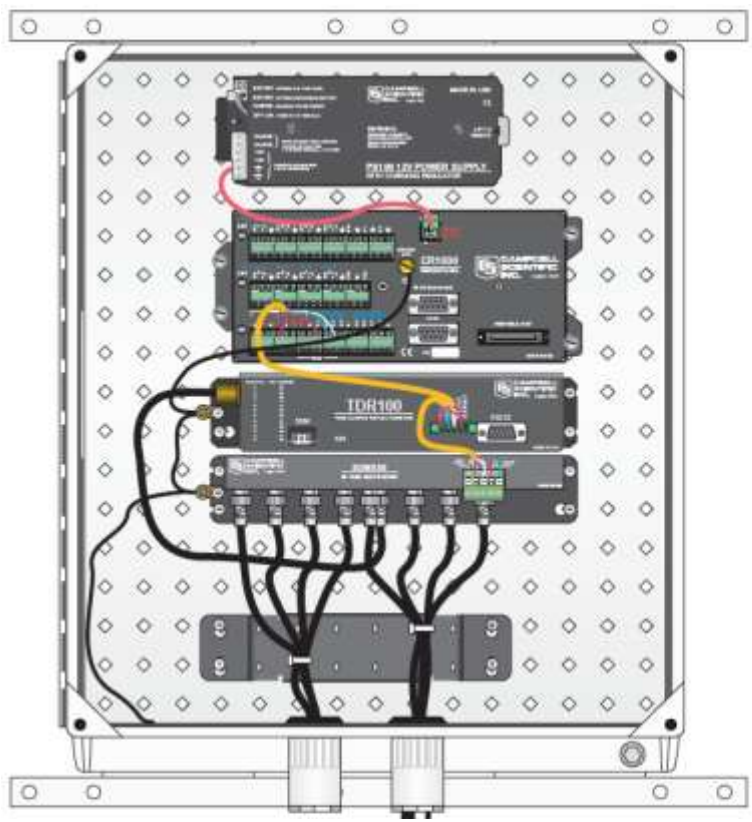
Press button to view

	Assembly ID	Record No	Rain	Time Stamp	Meas ID	View
	1	2885	4,9	26/5/2011 1:00:...	1873	View
	4	70	3,3	29/11/2011 1:00...	6527	View
▶	11	630	2,7	21/2/2011 2:00:...	16830	View
	1	1048	2,6	11/3/2011 12:00...	36	View
	4	63	2,4	29/11/2011 6:00...	6520	View
	4	68	2,1	29/11/2011 11:0...	6525	View
	7	3310	2	12/4/2012 1:00:...	10438	View



OLD SETUP

- Measurement equipment was bulky, power-hungry, and prohibitively expensive.
- Minimum inner dimensions WxLxH = 30x36x15 cm = **16.000 cm^3**



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New Setup - Components

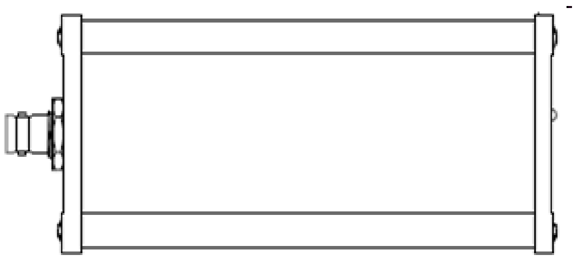
- Minimum inner dimensions WxLxH = 130x200x80 mm = 2.000 cm^3

Raspberry Pi B+

85 x 56 x 21 mm

LiPo batterry 7200 mAh

137 x 46 x 23 mm



HL1101 TDR

127 x 61 x 37 mm

Multiplexer

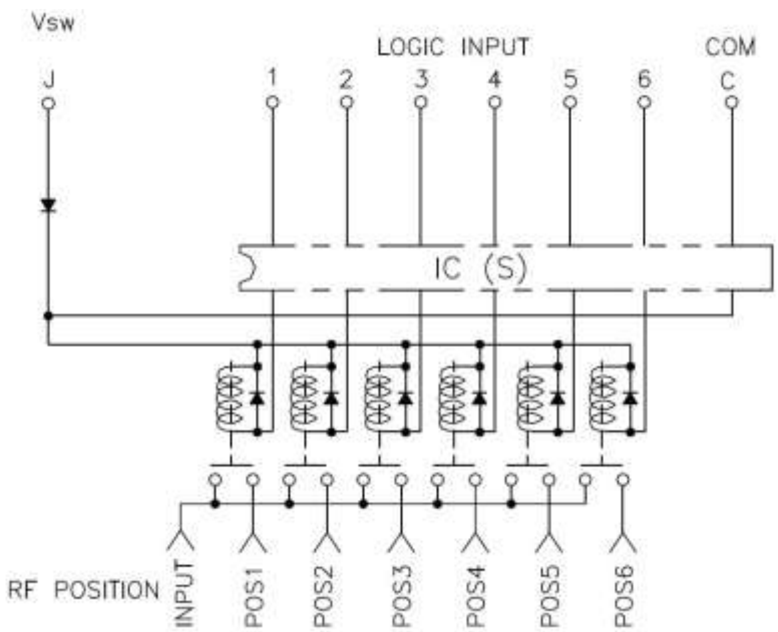
50 x 50 x 50 mm

MAR SOL MANAGED AQUIFER RECHARGE SOLUTIONS

RF SWITCH

We use electromechanical **RF switches** instead of the SDM8X50 Campbell Scientific multiplexer because:

- More compact
- Lower insertion loss
- Many suppliers, cheaper

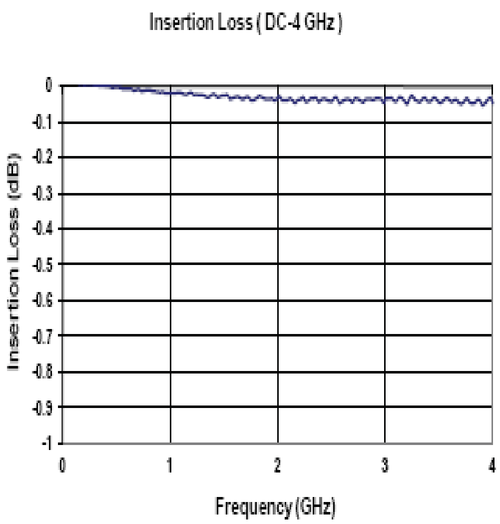


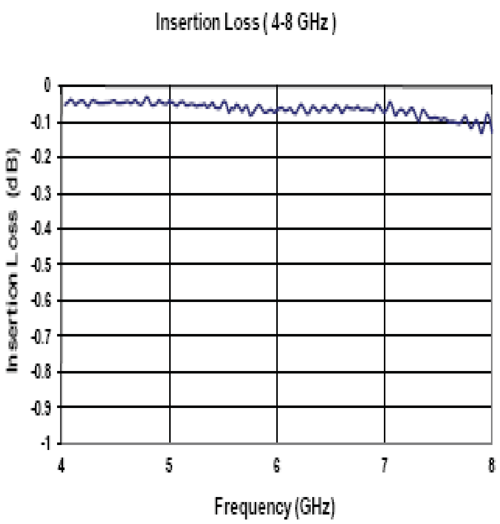
RF Switch – Insertion loss

TDR waveforms are very high frequency signals

- RF switches are more compact.
- Have a significantly lower insertion loss even at higher frequencies.
- And most important we have many suppliers.

RF switch insertion loss:





Power Efficiency

- Older systems were power hungry
- We use adaptive power management controlled by an Arduino Pro Mini:

- Power when idle: **<1mW**
- Power during measurement (duration less than 10 sec): **<4W**

MAR SOL MANAGED AQUIFER RECHARGE SOLUTIONS

WATER CONTENT

- We use the Todoroff et. al. (2001) inverse modeling approach to compute water content resulting in an apparent relative dielectric permittivity profile of the surrounding medium along the TDR probe length
- Challenge: Thorough theoretical analysis is needed → Research in the field of Computational Electromagnetics
- Implementation Problems
  - The water content variations between two layers, and therefore the reflection coefficients, must generally be close to zero.
  - Problem of truncation and error propagation using fixed-point arithmetic in embedded systems.

Inverse Modelling Process

- Todoroff and Lan Sun Luk (2001) present a numerical one dimensional model to compute water content profile along TDR sensor from TDR signal traces.
- It is also called inverse model since the first stage of the model (direct) which computes simulated signal traces from water content distribution of the propagation medium is applied in reverse order to compute water content profile from measured signal traces from TDR measurement.

INVERSE MODELLING PROCESS

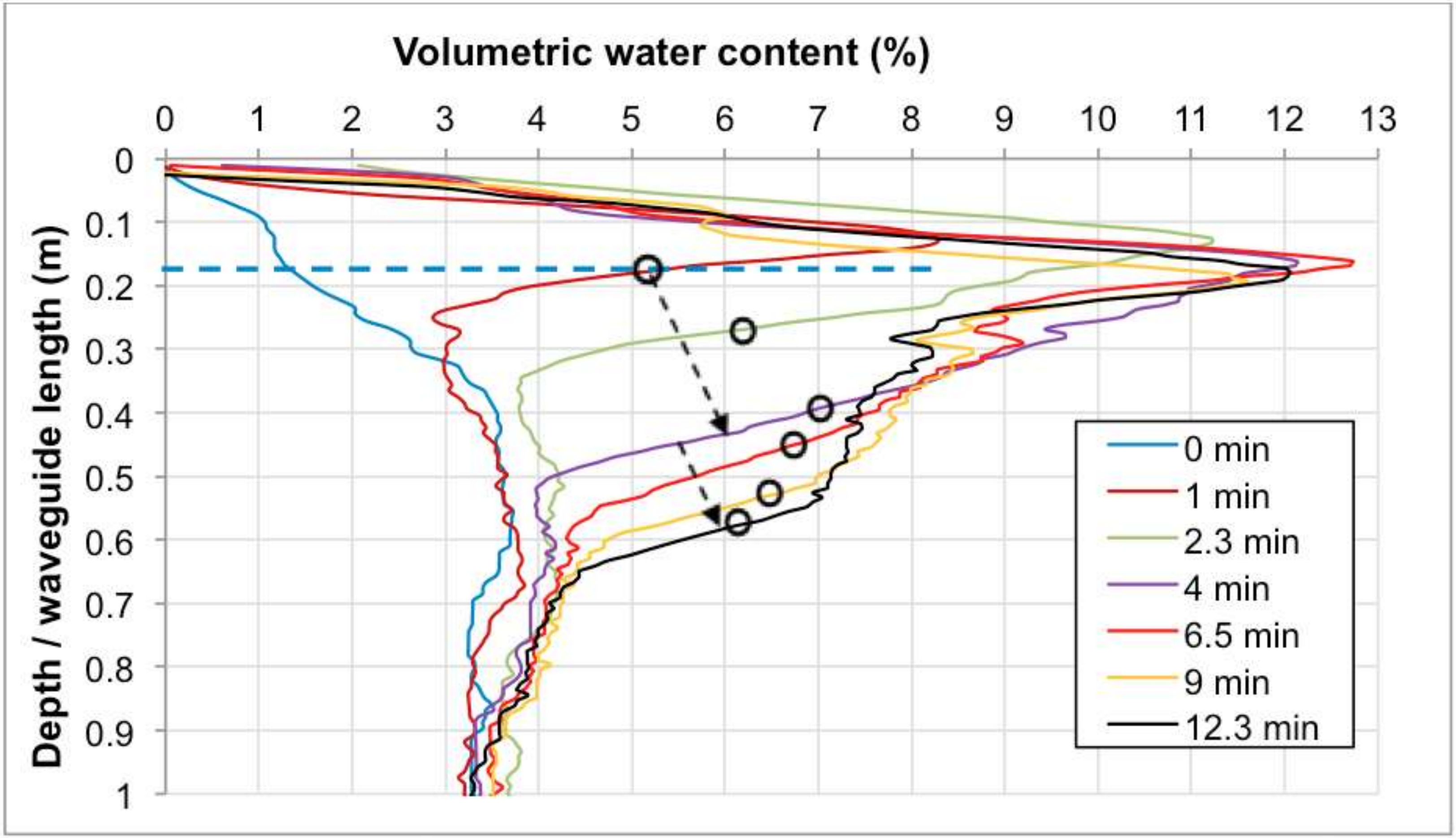
- The impedance at the beginning of the transmission line is considered the characteristic impedance of the coaxial cable.

Where Z_i and Z_(i-1) represent the impedance of each segment i and (i-1) and ρ_i is the reflection coefficient of the junction between these two segments

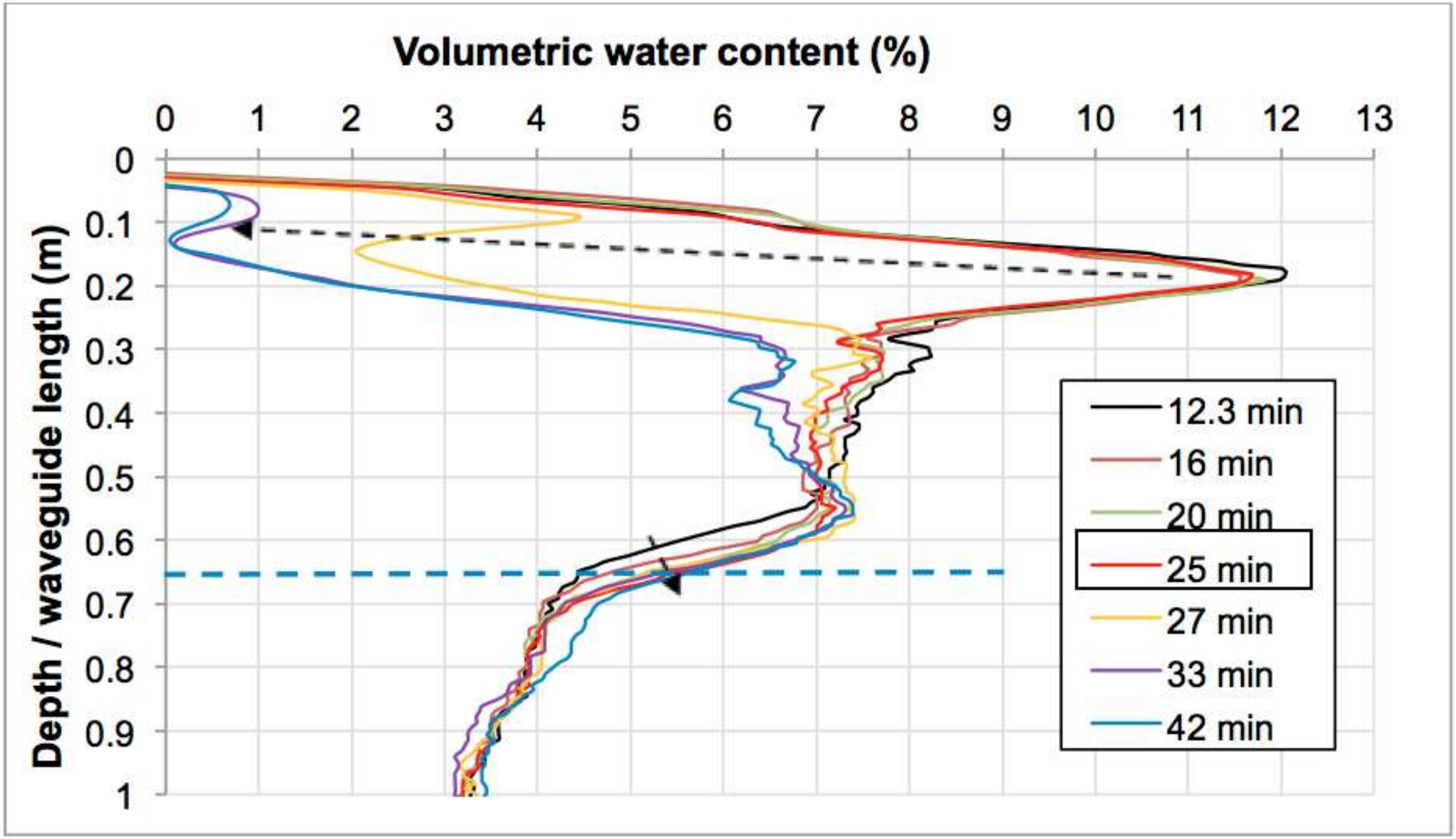
- The apparent relative dielectric profile of the surrounding medium of TDR sensor is achieved as a result of this inverse modeling approach which is required to convert into water content profile applying a suitable calibration function

Where ϵ_ai is the apparent relative dielectric permittivity of each segment i, Z_i is the impedance of each segment i and Z_c is the characteristic impedance of the transmission line in the air

Inverse Modelling Process

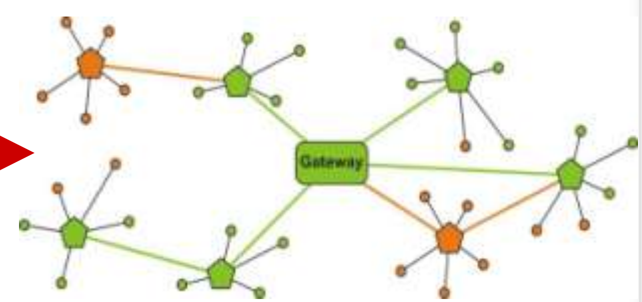


INVERSE MODELLING PROCESS



EMBEDDED PROCESSING

- The processing software can be easily be ported to a single board computer (Raspberry Pi)
- Also act as the TDR network interface
- Integrate temperature and water level sensors
- Raspberry Pi cost: $35



Embedded Processing: Compression

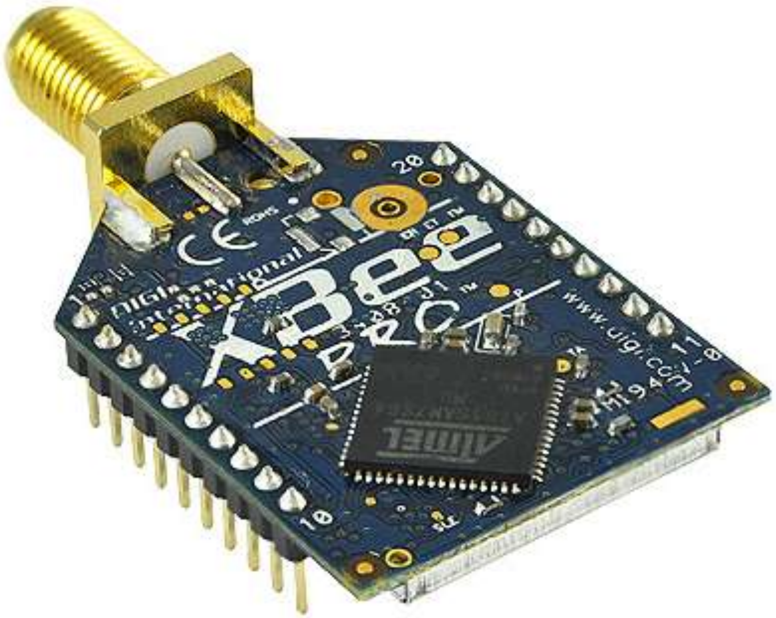
- All measurement data has to be communicated to the gateway node.

- Compression ratio: < 8%
- Waveform + metadata after compression: < 350 bytes

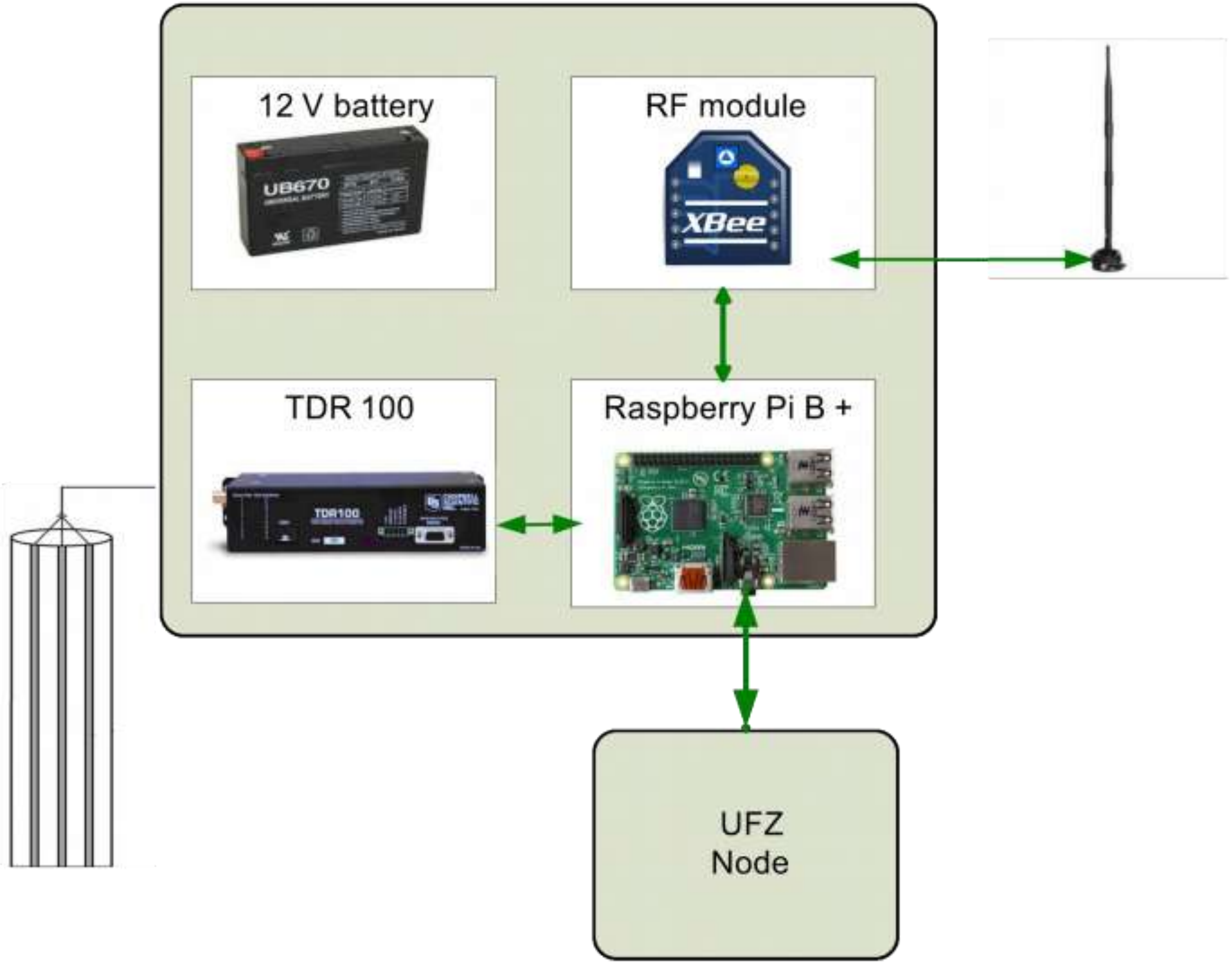
LONG-RANGE RF CONNECTIVITY

- XBee-PRO® 868

- 868 MHz short-range device
- Outdoor RF line-of-sight range up to 80 km peer-to-peer or point-to-multipoint topology
- Low cost: $45

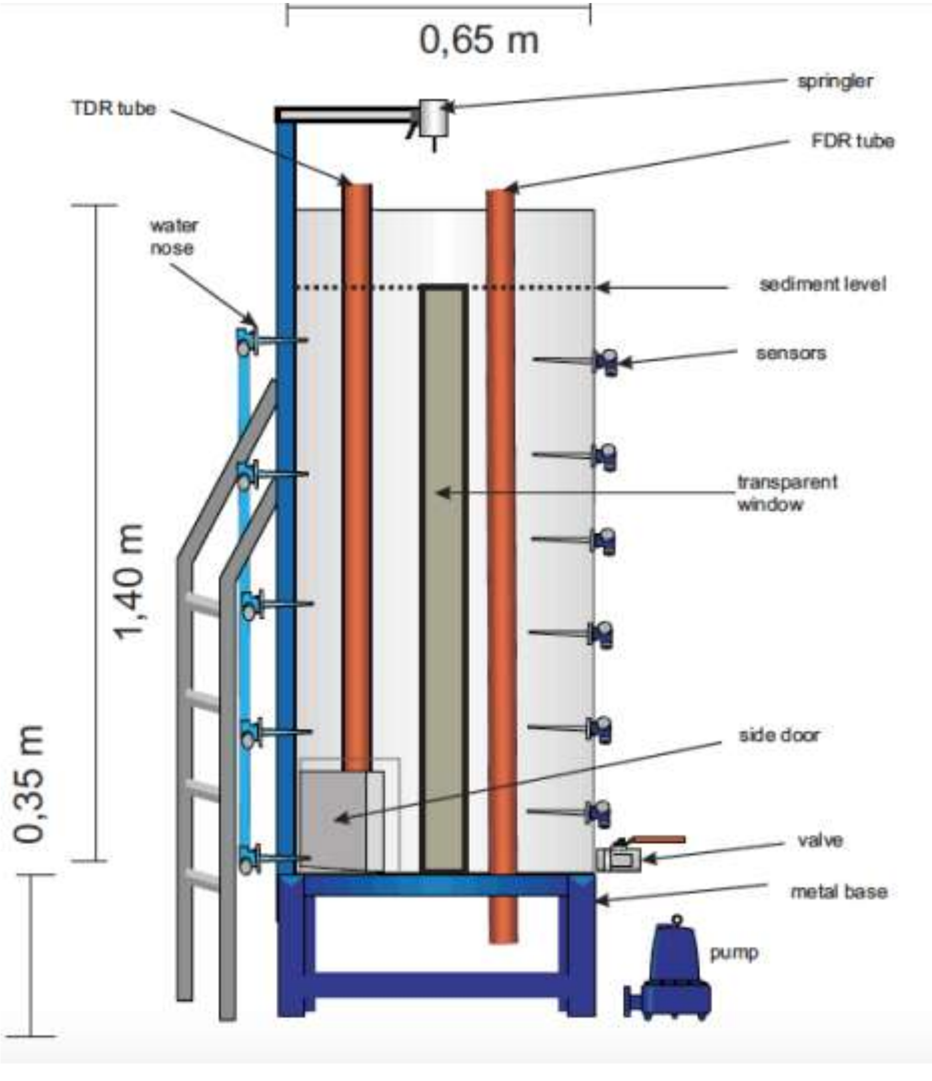


TDR – NODE HARDWARE INTEGRATION

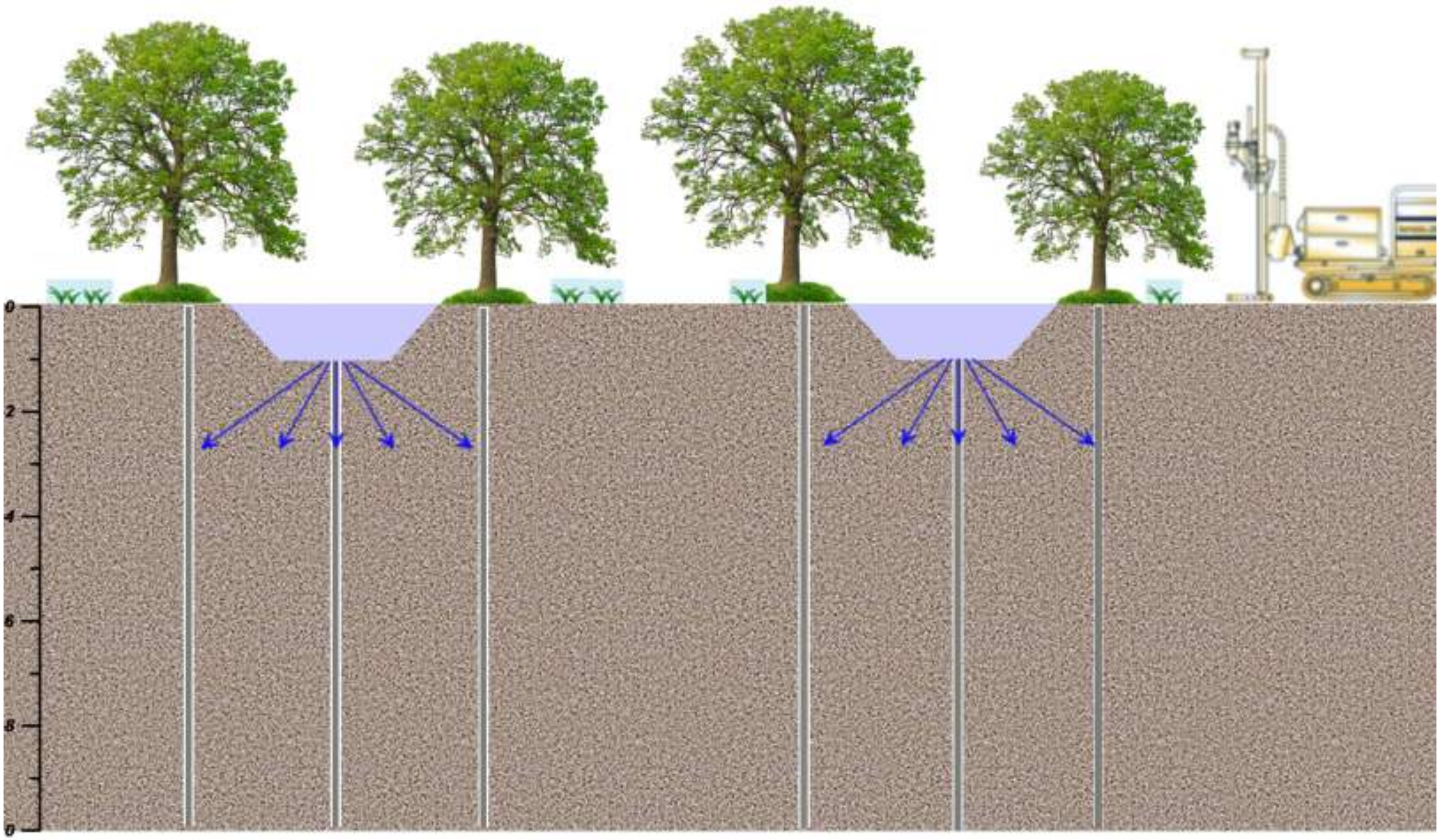


Soil Column Experiments

- TDR-FDR-CW radar Integration
- Joint activities ICCS-UFZ-TUDa-EYDAP



TDR APPLICATIONS IN MAR (1)

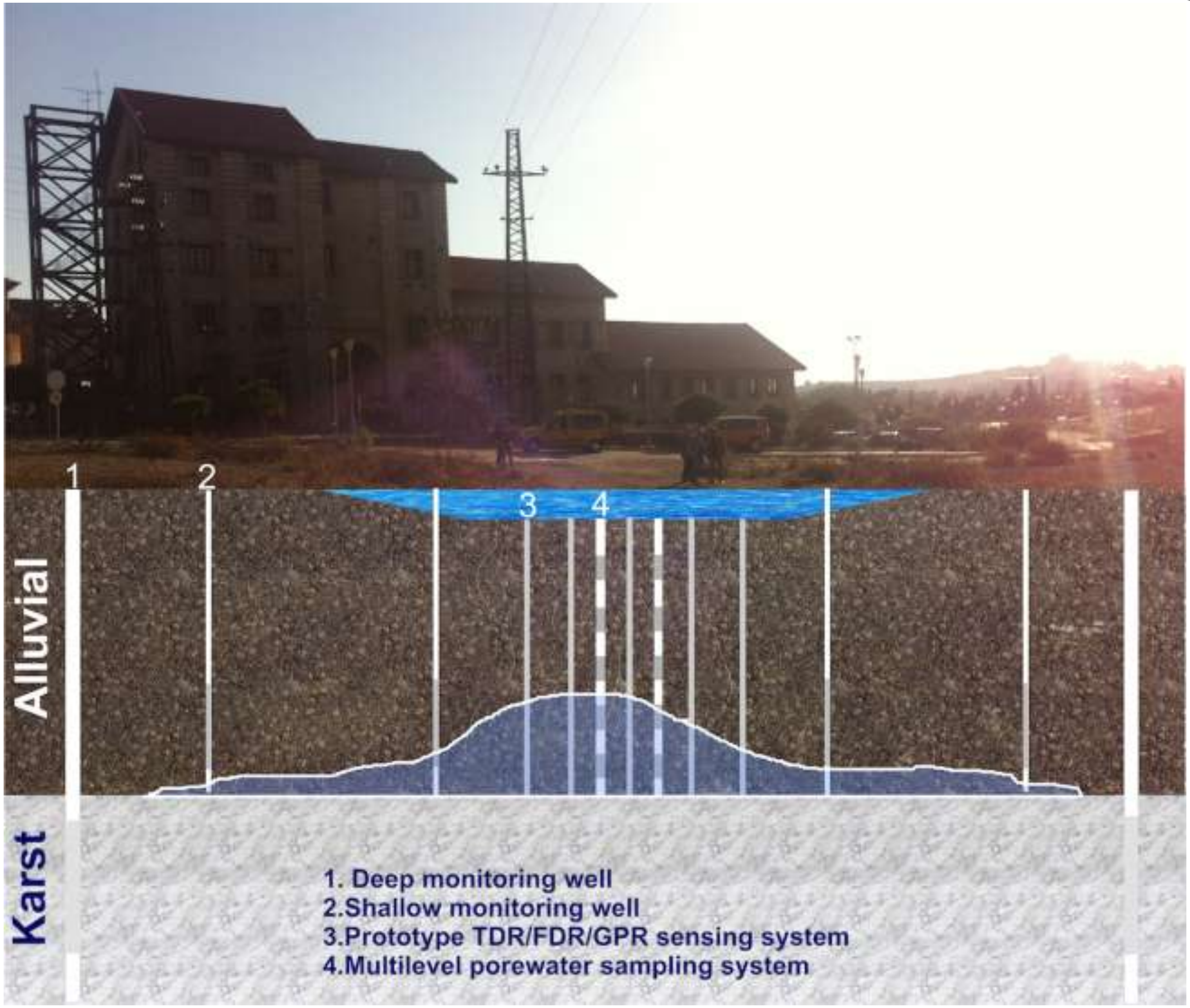


TDR Applications in MAR(1)

The above TDR sensors have the following characteristics:

- Schiavon Site:
  - TDR_1: Sensor length 2,80m
  - TDR_2: Sensor length 3.00m
- Loria Site:
  - TDR_3: Sensor length 3.00m
  - TDR_4: Sensor length 3.00m

TDR Applications in MAR (2)



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TDR Applications in MAR (2)

- Installation of TDR sensors at various depths
- Coverage of the entire unsaturated zone
- Different characteristics
  - Waveguide design
  - Co-axial/waveguide integration
  - Pulse generator/measuring system
- Different recharge water
- Experimental scenaria