

Multi-Depth Systems: Revolutionizing Groundwater Characterization Through High-Resolution Vertical Profiling

1 Introduction: The Need for High-Resolution Vertical Groundwater Data

A multi-level or multi-depth system (MDS) refers to engineered installations designed to measure hydraulic head and collect groundwater samples from multiple depths within a single borehole, offering a more efficient alternative to conventional approaches such as well clusters and well nests (Fig. 1). All MDSs share several key components (Fig. 1c): a central casing, access ports that allow groundwater to enter through openings in the casing for head or pressure measurement, and seals that isolate the monitoring zones associated with each port from the zones above and below. This vertical isolation of individual monitoring intervals is what enables depth-discrete data acquisition, allowing for high-resolution characterization of hydrogeological conditions from the borehole.

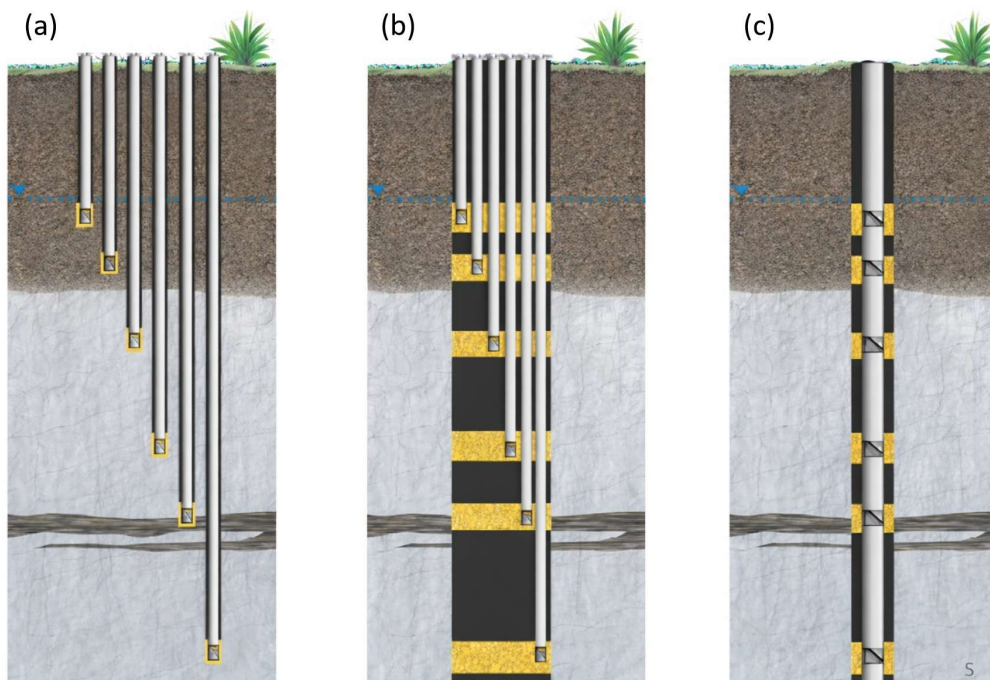


Figure 1. General options for depth-discrete monitoring: a) well cluster with well screens isolated in separate holes; b) well nest with several well screens isolated within a single large diameter hole; c) generic MDS with ports and seals (from Cherry et al 2017)

The primary impetus for MDSs is to acquire data from many depth intervals within each borehole, thereby capturing vertical heterogeneity that would otherwise be masked by depth-averaged measurements from conventional wells. In addition to this core advantage, MDSs offer several practical benefits:

- **Rapid hydraulic response:** Due to the small water storage volume within each discrete monitoring interval — typically a small-diameter tube — pressure transducers respond quickly to changes in formation pressure, enabling high-temporal-resolution monitoring.
- **Efficient sampling with minimal purge volume:** The volume of water that must be purged prior to sampling is significantly smaller than in conventional wells. This reduces sampling time and minimizes handling requirements — a critical advantage when dealing with contaminated or potentially hazardous groundwater.
- **Reduced environmental footprint:** Drilling a single borehole per location minimizes surface disturbance and reduces the volume of drill cuttings brought to the surface. This is especially beneficial at contaminated sites, where disposal of potentially hazardous materials requires special handling and adds cost.

Together, these features make MDSs not only scientifically superior for resolving subsurface complexity but also operationally and environmentally advantageous in a wide range of field settings.

2 Evolution and Comparison of Multi-Depth System Technologies

Numerous manufactured MDSs are available today, which can be grouped into five generic categories:

1. Valve-based system – Westbay (first commercialized in 1978)
2. Flexible tubes inside PVC casing – Waterloo (developed in 1982)
3. Flexible tubes inside flexible fabric – WaterFlute (introduced in 1997)
4. Continuous modular tubing – CMT (launched in 2002)
5. Stiff plastic tubes inside PVC casing – HKU (first installed in 2017)

Table 1: Comparison of different MDS designs

Name (Date, Source)	Main Design Features	Max No. of Ports	Most Common Use	Depth of Use	Best Features	Worst Features	Availability	Installation Difficulty
1 Westbay MP (1978, Westbay)	Valves embedded in ports in coupled PVC or stainless steel casing. Instruments are lowered to connect to a port for head measurement and sampling.	20-40 ports in a 100m hole typical.	Fractured rock in cored holes. Uses inflatable packers for seals. Best installed inside drill casing.	Up to 1000 m (mostly 100-600 m)	Deep deployment. High number of ports. Good in unstable rock holes.	Cannot have permanent transducers on each port. Expensive. Technician-intensive data acquisition.	Only from Westbay. Specialized manufacturing.	High. Technicians or extensive training required. 1-2 days per installation.
2a Waterloo (Original) (1982, U Waterloo)	Lengths of flexible tubing inside coupled PVC casing. Each tube is attached to a port. Seals created with filter packs & bentonite.	Limited by tube & casing diameter.	Originally for research purposes.	Shallow (not robust for deep field use)	Simple to produce. Low cost.	not robust for many field situations.	can be constructed by any organization with new, better materials. Plans available free.	Low. Simple construction and emplacement.
2b Waterloo (Commercial) (1987, Solinst Canada)	Commercial version of 2a, with enhanced materials and design.	Limited by tube & casing diameter.	Commercial groundwater monitoring.	robust for field use (up to 300m)	Commercially available.	Higher cost than 2a	from Solinst Canada Ltd. in a few configurations.	Medium. Professional installation recommended.
3 WaterFlute (1997, Solinst Canada)	Flexible tubes inside a flexible fabric tube (casing). Ports have valves. Seals are created by a unique method.	Limited by system design.	Limited, specialized applications.	Varies	Unique sealing method.	Relatively expensive. Least overall usefulness of the MLSs.	Available from Solinst Canada Ltd.	Medium-High. Specialized technique.
4 CMT (2002, Solinst / China Geol. Survey)	A continuous poly tube. Holes are drilled to create ports for each tube.	Fixed: 3 or 7 ports per system.	Overburden / unconsolidated deposits.	Generally < 30 m	Low cost	Limited to shallow depths, primarily in overburden	Solinst (global, small diameter). China Geological Survey (, larger diameter).	Low. Simple emplacement.

Name (Date, Source)	Main Design Features	Max No. of Ports	Most Common Use	Depth of Use	Best Features	Worst Features	Availability	Installation Difficulty
5 HKU System (2019, HKU)	Plastic tubes contained inside coupled PVC casing. Each tube is connected to a port.	Limited by sensor & well diameters.	Designed for versatile applications in rock and overburden.	10s to 100s of m	Robust design. Low-cost. Versatile for various ground conditions	Relatively new system.	Available as a manufactured product from the HK. Non-profit initiative (HKU-DHS).	Low-Medium. Designed for easier installation.

Figure 2 illustrates the key design features of each of these MDSs, while Table 1 provides a comparative summary of their relevant characteristics. With the exception of the WaterFlute, all systems employ seals—either inflatable packers or emplaced filter packs and bentonite—to achieve hydraulic isolation and enable depth-discrete data acquisition. The WaterFlute, by contrast, uses a distinct sealing mechanism based on a flexible liner that conforms to the borehole wall.

Except for the WaterFlute, these systems also share a common casing design consisting of standard PVC pipe sections. Stainless steel casing is an available, albeit significantly more expensive, alternative used in specific situations requiring greater durability or corrosion resistance.

Category 1: Westbay System

The Westbay system uses valves as access ports that allow groundwater to enter into a casing composed of coupled sections of standard PVC or stainless steel pipe. The sampling and measuring device operates similarly to an elevator: it travels to different ports to measure water levels or collect groundwater samples, much like an elevator moves between floors to pick up passengers. However, there's a key difference — the device can only access one port at a time, then returns to the surface to deliver the sample or data. In contrast, a building elevator can transport multiple passengers from different floors simultaneously.

Inflatable packers are mounted on the casing at predetermined intervals to provide hydraulic seals between monitoring zones; alternatively, filter packs and bentonite seals can be emplaced between zones to achieve isolation. The valves enable selective access to specific depths for head measurement or sampling. As the first commercially available MDS, Westbay remains a benchmark for high-precision, deep, and long-term monitoring. However, it is mechanically complex to manufacture and install, requiring specialized expertise. Westbay Instruments Inc. is the sole global supplier, which may limit accessibility and increase costs or lead times—particularly outside North America. Its robust engineering suits deep boreholes and challenging environments, but its proprietary nature and higher price point may deter budget-constrained projects.

Category 2: Waterloo System

This system consists of a casing made of coupled PVC pipe sections, within which multiple lengths of flexible polyethylene tubing are installed. Each tube extends from the surface to a specific depth and is connected to a port—formed by a hole in the casing—allowing access to a discrete monitoring interval.

The Waterloo system was originally developed at the University of Waterloo for research purposes. The initial design was simple and low-cost but lacked durability for many field applications. In 1987, Solinst Canada Ltd. redesigned the system to improve robustness, though at a significantly higher cost. This commercial version remains available in several configurations (see Solinst website). However, recent advances in materials have enabled a resurgence of the original Waterloo design—now more durable, low-cost, and versatile. Full construction details will soon be made freely available, allowing organizations worldwide to build the system locally and affordably.

Category 3: WaterFlute System

In the WaterFlute system, the casing is a flexible fabric tube installed in the borehole, which conforms to the borehole wall to create a seal. Inside this fabric liner, multiple flexible polyethylene tubes are positioned, each connected to a dedicated port equipped with a valve. The ports allow discrete access to groundwater at different depths, with isolation achieved through the intimate contact between the fabric liner and the borehole wall.

The WaterFlute system, initially developed by Flexible Underground Technologies Limited, is now commercially available through Solinst Canada Limited (see website). While it offers unique design features, it is relatively expensive and has limited overall applicability compared to other MDSs.

Category 4: CMT

The CMT system features a continuous extruded polyethylene tube containing either three or seven internal access channels that run the full length of the borehole. At each monitoring depth, a small hole is drilled through the wall of one of the internal tubes, creating a port that connects that channel to the surrounding groundwater. Each access tube is dedicated to a specific port, enabling depth-discrete monitoring.

The CMT system has been distributed globally by Solinst Canada since 2004 in two small-diameter variants. A larger-diameter version is manufactured in China by the China Geological Survey for domestic use and, upon arrangement, for other users within China (see website). The Solinst CMT system is typically limited to depths of less than 30 meters and is best suited for unconsolidated overburden environments. It was historically the most cost-effective MDS option until the invention of the HKU system.

Category 5: HKU System

The HKU MDS System, or simply HKU system, also known as the HKU Dual Purpose System, is one of eight technologies within the HKU Depthwise HydrogeoSystem (HKU-DHS). It is called a “dual purpose” system because it supports both water level

measurements and groundwater sampling. In contrast, another system within the HKU-DHS — the HKU Groundwater Sampler — consists of small-diameter tubes designed exclusively for multi-depth water sampling.

The HKU system employs stiff plastic tubes housed within a casing made of coupled PVC pipe sections. Each stiff tube is connected to a port (a section of screen) at a specific depth, allowing discrete access to groundwater.

The HKU system, initially developed by the Hydrogeology Group at the University of Hong Kong for research purposes, is available as a manufactured product from Hong Kong. Designed for greater durability and adaptability in challenging geological settings, it represents a recent advancement in MDS technology.

Each of these design options has distinct merits, which may be viewed as advantages or disadvantages depending on the specific hydrogeological conditions and objectives of the investigation. A key challenge in employing MDSs is selecting the most appropriate design for the intended application.

Most of the MDSs has a limited number of ports, as each port is connected to a tube that runs from the monitoring depth to the surface inside the casing. The number of ports is constrained by the tube diameter, the casing diameter (which depends on the borehole size), and, when automatic sensors are installed in the MDS for water level measurement, the size of the sensor itself.

MDSs are essential for collecting data from various depths in a single borehole, which minimizes bias and prevents misinterpretation of groundwater systems. Despite this advantage, conventional monitoring wells—which provide limited data—are still used far more frequently. A primary reason for this disparity is the perceived excessive cost of MDS technology. However, recent invention of the HKU system makes cost a negligible factor. This advancement enables any organization to easily build its own systems or source them through HKU DepthWise HydrogeoSystem (HKU-DHS), a nonprofit initiative dedicated to advancing global groundwater science.

3 Advanced Port Design: Enabling Accurate Aquifer Testing with MDSs

Conventional MDSs have small holes open to the groundwater in the formation (Fig 2). While adequate for basic water-level monitoring and sampling, these systems introduce significant limitations for aquifer testing: the hydraulic conductivity of their narrow ports often falls below that of the surrounding formations, creating artificial constraints that distort permeability estimates during pumping or slug tests.

The HKU-MDS overcomes this limitation through 3D-printed port screens, enabling precise customization of slot length, aperture size, and geometric patterns to match site-specific sediment characteristics. This adaptability ensures port conductivity exceeds formation permeability across diverse lithologies—from fine sands to coarse gravels—eliminating measurement artifacts.



Fig. 3. Various designs of well screens tailored to meet the requirements of different geological formations. The screen section here is ~15 cm long and can be extended as needed.

Consequently, the HKU-MDS transcends conventional systems by supporting both routine monitoring and rigorous aquifer testing within a single installation. This dual capability—validated through direct hydraulic testing—resolves a fundamental limitation in multi-depth monitoring technology, enabling accurate permeability characterization without compromising sampling integrity.

4 Innovations in Hydraulic Isolation: From Packers to the HKUniversal Seal

A critical requirement for MDS is the reliable isolation of each sampling port using impermeable seals. For temporary installations — where systems are removed after deployment — inflatable packers expanded via air or water pressure are commonly used (Fig. 4a). For permanent installations in stable formations, the traditional approach involves backfilling the annulus with alternating zones of sand and bentonite (Fig. 4b). In

unstable boreholes prone to collapse — such as those in weak rock or soil — a hybrid method is often employed (Fig. 4c): a multi-screen casing is first installed using drilling mud for borehole stabilization, followed by insertion of the MDS and subsequent removal of the mud through conventional well development techniques.

However, a major challenge with these backfill methods is the difficulty of accurately placing sealing materials at precise depths. This process relies heavily on experienced workmanship and becomes increasingly complex in deep boreholes with numerous monitoring ports. While pre-made expanding seals offer an alternative, they are often cost-prohibitive.

As part of the development of the HKU system, a new type of packer seal was invented — the HKUniversal Seal (Fig. 4d). Made from a low-cost, rubber-like material sourced in various sizes from China, this seal swells strongly upon contact with water and offers superior performance and versatility compared to bentonite. A patent for this seal has been submitted.

Unlike traditional methods using bentonite, the HKUniversal Seal is wrapped onto the MDS casing at designated depths on the surface, prior to insertion into the borehole. Upon contact with groundwater, the seal hydrates and expands to form a tight, impermeable barrier isolating each port. Its expansion is salinity-dependent: in fresh water, expansion is rapid; in saline environments like seawater, it is significantly slower. For example, in distilled water, a 10 cm³ seal can expand to 49 cm³ within 4 hours, whereas the same expansion in seawater may take several days (Fig. 5). Specialized formulations of the seal are available for speeding its expansion in high-salinity conditions.

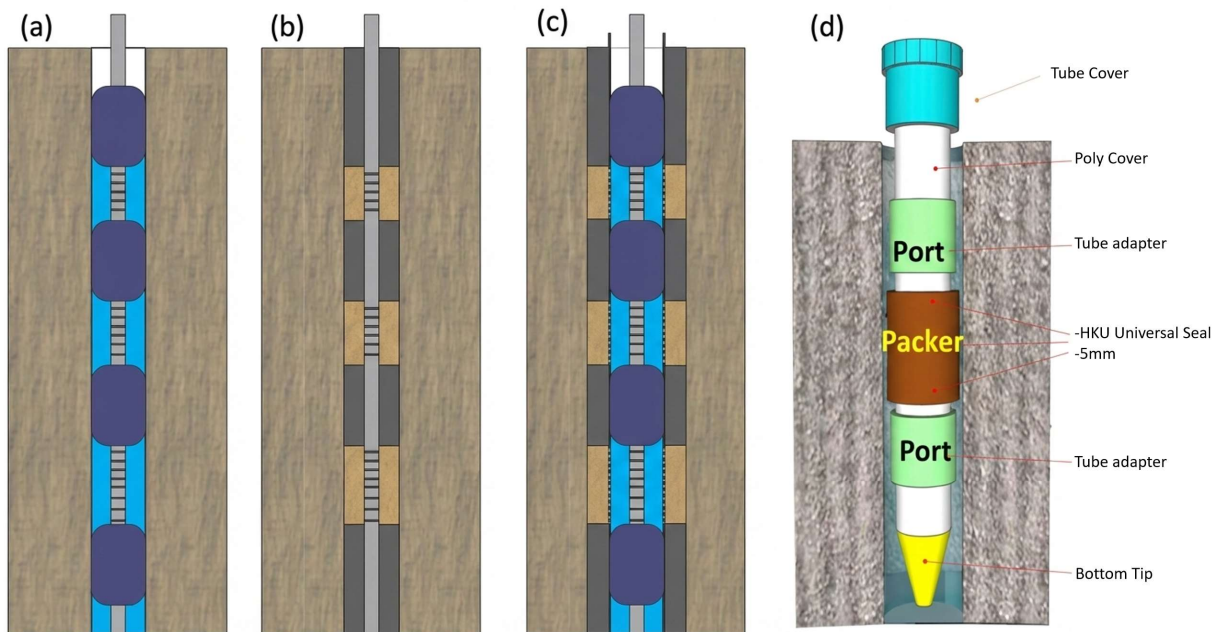


Figure 4. MDS Installation Methods: a) packers, b) backfilling, c) packers in backfilled casing with multiple screens where the multiple screen casing is installed using conventional water well drilling methods and then the MLS is installed inside the casing, d) HKU Universal seals that expands after in contact with water (modified from Cherry et al 2017)

It is not recommended to rely on the seal's maximum expansion capacity — which can reach up to 9 times its original volume after one week in freshwater — as the seal becomes overly soft and loses mechanical strength needed to maintain firm contact with the borehole and casing walls. For most installations, a target expansion of approximately 100% is advised. This allows a 10 mm-thick seal to effectively fill an annular space of ~20 mm — a significant advantage over traditional bentonite balls (typically 20–40 mm), which require a much larger annulus or borehole diameter. As a result, more sampling ports can be installed within the same borehole diameter. Additionally, the seal's ability to conform to irregular borehole surfaces makes it highly effective in rough or uneven wall conditions.

The expansion rate is a key consideration in MDS installation planning. For a typical 200-meter-deep system, the 4-hour expansion window aligns well with field deployment timelines. For deeper installations, specially formulated slower-expanding seals are available to ensure proper seating before full expansion occurs.

The HKU Universal Seal of course is not limited to the HKU system. Its design allows easy adaptation to other commercial MDS platforms. For instance, it can be used with CMT systems to extend their applicability to fractured rock environments in small-diameter,

rock-cored boreholes. It can also be integrated into the Westbay MP system, where it has the potential to significantly reduce both manufacturing costs and installation time.

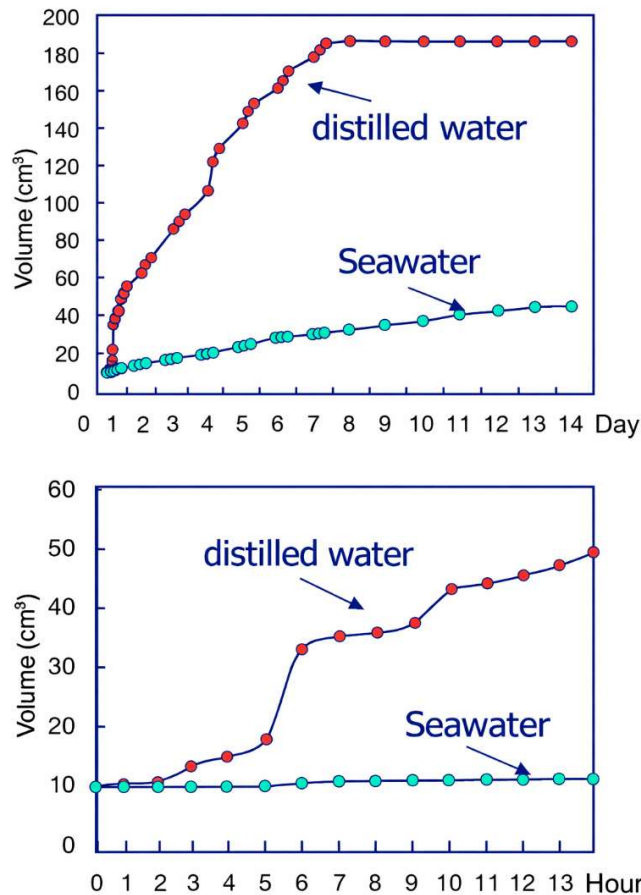


Fig. 5. Chang of HKUniversal seal volume over time in different water types. The seal expanded from 10 cm³ to 49 cm³ in distilled water within 4 hours, but required 4 days to merely double in volume in seawater.

5 Sensor Miniaturization: Maximizing Port Density and Spatial Resolution

Beyond the borehole size, the diameter of the water level sensors is a critical factor determining the number of monitoring ports achievable within a single MDS. To maximize port density, sensor miniaturization is essential. Conventional market-leading sensors typically have a diameter of 18–19 mm and integrate an internal CPU and battery. In contrast, advanced micro-machining techniques in China have enabled the development of miniature sensors with diameters as small as 5 mm. This significant reduction requires a fundamental redesign: these miniature variants forgo onboard

electronics, instead operating on power drawn from an external source — such as land surface-level electricity or solar panels — with data logging performed above ground.

This capability was demonstrated in a field installation where an HKU-MDS was deployed for groundwater monitoring in a 40-meter borehole within a multi-layered sandstone-shale slope in Taiwan. The system's 114-mm outer casing accommodated 18 piezometer pipes: one 35-mm-diameter pipe housing a conventional large-diameter sensor and seventeen 18-mm pipes, each fitted with a 6-mm-diameter miniature sensor (Fig. 6). This configuration highlights the HKU-MDS's unique adaptability, allowing for fully customizable port arrangements to meet specific site and user requirements — a capability unmatched by commercial alternatives. Had all ports utilized the smaller sensors, the system could have supported over 20 monitoring ports, enhancing spatial data resolution within the same borehole. The asymmetrical layout of the tubes added complexity to the system's design and assembly, which required approximately four hours at the site. The subsequent installation into the borehole, however, was efficient, requiring only half an hour.

However, a major issue with the current sensors from the commercial marketplace is their relatively high cost. In some cases, the total cost of these devices can exceed the cost of the HKU MDS itself. This highlights the need to develop low-cost versions of these sensors and data loggers. The prospects for achieving this are promising because the cost of the individual components used in sensors and data loggers is a fraction of the commercial price for the fully assembled units. Therefore, it may be possible to create affordable alternatives that maintain the necessary functionality and accuracy.

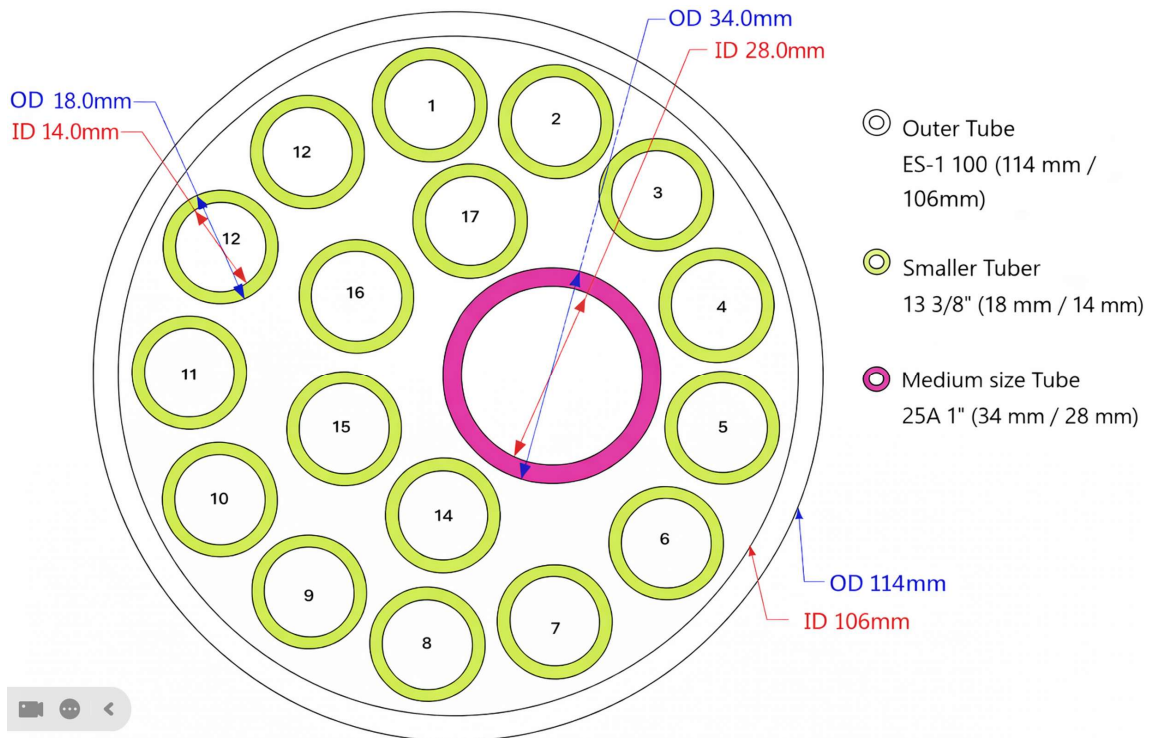


Fig 6 the PVC piezometer pipes arrangement for the MDS in Taiwan

6 Critical Applications: Where MDSs Provide Unmatched Clarity and Insight

The twelve example types outlined below have in common large variations in water pressure, water age and/or chemical concentration over small vertical distances and the zones of highest or anomalous pressure or highest chemical concentration are generally most important to the problems of most relevance. These occurrences are common because hydraulic conductivity over many orders of magnitudes in geologic media, flow lines often convergence and mixing of solutes between zones is often weak. Therefore, depth-discrete profiles are essential for recognition of the zones of importance.

- Whether a slope remains stable or fails as a landslides is dependent on groundwater. Slopes do not fail due to changes in the averaged water pressure but rather they fail when an abnormally high water pressure occurs within a thin layer or fracture, usually one that is well connected to groundwater recharge from rainfall.
- Sea water intrusion is common along coasts and beneath islands and the mixing interface between the freshwater and the underlying saline water is commonly thin with the position varying with time. Sea water intrusion can be difficult to reverse and to avoid this ongoing profile monitoring is most effective

- Pollution is common beneath old industrial lands where chemicals occur in slow moving zones with little mixing. Chemical concentration profiles commonly show orders of magnitude variations. Many contaminated sites are subjected to cleanup actions and the most reliable approach to determining the degree of success in the groundwater context is to conduct MDS monitoring.
- To understand the impacts of chemical agriculture on groundwater, detailed profiles are needed to locate the maximum concentrations of fertilizers and pesticides that typically occur thin zones at variable depth across the cropland
- Geogenic contaminants such as arsenic impact an estimated two hundred million people around the world. The arsenic typically occurs in zones influenced by the local geology and groundwater flow. To identify the zones with water safe to drink from those (baseflow) that are unsafe is challenging and success has come from going beyond conventional monitoring
- The water flowing in rivers during much of the time when there is no rainfall is from groundwater seepage (baseflow) provided from groundwater flow paths fed from local recharge with some originating far away. Flow path convergence at river valleys and riverbeds and overall to examine water origins and chemistry, closely spaced monitoring points are needed, especially for investigating the hyporheic zone and groundwater dependent ecology.
- The depth and shape of the water table is the most important feature in most hydrogeologic circumstances, and this includes the occurrence of perched water tables however typically in groundwater investigations monitoring leaves much uncertainty about the actual position and nature of the water table including the occurrence or lack thereof of perched water, transient or permanent that can be determined by use of MDSs.
- There are many thousands of freshwater lakes in the world, many in forests or other natural ecological terrain in the northern hemisphere. Many are polluted with sewage effluent from latrines, septic systems and/or agriculture. To investigate this type of ecologic damage, groundwater monitoring using MDSs can be most effective.
- Groundwater issuing from springs is a source of drinking water for hundreds of millions of people globally, but commonly spring water has one or more contaminants due to human activities on the nearby land about which there is little understanding due to inadequate investigations aimed at determining profiles of pressure and water chemistry.
- Land subsidence from reduction of groundwater pressure due to over-pumping is common around the globe and threatens the well being of hundreds of millions of people. Nearly all this subsidence comes from compaction of the clayey strata or zones within the aquifer system and therefore to comprehensively understand the

subsidence, it is necessary to monitor the groundwater pressure in both the aquifer hydrogeologic units and the clayey units and for this, MDSs are most effective

- The monitoring of groundwater in urban areas using advanced technologies and related concepts is rarely done in cities as an acknowledged or clear priority, even in cities where groundwater is a significant source of drinking water. MDSs offer many advantages including minimal land use, fitting the installation activity for the monitoring stations into small spaces within the urban infrastructure and once they are installed, the ease of hiding monitoring stations to avoid vandalism.
- Cities that are not dependent on groundwater for drinking are vulnerable to water terrorism because surface waters are relatively easy to purposely contaminate. The most difficult water source to purposely contaminate is a water well because wells can easily be hidden and protected. The volume of safe water needed to supply a city for the drinking only purpose is relatively small so that the size of aquifers needed are generally small and to identify and monitor them MDS are effective. These wells are needed to achieve backup low risk drinking water.

References:

Cherry JA, Parker BL, Chapman SW, Meyer JR, Pierce AA. Depth discrete multilevel monitoring in fractured rock: State of the technology and implications. InGWB Biannual Conference 2017 (pp. 1-12).