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.

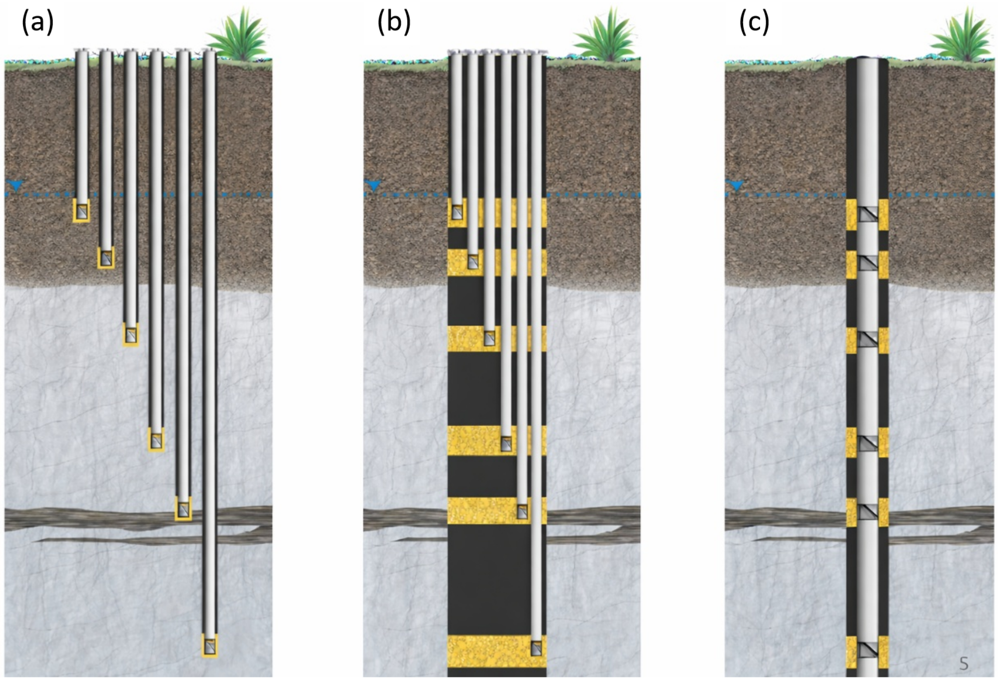

Figure 1. General options for depth-discrete monitoring: a) well cluster with well screens isolated in separate holes; b) well nest with several well screens isolated within a single large diameter hole; c) generic MDS with ports and seals (from Cherry et al 2017)

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.

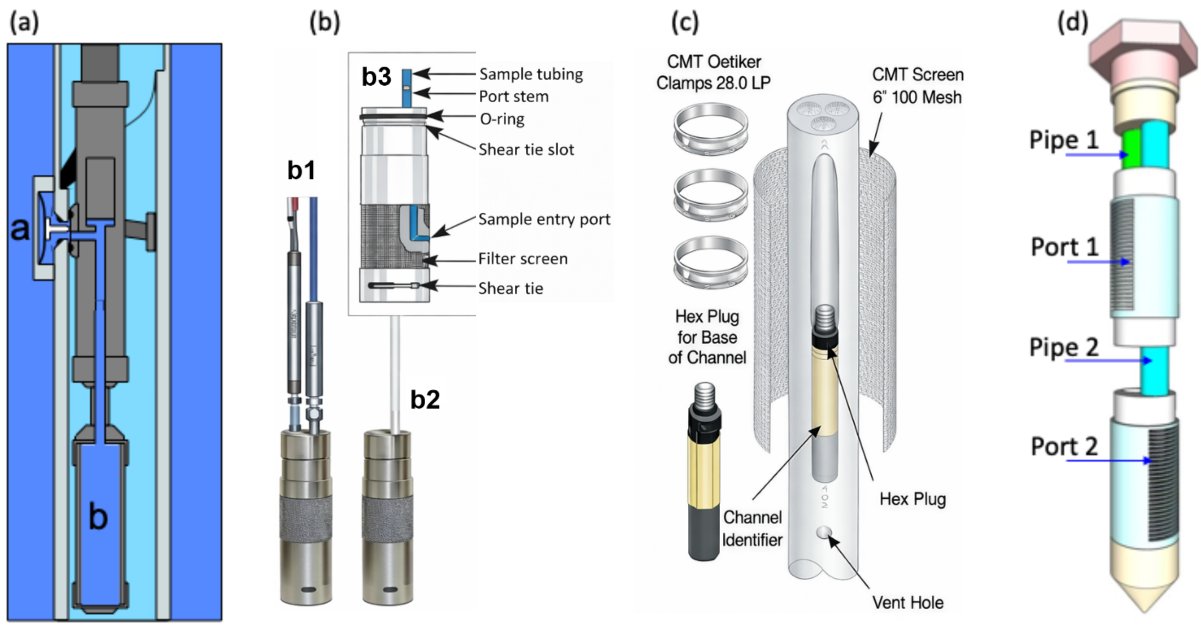

Fig 2. Key structure of MDSs for each category: (a) Sampling port and devices for WestBay system: a is the port and b is the pressure sensor or sampling bottle; (b) Stainless ports for Waterloo system: pump and pressure transducer version (b1), single tube version (b2), stainless steel version, and details of the port (b3); (c) structure of a port of a CMT of 3 channels; (d) HKU MDS system with two ports as an example. For clarity, the outer protective PVC casing surrounding the internal pipes is not shown.

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.

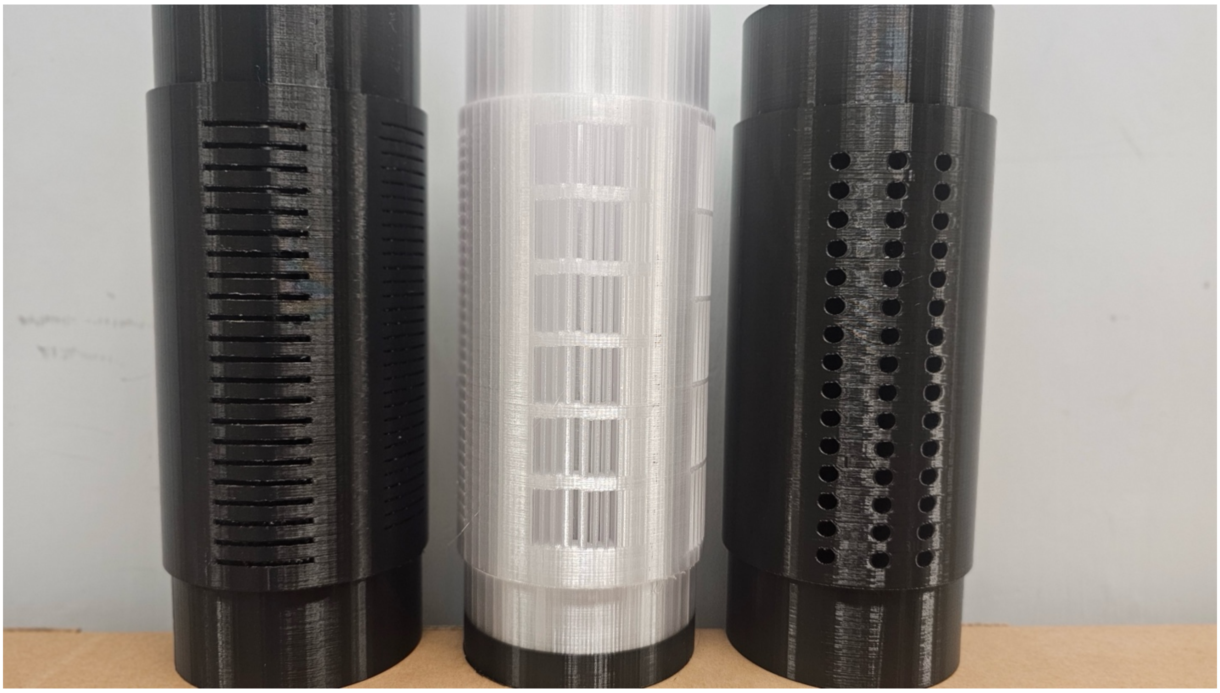

Fig. 3. Various designs of well screens tailored to meet the requirements of different geological formations. The screen section here is ~15 cm long and can be extended as needed.

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.

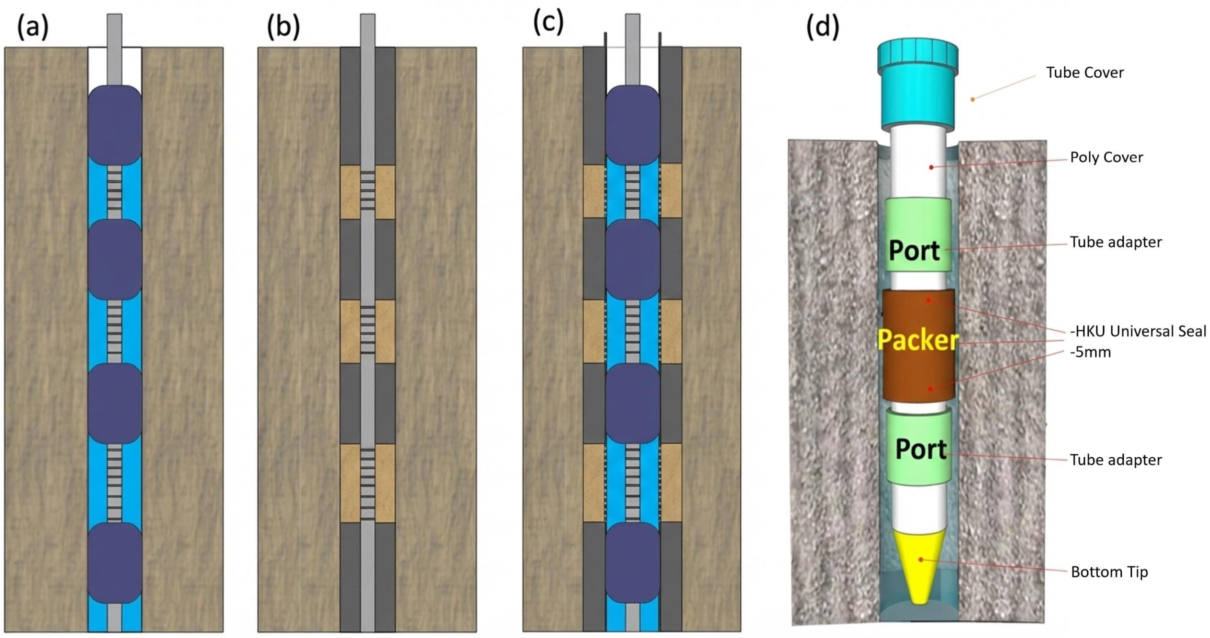

Figure 4. MDS Installation Methods: a) packers, b) backfilling, c) packers in backfilled casing with multiple screens where the multiple screen casing is installed using conventional water well

drilling methods and then the MLS is installed inside the casing, d) HKUniversal 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 HKUniversal 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.

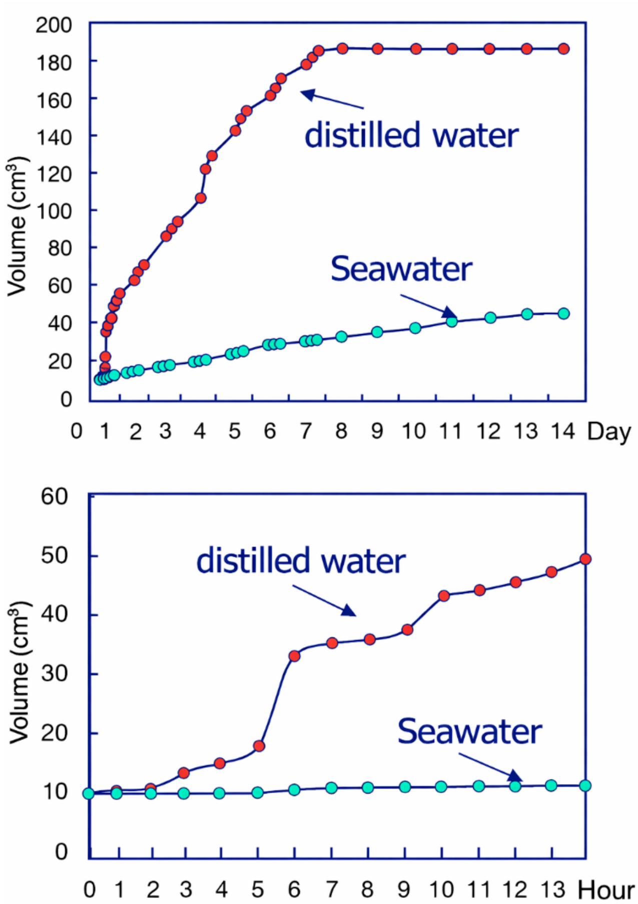

Fig. 5. Chang of HKUniversal seal volume over time in different water types. The seal expanded from 10 cm³ to 49 cm³ in distilled water within 4 hours, but required 4 days to merely double in volume in seawater.

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.

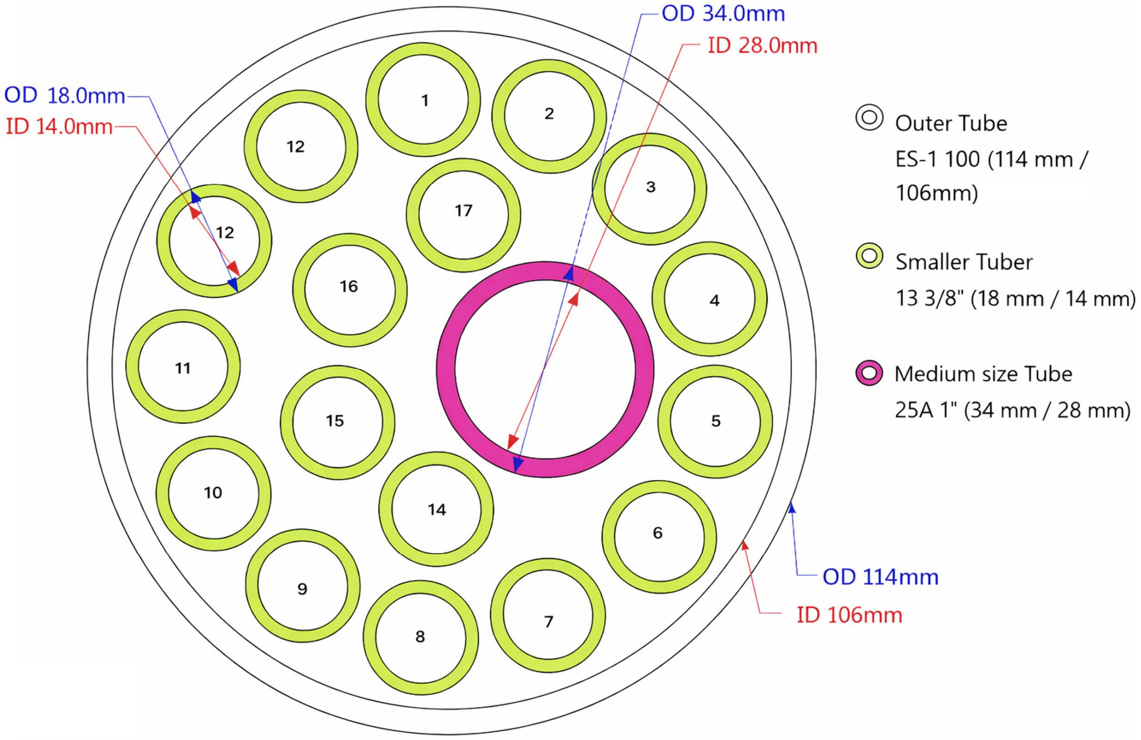

Fig 6 the PVC piezometer pipes arrangement for the MDS in Taiwan

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 chemixcal 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 underying saline water is commonly thin with the position varying with time. Sea water intrusion can be difficuilt 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 determing 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.

7 Case Studies: Scientific Discoveries Enabled by Multi-Depth Profiling

Groundwater flow systems are inherently three-dimensional, yet conventional monitoring wells obscure vertical heterogeneity by hydraulically connecting multiple aquifers and producing depth-averaged measurements. Only MDSs provide discrete, depth-resolved profiles of hydraulic head and geochemistry that accurately characterize 3D flow dynamics—revealing vertical connectivity, recharge pathways, and contaminant transport mechanisms impossible to resolve with traditional single-borehole approaches. The following case studies demonstrate how MDS has fundamentally transformed our understanding of subsurface processes, uncovering previously hidden phenomena that have reshaped hydrogeological paradigms. The multi-depth data were obtained from various MDSs ranging to primitive piezometer clusters to advanced Westbay.

7.1 Beyond the Core: Using MDS Hydraulic Profiles to Redefine Aquitards and Uncover Hidden Flow Barriers in Fractured Rock

This first case study focuses on a complex, layered aquifer system in fractured sedimentary rock in Dane County, Wisconsin — a region underlain by Cambrian-Ordovician sandstones, siltstones, shales, and dolostones, including the regionally significant Mt. Simon aquifer and the overlying Eau Claire Formation, traditionally regarded as a thick, low-permeability aquitard. At the heart of this investigation is corehole MP-6, drilled and cored to 131 meters and instrumented with a high-resolution Westbay MDS featuring 36 discrete monitoring intervals. This exceptional dataset (Meyer et al.2008) provides the critical evidence needed to redefine the site's hydrogeologic architecture, revealing that conventional methods based on lithology or gamma logs alone are fundamentally misleading.

The core finding is that detailed, depth-discrete hydraulic head profiles are indispensable for accurately identifying hydrogeologic units (HGUs) in such settings. The MP-6 profile, consistent across four measurement periods spanning two years, exhibits eight distinct, repeatable head inflections (A–H), each representing a zone of abrupt head loss. These inflections served as the primary basis for delineating eleven stacked HGUs — not by matching lithostratigraphic boundaries, but by pinpointing interfaces where vertical connectivity between fracture networks in adjacent permeable units is poor, effectively segmenting the aquifer system into discrete, hydraulically isolated layers.

Crucially, Patton et al (2025) frame this case as a textbook example of overcoming "confirmation bias." Relying on traditional gamma logs would have defined the Eau Claire "aquitard" as ~10 meters thick. The high-resolution head data, however, revealed that the hydraulically active barrier (HGU2) responsible for the head drop is a mere ~2.7 m thick interval within that sequence. This has profound implications: overestimating aquitard thickness leads to underestimating vertical gradients, which in turn compromises well design, contaminant transport predictions, and remediation strategies. Patton et al (2025) emphasize that no other dataset — not core descriptions, not geophysics — could have revealed these hidden hydraulic discontinuities.

Patton et al. elevate the MP-6 profile as a “Golden Spike” — an initial, high-density dataset that provides an unbiased, evidence-based visualization of the true subsurface flow architecture. This allows practitioners to move from an inductive (assumption-driven) model to a deductive (data-driven) one. The profile doesn’t just add detail; it fundamentally corrects the conceptual model. As such, it should be said that high-resolution MLS data are not a luxury but a necessity for defensible site characterization, risk management, and life-cycle monitoring in complex fractured rock systems. The MP-6 data set exemplifies how investing in high-quality, high-resolution field measurements ultimately reduces project risk and cost by preventing costly misinterpretations downstream.

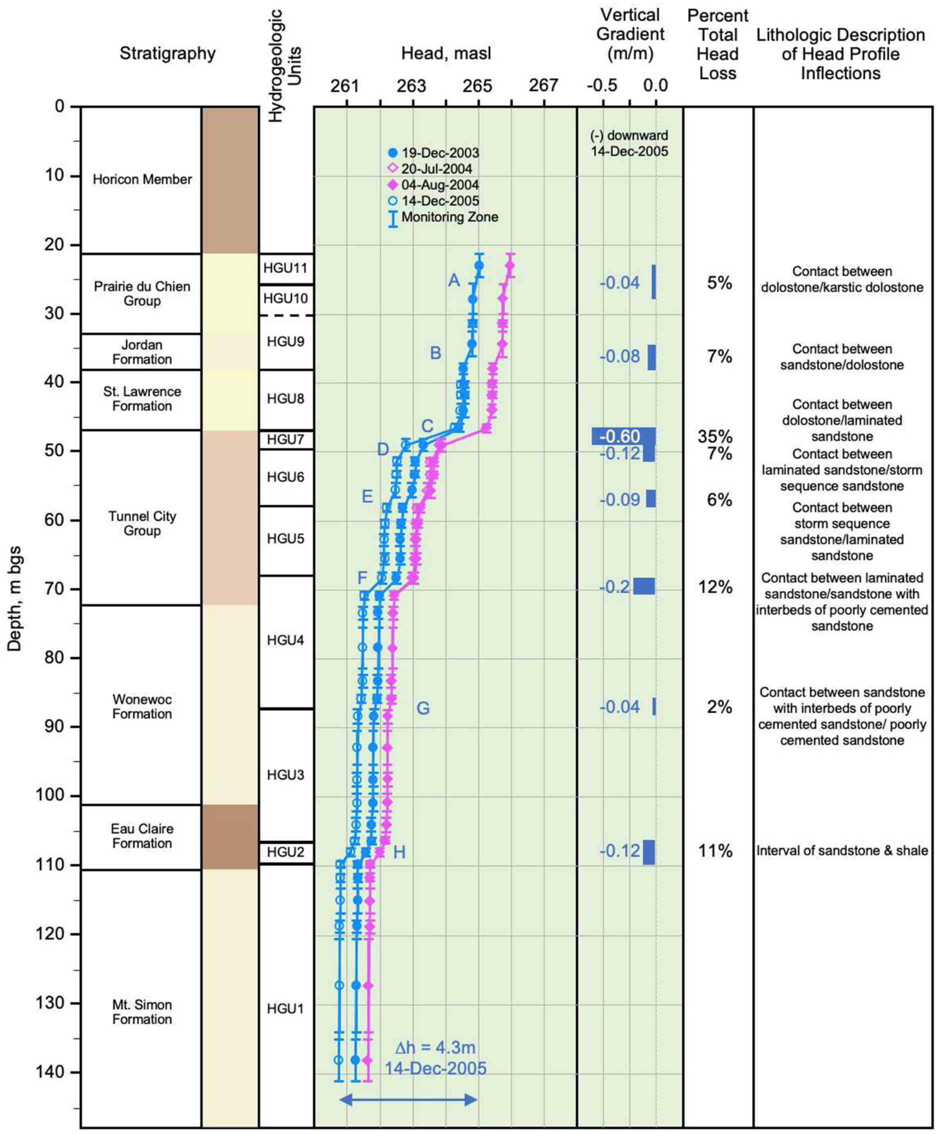

Figure 7. Head profiles measured over two years from Drill hole MP-6 at a site in Wisconsin (from Patton et al 2025) using data from Meyer et al., (2008).

7.2 How a DNAPL Source Evolved: MDS Reveals Deep Penetration & Back-Diffusion in Fractured Rock

At a former pesticide facility in Ontario, Canada, metolachlor — a dense non-aqueous phase liquid (DNAPL) — was released between 1978–1981 (Fig 8). The contaminant migrated into a fractured Silurian dolostone aquifer overlain by 30 m of glacial sediments. Initial investigations using conventional monitoring wells (long screened intervals) detected low metolachlor concentrations in the upper bedrock and concluded contamination arrived via dissolved-phase transport from DNAPL trapped in overburden. This model, however, failed to explain how contamination reached depths >70 m or why the plume remained stable and dilute (<2 µg/L in SW1) for decades — even reaching a municipal well 930 m down-gradient in 2000. Conventional wells, by vertically averaging data, masked the true complexity.

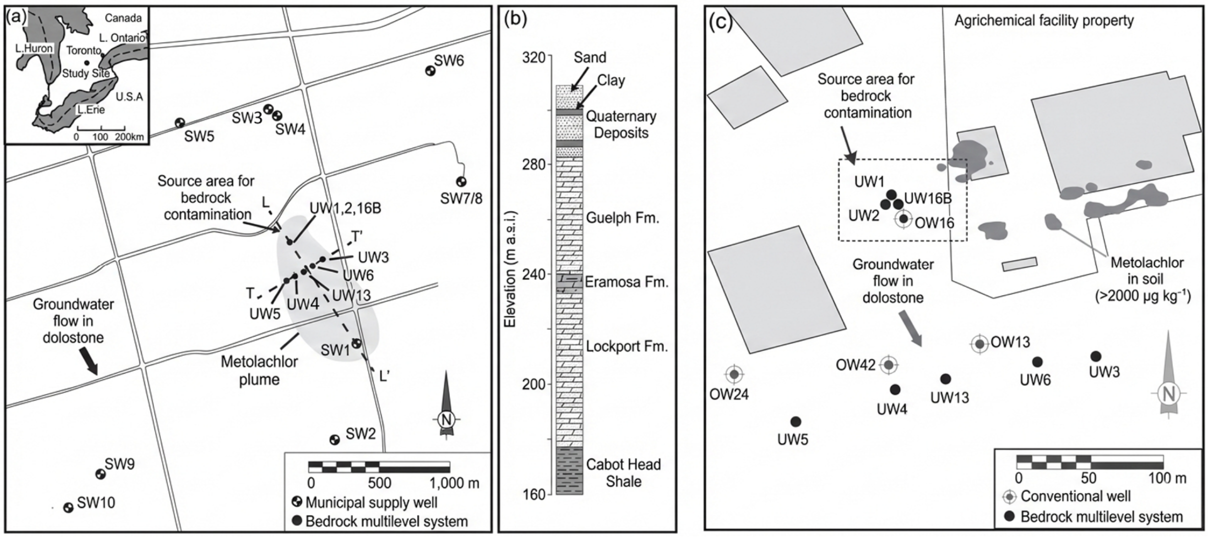

Fig. 8. Location of the study site and extent of the metolachlor plume delimited from conventional monitoring wells and multi-level systems (a), Local stratigraphy: Quaternary glacial sediments overlying fractured bedrock of Silurian dolostone (b), and (c) Detailed map of the study area showing the areas where metolachlor was detected in the soil, and the locations of conventional monitoring wells and the bedrock multi-depth systems installed in the dolostone bedrock aquifer (from Parker et al., 2018).

The breakthrough came with installation of high-resolution, depth-discrete MDSs— primarily FLUTe™ liners and one Westbay system — in the source zone (UW16B) and down-gradient transect (UW3–UW6, UW13). These systems provided two revolutionary datasets impossible with conventional wells: depth-discrete hydraulic head profiles, revealing true vertical flow dynamics and depth-discrete groundwater concentrations, capturing the plume's complex vertical structure. Critical findings enabled only by MLS include:

a) Proof of Deep DNAPL Penetration
MDS data from UW16B showed metolachlor in groundwater at 72 m depth — far deeper than predicted by dissolved-phase transport. Crucially, concentrations did not decrease monotonically with depth; instead, they showed peaks (e.g., at the Eramosa shale unit), indicating DNAPL pooling in horizontal fractures. This vertical fingerprint is a hallmark of DNAPL migration and was completely invisible to conventional wells.

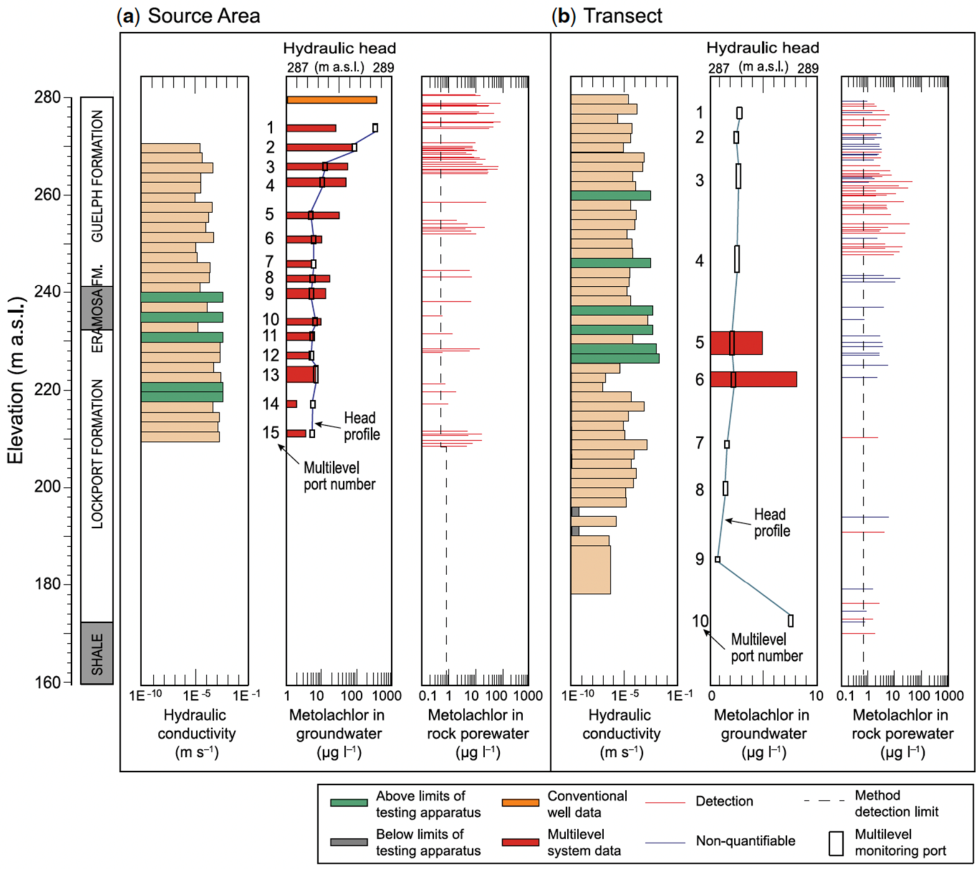

Fig. 9. Hydraulic and chemical data montage for (a) UW16B (source zone) and (b) UW13 (transect). The hydraulic conductivity derived from hydraulic tests performed in intervals isolated by straddle packers shows areas of high transmissivity (green); the lower and upper limits of the apparatus are 5 × 10^{-11} and 5 × 10^{-5} m/s, respectively.Metolachlor concentrations in rock core are present at depth in both coreholes. The absence of metolachlor below 210 m a.s.l. in UW16B is attributed to a higher detection limit for the analysis when the corehole was deepened (from Parker et al., 2018).

b) Quantification of Hydraulic Anisotropy
MDS head profiles revealed a strong downward gradient only in the upper 25 m of bedrock — below which flow was essentially horizontal (Fig 10). This proved that dissolved-phase advection could not transport contaminants to depth. The only viable mechanism: density-driven DNAPL flow. MDS provided the direct field evidence to confirm this.

c) Mechanism for Plume Stability and Attenuation
Down-gradient MDSs (e.g., UW13) showed the plume's maximum concentrations centered around 50–60 m depth, not near the top of the aquifer (Fig 10). Combined with

rock core data, this revealed that DNAPL had rapidly dissolved, with mass diffusing into the rock matrix. Decades later, the persistent, dilute plume is sustained by back-diffusion from the matrix — not by ongoing DNAPL dissolution. MDS data made this process spatially and temporally quantifiable.

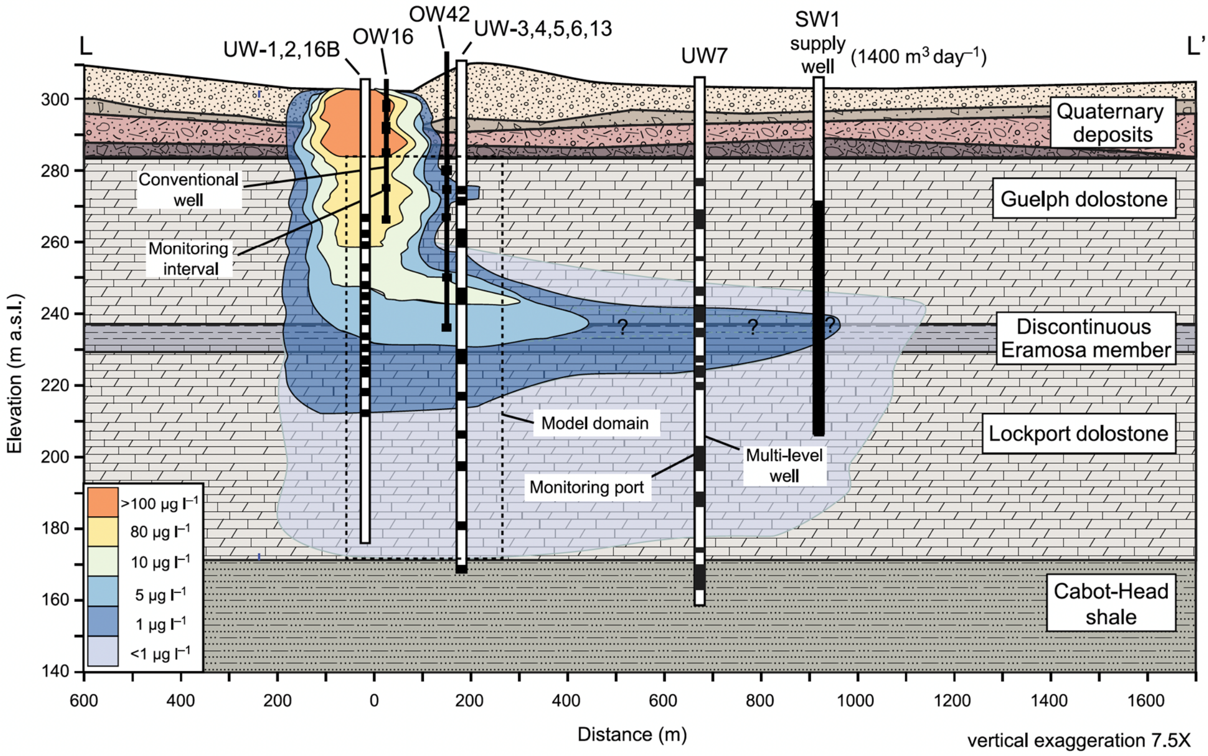

Fig. 10. Vertical long-section across plume-impacted site area from source zone to down-gradient supply well (SW1) showing the relative thickness of the overburden and the dolostone formation. Groundwater concentration contours are inferred from MDSs and conventional well data (from Parker et al., 2018).

In summary, this study demonstrates that MDS is not an incremental tool — it is transformative. Without its depth-discrete resolution, the site would still be misinterpreted as a simple dissolved plume, leading to incorrect predictions of plume expansion and potentially unnecessary remediation. Instead, MDS revealed a complex history of DNAPL penetration, rapid dissolution, matrix diffusion, and long-term back-diffusion — explaining the plume's remarkable stability and allowing safe, continued use of the municipal aquifer. For fractured rock sites, MDS is not optional; it is essential for accurate conceptual modeling and effective management.

7.3 Trapped in Time: MDS Profiling Reveals a 9,000-Year-Old Paleo-Seawater Reservoir Preserved by an Undetected Low-Permeability Laye

MDSs have been employed to investigate groundwater flow and hydrogeochemical processes in the coastal region of the Pearl River Delta, China. Figure 11 displays the core image from a borehole in Mingzhong town in the Pearl River Delta. The borehole is located less than 10 km from the shoreline. The formation consists of organic-rich, low-permeability marine mud deposits.

Figure 12 presents water level depth measurements from a traditional well cluster comprising nine piezometers alongside salinity and hydrogen isotope (δ^2H) profiles based on the water samples obtained using an HKU-MDS nearby. The salinity profile reveals surface values of approximately 5 g/L increasing to 27 g/L below 15 m depth—significantly exceeding modern seawater salinity at the river mouth (15 g/L during dry seasons; Li and Chen, 1998). This anomalous deep-salinity signature, coupled with δ^2H values indicating meteoric water modification in the near-surface zone and seawater-like composition below 15 m. The high salinity cannot be attributed to contemporary seawater intrusion because the current seawater salinity is only 15 g/L. Further ^{14}C dating confirms that groundwater below 20 m exhibits ages of 6–9 ka, demonstrating that this brine represents paleo-seawater entrapped during the Holocene marine transgression (Sheng et al., 2024).

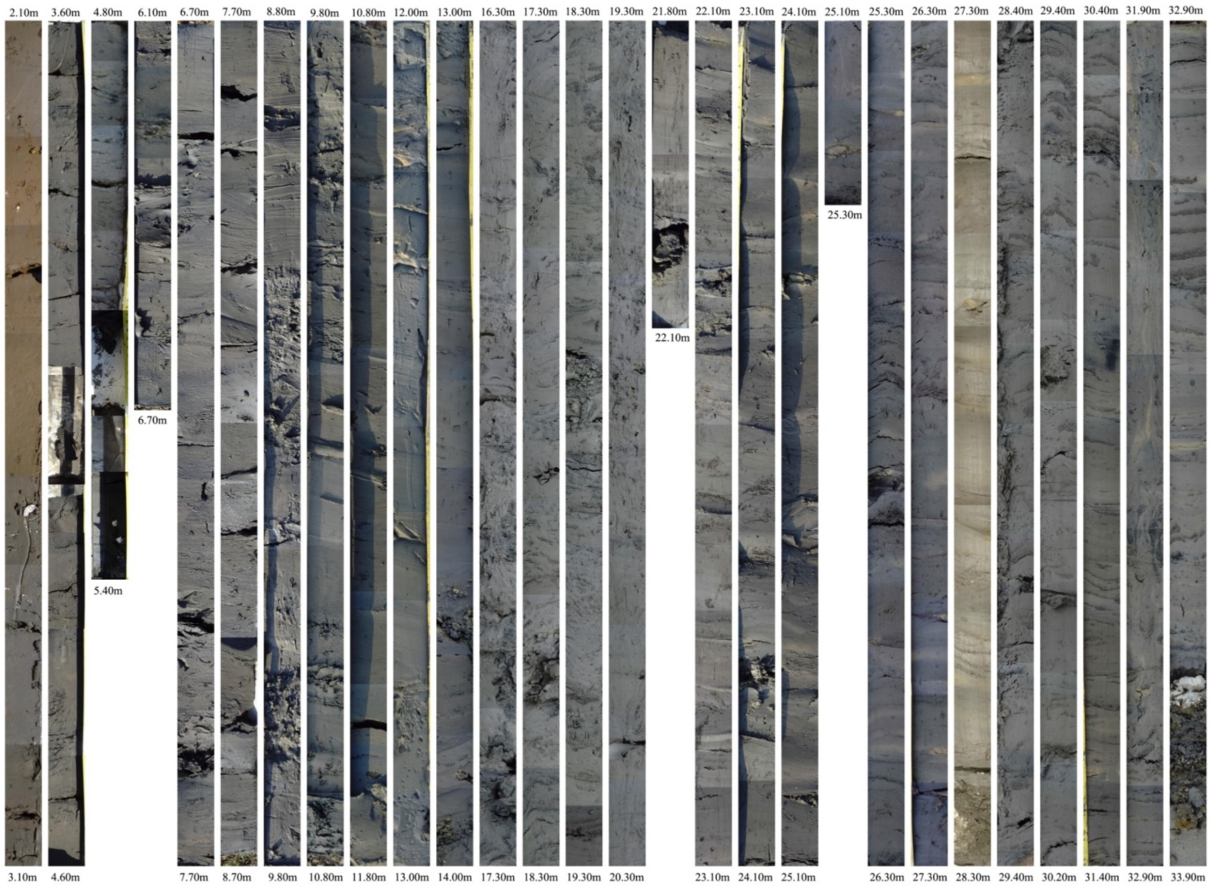

Fig 11 Image of cores from borehole in Mingzhong. It is hard to identify the materails change using naked eyes. Note the yellowish color from 27.30 m to 28.30 m was caused by the flashing of the camera when the photo was taken in the evening.

The water level profile indicates predominantly downward flow throughout the system. Although the core image confirms the generally low-permeability nature of the marine mud, two distinct inflection points around 18 m and 27 m deep suggest the presence of an extremely low-permeability zone spanning roughly 10 m (Fig 12). This critical hydrogeological feature would be virtually undetectable through visual examination of the core alone (Fig 11). This previously unrecognized low-permeability layer likely serves as the key mechanism enabling the preservation of deep paleo-saline groundwater by restricting vertical mixing and protecting the ancient brine from modern freshwater recharge.

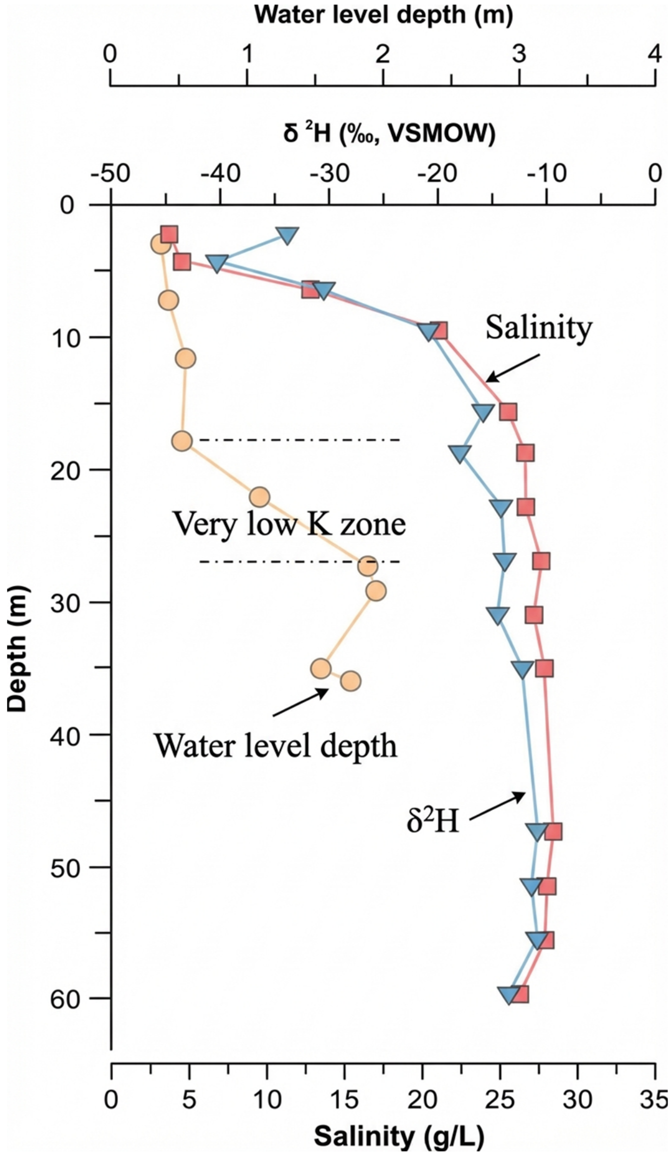

Fig 12. Water level depth, salinity and δ²H change with depth in the marine mud in Mingzhong town, the Pearl River Delta.

This case exemplifies how high-resolution vertical profiling enables critical scientific insights: the HKU-MDS data directly revealed the paleohydrological origin of the brine, redirecting research focus from contemporary intrusion mechanisms to Holocene sea-level change impacts on coastal aquifers. It also shows that the water level profile can provide more reliable information on changes in permeability than visual inspection of aquifers or aquitards based on the cores, as concluded also in the previous case study 7.1.

7.4 Mapping the Subsurface "Plumbing": MDS Data Validates Tóthian Theory by Delineating Hierarchically Nested Flow Systems on the Ordos Plateau

Zhang et al. (2021) present a large-scale field study characterizing hierarchically nested groundwater flow systems using multi-depth water level and geochemical data from two deep wellbores (K1 and K2) on China's Ordos Plateau (Fig 13). The study employed a double-packer system to isolate and sample discrete intervals (~10 sections per borehole) down to ~700 m depth. The hydrogeologic setting comprises a thin, unconfined Quaternary sandy aquifer (<10 m thick) overlying a thick, semi-confined Cretaceous sandstone aquifer. The Cretaceous unit is subdivided into two formations (K_1h and K_1l) with distinct hydraulic conductivities but similar lithology, underlain by an impermeable Jurassic mudstone aquitard. Well K1 is located near H. Lake, while K2 is situated near D. Lake.

Key findings from the depth head profile are: the hydraulic head profile in Well K1 indicates consistent upward flow throughout the borehole, with a distinct inflection point at approximately 360 m depth coinciding precisely with the K_1h/K_1l formation interface—suggesting this geological boundary demarcates a flow system transition (Fig 14). This inflection aligns closely with corresponding trends in the groundwater age profile. In contrast, Well K2 exhibits weak vertical flow between the surface and 500 m depth, with downward flow dominating below this depth. Here, inflection points at approximately 80 m (corresponding to the Quaternary/bedrock interface) and 500 m (corresponding to the boundary between Cretaceous subunits) are corroborated by matching transitions in the groundwater age profile, notably at sampling points K2-5 and K2-6. These depth-dependent patterns in hydraulic head and groundwater age provide critical evidence for identifying flow system boundaries within the nested hierarchy.

By synthesizing hydraulic head, groundwater age, geochemical, and numerical modeling data, Zhang et al. (2021) identified a complex hierarchy of nested flow systems beneath the plateau (Fig 14a). These systems—classified as local, intermediate, and regional—are separated by formation interfaces and stagnation points (SP1 and SP2). Well K1 displays a "classic" vertical sequence (Local → Intermediate → Regional flow), whereas Well K2 reveals a more complex arrangement: two stacked local flow systems overlying a regional system, separated by stagnation point SP2 (Fig 14). Critically, inflection points in depth-dependent age and geochemical profiles provided empirical evidence to delineate these otherwise invisible flow structures.

This study represents the first large-scale field validation of a regional Tothian groundwater flow system (Tóth, 1962) using multi-depth head and chemical data, demonstrating the efficacy of multi-depth deep-well profiling for characterizing subsurface flow architecture.

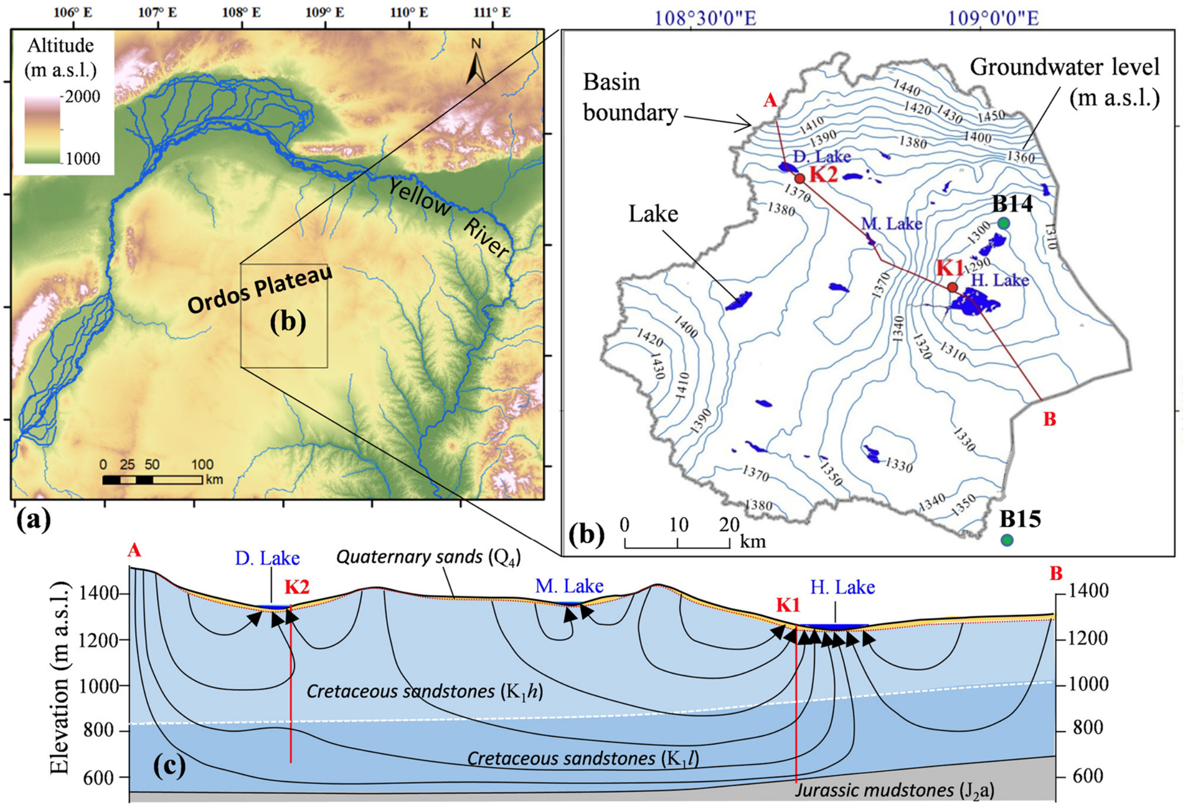

Figure 13 Location map of the study area in Ordos Plateau, China (a), water table contours (b), and speculated flow along the cross-section A-B in the study area based on topography and water level distribution (c) (from Zhang et al., 2021)

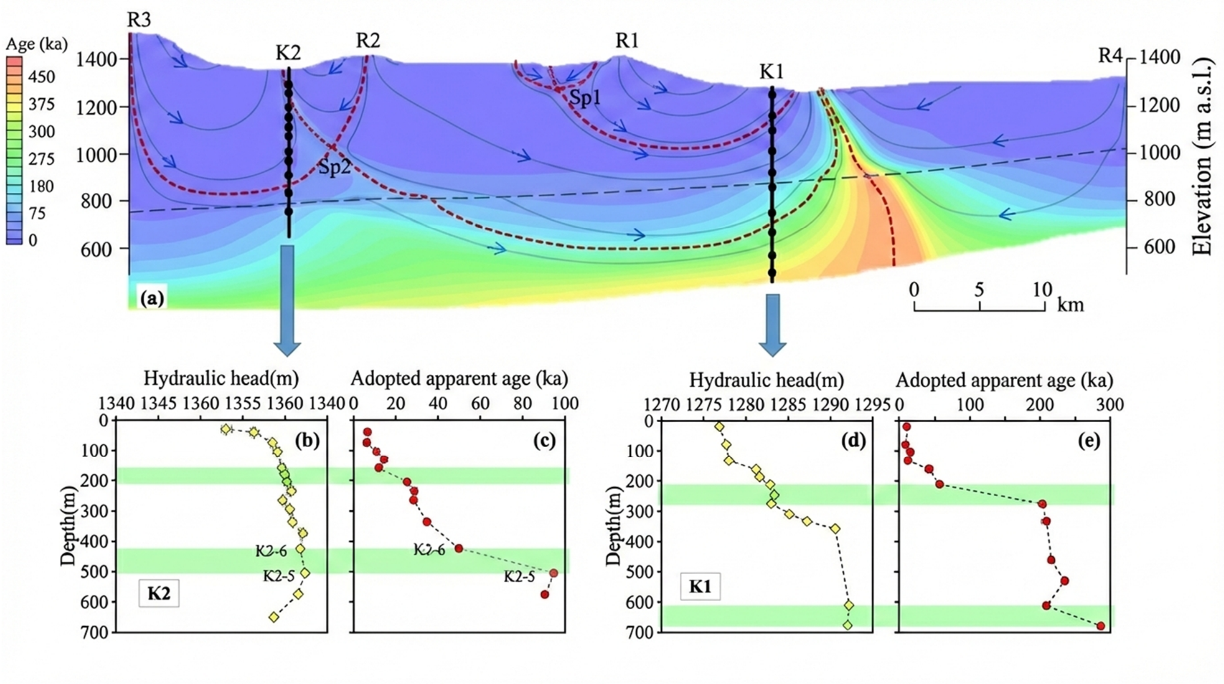

Figure 14. 2D modeling results (a) based on measured water level and groundwater age profiles (b-e) extracted along K1 and K2. The dots along K1 and K2 in (a) are the multi-depth data points and the blue broken line is the boundary between the formation of K_1h and K_1l. The green blocks in (b-e) show the depths of inflection points along the groundwater age profile (from Zhang et al., 2021).

7.5 The SGD End-Member Problem: High-Resolution MDS Sampling Exposes Extreme Geochemical Heterogeneity, Challenging Conventional SGD Estimates

Natural geotracers, particularly radium (Ra) isotopes, have become a fundamental tool for quantifying Submarine Groundwater Discharge (SGD). This methodology, pioneered by marine chemists, typically involves establishing a mass balance budget for radium within a defined coastal study area. The budget equation accounts for various source terms—including riverine input, SGD, desorption from sediments, and diffusion from porewaters—and loss terms, such as radioactive decay and tidal mixing. After quantifying all other fluxes, the remaining radium flux is attributed to SGD. The SGD rate is then calculated by dividing this flux by the concentration of radium in the coastal groundwater, a value known as the "Ra end-member."

Conventionally, the major research effort is devoted to extensive seawater sampling and complex balance analysis. In contrast, groundwater sampling has often been conducted with less rigor and the groundwater end-member value is often determined through convenience sampling, frequently obtained from existing potable wells located far inland within freshwater zones. This practice assumes that samples from wells tens or even hundreds of meters from the shoreline are representative of the geochemically complex aquifer-seawater interface. As noted by Jiao and Post (2019), this approach introduces significant error into SGD flux estimates, as the end-member concentration is a critical divisor in the calculation. Despite this, many SGD studies have historically relied on this simplified method without fully interrogating the intricate spatial distribution of radium within coastal aquifers.

The necessity for a more rigorous approach was compellingly demonstrated by researchers from the University of Hong Kong (Liu et al., 2019). In a study of a beach aquifer in Tolo Harbour, they installed a permanent multi-level sampling system consisting HKU miniature drive-point wells along a transect perpendicular to the shoreline (Fig 15) (Luo et al, 2017). This system, comprising 11 sites with multiple depth-specific sampling ports, allowed for high-resolution characterization of radium isotopes across distinct hydrogeochemical zones: the fresh groundwater zone, the saline-fresh transition zone, and the high-salinity zone.

Data from this MDS (Fig 16) revealed an extreme spatial heterogeneity in radium activities, particularly for 224Ra, which varied by over two orders of magnitude within a small (3 m x 100 m) domain. This finding raises serious concerns about the representativeness of a single, conveniently located groundwater sample. The study suggests that a more appropriate end-member value may be an average or median of measurements taken across the intertidal zone. Critically, it demonstrates that using samples from distant inland wells, which typically yield lower Ra activities, leads to a significant overestimation of SGD flux.

Ultimately, the high-resolution data from the MDS served a catalytic role, challenging entrenched assumptions and shifting the field's focus. It highlighted that an over-reliance on sea-side budget calculations is insufficient; the paramount challenge—and the key to accurate quantification—lies in characterizing the extreme geochemical heterogeneity of the coastal aquifer itself. This underscores a fundamental tenet of science: while the devil is in the details, so too is the discovery. Without embracing this complexity, a false confidence in conventional, yet potentially flawed, estimations of SGD may arise.

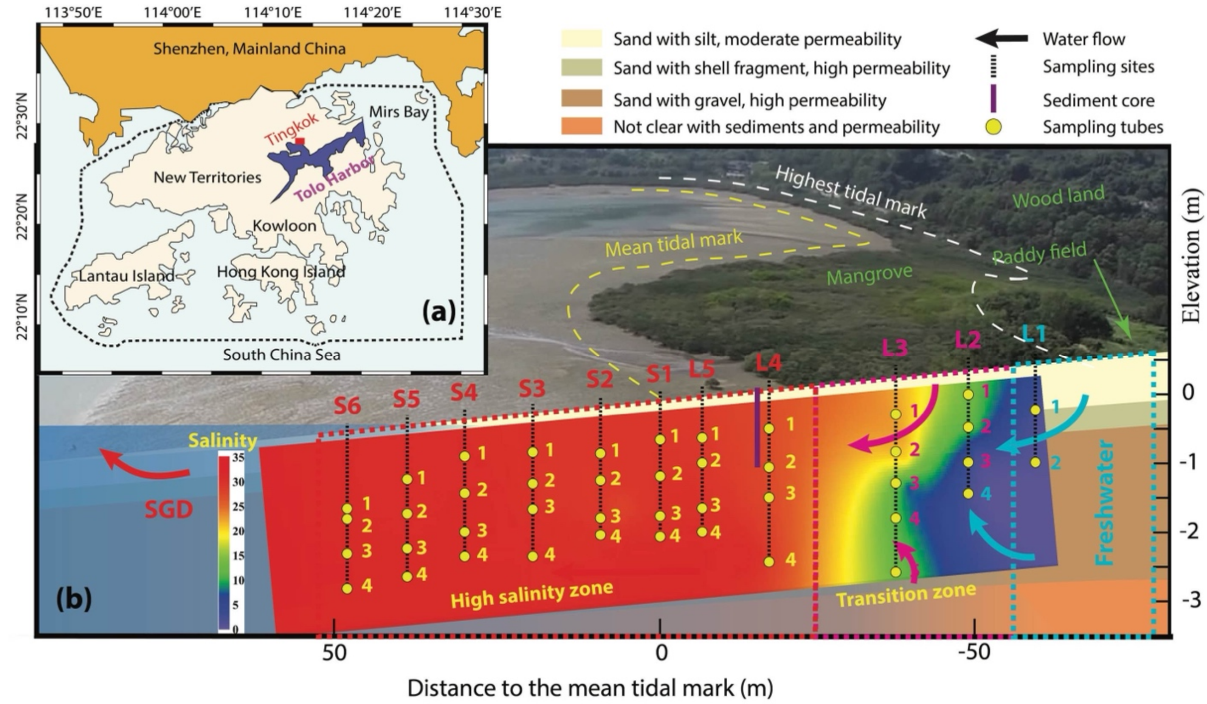

Figure 15 (a) The locations of Tolo Harbor and study site, (b) the location of permanent multi-depth sampling tubes in the sandy aquifer near Ting Kok. The red-blue color contours indicate the salinity distribution in February 2017. Three zones, that is, high salinity zone (red), transition zone (between blue and red), and fresh groundwater zone (blue), are identified according to the salinity distribution (from Liu et al., 2019).

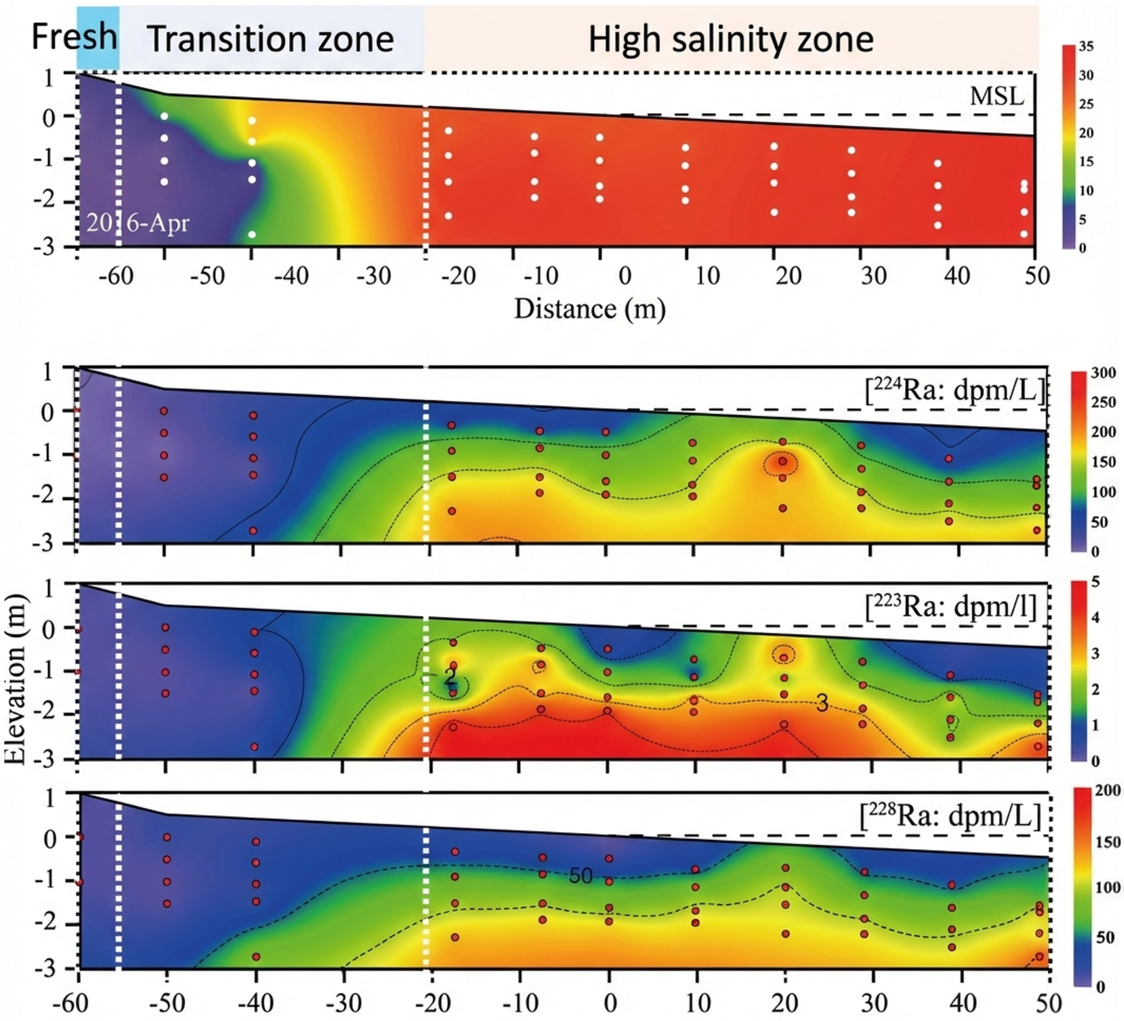

Figure 16 The spatial variation of ^{224}Ra, ^{223}Ra and ^{228}Ra (dpm l^{-1}) on 25 April 2016 measured in samples from a MDS in the beach aquifer of Tolo Harbour, Hong Kong (from Liu et al., 2019).

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).

Liu Y, Jiao JJ, Mao R, Luo X, Liang W, Robinson CE. Spatial characteristics reveal the reactive transport of radium isotopes (224Ra, 223Ra, and 228Ra) in an intertidal aquifer. *Water Resources Research*. 2019 Dec;55(12):10282-302.

Li, Y. and Chen, J.C., 1998. Detection of fronts as paths of river inputs into estuary system, Pearl River estuary, China.

Luo X, Kwok KL, Liu Y, Jiao JJ. A permanent multilevel monitoring and sampling system in the coastal groundwater mixing zones. *Groundwater*. 2017 Jul;55(4):577-87.

Meyer, J.R., Parker, B.L. and Cherry, J.A., 2008 – “Detailed hydraulic head profiles as essential data for defining hydrogeologic units in layered fractured sedimentary rock.” *Environ. Geol*., 56 (1), 27-44.

Parker, B. L., Bairos, K., Maldaner, C. H., Chapman, S. W., Turner, C. M., Burns, L. S., Plett, J., Carter, R., & Cherry, J. A. (2018). Metolachlor dense non-aqueous phase liquid source conditions and plume attenuation in a dolostone water supply aquifer. In U. Ofterdinger, A. M. MacDonald, J.-C. Comte, & M. E. Young (Eds.), *Groundwater in Fractured Bedrock Environments* (Geological Society, London, Special Publications, Vol. 479, pp. 227–258). The Geological Society of London

Patton, F. D., Black, W. H., & Larssen, D. (2025). Field Measurements and Monitoring for Unbiased Visualization of Groundwater Data. *The Groundwater Project*.

Sheng C, Jiao JJ, Zhang J, Yao Y, Luo X, Yu S, Ni Y, Wang S, Mao R, Yang T, Zhan L. Evolution of groundwater system in the Pearl River Delta and its adjacent shelf since the late Pleistocene. *Science Advances*. 2024 Apr 10;10(15):eadn3924.