SCIENTIFIC BRIEFING

HYDROLOGICAL PROCESSES
Hydrol. Process. (2011)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/hyp.8212

An inexpensive and portable drill rig for bedrock groundwater studies in headwater catchments

C. P. Gabrielli*
and J. J. McDonnell

Department of Forest Engineering, Resources and Management, Oregon State University, Corvallis, OR 97331, USA

*Correspondence to:
C. P. Gabrielli, Department of Forest Engineering, Resources and Management, Oregon State University, Corvallis, OR 97331, USA. E-mail: chris.gabrielli@oregonstate.edu

Received 6 February 2011
Accepted 21 June 2011

Abstract

Bedrock groundwater dynamics in headwater catchments are poorly understood and poorly characterized. Here, we present an inexpensive and portable bedrock drilling system designed for use in remote locations. Our system is capable of drilling bedrock wells up to 11 m deep and 38 mm in diameter in a wide range of bedrock types. The drill consists of a lawn mower engine adapted to rotate a diamond tipped coring bit, a small water pump to cool and flush the drill bit and a scaffolding platform for stable footing on steep slopes. The complete drilling assembly costs under $2000 USD. Here, we show proof-of-concept of our approach with 40 successful wells drilled in different geological substrates, including a conglomerate at the Maimai experimental catchment in New Zealand, volcanic breccias at the HJ Andrews experimental watershed in Oregon, USA, sandstone and siltstone at the Alsea watershed in Oregon, USA, and basalt at the Los Gavilanes experimental watershed in Veracruz, Mexico. We also present a transparent comparison between our design and other portable bedrock drilling systems and outline the strengths and weaknesses of each system. Copyright © 2011 John Wiley & Sons, Ltd.

Key Words portable bedrock drill; bedrock groundwater; runoff generation processes; subsurface stormflow

Introduction

Tracer studies have shown the importance of groundwater in storm runoff generation for some time (Crouzet *et al*., 1970; Sklash and Farvolden, 1979). Nevertheless, mechanistic assessment of headwater and groundwater dynamics is still in its infancy. The dominance of headwaters as runoff generation sources and their associated steepness and inaccessibility has made for a difficult combination for such hydrological studies. While tracers continue to be the most common tool to quantify groundwater contributions to headwater streams (Uchida *et al*., 2003), there remains a pressing need to directly access bedrock groundwater in the headwaters to understand its role in stream channel response. Such access to the groundwater in the headwaters is necessary for the understanding of the connectivity of shallow, subsurface stormflow in soil, deeper groundwater dynamics in weathered subsoil and bedrock, and ultimately, how subsurface boundary conditions influence transit time distributions (McDonnell *et al*., 2007).

The location of the headwaters in steep, remote and often roadless terrain limits traditional, commercial well drilling operations. Only a handful of headwater watersheds have been equipped with boreholes into bedrock that enable hydrometric observations of bedrock groundwater dynamics (as noted by McDonnell and Tanaka, 2001). Of these, some have been drilled using truck-mounted commercial drill rigs requiring road access (e.g. Wilson and Dietrich, 1987; Haria and Shand, 2004), while some have been drilled using a hand-held electric hammer drill but were restricted to maximum bedrock depths of only ~1 m (Kosugi *et al*., 2006). Recent bedrock groundwater data reported by Kosugi *et al*. (2008) was a result of a hydraulic feed-type boring machine that travels along a monorail

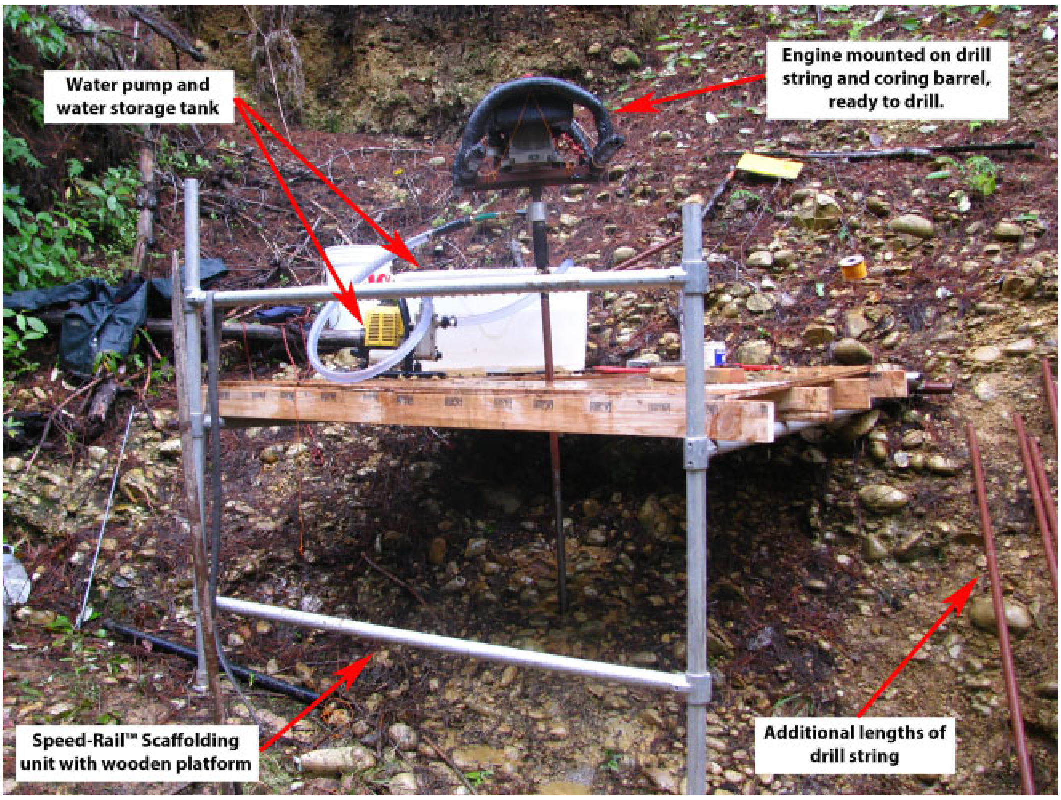


Figure 1. Full drill assembly, platform, water pump, and water storage bins setup at the Maimai experimental catchment in New Zealand. This specific location allowed for drilling directly into bedrock with no overlaying colluvium

system (Kosugi K, personal communication). This system, while excellent, is dedicated to a single catchment and beyond the scope of most research budgets in headwater systems. While portable, less expensive systems have been developed to drill into bedrock (e.g. MacDonald, 1988), these have come with design and safety issues, thus limiting their use. There is currently a pressing need for a portable, safe and inexpensive high-speed drill rig and platform for groundwater studies in the headwaters. Such a system would ideally be able to drill through both soil and bedrock of varying geology and extend at least 10 m below the soil surface.

Here, we present a new bedrock groundwater drill that responds to this need. This system is able to be transported via backpack through steep, roadless terrain in small portable units. The inexpensive high-speed drill rig and platform are suitable for headwater groundwater studies. The objectives of this Scientific Briefing are to:

1. Describe the detailed construction and use of the device to enable others to recreate our system.
2. Describe its effectiveness in drilling through different rock types (including conglomerate, breccia, sandstone, siltstone and basalt) and geologic core acquisition.
3. Compare the attributes to alternative designs and suggest possible improvements for future designs.

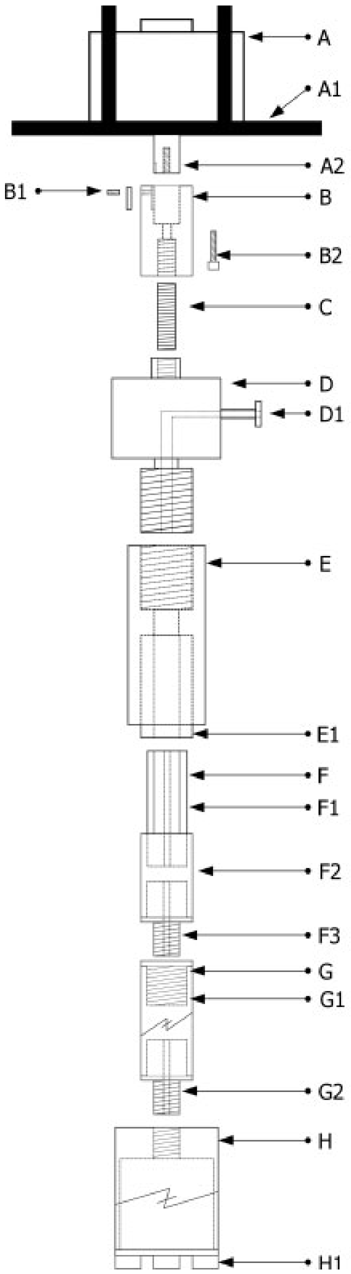
Description

Basic overview

The full drill assembly of our system consists of a gas powered engine, drill string, cutting bit, water pump and a scaffolding frame and platform. A small four-stroke lawn mower engine is adapted to spin hollow metal tubing (drill string) and a diamond tipped coring bit. A water pump provides the necessary water to cool the drill bit and flush away drilling fines, while a Speed-Rail™ scaffolding system supports a plywood platform to provide safe, level footing for drilling on hillslopes of up to 50° (Figure 1).

The ubiquitous nature of push lawn mower engines ensures availability and reduces cost. Units can be found for $150 new or as little as $50 used. The engine is removed from the lawn mower chassis and mounted to a simple metal frame which provides handles for holding and operating the drill (Figure 2A).

The engine output shaft connects to a water swivel which then connects to lengths of drill string. The water swivel transfers rotation from the engine while allowing water to be pumped down the inside of the drill string. The drill string for this assembly is fabricated from lengths of 4130 steel tubing and has custom-fabricated threaded plugs bronze brazed to each end. The plugs allow lengths of drill string to be threaded together as drilling depths advance. A diamond tipped coring barrel



A	**5 HP 4-Stroke push lawnmower engine**. Connected to the frame (A1) through preexisting engine block mounting holes.
A1	**Engine frame**. Constructed from angle iron and mild steel tubing bolted together and wrapped in foam.
A2	**Engine output shaft.** 22.2 mm OD, threaded 3/8"-24* through its axis with 6.4 mm keyway.
B	**Engine Adaptor.** Top portion slips over A2 and is secured in place by a 30 mm long screw with 3/8"-24 thread (B2) that inserts through the bottom of the adaptor. The 6.4 mm key and set screw prevent rotational slippage(B1).
B1	6.4 mm key and ¼ "- 20 setscrew.
B2	**Engine Adaptor Anchoring Screw.** 30 mm long, 3/8"-24 thread.
C	**All-thread.** 55 mm long 5/8" - 11 thread. This piece threads into the bottom of the Engine Adaptor (B) and has approximately 25 mm projecting out from the adaptor for the water swivel (D) to thread onto.
D	**MK Diamond Water Swivel**. 1-1/4"-7 Spindle to 5/8"-11 Female
D1	**Water port.** Water is pumped into the water swivel and into the drill string.
E	**Water Swivel Adaptor.** Top portion is threaded 1-1/4"-7 to accept water swivel. The bottom portion is bored out and a 22 mm impact socket is inserted and welded in place. The center of the adaptor is bored out to allow the passage of water.
E1	**Impact socket.** 22 mm. The OD of the impact socket will vary by manufacturer and the boring in the Water Swivel Adaptor needs to match this size.
F	**Drill String Adaptor**. Constructed from a piece of hex bar (F1), drill string tubing (F2) and a male drill string plug (F3). The lathed end of the hex bar and the drill string plug are bronze brazed to the drill string tubing.
F1	**Hex Bar.** 22 mm hex, 80 mm long with 25 mm of one end lathed to an OD of 22 mm. An 8 mm through hole is bored through the center to allow the passage of water.
F2	**Drill string tubing** (4130 Steel Tubing, 25.4 mm OD, 1.6 mm wall thickness) cut to a length of 80 mm.
F3	**Male drill string plug**. See Figure 3 for additional detail.
G	**Drill String Length.** Drill string is fabricated by bronze brazing male and female drill string plugs to lengths of 4130 Steel Tubing (25.4 mm OD, 1.6 mm wall thickness). Sixty cm, 120 cm, and 240 cm lengths were fabricated.
G1	**Female Drill String Plug**. See Figure 3 for additional detail.
G2	**Male Drill String Plug.** See Figure 3 for additional detail.
H	**Diamond tipped coring bit**. The barrel is 1 m long and has a 38.1 mm OD. The bit threads directly to the drill string.
H1	**Diamond impregnated cutting crown**. The openings allow water and drilling fines to flush from the cutting surface.

*Note: Threaded pieces follow US notation "X-Y" where X is major diameter in inches displayed as a fraction and Y is thread count per inch. As this is a size category, no exact metric equivalent exists.

Figure 2. Drill schematic displaying the individual parts of the drill assembly. Note, drawing is not to scale

threads to the bottom of the drill string and acts as the cutting/grinding portion of the drill assembly. The coring barrel enables recovery of core specimens from each well site which can be analyzed for additional geotechnical data.

Detailed construction

The push lawn mower engine is mounted to a simple metal frame which both protects the engine and provides handholds while operating the drill. The frame is constructed from readily available angle iron and steel tubing and is bolted, rather than welded, together to facilitate disassembly for shipping purposes. Additional machining is avoided using the pre-existing mounting holes on the engine block to attach the frame. The frame configuration will vary based on the mounting pattern of the engine block. The metal frame is wrapped in foam pipe-insulation to absorb engine vibration and ease operation.

The engine output shaft attaches to an MK Diamond™ water swivel via a custom-fabricated adaptor (Figure 2B). The adaptor slides over the output shaft and is secured with a screw inserted through the hollowed axis of the adaptor and threaded into the axis of the output shaft. The lower portion of the adaptor has female thread to fit a length of all-thread. A water swivel threads to the all-thread and is secured to the engine. A second adaptor connects to the output shaft of the water swivel

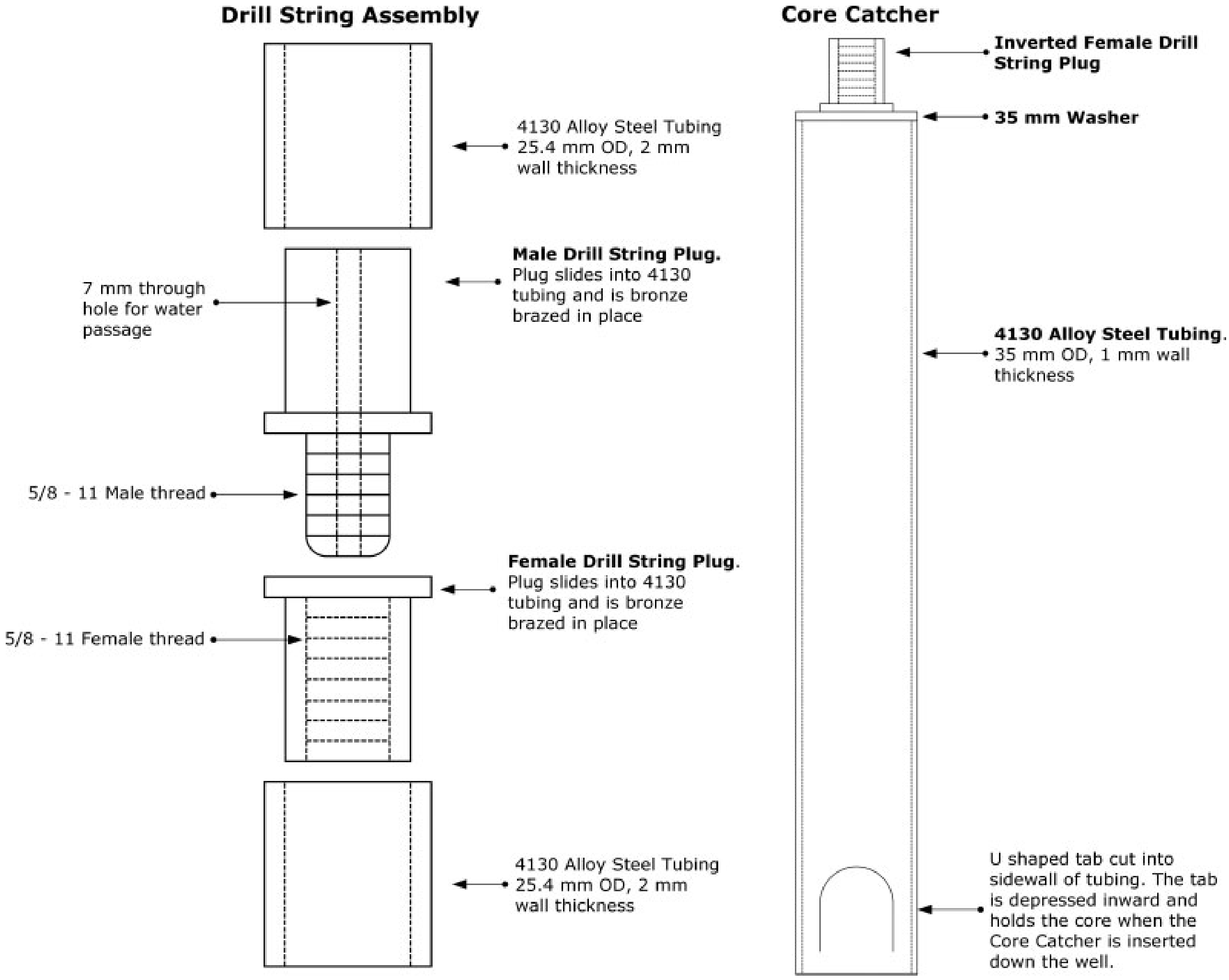


Figure 3. Schematic of drill string components and core catcher components. Note, drawing is not to scale

(Figure 2E). The top end of this water swivel adaptor is female threaded to accept the male thread of the water swivel output shaft. The lower end is bored out to accept a 22·2-mm impact socket which is welded into the adaptor (OD of impact sockets will vary and the adaptor size will need to be adjusted as necessary).

A sliding connection exists between the water swivel adaptor and the subsequent drill string adaptor. This connection serves three purposes: transfer rotation from the engine to the drill string, allow water to pass from the water swivel into the drill string and act as a quick release joint to facilitate adding additional lengths of drill string as drilling advances. The drill string adaptor consists of a short length of drill string tubing with a 22·2-mm hex bar brazed to the top and a male drill string plug brazed to the bottom end (Figure 2F). The hex bar slides into the impact socket of the water swivel adaptor, providing a quick release connection to the main engine assembly. The male drill string plug on the bottom end permits connection to full lengths of drill string. An 8-mm hole is bored through the hex bar to provide a passage for water through the drill string. This design allows for quick and easy removal of the engine when adding additional lengths of drill string as drilling progresses.

Drill string is constructed from 4130 steel tubing (25·4 mm OD, 2 mm wall thickness) and custom-fabricated male and female threaded plugs (machined from 1144 steel bar stock). The plugs are inserted into each end of a length of tubing and bronze brazed into place forming a single drill string length (Figures 2G and 3). These drill string lengths can then be threaded into one another as drilling depths advance. Sixty, 120 and 240 cm lengths were produced. Both the 4130 steel tubing and 1144 steel bar stock can be purchased from local metal dealers or online. Fabrication of these parts should be within the capacity of most local machine shops. Total cost of the drill string is approximately USD $1300 and constitutes the most expensive component of the complete drill system. Brazing of the drill string plugs into the tubing is quite straightforward (and was done by the senior author, who had no previous welding experience).

The drill bit, also known as a core barrel, is a 1-m long barrel with a diamond impregnated cutting crown or segments brazed to its end. The barrel threads directly to the drill string. Cutting crowns consist of diamonds impregnated in a soft metal matrix. As surface diamonds dull, the matrix wears, releasing the dulled diamonds and exposing fresh ones. It is important to match matrix hardness with rock type to ensure optimal drilling performance and bit life. Softer rock requires a harder metal matrix, while harder rock requires a softer matrix. Drill bit manufacturers should be consulted to match crown hardness with bedrock type for optimal drilling performance. Crowns are designed slightly larger in outside diameter and slightly smaller in inside diameter than the coring barrel. This allows the barrel to travel down the borehole and the core to travel up the inside of the barrel with limited sidewall friction.

Coring barrels can be custom ordered to any desired length across an interval of set diameters. It is important to note that the thread size and thread count for drill barrels are set by the industry. Custom-fabricated drill string plugs must match the core barrel thread specifications otherwise an additional adaptor is necessary to connect the two components. Manufacturers can be easily found on the internet. A 38-mm diameter, 1-m barrel was used for most wells, costing approximately $130 with replacement crowns costing $50 each (Pinnacle Construction Products, http://www.PinnacleDiamond.com). Crown wear rate depends on the material being drilled and drilling technique. It was found that a single crown lasts between 20 and 80 m of drilling in most instances. When a crown wears completely, it is lathed off and a new crown is silver brazed in place.

Field operation

The entire drill assembly, platform, water pump and water storage bins are broken down into approximately six carrying units and backpacked into remote field sites. The entire system weighs approximately 100 kg with no single carrying unit weighing more than 20 kg. Once a drill site is located, the drill platform is assembled directly over the site and a pilot hole is placed through the soil mantel with a hand auger. A PVC pipe is inserted into the hole to prevent collapse of the surrounding strata. Water is pumped from a local source to a 120-l holding tank located on the drill platform. A small two-stroke gas powered water pump rated at 5700 l h^{-1} is used for drilling. The drill is setup by connecting the engine, water swivel, drill string and coring barrel together. The engine should start approximately waist high above the platform. The water pump is attached to the water swivel via a short length of garden hose and quick-connect hose fitting. Once the water pump is turned on, the drill is started and drilling commences. While drilling, the operator holds the engine frame and guides the drill as it cuts through the bedrock. A drilling session ends when the engine has progressed down to the level of the platform. The engine is then removed and the drill string is pulled up from the borehole and the core is retrieved. An additional length of drill string is then added and drilling continues.

Two aspects of the design restrict the length to which the operator can advance the drill with each 'drill session'. The first is the starting height of the engine assembly from the platform. Beyond approximately 1 m, the engine is too high for the operator to safely start and run. The second limitation is length of the core barrel. The core that is produced while drilling cannot pass through the joint where the core barrel and drill string connect, thus the rock core must be retrieved each time the core barrel fills to its length. An efficient drill system is achieved when the core barrel is the same length or longer than the maximum height at which the system can be started from the platform (i.e. ~1 m). Under this design, the rock core has to be retrieved at the same interval that additional lengths of drill string are added, reducing the number of times the system has to be assembled and dissembled.

To minimize the number of drill string lengths needed, we recommend that each length be divisible by the maximum length of advancement achievable with each drill session. For example, with this design the drill can be advanced ~0·6 m with each session. A 0·6-m drill string is used for the first advancement then removed and replaced with a 1·2-m length (effectively adding 0·6 m of length). Once advanced, the 0·6-m section is added on top of the 1·2-m section to supply the next 0·6 m increment. Once this section is advanced, both the 0·6- and 1·2-m sections are removed and replaced by a single 2·4 m section. This rotation of drill string sections continues as the well gets progressively deeper and requires that only one 0·6 m length and one 1·2 m length of drill string are needed with all additional lengths being 2·4 m.

Drill rates vary between 0·5 and 0·1 m min^{-1} depending on material being drilled and water supply to the cutting surface. It is important to stress that a constant supply of water is the most essential aspect of effective drilling. Water requirements vary widely depending on bedrock material; however, on average a 6-m well will require approximately 100 l of water. In softer material, drilling rates are faster and a greater rate of water supply is needed to remove the additional cuttings. Although the rate of water use is higher, less time is needed to drill to depth and often the total quantity of water required is less. The opposite is often true of harder material. It is prudent to err on the side of too much water, as a cementing mud is created in water-starved drilling situations and can make removal of the drill string a tedious task. Under this drilling system, used drill water is unable to be recycled for further use as it most often escapes into the surrounding soil column or through fractures in the bedrock.

When removing the drill string from the well to retrieve the core, the core is often lodged inside the core barrel. Tapping the core barrel lightly with a rubber or wooden mallet will easily dislodge the rock fragments. In the instance that the rock core remains at the bottom of the borehole, a device known as a core catcher is used to retrieve the core segments. The core catcher is a thin-walled metal tube (4130 steel tubing, 35 mm OD, 1·0 mm wall thickness) that is slightly larger in diameter than the core, and has a small upside-down U-shaped tab cut into its sidewall near its bottom edge (Figure 3). A female threaded drill string plug is welded to its top, enabling the core catcher to be attached to the drill string and lowered into the borehole. The rock core slides into the core catcher and the depressed U-shaped tab grips the core preventing it from falling out when the assembly is pulled up.

Well completion

Proper completion of the borehole is critical to ensure accurate measurement of groundwater dynamics. Although casing of the entire borehole is not necessary for continuous measurements of the groundwater table, it is recommended for many bedrock types to protect against collapse of the sidewall which may trap instrumentation or render the borehole unusable. Boreholes must be sealed with bentonite or drilling grout at the soil–bedrock interface to prevent direct surface water infiltration into the bore hole. We found that it was advantageous to place the bentonite seal at least 0·6 m into the bedrock to prevent local surface fractures from routing surface water around the seal. A shale trap (i.e. a small flange surrounding the casing) can be attached to the casing at this location to act as a physical barrier that fills the annulus between the well casing and the borehole wall. Bentonite is then backfilled down the annulus and the seal is complete.

Drill locations

We tested the new drill design at four well known and previously described field sites: the Maimai experimental catchment in New Zealand (previously described in detail by McGlynn *et al*., 2002), the HJ Andrews experimental watershed in Oregon, USA (previously described in detail by McGuire and McDonnell, 2010), the Alsea watershed in Oregon, USA (previously described by Ice *et al*., 2003) and the Los Gavilanes experimental watershed in Veracruz, Mexico (previously described by Muñoz-Villers *et al*., 2011). Similar to many headwater research watersheds around the world, these sites were steep (all steeper than 30°) and roadless. Each watershed had different soil mantle depth and bedrock type: firmly compacted, early Pleistocene age conglomerate at Maimai (Mosley, 1979); Oligocene–lower Miocene age breccias and tuffs at the HJ Andrews (Harr, 1977), middle Eocene age marine-derived sandstone and siltstone at Alsea (Lovell, 1969) and Oligocene–Neogene age basalt at Los Gavilenes. We point the reader to the previously published work that describes in detail each of these sites.

Table I. Drilling statistics for various bedrock geologies

Bedrock material	Drill rate ($m\ min^{-1}$)	Maximum depth (m)	Wells drilled
Basalt	0·1	8	5
Breccia	0·1	8	19
Siltstone	0·2	10	3
Sandstone	0·2	10	4
Gravel conglomerate	0·5	8	6
Regolith	1	11	3

Results

Table I shows the results of drilling in different geological substrates and encompasses over 300 m of rock drilled with our system. Drill rates were fastest where rock density was least: we achieved a well drilling rate of 0·2 $m\ min^{-1}$ in sandstone and mudstone; for basalt and breccias, this reduced to 0·1 $m\ min^{-1}$. Maximum drill depth was related to rock hardness, where 10-m wells were easily achievable in sandstone and siltstone, but 8 m was our maximum depth in basalt and breccias. At depths beyond 6 m, vibrations often cause the drill string to bounce off the side of the well walls. Harder bedrock amplifies these vibrations and often renders further drilling impossible. Softer bedrock such as sandstone or conglomerate dampens the vibrations and greater well depths were achieved. In addition, wells were often drilled to target depths rather than maximum attainable depths, such as with cluster wells or to isolate specific fracture zones. Unfractured competent bedrock proved to be the easiest and fastest material to drill through, while fractured material often slowed drilling progress owing to small fragments jamming in the drill bit or between the well walls. Notwithstanding, wells were still attainable in highly fractured bedrock.

Core samples were retrieved after each drill session or when core fragments would jam in the drill bit and prevent further drilling. Harder bedrock types such as breccias or basalt produced large intact core samples as shown in Figure 4 core A. Cores of 200 mm long were common and maximum lengths up to 400 mm were achieved. When drilling intersects fracture zones, core length is determined by fracture density. Significant water-bearing fractures were easy to identify through brown oxidation deposits on the fracture surface (Figure 4 core B, red arrow). Figure 4 core C shows a core segment which has fractured as a result of the drilling process. These fractures occur in areas of weakness and are easy to identify by their clean and unweathered fracture surface.

Softer bedrock types, such as sandstone or conglomerate, often produce small rounded core segments or no

Figure 4. Example of cores retrieved while drilling. These specific cores come from the HJ Andrews experimental site in Oregon, USA. Core A is tuff and core C, breccias, while core B shows a transition between the two lithologies. core B also shows fractures in the bedrock that the well intersected during drilling. The red arrow points to the dark brown oxidized surface of the fracture face. Length of intact core was affected by rock type and fracture density

core at all. The high speed of the drill bit combined with drill water and drilling fines abrade the bedrock core as it is produced. This limits the geologic information that can be inferred from such well sites. Nevertheless, larger scale geologic observations can still be made. For example, if a well site alternates between producing core and not producing core, it can be concluded that significant stratification exists which may influence subsurface water movement.

The local geology at each well site can be reconstructed using the full length of retrieved core. The core can be analysed to produce a well schematic such as the one shown in Figure 5. This well diagram is invaluable as it offers a single visual that displays all of the known information for a well such as soil depth, bedrock type and depth, bedrock stratigraphy, fracture positioning and characteristics, water table characteristics and much more. Understanding the local geology provides insight into possible hydrologic processes that govern movement of bedrock groundwater through the hillslope. The well in Figure 5 is located at the HJ Andrews experimental watershed. It shows significant layering and fracturing in the bedrock and shows very small amplitude in measured water table change. This small amplitude may be because of highly transmissive fractures capping maximum water table rise, or simply because the well is disconnected from local hydrologic processes owing to inactive fractures or competent bedrock. Core analysis shows tight insignificant fractures in the water bearing region of the well, which enables us to conclude that the well is most likely hydrologically inactive rather than in a zone of highly transmissive fractures. Core retrieval has proven to be an invaluable addition to hydrometric data for determining the processes that may govern bedrock groundwater in the headwaters.

Discussion

Comparison to previous portable drill units

Our new design described in this article has proven capable of drilling 40 wells up to 11 m in depth, in multiple geologic materials. Its portability has enabled us to take it around the world to different sites as checked baggage on commercial flights. The four-stroke engine rotates at approximately 2000 rpm making it very efficient at cutting rock. The low torque engine eliminates the danger of throwing the operator, as a jammed drill string will simply bog down the engine and it will harmlessly shut off. In addition, our system has proven itself to be robust and field maintainable, both valuable attributes in remote field locations.

Table II shows a comparison of our system with other available headwater drill systems. The portability of our design contrasts with the stationary monorail system used by Kosugi *et al*. (2008) and allowed us to access remote, roadless catchments and provided the opportunity for multisite comparisons. MacDonald (1988) designed a similar portable bedrock drilling system. It used a two-person auger engine that produced high torque and low revolutions ($\sim$300 rpm; Table II). As the speed of the engine was too slow, it was unable to use the diamond tipped coring bit efficiently and considerably increased drill time over our system. While MacDonald (1988) did not mention safety concerns, use of his system in Montgomery *et al*. (1997) brought safety issues to light (Dietrich W, personal communication). Such high torque engines can pose a safety concern to the operator as a jammed drill string has the potential to throw operators from the drill system.

Safety

Safety is an important aspect of any fieldwork, especially while operating machinery in remote locations. Working in teams of two or more is necessary to ensure operator safety. Entanglement in the drill string poses the greatest hazard; however, its smooth surface reduces this risk and allows for safe operation. As an additional level of safety, a dead man switch was added to the engine. This requires the operator to hold a switch fully engaged while the engine is running. As soon as the switch is released the engine automatically shuts off preventing a 'run away' situation. This switch can be easily wired to most engines. As with the use of any machinery, the operator should be acutely aware of the hazards present and should take all necessary precautions to reduce the risk of injury. Proper personal protective equipment including footwear, eye and ear protection, and gloves are recommended.

Table II. Comparison of different portable bedrock drilling systems and suggestions for alternative designs

	Our system	MacDonald (1988)	Shaw Tools Ltd (Commercial)	Mark Schulze, Andrews HJ (personal communication)	Alternative design 1	Alternative design 2
Engine						
A. Style	**A. Tecumseh™ push lawn mower**	A. 2-Person Power Auger	A. Tanaka™ 270 PFDH Auger	A. Tanaka™ 270 PFDH Auger	A. Tanaka™ 270 PFDH Auger	A. Push lawn mower
B. Type	**B. 4-stroke gasoline**	B. 2-stroke gasoline	B. 2-stroke gasoline	B. 2-stroke gasoline	B. 2-stroke gasoline	B. 4-stroke gasoline
C. RPM	**C. ~1500–2500**	C. ~300	C. ~1900 with modified gear box	C. ~300 unmodified gear box	C. ~1900 with modified gear box	C. ~1500–2000
D. Centrifugal Clutch (CC)?	**D. No**	D. Yes	D. Yes	D. Yes	D. Yes	D. Yes, after market modified
E. Throttle?	**E. No**	E. Yes	E. Yes	E. Yes	E. Yes	E. Yes, after market modified
F. Price	**F. \$50–\$150**	F. \$300–\$500	F. \$1000	F. \$350–\$450	F. \$1000	F. ~\$300, includes modifications
G. Torque	**G. Low**	G. High	G. Low	G. Low	G. Low	G. Low
			Drill String			
A. Type	**A. Custom fab 4130 steel**	A. NQ Drill Rod (Commercial built)	A. Custom stainless	A. Continental tube	A. Continental tube	A. Continental tube
B. Connection style	**B. Custom fab threaded plugs**	B. Threaded	B. Bayonet style	B. Threaded	B. Threaded	B. Threaded
C. Cutting bit[a]	**C. Core barrel**	C. Crown	C. Crown	C. Crown	C. Crown	C. Crown
D. Diameter	**D. 25·4–63·5 mm in 3·2 mm increments**	D. 45 mm	D. 25·4 mm, 50·8 mm	D. 25·4–101·6 mm in 3·2 mm increments	D. 25·4–101·6 mm	D. 25·4–101·6—mm
E. Engine/drill string connection	**E. Quick release via custom fab design**	E. Quick release via custom fabricated design	E. Quick release via bayonet fitting	E. Threaded, non-quick release	E. Quick release via custom fab design or threaded non-quick release	E. Quick release via custom fab design or threaded non-quick release
Water swivel (WS)	**MK Diamond WS, requires custom fab adaptors to fit drill string and engine**	Custom Designed	Commercially designed to accept bayonet fitting	Tanaka™ WS designed to fit engine	Tanaka™ WS designed to fit engine	MK Diamond WS, requires custom fab adaptors to fit engine
Water supply	**2-stroke gas powered water pump**	2-stroke gas powered water pump	Pump style yard sprayer	Pump style yard sprayer	2-stroke gas powered water pump	2-stroke gas powered water pump
Pros	**• Inexpensive • Fast cutting speed • Greatest drilling depth**	• Easy to fabricate • Throttle control • Inexpensive • Simple design	• Commercially designed • Fast cutting speed • Easy to start and run • Throttle control	• All commercial parts • Inexpensive • Easy to start and run • Throttle control	• Inexpensive • Fast cutting speed • Easy to start and run • Throttle control	• Inexpensive • Fast cutting speed • Easy to start and run • Throttle control

Cons	• **Can be difficult to start because of lack of CC** • **No throttle control** • **Custom fabrication**	• High torque is dangerous • Slow cutting speed • Some custom fabrication	• Expensive • May need higher volume water supply for boreholes greater than 25·4 mm (i.e. gas powered water pump)	• Very slow drilling rates • May need higher volume water supply for boreholes greater than 25·4 mm (i.e. gas powered water pump)	• Some custom fabrication, but less than alternative design 2	• Some custom fabrication
Approximate cost	$2000	$1500 ca. 1988	$10 000	$1500	$2200	$1500

[a] A crown cutting bit implies that the rock core can travel the entire length of the drill string *and* the drill string diameter equals the borehole diameter. A core barrel implies that the rock core can only travel the length of the barrel and requires the drill string be pulled from the borehole and the core retrieved each time the drill is advanced the length of the barrel. Borehole diameter is determined by core barrel diameter and not necessarily by drill string diameter.

Alternative future designs

Similar to any mechanical device, design and operation improvements are ongoing. The significant amount of custom fabrication in our system allows for flexibility in design; however, it also increases the complexity. In addition, hand-built drill string cannot achieve the machining accuracy or tolerances of a commercially designed and fabricated drill string. This becomes critical when drilling at greater depths, since all lengths of drill string must be perfectly concentric or the slightest misalignment will cause severe vibration in the system and prevent further drilling. To this end, the purchase of commercial drill string is recommended over custom fabrication. K2 Diamond based out of Torrance, CA carries Continental Tubing™ with adaptors to connect to standard-sized water swivels. This eliminates the need for custom-fabricated drill string and adaptors, and offers a wide variety of drill string diameters.

Four-stroke engines, unlike most two-stroke engines, are not equipped with a centrifugal clutch. A centrifugal clutch allows the engine to start with the drive shaft disengaged. A direct drive engine, such as the one used in our design, rotates the output shaft as the engine is started. The more mass attached to the output shaft, the more difficult it becomes to start the engine. When drilling depths reach greater than 6 m, the mass of the drill string attached to the output shaft begins to inhibit starting the engine. Therefore, an engine with a centrifugal clutch is recommended. After our drill was designed, it was discovered that centrifugal clutches can be easily installed on four-stroke lawn mower engines with minimal difficulty.

Engine speed is a critical aspect of drilling and an output rpm between 1500 and 2000 is most desired. Slower outputs of ~300 rpm, however, are most common for two-stroke engines designed for drilling or auguring. Four-stroke lawn mower engines have a standard engine output of ~1500–2000 rpm with no engine modification. This optimal engine output combined with their ubiquitous nature and low cost make them an attractive option in a drill design. These engines, however, do not have a centrifugal clutch and also require a custom-fabricated adaptor to join to the water swivel. The price of a four-stroke lawn mower engine modified with a centrifugal clutch and a custom-fabricated adaptor to fit the engine and water swivel is on the order of $300.

Lastly, Table II offers two alternative designs that we believe would be successful in the future. These alternatives are based on the strengths and weaknesses of all previous designs and balance ease of fabrication, cost and ease of field use to produce a drill which rivals current designs. The commercial system sold by Shaw Tool Ltd (http://www.backpackdrill.com/) offers a readymade, efficient and easy-to-use system. The two-stroke Tanaka™ engine has been modified by Shaw Ltd to output at ~1900 rpm, which allows for much greater

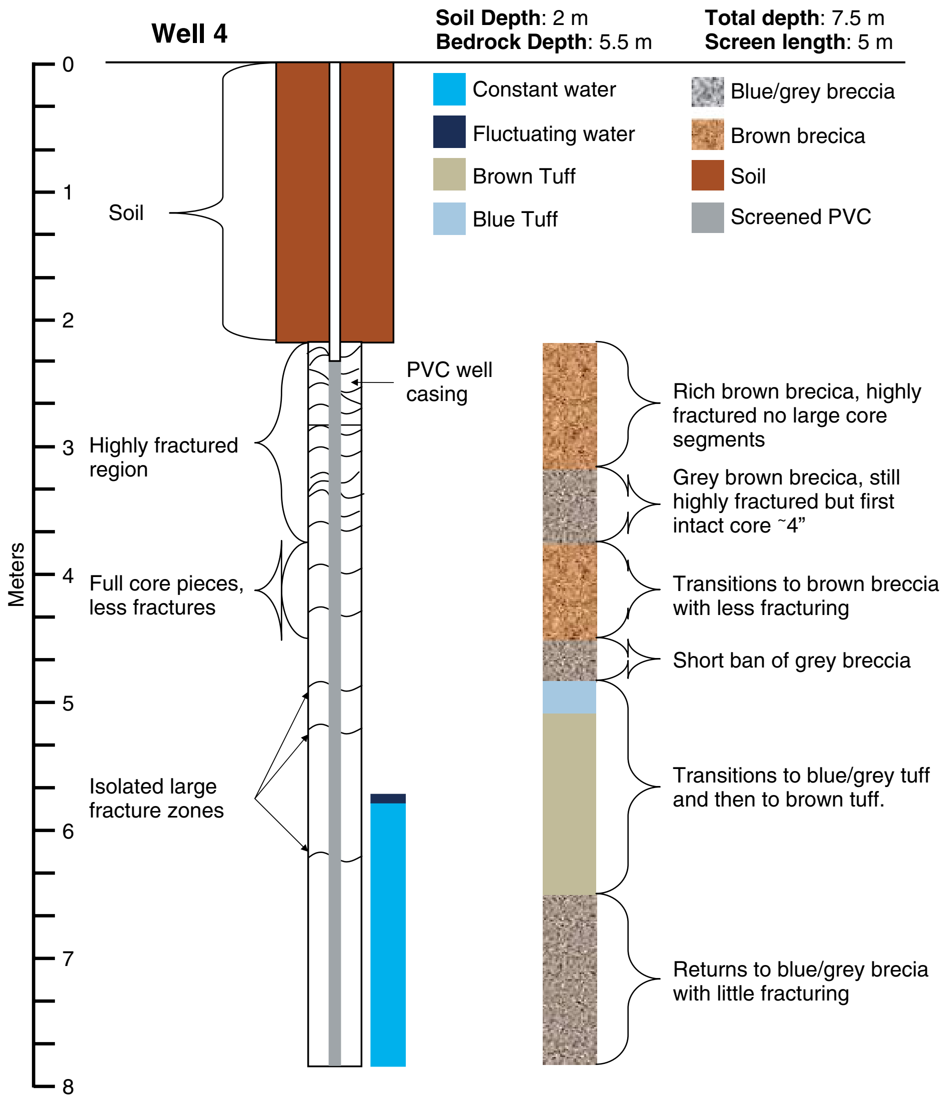


Figure 5. Example of a well schematic that can be assembled from the geologic and fracture data obtained from core retrieval. This well description comes from the HJ Andrews experimental site in Oregon, USA and displays the basic well characteristics such as soil and bedrock depth, bedrock type, stratification, and fracture location and density. Hydrometric data is also displayed, showing the depth of a permanent water table as well as its range of fluctuation

drilling speeds. The system, however, is designed as a prospecting tool where smaller diameter (25·4 mm) and shallow depth bore holes are desired. Larger diameter and greater depth boreholes are still possible, in theory. The Shaw unit costs approximately $10 000. This is in contrast with the cost of our system—on the order of $1300 for the drill string and adaptors, $300 for the water pump and lawn mower engine, $150 for the water swivel, $200 for the core barrel and replacement crowns and an additional $200 for other basic supplies for a total cost of approximately $2000.

Researchers at the HJ Andrews Experimental Forest have recently built a drill system based off the Shaw Design (Table II). However, it uses an unmodified Tanaka™ engine and a drill string manufactured by Continental Tubing™ rather than Shaw's proprietary design (Schulze M, personal communication). The system is inexpensive and easy to use; however, the slow rotation of the engine (~300 rpm) considerably increases drilling time. Drill rates are on the order of 0·015 m min^{-1} as opposed to 0·1 m min^{-1} with our design, a reduction in drilling speed of almost 700%.

Conclusions

The drill system presented in this article represents a qualitative advancement for a safe, inexpensive, high-speed drill rig and platform for groundwater studies in the headwaters. Our system has been successful in drilling 40 test holes totalling >300 m of drilling length and in a variety of bedrock material including basalt, breccias, sandstone, siltstone and conglomerate. Moreover, the system has been flown as standard luggage to international field research sites. The drill unit as outlined in this Scientific Briefing can be easily reproduced with little or no mechanical or metal-working background. The overall price may be reduced greatly if local resources allow for a design which does not rely so heavily on custom-fabricated parts.

Acknowledgements

We thank Milo Claussen for his guidance and knowledge through the design and fabrication of the drill system. Todd Jarvis is thanked for his comments along the way. Adan Hernandez, Sergio CruzMartinez, Lyssette Munoz and Friso Holwerda assisted with drilling in Mexico; Rosemary Fanelli, Cody Hale and Tina Garland in Oregon and Marcel Marceau and John Payne in New Zealand. All prices quoted are in USD at the time of writing. Use of trademarks and trade names does not imply endorsement. This work was sponsored by NSF Grant NSF/DEB 0746179.

References

Crouzet E, Hubert P, Olive PH, Siwertz E, Marce A. 1970. Le Tritium dans les mesures d'hydrologie de surface. Détermination expérimentale du coefficient de ruissellement. *Journal of Hydrology* **11**: 217–229.

Haria A, Shand P. Evidence for deep sub-surface flow routing in forested upland Wales: implications for contaminant transport and stream flow generation. *Hydrology and Earth System Sciences* **8**: 334–344.

Harr RD. 1977. Water flux in soil and subsoil on a steep forested slope. *Journal of Hydrology* **33**: 37–58.

Ice GG, Schoenholtz S. 2003. Understanding how extremes influence water quality: experience from forest watersheds. *Hydrological Science and Technology* **19**: 99–107.

Kosugi K, Katsura S, Katsuyama M, Mizuyama T. 2006. Water flow processes in weathered granitic bedrock and their effects on runoff generation in a small headwater catchment. *Water Resources Research* **42**: DOI: 10.1029/2005 WR004275.

Kosugi K, Katsura S, Mizuyama T, Okunaka S, Mizutani T. 2008. Anomalous behavior of soil mantle groundwater demonstrates the major effects of bedrock groundwater on surface hydrological processes. *Water Resources Research* **44**: W01407. DOI:10.1029/2006WR005859.

Lovell JPB. 1969. Tyee formation: underformed turbidities and their lateral equivalents: minerology and paleogeography. *Geological Society of America Bulletin* **80**: 9–22.

MacDonald LH. 1988. An inexpensive, portable system for drilling into subsurface layers. *Soil Science Society of America Journal* **52**: 1817–1819.

McDonnell JJ, Sivapalan M, Vache K, Dunn S, Grant G, Haggerty R, Hinz C, Hooper R, Kirchner J, Roderick ML, Selker J, Weiler M. 2007. Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology. *Water Resources Research* **43**: 359–389. DOI:10.1029/2006WR005467.

McDonnell JJ, Tanaka T. 2001. On the future of forest hydrology and biogeochemistry. *Hydrological Processes* **15**: 2053–2055.

McGlynn B, McDonnell JJ, Brammer D. 2002. A review of the evolving perceptual model of hillslope flowpaths at the Maimai catchment, New Zealand. *Journal of Hydrology* **257**: 1–26.

McGuire KJ, McDonnell JJ. 2010. Hydrological connectivity of hillslopes and streams: characteristic time scales and nonlinearities. *Water Resources Research* **46**: W10543. DOI:10.1029/2010WR009341.

Montgomery DR, Dietrich WE, Torres R, Anderson SP, Heffner JT, Loague K. 1997. Hydrologic response of a steep, unchanneled valley to natural and applied rainfall. *Water Resources Research* **33**: 91–109.

Mosley MP. 1979. Streamflow generation in a forested watershed, New Zealand. *Water Resources Research* **15**: 795–806.

Muñoz-Villers LE, Holwerda F, Gómez-Cárdenas M, Equihua M, Asbornjsen H, Bruijnzeel LA, Marín-Castro BE, Tobón C. 2011. Water balances of old-growth and regenerating tropical montane cloud forests in central Veracruz, Mexico. *Journal of Hydrology, Special Issue on Tropical Hydrology*. In press.

Sklash MG, Farvolden RN. 1979. The role of groundwater in storm runoff. *Journal of Hydrology* **43**: 45–65.

Uchida T, Asano Y, Ohte N, Mizuyama T. 2003. Seepage area and rates of bedrock groundwater discharge at a granitic unchanneled hillslope. *Water Resources Research* **39**: 1018–1129. DOI: 10.1029/2002WROO1298.

Wilson CJ, Dietrich WE. 1987. The contribution of bedrock groundwater flow to storm runoff and high pore water pressure development in hollows. *International Association of Hydrological Sciences Publication* **165**: 49–59.