

AN ABSTRACT OF THE THESIS OF

Christopher P. Gabrielli for the degree of Master of Science in Water Resources Engineering presented on October 17, 2011

Title: The Role of Bedrock Groundwater in Rainfall-Runoff Response at Hillslope and Catchment Scales

Abstract approved:

Jeffrey J. McDonnell

Bedrock groundwater dynamics in headwater catchments are poorly understood and poorly characterized. Direct hydrometric measurements have been limited due to the logistical challenges associated with drilling through hard rock in steep, remote and often roadless terrain. Here we develop and use an inexpensive, portable bedrock drilling system to explore bedrock groundwater dynamics aimed at quantifying bedrock groundwater contributions to hillslope flow and catchment runoff. We present results from Watershed 10 (WS10) at the HJ Andrews Experimental Forest in Oregon and at the Maimai M8 research catchment in New Zealand. WS10 is underlain by weathered and fractured tuff and breccias, while Maimai is underlain by a moderately weathered conglomerate composed of clasts of sandstone, granite and schist in a clay-sand matrix. Analysis of bedrock groundwater levels at Maimai, through a range of flow conditions, showed that the bedrock water table remained below the soil-bedrock interface, suggesting that bedrock groundwater has minimal direct contributions to hillslope runoff. However, groundwater levels did respond significantly to storm events indicating that there is a direct connection between soil water and the

underlying bedrock aquifer. WS10 groundwater dynamics were dominated by fracture flow. Preliminary findings show a highly fractured and transmissive region within the upper 1 meter of bedrock that acts as a corridor for rapid lateral subsurface stormflow and lateral discharge. The interaction of subsurface storm flow within bedrock has implications for hillslope response, mean residence time and solute transport. This research shows bedrock groundwater to be an extremely dynamic component of the hillslope hydrological system and comparative analysis outlines the potential range of hydrological and geological controls on runoff generation in headwater catchments.

©Copyright by Christopher P. Gabrieli
October 17, 2011
All Rights Reserved

The Role of Bedrock Groundwater in Rainfall-Runoff Response at Hillslope and
Catchment Scales

by
Christopher P. Gabrielli

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented October 17, 2011
Commencement June 2012

Master of Science thesis of Christopher P. Gabrielli
presented on October 17, 2011

APPROVED:

Major Professor, representing Water Resources Engineering

Director of the Water Resources Graduate Program

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Christopher P. Gabrielli, Author

ACKNOWLEDGEMENTS

I need to thank my advisor, Jeff McDonnell, for taking a chance on an unknown wood scientist who one day knocked on his door looking for a way into the world of Hydrology. Jeff has provided me with more opportunities and experiences over the last few years than I could have ever imagined and I am grateful for his unending support and his infectious passion for science and research. Thank you, Jeff.

When I sat down in Jeff's office on Day 1 and agreed to build this bedrock drilling machine, I had no idea I was secretly signing a contract with the drilling-devil. Drilling bedrock is by no means an easy task, and it is also by no means a 1-person task. I have to thank everyone who has ever shared even a single moment on the drilling platform with me. Your help, assistance, and support were more valuable than I am able to express. Specifically, I need to thank Adan and Sergio who labored with me through the steep wet terrain of Mexico and who were endlessly willing to help and learn. You two are an inspiration. Thank you also to Lysette and Friso for providing me the opportunity to drill in Mexico, helping in the field and making the whole trip fantastic. Thank you to Rosemary Fanelli and Travis Roth for drilling with me at the HJA; Tina Garland, Cody hale, Aimee Brown and Jeff Hazboun for help in the Coast Range; Marcel Marceau, for your tea breaks and friendship through the cold, wet days at the Maimai; Maarten Smoorenburg and Nina Volze for giving me the opportunity to see Drill 2.0 come to life and for sharing the Swiss mountains with me. I want to thank the amazing people at the HJ Andrews: Terry, Kathy, John and others, you have all made your mark on this project in one form or another and I thank you so

much for always welcoming me and for sharing the magic that is the HJ Andrews. Thank you to Todd Jarvis for his thoughtful discussions and challenging questions that always kept me on my toes and forced me to critically analyze my work. Thank you to John Payne at Landcare New Zealand for your help showing me around Maimai getting me on my feet on the other side of the world. A big thanks to Ross Woods and Hillary McMillan at NIWA in Christchurch for their support, guidance, and use of equipment during my stay in New Zealand. Thank you to my other committee members, Kellie Vache and Chris Surfleet for your encouragement and thoughtful comments. I also want to thank Paris Edwards, Iris Pitt, Michael Schwab and Cristina Mateus for field help at the HJA.

Milo Clauson needs to be recognized above all others as the key to the success of the drill. I walked out of Jeff's office after agreeing to build the drill and I went straight to Milo and begged for help. Milo guided me through every aspect of construction, drafted prints for custom fabricated parts, taught me how to weld and braze, passed on his knowledge of metals and even donated the lawnmower engine that still powers the unit today. Thank you Milo, you are a great friend.

I am most grateful for my friends and family that have surrounded and supported me through 5 dislocated shoulders and 3 shoulder surgeries during the course of this degree. It is because of you that I have kept a positive attitude and a smile on my face despite the hard times I have endured.

Financial support for my graduate program was provided by NSF Grant NSF/DEB 0746179 and a fellowship through the College of Forestry at Oregon State University.

CONTRIBUTIONS OF AUTHORS

Chapter 1: Jeff McDonnell provided writing guidance and editing.

Chapter 2: Todd Jarvis assisted with data interpretation and provided guidance with the development of our perceptual model, as well as manuscript reviews. Jeff McDonnell provided critical guidance with manuscript development through discussions and editing and manuscript revisions.

TABLE OF CONTENTS

	<u>Page</u>
1 INTRODUCTION	1
1.1 INTRODUCTION	2
1.2 DESCRIPTION OF CHAPTERS.....	4
1.2.1 Chapter 1. An Inexpensive and Portable Drill Rig for Bedrock Groundwater Studies in Headwater Catchments	4
1.2.2 Chapter 2. The Role of Bedrock Groundwater in Rainfall-Runoff Response at Hillslope and Catchment Scales	5
1.3 REFERENCES	6
2 AN INEXPENSIVE AND PORTABLE DRILL RIG FOR BEDROCK GROUNDWATER STUDIES IN HEADWATER CATCHMENTS	8
2.1 INTRODUCTION	9
2.2 DESCRIPTION	11
2.2.1 Basic Overview	11
2.2.2 Detailed Construction.....	12
2.2.3 Well Completion	15
2.2.4 Drill Locations	15
2.3 RESULTS	16
2.5 DISCUSSION.....	18
2.5.1 Comparison To Previous Portable Drill Units	18
2.5.2 Safety.....	19
2.5.3 Alternative Future Designs	20
2.6 CONCLUSIONS	23
2.7 ACKNOWLEDGMENTS	23
2.8 REFERENCES	24
3 THE ROLE OF BEDROCK GROUNDWATER IN RAINFALL-RUNOFF RESPONSE AT HILLSLOPE AND CATCHMENT SCALES.....	35
3.1 INTRODUCTION	36
3.2 STUDY SITES	40
3.2.1 Maimai M8.....	41
3.2.3 HJ Andrews WS10.....	42
3.3 methods.....	44
3.3.1 Maimai M8.....	45
3.3.3 HJ Andrews WS10.....	48
3.4 RESULTS	50
3.4.1 Bedrock structure	50
3.4.1.1 Maimai M8 Bedrock Structure	50
3.4.1.2 HJ Andrews WS10 Bedrock Structure	52
3.4.2 Groundwater Dynamics	53
3.4.2.1 Maimai M8 Groundwater Dynamics	53

TABLE OF CONTENTS (CONTINUED)

	<u>Page</u>
3.4.2.2 HJ Andrews WS10 Groundwater Dynamics	56
3.4.3 Bedrock Groundwater Contributions to Hillslope Discharge	59
3.4.3.1 Bedrock Groundwater Contributions at Maimai M8.....	59
3.4.3.2 Bedrock Groundwater Contributions at HJ Andrews WS10.....	60
3.5 DISCUSSION.....	61
3.5.1 An Evolving Perceptual Model of Hillslope Hydrology at Two Benchmark Sites	61
3.5.1.1 Maimai M8	61
3.5.1.2 HJ Andrews WS10	65
3.5.2 Similar Hillslope Forms Can Hide Radically Different Plumbing	68
3.5.3 Final remarks.....	73
3.6 CONCLUSION.....	74
3.7 ACKNOWLEDGEMENTS.....	76
3.8 REFERENCES	76
4 CONCLUSIONS.....	96
4.1 CONCLUSIONS	97
4.2 FUTURE WORK.....	98
5 BIBLIOGRAPHY	99

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
2.1 Full drill assembly.....	29
2.2 Drill schematic	31
2.3 Schematic of drill string components and core catcher components	32
2.4 Example of cores retrieved while drilling.....	33
2.5 Example of a well log	34
3.1 Vicinity and catchment map.....	85
3.2 Profile of instrumented hillslopes	87
3.3 Water table elevation data.....	89
3.4 Relationship between runoff and change in water table	91
3.5 Isotopic time series data.....	93
3.6 Perceptual models	95

LIST OF TABLES

<u>Table</u>	<u>Page</u>
2.1 Drilling statistics for various bedrock geologies.....	26
2.2 Comparison of different portable bedrock drilling systems.....	27
2.3 Suggested alternative designs	28
3.1 M8 and WS10 hillslope and catchment characteristics.....	83
3.2 M8 and WS10 well characteristics.....	84

1 INTRODUCTION

1.1 INTRODUCTION

Process understanding of the rainfall-runoff response of steep hillslopes and headwater catchments has evolved greatly since the early work of Hursh (1936). Early reviews (Dunne, 1978) and more recent reviews (Bachmair and Weiler, 2011; Bonell, 1998) have chronicled the development of ideas on rapid subsurface stormflow development and the integration of individual hillslope responses that create the catchment response. Despite extensive research that has revealed dominant processes in different environments, the majority of the work to date has focused exclusively on lateral flow in the soil mantle (Buttle, 1998; Hewlett and Hibbert, 1967; McDonnell, 1990; Tsuboyama et al., 1994).

Early work by Wilson and Dietrich (1987) in a zero order hollow in California showed the potentially significant hydrologic influence of underlying bedrock in rainfall-runoff delivery at the hillslope scale. Later work at the Coos Bay Oregon site by Montgomery et al. (1997) and Anderson et al. (1997) also noted subsurface flow paths that traversed the soil and bedrock zones in steep unchanneled slopes. More recently, Kosugi (2008), building upon other important work in Japan (Katsuyama et al., 2005; Onda et al., 2001; Uchida et al., 2003), showed the importance of bedrock groundwater in a granitic catchment in Central Japan.

Despite growing awareness of the potential significance of bedrock groundwater to hillslope and catchment hydrology, there still remains a very limited number of studies that have monitored hillslope groundwater in competent and fractured bedrock (McDonnell and Tanaka, 2001). Access remains the key logistical

hurdle limiting studies in the characteristically steep, unstable, and often roadless headwater terrain. Where access has been limited, many studies have inferred catchment groundwater dynamics through intensive studies of spring discharge, rather than direct measurements taken within the bedrock itself (Iwagami et al., 2010; Katsuyama et al., 2005; Uchida et al., 2003). While useful, these point-based spring studies limit our ability to conceptualize the dynamics of internal bedrock groundwater and its connection to hillslope processes in the soil mantle. Indeed, in hillslope and catchment hydrology we struggle to know more generally the involvement, if at all, of bedrock groundwater in forming saturation at the soil-bedrock interface where large anisotropy and rapid generation of lateral subsurface stormflow has been widely observed (Weiler et al., 2006). We lack, particularly at previously well-monitored and well-documented sites, an understanding of how bedrock groundwater couples to rapid event runoff generation and flow sustenance in the stream between events.

Here we tackle fundamental questions of bedrock groundwater contributions through a comparative analysis of two well-studied hillslopes. We capitalize on a new portable drill system developed by Gabrielli and McDonnell (2011) that offers an inexpensive solution to the bedrock groundwater inaccessibility issue in remote headwaters. Capable of drilling wells up to 10 m deep in a variety of geological formations (colluvium, saprolite, competent and fractured bedrock), this drill system can be carried into field sites, previously inaccessible by standard truck mounted drill rigs. Few, if any bedrock groundwater studies to date have been conducted at sites with rich histories of hillslope experimental studies. We investigate how bedrock

structure affects hillslope response to storm events at the M8 experimental hillslope and catchment at Maimai in New Zealand, and the Watershed 10 experimental hillslope and catchment at the HJ Andrews in the Cascade Range in Oregon, USA. Beven (2006) has characterized each site as benchmarks in the field; Maimai for its quintessential wet, steep, humid, forested catchment and early foundational work by Mosely (1979) and the HJ Andrews as another such wet, steep, humid, forested catchment and early foundational work by Harr (1977).

1.2 DESCRIPTION OF CHAPTERS

1.2.1 Chapter 1. An inexpensive and portable drill rig for bedrock groundwater studies in headwater catchments

The focus of Chapter 1 is on the development and use of an inexpensive portable bedrock drilling system designed specifically for roadless terrain where access limits more traditional truck mounted drilling systems. We highlight the need for a better understanding of bedrock groundwater dynamics in the headwaters and offer a detailed technical paper outlining the basic components and construction of our drill unit, as well as noting its success in drilling more than 40 wells in a range of bedrock geologies. We provide a comparative analysis with previous and current portable drill designs, and offer possible alternative designs for future development. Specifically, the goals of this chapter are to:

- A. Describe the detailed construction and use of the portable bedrock drill.

- B. Describe the portable bedrock drill's effectiveness in drilling through different rock types, including conglomerate, breccia, sandstone, siltstone and basalt, including geologic core acquisition.
- C. Compare the attributes to alternative portable bedrock drill designs and suggest improvements for future designs.

1.2.2 Chapter 2. The role of bedrock groundwater in rainfall-runoff response at hillslope and catchment scales

Chapter 2 characterizes the bedrock groundwater dynamics at two benchmark catchments and highlights the important influences of bedrock structure on lateral subsurface stormflow generation at the hillslope scale. We utilized the drill described in Chapter 1 to drill wells up to 9 m into bedrock at the M8 experimental hillslope and catchment at Maimai in New Zealand, and the Watershed 10 experimental hillslope and catchment at the HJ Andrews in the Cascade Range in Oregon, USA. Through time series analysis of water table fluctuations and through structural analysis of well logs and bedrock cores we address the following questions:

- A. What are the features and structure of bedrock that drive interactions between bedrock groundwater (BGW) and hillslope hydrology?
- B. How do the BGW tables react to storm events? More specifically, what are the time lags between the beginning of a storm event and the response to the water table in the bedrock (peak to peak, event initiation to response initiation) and what is the effect of precipitation on the magnitude and rate of BGW change?
- C. Does BGW contribute directly to hillslope discharge (trenchflow)?

Overall, this thesis and the compilation of Chapters 1 and 2 provide insight into the role of bedrock groundwater in rainfall-runoff response at hillslope and catchment scales.

1.3 REFERENCES

- Anderson, S.P. et al., 1997. Subsurface flow paths in a steep, unchanneled catchment. *Water Resour. Res.*, 33(12): 2637-2653.
- Bachmair, S., Weiler, M., 2011. New Dimensions of Hillslope Hydrology Forest Hydrology and Biogeochemistry. In: Levia, D.F., Carlyle-Moses, D., Tanaka, T. (Eds.). *Ecological Studies*. Springer Netherlands, pp. 455-481.
- Beven, K.J. (Ed.), 2006. Streamflow generation processes. Benchmark papers in hydrology, 1. International Association of Hydrological Sciences, Wallingford.
- Bonell, M., 1998. Selected challenges in runoff generation research in forests from the hillslope to headwater drainage basin scale. *Journal of the American Water Resources Association*, 34(4): 765-785.
- Buttle, J. (Ed.), 1998. Fundamentals of small catchment hydrology. *Isotope Tracers in Catchment Hydrology*. Elsevier, Amsterdam, 1-43 pp.
- Dunne, T. (Ed.), 1978. Field studies of hillslope flow processes. *Hillslope Hydrology*. Wiley, Chichester, 227-293 pp.
- Gabrielli, C.P., McDonnell, J.J., 2011. An inexpensive and portable drill rig for bedrock groundwater studies in headwater catchments. *Hydrol. Processes*.
- Harr, R.D., 1977. Water flux in soil and subsoil on a steep forested slope. *J. Hydrol.*, 33(1-2): 37-58.
- Hewlett, J., Hibbert, A., 1967. Factors affecting the response of small watersheds to precipitation in humid areas, In: Sopper WE, Lull HW (eds) *Procc Int Symp on Forest Hydrology*. Pergamon Press, Oxford, pp. 275-290.
- Hursh, C., 1936. Storm-water and adsorption, AGU, 17. *Eos Trans*, pp. 301-302.
- Iwagami, S., Tsujimura, M., Onda, Y., Shimada, J., Tanaka, T., 2010. Role of bedrock groundwater in the rainfall-runoff process in a small headwater catchment underlain by volcanic rock. *Hydrol. Processes*, 24(19): 2771-2783.

- Katsuyama, M., Ohte, N., Kabeya, N., 2005. Effects of bedrock permeability on hillslope and riparian groundwater dynamics in a weathered granite catchment. *Water Resour. Res.*, 41(1): W01010.
- Kosugi, K.i., Katsura, S.y., 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 Resour. Res.*, 44(1): W01407.
- McDonnell, J.J., 1990. A Rationale for Old Water Discharge Through Macropores in a Steep, Humid Catchment. *Water Resour. Res.*, 26(11): 2821-2832.
- McDonnell, J.J., Tanaka, T., 2001. On the future of forest hydrology and biogeochemistry. *Hydrol. Processes*, 15(10): 2053-2055.
- Montgomery, D.R. et al., 1997. Hydrologic response of a steep, unchanneled valley to natural and applied rainfall. *Water Resour. Res.*, 33(1): 91-109.
- Mosley, M.P., 1979. Streamflow generation in a forested watershed, New Zealand. *Water Resour. Res.*, 15(4): 795-806.
- Onda, Y., Komatsu, Y., Tsujimura, M., Fujihara, J.-i., 2001. The role of subsurface runoff through bedrock on storm flow generation. *Hydrol. Processes*, 15(10): 1693-1706.
- Tsuboyama, Y., Sidle, R.C., Noguchi, S., Hosoda, I., 1994. Flow and solute transport through the soil matrix and macropores of a hillslope segment. *Water Resour. Res.*, 30(4): 879-890.
- Uchida, T., Asano, Y., Ohte, N., Mizuyama, T., 2003. Seepage area and rate of bedrock groundwater discharge at a granitic unchanneled hillslope. *Water Resour. Res.*, 39(1): 1018.
- Weiler, M., McDonnell, J.J., Tromp-van Meerveld, I., Uchida, T., 2006. Subsurface Stormflow, *Encyclopedia of Hydrological Sciences*. John Wiley & Sons, Ltd.
- Wilson, C.J., Dietrich, W.E., 1987. The contribution of bedrock groundwater flow to storm runoff and high pore pressure development in hollows, *Erosion and Sedimentation in the Pacific Rim*. IAHS, Corvallis, OR.

**2 AN INEXPENSIVE AND PORTABLE DRILL RIG FOR BEDROCK
GROUNDWATER STUDIES IN HEADWATER CATCHMENTS**

Gabrielli, C.P.

McDonnell, J.J.

Journal: *Hydrological Processes*

John Wiley and Sons, Ltd. Massachusetts, USA

Article first published online: 29 JUL 2011. DOI:10.1002/hyp.8212

2.1 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 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 the role of bedrock groundwater 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. Haria and Shand (2004) and Wilson and Dietrich (1987)), 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 system (K. Kosugi, personal communication, Dec. 2009). 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. Thus, 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 and can be used safely by a single operator. The inexpensive high speed drill rig and platform are suitable for headwater groundwater studies. The objectives of this Scientific Briefing are to:

- A. Describe the detailed construction and use of the device to enable others to re-create our system.
- B. Describe its effectiveness in drilling through different rock types, including conglomerate, breccia, sandstone, siltstone and basalt, including geologic core acquisition.
- C. Compare the attributes to alternative designs and suggest possible improvements for future designs.

2.2 DESCRIPTION

2.2.1 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 4-stroke lawnmower 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 degrees (Figure 1).

The ubiquitous nature of push lawnmower 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 lawnmower chassis and mounted to a simple metal frame which provides handles for holding and operating the drill (Figure 2, A).

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 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.

2.2.2 Detailed Construction

The push lawnmower 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 by using the preexisting 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 2, B). 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 2, E). 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 2, F). 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, 1.6 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 (Figure 2, G and Figure 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 \$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 meter 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 is 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 meter 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 to 80

meters of drilling in most instances. When a crown wears completely, it is lathed off and a new crown is silver brazed in place.

2.2.3 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.

2.2.4 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 and Schoenholtz (2003)) and the Los Gavilanes experimental watershed in Veracruz, Mexico (previously described by Muñoz-Villers et al., (2011)). Like many headwater research watersheds around the world, these sites were steep (all steeper than 30 degrees) 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 Gavilanes. We point the reader to the previously published work that describes in detail each of these sites.

2.3 RESULTS

Table 2.1 shows the results of drilling in different geological substrates and encompass 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 in sandstone and mudstone; for basalt and breccias, this reduced to 0.1 m/min. 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. Additionally, 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 due 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 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 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 analyzed 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 due to highly transmissive fractures capping maximum water table rise, or simply because the well is disconnected from local hydrologic processes due 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.

2.5 DISCUSSION

2.5.1 Comparison To Previous Portable Drill Units

Our new design described in this paper has proven capable of drilling 40 wells up to 11 meters in depth, in multiple geological materials. Its portability has enabled

us to take it around the world to different sites as checked baggage on commercial flights. The 4-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. Additionally, our system has proven itself to be robust and field maintainable, both valuable attributes in remote field locations.

Table 2.2 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 (~300 rpm; Table 2.2). The slow speed of the engine 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 (W. Dietrich, personal communication, July 2009). Such high torque engines can pose a safety concern to the operator as a jammed drill string has the potential to throw operators from drill system.

2.5.2 Safety

Safety is an important aspect of any fieldwork, especially while operating machinery in remote locations. Although our drill system can be safely operated by a

single person it is recommended to always work in teams of two or more.

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.

2.5.3 Alternative Future Designs

Like 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. Additionally, 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.

4-stroke engines, unlike most 2-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. It was discovered after our drill was designed, that aftermarket centrifugal clutches can be easily installed on 4-stroke lawnmower 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 2-stroke engines designed for drilling or auguring. 4-stroke lawnmower 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 4-stroke lawnmower 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 2.3 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 2-stroke Tanaka™ engine has been modified by Shaw Ltd to output at ~1900 rpm, which allows for much greater 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 lawnmower 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 2.2). However, it uses an unmodified Tanaka™ engine and a drill string manufactured by Continental Tubing™ rather than Shaw's proprietary design (M. Schulze, personal communication, Jan. 2011). 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 as opposed to 0.1 m/min with our design, a reduction in drilling speed of almost 700%.

2.6 CONCLUSIONS

The drill system presented in this paper 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 totaling >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.

2.7 ACKNOWLEDGMENTS

We thank Milo Clauson 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, 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

2.8 REFERENCES

- Crouzet, E., Hubert, P., PH, O., Siwertz, E., Marce, A., 1970. Le Tritium dans les mesures d'hydrologie de surface. Détermination expérimentale du coefficient de ruissellement. *J. Hydrol.*, 11: 334-344.
- David R. Montgomery, W.E.D., Raymond Torres, Suzanne Prestrud Anderson, John T. Heffner, Keith Loague, 1997. Hydrologic response of a steep, unchanneled valley to natural and applied rainfall. *Water Resour. Res.*, 33(1): 91-109.
- Haria, A.H., Shand, P., 2004. Evidence for deep sub-surface flow routing in forested upland Wales: implications for contaminant transport and stream flow generation. *Hydrol. Earth Syst. Sci.*
- Harr, R.D., 1977. Water flux in soil and subsoil on a steep forested slope. *J. Hydrol.*, 33(1-2): 37-58.
- Ice, G., Schoenholtz, S., 2003. Understanding how extremes influence water quality: Experience from forest watersheds. *Hydrol. Sci. Technol.*, 19: 99 - 107.
- Kosugi, K.i., Katsura, S.y., Katsuyama, M., Mizuyama, T., 2006. Water flow processes in weathered granitic bedrock and their effects on runoff generation in a small headwater catchment. *Water Resour. Res.*, 42(2): W02414.
- Kosugi, K.i., Katsura, S.y., 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 Resour. Res.*, 44(1): W01407.
- Lovell, J., 1969. Tyee formation: Underformed turbidities and their lateral equivalents: Mineralogy and paleogeography. *Geol. Soc. Am. Bull.*, 80: 9-22.
- MacDonald, L.H., 1988. An Inexpensive, Portable System for Drilling into Subsurface Layers. *Soil Sci. Soc. Am. J.*, 52(6): 1817-1819.
- McDonnell, J. et al., 2007. Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology. *Water Resour. Res.*, 43: 359-389.
- McDonnell, J.J., Tanaka, T., 2001. On the future of forest hydrology and biogeochemistry. *Hydrol. Processes*, 15(10): 2053-2055.
- Mosley, M.P., 1979. Streamflow generation in a forested watershed, New Zealand. *Water Resour. Res.*, 15(4): 795-806.

- Muñoz-Villers, L. et al., 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, M., Farvolden, R., 1979. The role of groundwater in storm runoff. *J. Hydrol.*, 43: 45-65.
- Uchida, T., Asano, Y., Ohte, N., Mizuyama, T., 2003. Seepage area and rate of bedrock groundwater discharge at a granitic unchanneled hillslope. *Water Resour. Res.*, 39(1): 1018.
- Wilson, C.J., Dietrich, W.E., 1987. The contribution of bedrock groundwater flow to storm runoff and high pore pressure development in hollows, *Erosion and Sedimentation in the Pacific Rim*. IAHS, Corvallis, OR.

Table 2.1. Drilling statistics for various bedrock geologies.

Bedrock Material	Drill Rate (m/min)	Max 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	.5	8	6
Regolith	1	11	3

Table 2.2: Comparison of different portable bedrock drilling systems and suggestions for alternative designs.

	Our system	MacDonald (1988)	Shaw Tools Ltd (Commercial)	Mark Schulze, HJ Andrews (Personal Communication)
Engine A. Style B. Type C. RPM D. Centrifugal Clutch (CC)? E. Throttle? F. Price G. Torque	A. Tecumseh™ push lawnmower B. 4-Stroke gasoline C. ~1500-2500 D. No E. No F. \$50-\$150 G. Low	A. 2-Person Power Auger B. 2-Stroke gasoline C. ~300 D. Yes E. Yes F. \$300-\$500 G. High	A. Tanaka™ 270 PFDH Auger B. 2-Stroke gasoline C. ~1900 with modified gear box D. Yes E. Yes F. \$1000 G. Low	A. Tanaka™ 270 PFDH Auger B. 2-Stroke gasoline C. ~300 unmodified gear box D. Yes E. Yes F. \$350-\$450 G. Low
Drill String A. Type B. Connection Style C. Cutting Bit* D. Diameter E. Engine/drill string connection	A. Custom fab 4130 steel B. Custom fab threaded plugs C. Core Barrel D. 25.4 mm to 63.5 mm in 3.2 mm increments E. Quick release via custom fab design	A. NQ Drill Rod (Commercial built) B. Threaded C. Crown D. 45 mm E. Quick release via custom fabricated design	A. Custom stainless B. Bayonet style C. Crown D. 25.4 mm , 50.8 mm E. Quick release via bayonet fitting	A. Continental Tube B. Threaded C. Crown D. 25.4 mm to 101.6 mm in 3.2 mm increments E. 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
Water Supply	2-Stroke gas powered water pump	2-Stroke gas powered water pump	Pump style yard sprayer	Pump style yard sprayer
Pros	<ul style="list-style-type: none"> • Inexpensive • Fast cutting speed • Greatest drilling depth 	<ul style="list-style-type: none"> • Easy to fabricate • Throttle control • Inexpensive • Simple design 	<ul style="list-style-type: none"> • Commercially designed • Fast cutting speed • Easy to start and run • Throttle control 	<ul style="list-style-type: none"> • All commercial parts • Inexpensive • Easy to start and run • Throttle control
Cons	<ul style="list-style-type: none"> • Can be difficult to start due to lack of CC • No throttle control • Custom fabrication 	<ul style="list-style-type: none"> • High Torque is dangerous • Slow cutting speed • Some custom fabrication 	<ul style="list-style-type: none"> • Expensive • May need higher volume water supply for boreholes greater than 25.4 mm (i.e. gas powered water pump) 	<ul style="list-style-type: none"> • Very slow drilling rates • May need higher volume water supply for boreholes greater than 25.4 mm (i.e. gas powered water pump)
Approximate Cost	\$2000	\$1500 ca. 1988	\$10,000	\$1500

*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.

Table 2.3. Suggested alternative designs.

	Alternative Design 1	Alternative Design 2
Engine H. Style I. Type J. RPM K. Centrifugal Clutch (CC)? L. Throttle? M. Price N. Torque	A. Tanaka™ 270 PFDH Auger B. 2-Stroke gasoline C. ~1900 with modified gear box D. Yes E. Yes F. \$1000 G. Low	A. Push Lawnmower B. 4-Stroke gasoline C. ~1500-2000 D. Yes, after market modified E. Yes, after market modified F. ~\$300, includes modifications G. Low
Drill String F. Type G. Connection Style H. Cutting Bit* I. Diameter J. Engine/drill string connection	A. Continental Tube B. Threaded C. Crown D. 25.4 mm to 101.6 mm E. Quick release via custom fab design or threaded non-quick release	A. Continental Tube B. Threaded C. Crown D. 25.4 to 101.6 mm E. Quick release via custom fab design or threaded non-quick release
Water swivel (WS)	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
Pros	<ul style="list-style-type: none"> • Inexpensive • Fast cutting speed • Easy to start and run • Throttle control 	<ul style="list-style-type: none"> • Inexpensive • Fast cutting speed • Easy to start and run • Throttle control
Cons	<ul style="list-style-type: none"> • Some custom fabrication, but less than alternative design 2 	<ul style="list-style-type: none"> • Some custom fabrication
Approximate Cost	\$2200	\$1500

*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.

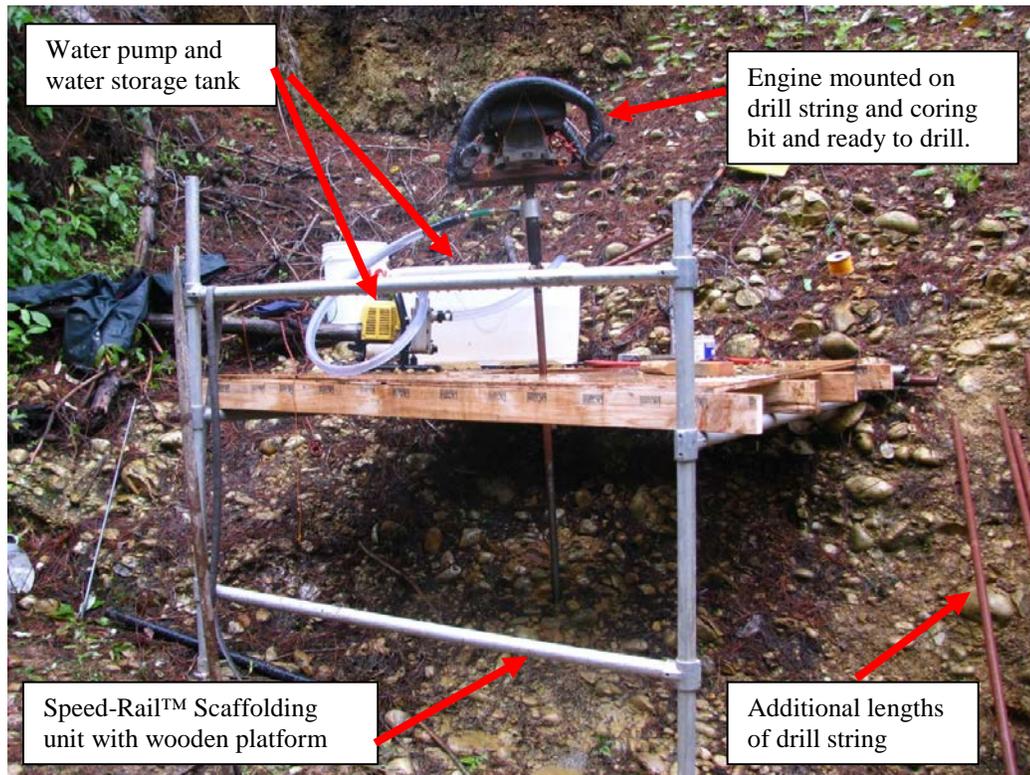


Figure 2.1. Full drill assembly, platform, water pump, and water storage bins setup at the Maimai experimental catchment in New Zealand. This specific location allowed for drilling directly into bedrock with no overlaying colluvium.

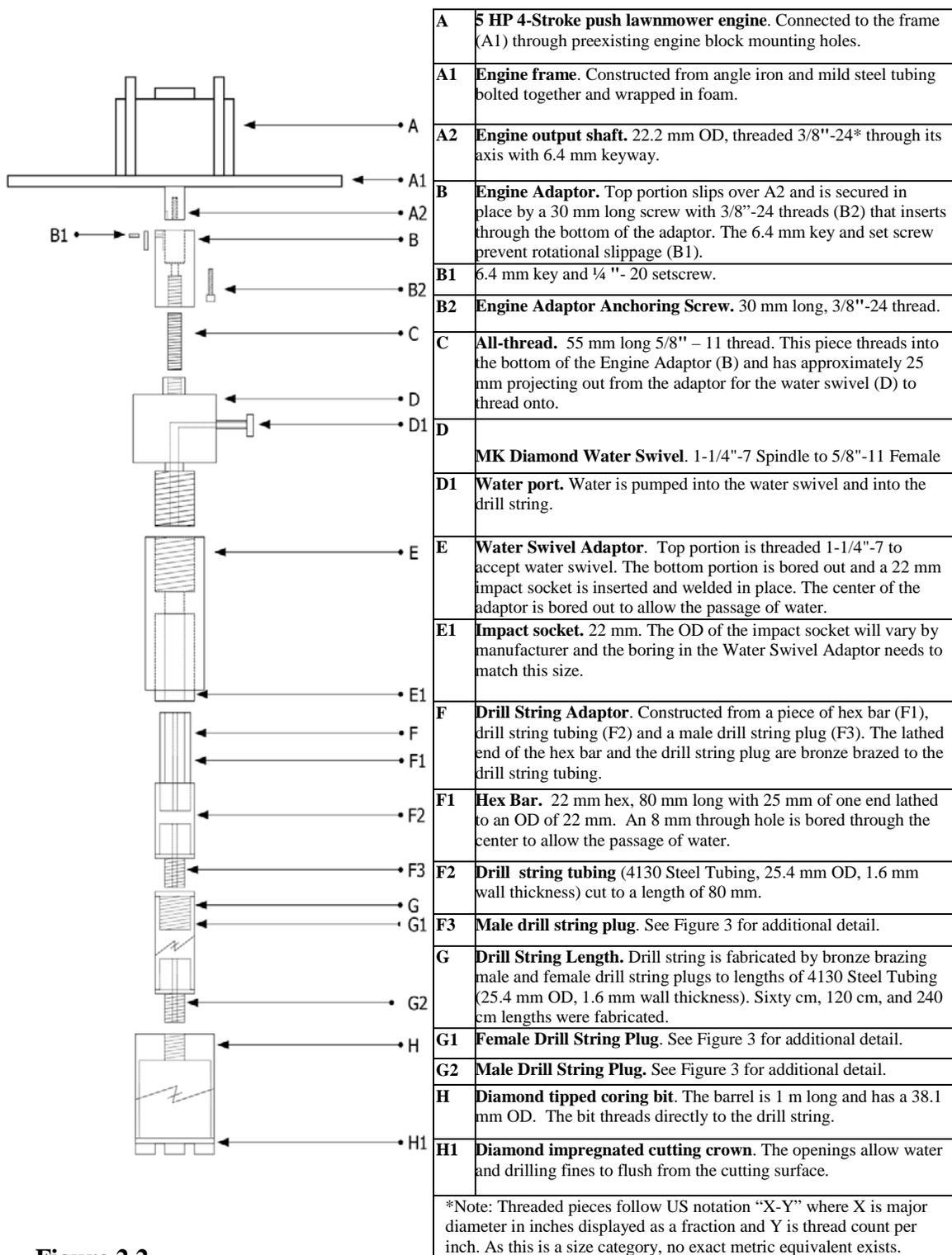


Figure 2.2

Figure 2.2. Drill schematic displaying the individual parts of the drill assembly. Note, drawing is not to scale.

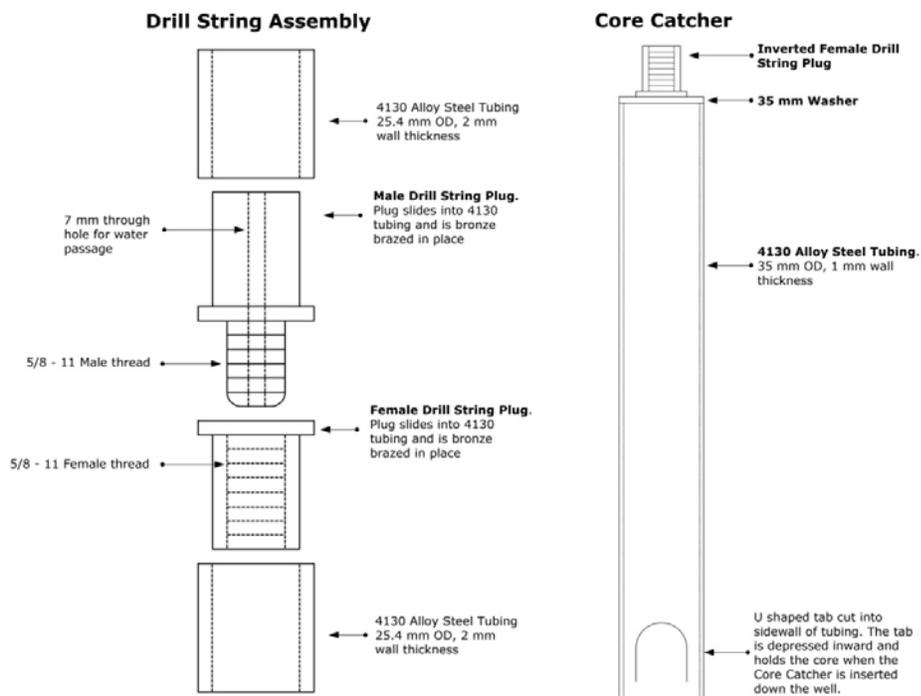


Figure 2.3. Schematic of drill string components and core catcher components. Note, drawing is not to scale.

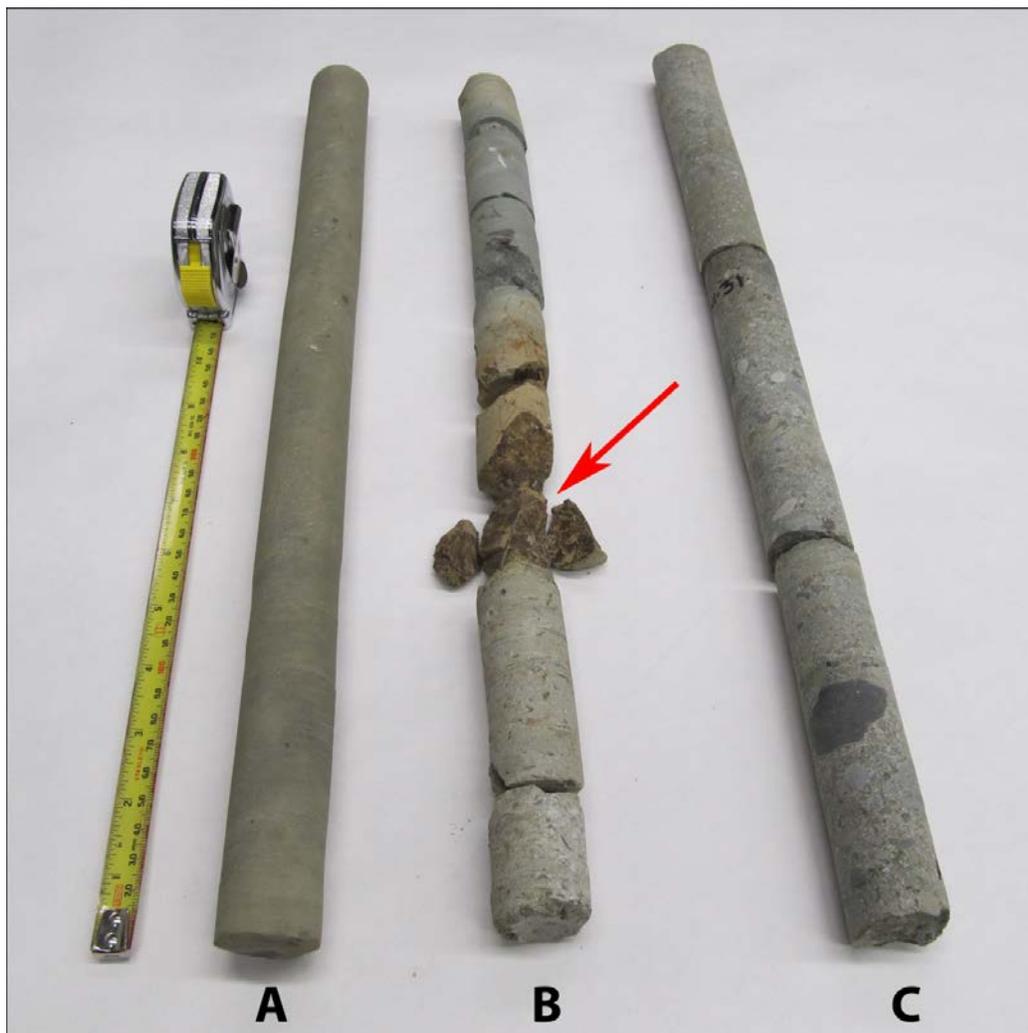


Figure 2.4. Example of cores retrieved while drilling. These specific cores come from the HJ Andrews experimental site in Oregon, USA. Core A is a tuff and Core C, breccias, while Core B shows a transition between the two lithologies. Core B also shows fractures in the bedrock that the well intersected 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.

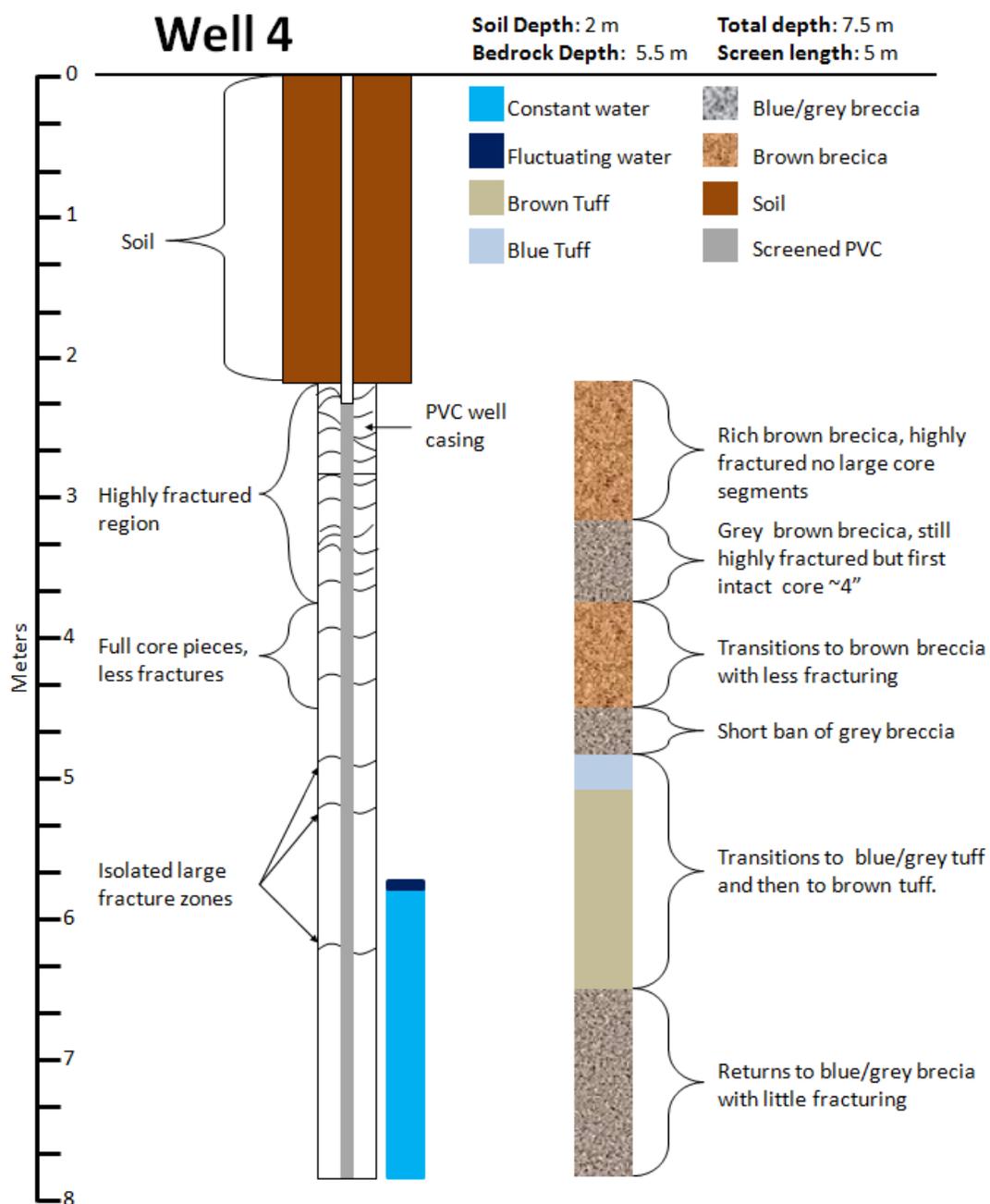


Figure 2.5. Example of a well log that can be assembled from the geological and fracture data obtained from core retrieval. This well description comes from the HJ Andrews experimental site in Oregon, USA and displays the basic well characteristics such as soil and bedrock depth, bedrock type, stratification, 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.

**3 THE ROLE OF BEDROCK GROUNDWATER IN RAINFALL-RUNOFF
RESPONSE AT HILLSLOPE AND CATCHMENT SCALES**

Gabrielli, C.P.

McDonnell, J.J.

Jarvis, T.

Journal of Hydrology

Elsevier Inc., Amsterdam, Netherlands

In preparation

3.1 INTRODUCTION

Process understanding of the rainfall-runoff response of steep hillslopes and headwater catchments has evolved greatly since the early work of Hursh (1936). Early reviews (Dunne, 1978) and more recent reviews (Bachmair and Weiler, 2011; Bonell, 1998) have chronicled the development of ideas on rapid subsurface stormflow development and the integration of individual hillslope responses that create the integrated catchment response. Despite extensive research that has revealed dominant processes in different environments, the majority of the work to date has focused exclusively on lateral flow in the soil mantle (Buttle, 1998; Hewlett and Hibbert, 1967; McDonnell, 1990; Tsuboyama et al., 1994).

Despite a largely soil-centric view of hillslope hydrology, early work by Wilson and Dietrich (1987) in a zero order basin in California showed the potentially significant hydrologic influence of underlying bedrock in rainfall-runoff delivery at the hillslope scale. They found that stormflow followed fracture pathways within the shallow weathered bedrock and interacted with the overlying colluvium when flows were forced upwards by more competent bedrock, creating zones of transient saturation. Later work at the Coos Bay Oregon site by Montgomery et al. (1997) and Anderson et al. (1997) also noted subsurface flow paths that traversed the soil and bedrock zones in steep unchanneled slopes in the CB1 catchment. Exfiltrating water from the bedrock during storm events and sprinkling experiments produced perched transient water tables at the soil-bedrock interface (SBI) that were believed to have caused slope instability and ultimately failure. Additionally, bromide tracer injections

showed rapid movement of bedrock flow to the catchment outlet identifying the importance of bedrock flow paths to catchment processes. More recently, Kosugi (2008), building upon other important work in Japan (Katsuyama et al., 2005; Onda et al., 2001; Uchida et al., 2003) showed the importance of bedrock groundwater in a granitic catchment in Central Japan. Anomalous behavior of saturated regions at the soil bedrock interface appeared connected to the rise and fall of deeper bedrock groundwater tables, and ultimately influenced the chemical, spatial and temporal characteristics of water movement into the stream channel.

In some bedrock groundwater environments, fracture flow may be a key feature controlling bedrock groundwater contributions to hillslope flow and catchment runoff response. Fracture flow through bedrock is controlled by fracture network density, geometry and connectivity (Banks et al., 2009) and can be extremely complex and heterogeneous by nature. Bedded fracture zones separated by competent bedrock may create compartmentalized aquifers, while faulting, weathering and other large scale geologic processes may help induce connectivity between fracture pathways (Dietrich, 2005). Haria and Shand (2004) found complex flow processes occurring at depth-specific horizons in fractured bedrock in the riparian and lower hillslope region of the Hafren catchment in Plynlimon, Wales. The dual-porosity environment of fractured bedrock can promote rapid storm response and minimal storage on a storm event time scale (Dietrich, 2005; Haria and Shand, 2004; Haria and Shand, 2006).

Despite growing awareness of the potential significance of bedrock groundwater to hillslope and catchment hydrology, there still remains a very limited

number of studies that have monitored hillslope groundwater in competent and fractured bedrock (McDonnell and Tanaka, 2001). Access remains the key logistical hurdle limiting studies in the characteristically steep, unstable, and often roadless headwater terrain. Where access has been limited, many studies have inferred catchment groundwater dynamics through intensive studies of spring discharge, rather than direct measurements taken within the bedrock itself (Iwagami et al., 2010; Katsuyama et al., 2005; Uchida et al., 2003). While useful, the black box nature of spring studies limit our ability to conceptualize the dynamics of internal bedrock groundwater and its connection to hillslope processes in the soil mantle. Indeed, in hillslope and catchment hydrology we struggle to know the general involvement, if at all, of bedrock groundwater in forming saturation at the soil-bedrock interface where large anisotropy and rapid generation of lateral subsurface stormflow has been widely observed (Weiler et al., 2006). We lack, particularly at previously well-monitored and well-documented sites, an understanding of how bedrock groundwater couples to rapid event runoff generation and flow sustenance in the stream between events.

Here we tackle fundamental questions of bedrock groundwater contributions through a comparative analysis of two well-studied hillslopes. We capitalize on a new portable drill system developed by Gabrielli and McDonnell (2011). Capable of drilling wells up to 10 m deep in a variety of geological formations (colluvium, saprolite, competent and fractured bedrock), this drill system can be carried into field sites, previously inaccessible by standard truck mounted drill rigs and presents an inexpensive solution to directly access bedrock groundwater in the headwaters. Few,

if any bedrock groundwater studies to date have been conducted at sites with rich histories of hillslope experimental studies. Our null hypothesis going into this work is that bedrock groundwater does not contribute materially to hillslope or catchment runoff dynamics. We then investigate how bedrock structure affects hillslope response to storm events at the M8 experimental hillslope and catchment at Maimai in New Zealand, and the Watershed 10 experimental hillslope and catchment at the HJ Andrews in the Cascade Range in Oregon, USA. Beven (2006) has characterized both site as benchmarks in the field; Maimai for work by Mosley (1979) and his fundamental insights into this quintessential, wet, steep, humid, forested catchment and the HJ Andrews for work by Harr (1977) and his characterization of subsurface flow processes at another such wet, steep, humid, forested catchment. Here we build upon these and the many studies at Maimai and HJ Andrews since then to answer the following questions in relation to the role of bedrock groundwater in rainfall-runoff response at hillslope and catchment scales:

- A. What are the features and structure of bedrock that drives interactions between bedrock groundwater (BGW) and hillslope hydrology?
- B. How do the BGW tables react to a storm event? More specifically, what are the time lags between the storm event hydrograph and the water table response in the bedrock (peak to peak, event initiation to response initiation) and what is the effect of precipitation on the magnitude and rate of BGW change?
- C. Does BGW contribute directly to hillslope discharge (i.e. measured trenchflow at the slope base)?

We address these questions by determining whether BGW reaches the soil-bedrock interface, thus contributing to the existing perceptions of lateral subsurface stormflow processes at the two sites. Our approach combines standard hydrometric approaches that include wells, hillslope trenches and gauging stations, with the new Gabrielli and McDonnell (2011) drilling system and stable isotope tracer analysis of storm event streamflow, hillslope trench water and bedrock groundwater. We targeted 9 and 16 week field campaigns during the wet season at the Maimai and HJ Andrews, respectively.

3.2 STUDY SITES

Two well-established benchmark experimental hillslopes and catchments were investigated: Watershed M8 (M8) at the Maimai in New Zealand and watershed 10 (WS10) at the HJ Andrews in Oregon, USA. From the outlet of their respective catchments, these watersheds appear nearly identical in many respects including size, physical hillslope characteristics and rainfall-runoff characteristics (Table 3.1). They differ significantly, however, in their underlying bedrock geologies. WS10 is dominated by layers of fractured pyroclastic tuff and breccias (Swanson and James, 1975). M8 is underlain by a firmly-compacted, early Pleistocene conglomerate with little or no fracturing (O'Loughlin et al., 1978).

3.2.1 Maimai M8

The M8 study site shown in Fig. 1a, is a 3.8 ha watershed located on the West Coast of the South Island of New Zealand (42.1° S, 171.8° E). McGlynn et al. (2002) provide a complete description as well as a historical review of the research conducted within the catchment. Our description here is based on their review. Low-intensity, long-duration storms produce an average annual rainfall of 2450 mm (Woods and Rowe, 1996). Monthly rainfall is distributed evenly between April and December, with slightly drier conditions existing between January and March. The catchment is very responsive and runoff ratios (catchment discharge/rainfall) are approximately 60 % annually (Rowe and Pearce, 1994). Slopes are short (<300 m) and steep (mostly above 35°) with a local relief of 100 m.

Hillslope soils are characterized as stony podzolized yellow brown earth (Blackball hill soils). Average soil profile is 0.60 m (range 0.25 to 1.30 m) and is deeper in hollows and at the toe of slopes where material has accumulated and shallower near ridgelines and spurs (Woods and Rowe, 1996). Hydraulic conductivity of the mineral soils range from 5 to 300 mm h⁻¹ and mean porosity is 45% (McDonnell, 1990). High annual rainfall and high storm frequency (average time between storms ~3 days) results in a soil profile that remains within 10% of saturation during most of the year (Mosley, 1979). Underlying the soils is a moderately weathered, firmly compacted, Early Pleistocene Conglomerate known as the Old Man Gravel formation. The conglomerate is comprised of clasts of sandstone, schist and granite in a clay-sand matrix (Rowe et al., 1994) and is considered poorly permeable

with estimated seepage losses of 100 mm/yr (Rowe and Pearce, 1994). More recent work by Graham et al. (2010b) has shown that Old Man Gravel Ksat may be on the order of 1-3 mm/hr, implying a larger annual and within-storm loss to bedrock.

The gauged hillslope at M8 has been the site of many 1990s era studies (Brammer, 1996; McDonnell, 1990; Woods and Rowe, 1996), as well as many recent studies (Graham and McDonnell, 2010; Graham et al., 2010b; McGlynn et al., 2004). First instrumented by Woods and Rowe (1996), this hillslope has maximum slope lengths of 50 m and slope angles greater than 35°. The planer slope has a 60 m long trench originally built by Woods and Rowe (1996) that is installed to the bedrock surface to collect subsurface flow from the hillslope. The trench is separated into 1.7 m sections, each of which can route flow to individual recording tipping buckets. Graham et al. (2010b) removed trench sections 10-13 and excavated an area of approximately 50 m² down to bedrock.

3.2.3 HJ Andrews WS10

WS10 is located at the H.J. Andrews Experimental Forest (HJA) and is part of a Long Term Ecological Research program in the west central Cascade Mountains of Oregon, USA (44.2° N, 122.25° W). McGuire et al. (2007) provide a synthesis of past research at the site and full description of site characteristics. Our description here is based on their review. Mild wet winters and warm dry summers characterize the Mediterranean climate at WS10. Annual mean precipitation is 2220 mm (averaged from 1990 to 2002) with 80% falling between October and April. A wet-up period

exists from the start of each water year through December, after which the catchment remains in a very wet and highly responsive state to additional precipitation events. Long duration, low to moderate intensity frontal storms characterize the rainfall regime. On average, 56% (28-76%) of rainfall becomes runoff (McGuire et al., 2005). Summer baseflows are approximately 0.2 L s^{-1} ($< 0.01 \text{ mm h}^{-1}$) and archetypal winter storms reach peak flows of approximately 40 L s^{-1} (1.4 mm h^{-1}) (McGuire and McDonnell, 2010). Transient snow accumulation is common, but rarely persists more than 1-2 weeks and generally melt within 1-2 days (Mazurkiewicz et al., 2008).

The 10.2 ha catchment ranges in elevation from 473 m at the gauged flume to 680 m at ridge top (Fig. 1b). The terrain is characterized by short ($< 200 \text{ m}$), steep slopes ranging from 30° to greater than 45° . Periodic debris flows (most recently in 1986 and 1996) have scoured the lower 60% of the stream channel to bedrock and removed the riparian zone, resulting in a catchment dominated by hillslope runoff with very little riparian volume or storage. Well-defined seeps flowing from the base of the hillslopes into the stream channel have been identified and are known to sustain a substantial portion of the summer low flow (Harr, 1977; Triska et al., 1984). Swanson and James (1975) and Harr (1977) established the origins of these hillslope seeps as either localized saturated zones controlled by the topographic convergence of the underlying bedrock or the presence of vertical andesitic dykes approximately 5 m wide that are located within the basin.

The gauged hillslope at WS10 has been the site of many 1970s era benchmark studies (Harr, 1977; Harr and Ranken, 1972; Sollins et al.; Sollins and McCorison,

1981), as well as many recent studies (McGuire and McDonnell, 2010; McGuire et al., 2005; McGuire et al., 2007; van Verseveld et al., 2009). The hillslope study area is located on the south aspect of WS10, 91 m upstream from the stream gauging station (Fig. 1a) (McGuire and McDonnell, 2010). The average slope angle is 37° , ranging from 27° near the ridge to 48° where it intersects the stream. The slope is slightly convex along its 125 m length from stream to ridgeline. Elevation ranges from 480 to 565 m. The hillslope comprises of residual and colluvial clay loam soils derived from andesitic tuffs (30%) and coarse breccias (70%) that formed as a result of ashfall and pyroclastic flows from the Oligocene-Early Miocene period (James, 1977; Swanson and James, 1975). Well-aggregated surface soils give way to more massive blocky structure and less aggregation at depths of 0.7-1.1 m (Harr, 1977). Average soil depth is approximately 3 m. Moderately to highly weathered parent material (saprolite) ranges in thickness from 0 to 7 m and emerges approximately 30 meters upslope from the stream channel and extends to ridgeline (Harr and McCorison, 1979; Sollins and McCorison, 1981). Across the first 30 m of hillslope, before the emergence of the saprolite layer, the soil mantle sits directly over ~1 m of highly-fractured, slightly-weathered bedrock. As depth into the bedrock increases the bedrock in this region of the hillslope becomes more competent with less fracturing.

3.3 METHODS

We combined physical, hydrogeologic, and environmental tracer measurements at each study site to characterize bedrock groundwater. A new portable

bedrock-drilling system (Gabielli and McDonnell, 2011) was utilized to drill boreholes into bedrock at each hillslope. Monitoring of the BGW table, as well as geologic information gained through bedrock core recovery provided the hydraulic and hydrogeologic data to characterize dynamics of the shallow bedrock groundwater response during storm events. Core specimens and surface samples of bedrock provided data for the geological interpretation of lithographic layers within each hillslope. When possible, well logs were constructed for each borehole using core specimens and drilling observations. These logs provided a visual reference to the geological structure of each borehole and the larger surrounding hillslope.

Storm sampling of rain, stream, trench and well water was conducted for a single precipitation event at each study site to evaluate isotopic composition of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ to identify flow paths and mixing processes within the hillslope. This featured storm occurred within the 9 and 16 week field campaign at each site (M8 and WS10, respectively), and focused on the wet season with the objective of capturing each hillslope in its wettest state, and hence, the most likely time for BGW involvement in subsurface lateral stormflow.

3.3.1 Maimai M8

This study used the same instrumented hillslope as Graham et al. (2010b) and Woods and Rowe (1996). Five bedrock wells, labeled 1-5, were installed along a transect perpendicular to the stream channel starting 15 m from the stream channel and spaced at approximately 6 m intervals (Fig. 2a). Wells ranged in depth from 3.4 to 5.5

m into the bedrock (Table 3.2). The first two wells in this transect were located within the region cleared of soil by Graham et al. (2010b), while the wells further upslope were installed through the overlying soil mantle. A sixth well (3a) was drilled at the same elevation as Well 3 but offset 5 m upstream of the transect.

Well installation started by drilling a 0.10 m diameter hole through the colluvial layer with a hand auger. PVC casing was inserted down to bedrock to prevent collapse of the surrounding soils. The portable bedrock drilling system design by Gabrielli and McDonnell (2011) was then used to drill through the Old Man Gravel. Each well was drilled to 64 mm in diameter for the initial 0.6 m of depth, after which, additional drilling was done at 38 mm in diameter. Thirty mm diameter PVC, screened along its entire length, was used to case each borehole. A plastic collar was placed around the outside of the PVC casing where the borehole transitioned from larger to smaller diameter. Bentonite was then backfilled into the annulus between the 63 mm borehole and the casing, effectively creating a watertight seal that extended from the soil surface down to 0.6 m into the bedrock. This seal ensured that soil water could not infiltrate into the well contaminating the bedrock groundwater. Wells were instrumented with an unvented Onset™ U20 pressure transducer capable of measuring water depths to 9 m within ± 5 mm. Ten minute recording intervals were used. A similar pressure transducer was placed in a research facility ~200 m from the hillslope to record barometric pressure, which was used to convert absolute pressure to water depth measurements in each well. Data was collected over a period of 65 days between 1 Jul, 2010 and 3 Sep, 2010.

Two 1.7 m sections of the hillslope trench, initially installed by Woods and Rowe (1996), were reestablished and equipped with 1 liter tipping buckets to record hillslope runoff. Trench sections 15 and 16 were used, and a description of the trench design can be found in Woods and Rowe (1996). An Ota Keiki tipping bucket rain gauge calibrated at 0.2 mm per tip recorded precipitation at ground level 5 m from the trenched hillslope (J. Payne, personal communication, July, 2010). Stream discharge was measured at a 90 degree v-notch weir installed 20 m upstream of the gauged hillslope. Two capacitance rods (Tru Track, Inc., model WTDL 8000) recorded stage height on 10 minute intervals.

A single 36 mm storm rainfall event was sampled for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotopic composition. Fifty ml samples were collected on an hourly basis through 3 hours past the peak of the hydrograph and then every 2-4 hours through the recession for a total sampling period of 47 hours. Stream water and Wells 1, 2, 3, and 5 were sampled during each sampling period. High frequency trench and rain water samples were collected for the duration of measurable water. Isotope analysis was conducted using an LGR liquid water isotope analyzer (LWIA-24d).

Slug and pumping tests were conducted for each well to help characterize the properties of the local bedrock and groundwater aquifer. A hand operated peristaltic pump was used for pump tests at a rate of 0.25 L min^{-1} for all wells. Well 1 was pumped for 60 minutes, while all other wells were only pumped for 10 minutes do to extremely slow recharge. Slug tests were conducted by instantaneously injecting 4 l of water into each well and recording the subsequent head drop using an Onset™ U20

pressure transducer recording water height every 10 seconds. Analysis was conducted using the Dagan method (Dagan, 1978).

Multiple bedrock samples of approximately 0.15 x 0.15 x 0.15 m in size were removed from the open bedrock surface using a metal pick and brought back to the lab to measure porosity. Samples were oven dried at 60° C until weight loss was negligible. The bedrock samples were then cooled to room temperature before being submerged in DI water at room temperature for 4 days. Saturated and oven-dry weights, as well as volumes calculated from displaced water volumes, were used to determine approximate porosity.

3.3.3 HJ Andrews WS10

Seven bedrock wells (A, B1, B2, B3, B4, C and D) were installed into the hillslope bedrock in a network configuration (Fig. 1b). Wells B1-B4 were drilled as a cluster to investigate vertical head gradients within the bedrock. Wells were spaced between 2 and 7 m from the stream channel and depths ranged from 0.9 to 7.5 m into bedrock (Table 3. 2). Overlying soil depth was between 0 and 1.5 m. Bedrock cores were recovered from each borehole and used to construct well logs for geotechnical information on the underlying bedrock. Difficulties with sealing the wells to prevent soil water from contaminating the bedrock groundwater required the use of well-packers instead of the sealing method used at M8. Well-packers are inflatable devices that are lowered into a borehole to a specific depth and then a rubber bladder inflates and seals against the sidewall of the borehole (J. Istok, personal communication, Oct.

2010). Small air leaks can sometimes cause the bladders to deflate over long periods of time, and therefore, the boreholes were also backfilled with bentonite up to the soil surface to ensure a waterproof seal. Unvented Onset™ U20 pressure transducers were placed below the inflatable packers to measure water depth. Fracture networks and borehole depths were used to determine the exact location of packer placement for each well and allowed for the isolation of specific fracture regions. A venting tube was placed from the surface through the well packer to provide atmospheric pressure conditions within each well. Data was collected over a period of 112 days from 12 Dec, 2010 to 1 Apr, 2011. Barometric pressure data, collected at the HJA Headquarters 1 km away, was used to convert absolute pressure to water depth.

The hillslope was instrumented with a 10 m long trench installed to bedrock at the intersection of the hillslope and stream channel. Hillslope runoff was directed through a 15° V-notch weir and two Tru-Trac™ capacitance rods recorded stage height at 10 minute intervals. Stream discharge was measured at a gauging station 90 m downstream of the hillslope, and rainfall data was collected 1 km away at the HJA Headquarters.

A single 34 mm storm event was sampled for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotopic composition. Fifty ml samples were collected on an hourly basis from the onset of the event until 3 hours after the hydrograph peak, after which samples were taken every 2-4 hours through the recession for a total sampling period of 42 hours. Water from Wells A and D, the trench and stream, were collected during each sampling round while the remainder of the wells were sampled as they wetted up through the event

and for the duration of measurable water. Rainfall samples were collected on an hourly basis for the duration of the event. Isotope analysis was conducted using an LGR liquid water isotope analyzer (LWIA-24d).

3.4 RESULTS

3.4.1 Bedrock structure

In this section we characterized the features of the bedrock structure that are relevant to BGW interactions, including drill rates, geology, presence and orientation of fractures, fracture density, presence of oxidized surfaces, and pump and slug test measurements.

3.4.1.1 Maimai M8 Bedrock Structure

The firmly packed conglomerate at M8 had characteristics that resembled saprolite or regolith more than true competent bedrock. Drill rates were as high as 0.5 m min⁻¹ and core retrieval was only ~10% (i.e. for every 1 m drilled, 0.1 m of core was recovered). The sandy matrix was easily friable, eroded when drilled and produced very little core compared to more competent hard bedrock drilled elsewhere as reported in Gabrielli and McDonnell (2011). These characteristics made it impossible to reconstruct an accurate well log based on sparse and sporadic core retrieval and anecdotal drilling evidence. Although some heterogeneity was detected during drilling (e.g. bedded layers of varying clast size), it was difficult to identify distinct bedrock features. No fracture zones within the bedrock could be detected and

an intensive visual inspection of 50 m² of open bedrock surface at the toe of the hillslope revealed no major fractures. Samples hand-excavated from the top 0.6 m of bedrock had oxidized surfaces at the clast-matrix boundary, indicating possible water flow through these regions. We were unable to determine whether or not oxidized surfaces existed further into the bedrock due to the erosive nature of the drilling process and minimal core recovery.

Slug tests of each well in the M8 hillslope transect revealed decreasing hydraulic conductivity with distance upslope (Table 3.2). Although precise K_{sat} values were difficult to quantify with such small volume slug tests (due to our narrow wells associated with our portable drill system), general order-of-magnitude values were achieved and offer insight to the spatial variation in bedrock characteristics from well to well across the hillslope. For instance, Well 1 at the toe of the hillslope had a hydraulic conductivity three orders of magnitude greater than Well 5, 30 m upslope.

Pump tests were also conducted on each well, however, due to insufficient pump rates and extremely slow recharge, the tests were unsuccessful. For instance, water table elevation at Well 1 remained constant despite 60 minutes of pumping at a rate of 0.25 L min⁻¹, a volume equivalent to 10 times the borehole storage. Pump rates could not be increased and therefore the well could not be stressed enough to produce accurate pump-test results. Wells 2-5, however, were also pumped at 0.25 L min⁻¹ but ran dry after only 5-10 minutes of pumping, suggesting a decrease in transmissivity with distance upslope (consistent with the slug test results). The bedrock samples cut from the free surface of the bedrock and measured in the lab for porosity had an

average value of 25% and are in the range of established general porosities for sandstone and packed gravel (Freeze and Cherry, 1979). Additionally, Ksat values between 0.0003 and 3.1 mm d⁻¹ measured through slug tests agree to within an order of magnitude of values measured by Graham et al. (2010b).

3.4.1.2 HJ Andrews WS10 Bedrock Structure

Maximum drill rates through the interlaid tuff and breccia at WS10 was 0.1 m min⁻¹ (5x slower than at M8), but core recovery was nearly 95% for all wells. The high core recovery and the use of a down-the-hole camera provided detailed information on the bedrock underlying WS10 and detailed wells logs were created. The bedrock displayed two distinct horizons within the hillslope: a highly-fractured, weathered region occupied the first meter of competent rock, while deeper drilling revealed less weathered rock with discrete isolated fractures and occasional deeper fracture zones. Fracture density within the first meter of bedrock ranged from approximately 18 to 29 fractures per meter, while deeper regions contained fracture densities of only 4 to 9 fractures per meter. Most fractures and fracture zones were arranged with an angle between horizontal and 45° downslope. Occasional isolated fractures were oriented vertically or with a slope greater than 60°, thus connecting the lower angled bedded fracture zones. Highly oxidized surfaces were noted on most fracture surfaces, indicating interaction with water. Additionally, active water movement was noted in some fractures by the down-the-hole camera, even during low flow summer periods.

Pump tests were conducted in some of the wells at WS10, however, wells ran dry after only 5-10 minutes despite slow pumping rates (0.1 l min^{-1}), indicating minimal storage or low permeability in the surrounding bedrock.

3.4.2 Groundwater Dynamics

In this section we present water table dynamics that were measured in bedrock wells to determine the spatial and temporal changes induced by rainfall events. We measured depth to groundwater, total elevation change and rate of change in water table elevations, and time lags between storm initiation and water table response. Additionally, comparison of stream discharge to bedrock water table fluctuations in each well were made, providing insight into hysteretic patterns and the spatial heterogeneity and connectedness of water movement through differing regions of hillslope bedrock at each study location.

3.4.2.1 Maimai M8 Groundwater Dynamics

Ten storm events with precipitation totals greater than 8 mm were recorded during the study period. Twenty-four hour precipitation totals ranged from 1 to 129 mm, with a 1-hour maximum rainfall intensity of 15 mm occurring during the Aug 1 event. Stream discharge ranged from a low of 0.007 mm hr^{-1} during a 3 week dry period to a maximum of 10.9 mm hr^{-1} during the Aug 1 event. Fig. 3a shows the time series data of bedrock water table elevations, the hydrograph and the hyetograph during the study period.

Fig. 3.3a displays water table dynamics in each well in the context of well location on the hillslope. All wells contained water during the study period except for Well 5, which dried during a 3 week period in mid-June. Depth to water table increased with distance upslope. At Well 1, the toe of the hillslope, the water table was located approximately 1.7 m below the SBI, while approximately 30 m upslope at Well 5, the water table was located 4.7 m below the SBI.

All wells showed a water table response to precipitation events. The amplitude of this response varied spatially across the hillslope. Table 3.2 includes the water table increase per millimeter of rain averaged across all storm events greater than 8 mm total precipitation for each well. Wells 1 and 2 had the smallest water table fluctuations during storm events with total changes of only 0.08 m and 0.17 m for Wells 1 and 2, respectively. The amplitude of water table fluctuation increased with distance upslope for Wells 3, 3a and 4, despite the depth to water table increasing into the bedrock. Well 3 had the largest response to a storm event with a change in water table elevation of 0.67 m during the Aug 1 rainfall event. As distance increased upslope, water table response began to decline and Well 5 showed decreased response to storm events compared to the middle wells (3, 3a and 4).

Timing and rate of well response to storm events was investigated to characterize the basic dynamics of water table fluctuations, as well as to identify spatial patterns within the hillslope and possible correlations between the timing of stream discharge and well fluctuations. The magnitude of water table response to storm events and the time lag from initiation of precipitation to initiation of well

response increased with distance upslope. Wells lower in the hillslope responded quickly (60-100 min) to the onset of precipitation, and also had the greatest rate of increase in water table, often tracking identically with the sharp rise and recession of the stream hydrograph. Water table response became more attenuated and delayed with distance upslope, although the middle wells (3, 3a and 4) still responded on the time scale of the storm event. At the upper end of the transect, water table dynamics in Well 5 were even more damped and attenuated.

Fig. 3.4a shows the relationship between the storm hydrograph and water table elevations in each of the wells. All wells showed an anti-clockwise hysteretic relation with streamflow, implying the near stream groundwater led the rising limb of the hydrograph, while the deeper bedrock groundwater farther upslope controlled the stream hydrograph falling limb. Spearman's rank correlation coefficient was calculated for these data (Table 3.2). This non-parameterized measure of statistical dependence measures the correlation between changes in the storm hydrograph and changes in water tables within each well, while also accounting for different relationships (e.g. linear, logarithmic, etc.) that may exist between the well fluctuations and the storm hydrograph (Seibert et al., 2003). Well 1 had the strongest correlation to the storm hydrograph, and although changes in the water table elevation were minimal (< 0.08 m), they followed closely with stream fluctuations despite being over 15 m from the stream channel. The correlation between well fluctuations and the storm hydrograph weakened with greater distance upslope as expected by the increasingly delayed and attenuated storm response.

3.4.2.2 HJ Andrews WS10 Groundwater Dynamics

Sixteen storm events with precipitation totals greater than 8 mm were recorded during the study period. Twenty-four hour precipitation totals ranged from 1 mm to 86 mm, with a 1-hour maximum rainfall intensity of 12 mm occurring during the Feb 15 event. Stream discharge ranged from a dry season low of 0.05 mm/hr to a maximum of 3.9 mm/hr during the Jan 16 event. Fig. 3.3b shows the time series data of bedrock water table elevations, the hydrograph and the hyetograph during the study period.

The bedrock groundwater dynamics at WS10 displayed an array of different characteristics depending on well depth, well location and intersection with conductive fracture zones. Table 3.2 shows the general hydrometric characteristics of the wells and Fig. 2b shows the well dynamics in context to their location on the hillslope. All wells retained some water during the study period except for the two shallow wells, B1 and B4, that wetted up only during storm events. Depth to water table and water table dynamics were influenced by the heterogeneity of the fracture network within the bedrock and, unlike the hillslope at M8, no pattern was observed with distance upslope.

Two bedrock horizons displayed distinct water table responses. The upper layer consisting of highly fractured, highly transmissive bedrock had measurable water tables only during storm events (Wells B1 and B4) and the deeper zone that remained permanently wet throughout the study period. Wells penetrating into the deeper zone had water tables that either fluctuated considerably during events (Wells A, B3 and D) or showed little or no response through the entire study period (Wells B2 and C).

Wells B1 and B4 only became active during storm events, and further, only became active when the water table elevation in Well D (upslope) reached a critical level. The drilling log for Well D showed a major fracture zone at this critical point (~1.7 m below the SBI) and we hypothesize that the water table rises up to this fracture zone in Well D and then spills over, initiating subsurface lateral flow through the bedrock that then initiates a water table response in Wells B1 and B4. Well logs for Wells B1 and B4 showed active fractures located just 0.3 m into the bedrock, indicating the fracture connecting these wells to Well D gets shallower with distance downslope. Additionally, during installation of these wells, drilling fluid (the silt laden water produced while drilling) was observed draining into this fracture pathway and then reemerging downslope in the hillslope trench, suggesting that this hydrologically active fracture zone initiates upslope of Well D, travels downslope through Wells B1 and B4 and pinches out at the soil bedrock interface above the trench. During storm events, the water table in well D would rise rapidly to the level of the fracture zone and then plateau with little or no further water table increase. This process, similar to transmissivity feedback in till mantled terrain (Bishop, 1991), creates a visual capping effect in the water table time series (Figure 3.3b) and was also noted in Well A suggesting the occurrence of significant subsurface lateral flow through the bedrock.

Well C remained wet for the duration of the study period, yet there was little or no response in the water table elevation and no long-term variations were observed through the duration of monitoring despite being located only 4 m from Well D which

responded rapidly to storm events and had water table fluctuations of up to 1.6 m. Additionally, water tables recovered quickly after a 30 minute pumping test that removed a volume of water equivalent to 3 times the borehole storage. It is likely that the bedrock groundwater aquifer accessed by Well C is compartmentalized and isolated from hillslope processes that occur on a storm-event time scale.

Wells A and B3 had similar water table elevations and similar water table dynamics during storm events, likely denoting the intersection of the same fracture zone by each well. Well B3 had slightly higher water table elevations indicating a downslope gradient towards Well A, and the water table in both of these wells remained above the elevation of the stream channel denoting a gaining reach in the stream.

Fig. 3.4b shows the relationship between the storm hydrograph and water table elevations in each of the wells. A similar relationship exists between Wells D and B1, reinforcing the idea that these wells have intersected the same fracture pathway. Spearman's rank correlation coefficients were also computed for each well and results are shown in Table 3.2. Although some wells were more correlated with fluctuations in catchment discharge than others, there was no discernible spatial pattern to the connectivity. The heterogeneity of the fracture network within the hillslope bedrock explains this lack of correlation.

3.4.3 Bedrock Groundwater Contributions to Hillslope Discharge

Our main approach in determining whether bedrock groundwater contributed to hillslope discharge was to ask whether water tables ever rose to or above the soil-bedrock interface. It was assumed that direct contribution of bedrock groundwater to hillslope runoff would occur if water tables within the bedrock rise into the highly transmissive soil mantle. Monitoring through a range of storm event sizes and antecedent conditions provided a strong test of this hypothesis. Additionally, we asked whether BGW was isotopically distinct from streamflow and hillslope trenchwater, providing supporting evidence to back-up or refute our hydrometric interpretation for groundwater contributions.

3.4.3.1 Bedrock Groundwater Contributions at Maimai M8

Water tables in the wells measuring bedrock groundwater in the M8 hillslope never rose to or above the soil-bedrock interface and thus, did not contribute directly to subsurface lateral flow from the hillslope. Well 1, located 15 m from the stream channel, had a water table closest to the soil bedrock interface.

Isotope sampling of the rainfall, groundwater wells, hillslope, trenchflow and stream support the well-based hydrometric evidence of little event-based mixing between the BGW and subsurface stormflow compartments. Isotope values in the wells showed minimal deflection towards that of rainfall (Fig. 5) and were all quite similar before, during and after the storm event. Isotope data collected during a 36 mm storm event is shown in Fig. 3.5a. The isotopic signature of the bedrock groundwater

collected from Wells 1, 2, 3 and 5 was distinct from that of the stream water and trench water (soil). The stream water shifted toward the heavier (more positive) isotopic signatures of the trench and rain water during the peak of the storm and then became lighter (more negative) after the storm peaked. The bedrock groundwater had a lighter isotopic signature than the stream and the trench (soil) water, and remained relatively unchanged through the duration of the event and well past the storm recession.

3.4.3.2 Bedrock Groundwater Contributions at HJ Andrews WS10

Water tables within the wells measuring bedrock groundwater in the WS10 hillslope never rose up to or above the soil-bedrock interface. The water table in Well B4 was nearest the surface, but never rose higher than 0.3 m into the bedrock. Fig. 3.5b shows the times series of isotope analysis during a 34 mm storm event. Here again, isotope sampling of the rainfall, groundwater wells, hillslope trenchflow and stream support the well-based hydrometric evidence of little event-based mixing between the BGW and subsurface stormflow compartments. Isotope values in the wells showed minimal deflection towards that of rainfall (Fig. 3.5). At the peak of the hydrograph the stream, trench, and Wells B1 and B4 shifted towards a lighter (more negative) isotopic signature indicating the addition of an isotopically lighter component not captured by the end member samples of rainfall, trenchflow and groundwater. We speculate that unsampled vadose zone water is the likely missing

end member. Once the storm peak passed and the recession began, the isotope composition of the stream, trench and wells shifted back to similar values.

3.5 DISCUSSION

3.5.1 An Evolving Perceptual Model of Hillslope Hydrology at Two Benchmark Sites

While a number of studies have addressed the influence of bedrock structure on catchment processes through indirect (i.e. spring or seepage analysis (Iwagami et al., 2010)) and direct measurements at single sites (Banks et al., 2009; Haria and Shand, 2004; Kosugi et al., 2008; Montgomery et al., 1997; Uchida et al., 2002; Wilson and Dietrich, 1987), we know of no studies that have compared hillslope and catchment-scale runoff processes through comparative analysis of directly monitored bedrock groundwater dynamics and core-based bedrock structure at previous benchmark hillslope hydrological sites. Our study, therefore, affords the ability to further the evolving perceptual model of hillslope hydrology at Maimai and HJ Andrews by contributing new insights on the role of bedrock groundwater to an already rich understanding of soil mantle, subsurface stormflow processes established in previous papers by different groups working at both sites.

3.5.1.1 Maimai M8

Early work by Mosely (1979), Pearce et al. (1986), Sklash et al. (1986) and McDonnell (1990) shaped our understanding of runoff behavior at Maimai, through

iterative study of mechanisms, with different approaches and different interpretations. Despite over 30 years of work dedicated to this single site, studies still emerge from this catchment with new perceptual models of how runoff is formed at the hillslope and catchment scales (Graham et al., 2010b; McGlynn et al., 2004). To date, the bedrock at Maimai has been described as “poorly permeable” (O'Loughlin et al., 1978), “effectively impermeable” (McDonnell, 1990), and “nearly impermeable” (McGlynn et al., 2002), despite the fact that no direct measurements were taken of its hydraulic conductivity or permeability. Graham et al. (2010b) challenged this perception with measured K_{sat} of $1-3 \text{ mm hr}^{-1}$, a value that suggests that bedrock groundwater could exert considerable influence on storm runoff.

Fig. 3.6a illustrates our new perceptual model of BGW contributions to hillslope and catchment flow at M8. This current study has shown the bedrock to be quite permeable and the bedrock structure promotes bulk water flow and significant storm response. For the storms monitored, bedrock groundwater did not rise above the soil bedrock interface, and therefore, did not contribute directly to the subsurface lateral stormflow. This interpretation was supported by isotopic evidence showing no deflection in the isotopic signature of bedrock groundwater towards either the soil water or precipitation values during a storm event, implying no mixing within the bedrock on the event time frame. Nevertheless, the dynamic response of bedrock water tables on a storm-event time scale (Fig. 3a) offers evidence of bedrock groundwater responsiveness and potential significance at the catchment scale. Indeed if one examines the runoff ratios at the hillslope and catchment scales at Maimai,

reported M8 hillslope runoff ratios are on the order of 13%, while the catchment wide runoff ratio is nearly 60% (Woods and Rowe, 1996). This strong dichotomy suggests that groundwater likely influences stream response independent of shallow, lateral flow paths that have been the focus on so many previous studies at the site (as reviewed by McGlynn et al. (2002)).

Event-based bedrock groundwater response to storm rainfall appears to have 3 distinct zones of behavior: a lower, middle and upper region that responds differently due to differing bedrock properties, hillslope location, and depth to water tables. The lower section is defined by higher transmissivities, as shown by our slug tests. Although this region exists as a flow convergence zone for the upslope area (similar to early, fundamental ideas put forward by Toth (1962) and many papers that have followed), as well as possible down-catchment flow, the region is able to accommodate greater flow without major increases in water table elevations due to its higher transmissivities. McGlynn et al. (2004) showed a strong correlation between riparian zone groundwater levels and runoff for the headwater catchments at Maimai. This, along with the high Spearman rank correlation coefficient between Well 1 and the stream, suggest that these regions may be tightly coupled with each other. Further, if the riparian zone is the location of re-emergence of bedrock groundwater, it offers in part, an explanation of why bedrock groundwater was isotopically distinct from stream water, even during low flow periods. The ability of the riparian zone to buffer the isotopic signature of hillslope discharge is well known (Hill, 2000), and can presumably be extended to bedrock groundwater discharge into this region.

Further upslope (Wells 3, 3a, and 4), groundwater dynamics lose their correlation to the storm hydrograph, while also having considerably larger fluctuations in water table elevations. Although the water table fluctuations have greater amplitude, they are more delayed and attenuated than down slope. The lower hydraulic conductivity, and thus lower transmissivity of this section of the hillslope helps to explain this observation. The water table in this region of the hillslope, however, is still close enough to the bedrock surface that responses occur on the storm-event time scale. With additional distance upslope (Well 5), the water table is deep enough into the bedrock (~ 5 m) and the hydraulic conductivity low enough that the storm signal becomes even more attenuated and delayed (on the order of days), thus removing any correlation between water table fluctuations and the stream hydrograph. Further, there exists some anomalous behavior of water table fluctuations within Well 5 that are difficult to explain with respect to rainfall input (e.g. water table increase prior to the Aug 2 storm event). One might suspect a faulty seal at the soil bedrock interface allowing event water moving vertically along the well annulus to contaminate the groundwater signal, however, we have isotope analysis during a storm event showing no deviation of water composition. An alternative hypothesis to explain these data may be changes in barometric pressure. Such changes are capable of producing considerable responses in water table elevations within wells (Rasmussen and Crawford, 1997), and appears that our observed rise in water table prior to the onset of the storm event precipitation may be a function of the barometric efficiency of the well.

Graham et al. (2010b) showed that the surface bedrock had a hydraulic conductivity high enough to account for > 1000 mm of water balance loss annually into the bedrock. Old Man Gravel as a bedrock unit is comparatively soft, weathered, and loosely consolidated. The friable sandy matrix is easily crumbled by hand and holds little structural capacity, lending it to a description more similar to saprolite or regolith than competent hard rock. Perhaps the best local proxy for our hydrogeological situation is a similar geological unit known as Moutere Gravel that exists north-east of the Old Man Gravel and has been extensively studied for its groundwater resources (Stewart and Thomas, 2002). The Moutere Gravel is comprised primarily of sandstone clasts in a clay-bound muddy sand matrix. The principal mechanism of groundwater recharge to shallow aquifers has been identified as direct rainfall infiltration through unconfined regions, consistent with our limited measurements at Maimai.

3.5.1.2 HJ Andrews WS10

Watershed 10 at the HJ Andrews, like M8 at Maimai, has been the site of a significant number of influential studies that have shaped the understanding of hillslope hydrology in steep, humid catchments. Harr's 1977 benchmark work shed light on the processes of subsurface storm flow, near stream saturated zones, and transient saturation at the soil-bedrock interface. Harr found that only the region within 12-15 m of the stream channel became saturated (at the soil-bedrock interface) during storm events, while upslope regions had transient saturated patches where

fluxes were high (i.e., 10-25 cm h⁻¹) if connected to the near-stream saturated zone. More recently, McGuire and McDonnell (2010) investigated hillslope-stream connectivity in this same catchment and found that far upslope areas contributed directly to subsurface runoff from the hillslope, implying the existence of preferential flow paths that short circuit traditional matrix flow through the soil. Our current work offers further evidence regarding the nature of the transient saturated zones and provides evidence for additional high flux pathways within the bedrock that are capable of connecting upslope with downslope regions and eventually with the stream channel.

Fig. 6b illustrates our new perceptual model of BGW contributions to hillslope and catchment flow at WS10. Our findings suggest that the bedrock groundwater table does not rise above the soil-bedrock interface and thus, does not contribute directly to lateral subsurface storm flow at the soil bedrock interface. We do have evidence, however, that the very shallow highly fractured bedrock in and around the soil-bedrock interface does exert an influence on runoff processes and contributes directly to lateral subsurface stormflow. We hypothesize that once subsurface storm flow occurs, some portion of the flow is lost as seepage to the fractured bedrock. Once in the bedrock, flow is controlled by the fracture network density, geometry and connectivity (Banks et al., 2009) and is extremely heterogeneous. Well dynamics shown in Fig. 3.3a provide evidence of differing flow paths within the fractured bedrock. Some flow follows deeper fracture pathways connecting to a deeper bedrock groundwater aquifer. This seepage does not play a direct role in the storm event

runoff, but instead follows classic groundwater discharge pathways that maintain baseflow conditions (Winter, 2007). Subsurface stormflow that follows shallow bedrock fracture pathways may either remerge at the soil bedrock interface if the fracture pinches out, or may directly bypass to the stream channel depending on the fracture network. In both cases, this water has a direct contribution to storm runoff. Graham et al. (2010a) showed that near surface fractured bedrock constituted a significant flowpath in the WS10 hillslope, nearly equal in volume to subsurface lateral flow in the soil during a sprinkler experiment that brought the WS10 instrumented hillslope up to steady state discharge. Highly fractured regions of bedrock can act to either prevent saturation due to highly transmissive fractures that transport water rapidly downslope, or augment saturation at the soil bedrock interface by acting as an exfiltration zone which transports and concentrates water from upslope regions to downslope regions. Similar findings have been reported by others. For example, Uchida et al. (2002) determined that exfiltrating bedrock groundwater was an important contributor to transient groundwater in upper hillslope regions in a zero-order catchment in central Japan. Wilson and Dietrich (1987) noted that bedrock return flow occurred where fractured bedrock encountered a competent zone that forced flow back up into the subsoil, creating a transient saturated zone. Montgomery et al. (2002) and Anderson et al. (1997) found that return flow from bedrock created zones of transient saturation at the soil bedrock interface, and deeper bedrock pathways carried tracers rapidly through the subsurface to the channel head.

Considering the heterogeneity of fractured bedrock, it is possible to conceive of a patchy network of saturated zones in upslope regions that are in part, controlled by the underlying bedrock. Saturated zones would occur on top of more competent regions, while unsaturated zone would occur over fractured regions. The hillslope would then display variably saturated conditions depending on rainfall amount, intensity, and antecedent conditions, similar to what both Harr (1977) and McGuire and McDonnell (2010) reported. The isotope time series (Fig. 5b) shows Wells B1, B4, and the trench all shifting away from the rain input signal towards lighter isotopic values immediately prior to the hydrograph peak. Although we cannot directly identify the water source that is causing this shift (although we hypothesize that it is unmeasured soil water/vadose water end member), we are able to rule out event water as the source of water into the bedrock.

3.5.2 Similar Hillslope Forms Can Hide Radically Different Plumbing

M8 and WS10 share strikingly similar catchment size, average slope angle, length and relief, soil properties, average yearly rainfall totals and catchment runoff ratios (see soil-based, comparative analysis by Sayama and McDonnell (2009)). Both catchments are highly responsive (Harr, 1977; Mosley, 1979) and if viewed from their respective outlets, catchment runoff ratios, water balances and total annual rainfall are nearly identical (Table 3.1). Despite these similarities, these catchments hide radically different underlying geologic composition and structure, and as such, their hillslopes store and transmit water through distinctly different mechanisms. Some indications of

this have been apparent from previous work (Sayama and McDonnell, 2009); most notably the distribution of soil depths at the two sites: Maimai shows a strong catenary sequence of thin, coarse soils on the ridges grading into deep colluvial filled hollows with infilling of fines (Mosley, 1979). WS 10 shows an almost reverse pattern whereby soil depths increase progressively from thin, permeable soils near the toe of the hillslope to >7 m soil and sub-soil depths at the ridge (Harr, 1977).

The M8 slope appears to lack the WS10 bedrock fracture flowpaths, however, the permeable bedrock at M8 provides a greater potential for more spatially uniform recharge across the whole bedrock surface as infiltration would be possible everywhere below the soil mantle (although we know that there is considerable convergence of flow along the soil bedrock interface, as shown by the soil removal experiments of Graham et al. (2010b) and that hollows in particular may be enhanced zones of deep, groundwater recharge). Alternatively, at WS10, the dual porosity bedrock structure facilitates flow through only the fracture pathways on a storm-event time scale, as opposed to the intergranular pore space of the bedrock matrix as seen at Maimai. Infiltration into the bedrock would then be directly controlled by not only the spatial heterogeneity of fractures at the bedrock surface at WS10, but also by the heterogeneity and anisotropy of the fracture properties, such as density, connectedness, and aperture size.

Comparing catchment versus hillslope runoff at each site reveals how these different structural geologies affect the hillslope and catchment flow regimes. As stated earlier, Woods and Rowe (1996) reported M8 hillslope runoff ratios of only

13%, while the catchment wide runoff ratio is nearly 60%. Aside from rainfall landing directly on the riparian zone and stream channel and assuming no interbasin transfer, this difference (47% minus stream and riparian interception) would likely be caused by water seeping into the hillslope bedrock (as shown elsewhere with direct experiments; Tromp van Meerveld et al. (2007); Graham et al. (2010b)). It is assumed that this loss to bedrock bypasses colluvial hillslope processes and discharges into the stream channel or riparian zone (below the hillslope toe as measured with our trench). Our findings are consistent with Graham et al. (2010b) who calculated a loss to bedrock at the hillslope scale of 41% of rainfall at M8, and also concluded that flow reemerged into the stream channel through deeper bedrock pathways supporting this claim.

Runoff ratios at WS10 are approximately 56 % of annual rainfall at the catchment scale (McGuire et al., 2005) and approximately 80 % at the hillslope scale (calculated from rainfall and hillslope discharge during the 2010-2011 wet season). The high hillslope runoff ratio is indicative of a hillslope that sheds the majority of its water into the stream channel with little loss to deeper bedrock seepage. Graham et al (2010a) calculated this deep seepage to be approximately 21% of precipitation during a sprinkler experiment that brought the WS10 hillslope up to steady state discharge. Although our work shows that both the upper (~1 m) and lower (~5 m) layers of bedrock were both shown to be hydrologically active during storm events, we hypothesize that the active upper layer returns flow back to the soil bedrock interface upslope of the stream channel on a storm-event time scale, thus accounting for the

high hillslope runoff ratios. Both of these findings - at Maimai and WS10 - highlight the sensitivity of how one calculates and compares hillslope vs. catchment runoff ratios based on trench placement. If the WS10 trench was located some meters upslope of its current position and likely capturing hillslope discharge without the deeper return flow, then the runoff ratio may have been more similar to that of the catchment. Alternatively, if the Maimai trench was located farther downslope and in or adjacent to the riparian area, then the hillslope flow recorded could have been augmented by bedrock groundwater returns.

One other notable difference between the M8 and WS10 catchments is the streamwater mean residence time. The M8 watershed has an isotope-computed mean residence time of about 4 months, as reported by Pearce et al. (1986). The WS10 streamwater mean residence time is on the order of 1.2 years, based on work reported by McGuire et al. (2005). The two subsurface, bedrock groundwater flow regimes help explain these measured mean residence time differences. Streamwater mean residence time is directly proportional to storage (i.e. an increase in storage results in an increase in mean residence time) and inversely proportional to flux (for review, see McGuire and McDonnell (2007)). Katsuyama et al. (2010) examined bedrock groundwater recharge/discharge dynamics at 6 nested catchments underlain by weathered granite and found bedrock permeability and bedrock groundwater dynamics to be a dominant control of mean residence time at each catchment. Specifically, they found that mean residence time decreased with increases in bedrock infiltration. Bedrock infiltration into our experimental hillslopes can be inferred from differences in runoff ratios

between the hillslopes and their catchments (the greater the difference the larger the flux into the hillslope), and storage capacity from the different bedrock structure at each hillslope (Graham et al., 2010a). The porous Old Man Gravel at M8 has greater storage but also much greater flux. This, combined with the continuous nature of the Maimai precipitation regime (only ~3 days between events on average through the hydrologic year, with little seasonality) causes a constant flushing of water through the system resulting in a shorter catchment-wide mean residence time. The fractured bedrock at WS10 has both minimal storage and minimal flux. While this does not completely explain the longer streamwater mean residence time, when coupled with the highly seasonal rainfall regime (80 % falling between the period November to March, as reported by Sayama and McDonnell (2009)) and the more tortuous flow paths taken by the water that sustains baseflow, these conditions lend themselves to longer mean residence times. Sayama and McDonnell (2009) indeed showed that streamwater mean residence time was largely influenced by the interactions between rainfall seasonality and soil mantle depth. During the wet season, runoff is high and residence time is low, while during the dry season when baseflow constitutes the majority of runoff the residence time is long. We hypothesize here that although greater volumes of younger-water discharge from WS10 than older water, the older water is disproportionately old due extremely tortuous flowpaths through deeper bedrock, resulting in a mean that is skewed towards longer timeframes. Our work, along with the work of Katsuyama et al. (2010), highlights the importance of

understanding bedrock structure and its larger influence on flowpaths within catchments and their imprint on mean residence time.

3.5.3 Final remarks

Whether bedrock groundwater contributes directly to subsurface stormflow or indirectly, it is intimately connected to the processes involved with hillslope response and catchment runoff generation. Common themes are beginning to emerge from both previously well-monitored and well-documented sites and in new research locations, all demonstrating the importance of bedrock groundwater in different facets of the larger catchment hydrological cycle.

Variable flow sources in subsurface storm flow are controlled by transient saturation at the soil bedrock interface (McDonnell, 2003). The permeability of the underlying bedrock has been shown to affect the spatial and temporal development of these transient saturated zones in the soil mantle (Anderson et al., 1997; Haria and Shand, 2004; Hopp and McDonnell, 2009; Katsura et al., 2008; Katsuyama et al., 2005; Kosugi et al., 2008; Montgomery et al., 1997; Tromp-van Meerveld et al., 2007; Uchida et al., 2003; Uchida et al., 2002; Wilson and Dietrich, 1987) as well as influence hillslope discharge into the riparian zone (Katsuyama et al., 2005), the overall catchment mean residence time (Katsuyama et al., 2010) the biogeochemistry of stormflow (Banks et al., 2009), and in some cases contribute considerably to storm runoff (Iwagami et al., 2010).

Our intercomparison of Maimai and WS10 revealed patterns and behaviors that could not otherwise have been identified through single hillslope analysis. The juxtaposition of similar catchment response despite wholly different geologies highlighted the fracture vs. bulk flow through different bedrock structures. The implications of this work clearly demonstrate a shifting need for catchment hydrology to utilize structural geology, hydrogeology and bedrock well drilling to better understand the flow processes and hydrological functioning at hillslope and catchment scales. Site access continues to remain an issue, however, drilling technologies exist to drill wells in moderately flat and accessible terrain to great depths (www.minex-intl.com/) and new technologies have been developed that offer light weight portable drilling systems capable of drilling bedrock in steep terrain inaccessible to normal drilling techniques (Gabrielli and McDonnell, 2011). Future work should exploit the dialog between experimentalist and modeler, where the complexities of bedrock flow, especially fracture flow can be explored within new model approaches that enable a holistic view of hillslope and catchment dynamics (Kollet and Maxwell, 2006; Maxwell and Miller, 2005; Sudicky et al., 2008).

3.6 CONCLUSION

We examined the spatial and temporal dynamics of bedrock groundwater and its contribution to rainfall-runoff response at catchment and hillslope scales. The study was conducted at two previously well-studied sites, Watershed 10 at the HJ Andrews in Oregon, USA and M8 at the Maimai in New Zealand. Wells were drilled into

bedrock using a new drilling system designed by Gabrielli and McDonnell (2011). We accepted our null hypothesis that bedrock groundwater does not contribute directly to lateral subsurface storm flow through the process of rising out of the bedrock and spilling laterally down the hillslope at the soil-bedrock interface. We found the bedrock structure of M8 to have a much greater permeability than previously thought, despite no evidence of surface fractures. Bulk water movement occurred primarily as seepage through the hillslope rather than as lateral subsurface stormflow along the soil-bedrock interface. Reemergence of hillslope bedrock groundwater appeared to occur in the riparian zone, resulting in a strong dichotomy between hillslope-scale and catchment-scale runoff ratios. The previously reported short mean residence time of streamwater appears to be a function of the permeable bedrock and high storm intervals causing a steady flushing of water through the catchment.

We found a complex and highly fractured bedrock structure underlying the hillslope at WS10. Water movement through the bedrock was determined by the extent of the fracture network, its connectivity, and geometry. The highly fractured upper layer of bedrock acted as a lateral preferential flow path, connecting saturated upslope areas with near stream saturated zones. The deeper bedrock aquifer appeared to be recharged through discrete and isolated vertical fractures that connect to the surface. Although rainfall-runoff ratios were high for both the catchment and the hillslope, the mean residence time of stream water was 4 times older than the M8 catchment. We hypothesize that old bedrock groundwater from deeper pathways

reemerges into the stream channel and skews the residence time towards older values despite being a small volumetric proportion of the total stream discharge.

3.7 ACKNOWLEDGEMENTS

This work was supported through funding from NSF Grant NSF/DEB 0746179. We thank Ross Woods, John Payne, Iris Pitt, Travis Roth, Rosemary Fanelli and Tina Garland for help in the field and Tim Burt, Keith Smettem, Todd Jarvis, Cody Hale, Lyssette Munos Villers for useful discussions.

3.8 REFERENCES

- Anderson, S.P. et al., 1997. Subsurface flow paths in a steep, unchanneled catchment. *Water Resour. Res.*, 33(12): 2637-2653.
- Bachmair, S., Weiler, M., 2011. New Dimensions of Hillslope Hydrology Forest Hydrology and Biogeochemistry. In: Levia, D.F., Carlyle-Moses, D., Tanaka, T. (Eds.). *Ecological Studies*. Springer Netherlands, pp. 455-481.
- Banks, E. et al., 2009. Fractured bedrock and saprolite hydrogeologic controls on groundwater/surface-water interaction: a conceptual model (Australia). *Hydrogeol. J.*, 17(8): 1969-1989.
- Beven, K.J. (Ed.), 2006. Streamflow generation processes. *Benchmark papers in hydrology*, 1. International Association of Hydrological Sciences, Wallingford.
- Bonell, M., 1998. Selected challenges in runoff generation research in forests from the hillslope to headwater drainage basin scale. *Journal of the American Water Resources Association*, 34(4): 765-785.
- Brammer, D., 1996. Hillslope hydrology in a small forested catchment, Maimai, New Zealand, State University of New York, Syracuse, 153 pp.
- Buttle, J. (Ed.), 1998. Fundamentals of small catchment hydrology. *Isotope Tracers in Catchment Hydrology*. Elsevier, Amsterdam, 1-43 pp.

- Dagan, G., 1978. A note on packer, slug, and recovery tests in unconfined aquifers. *Water Resour. Res.*, 14(5): 929-934.
- Dietrich, P., Helmig, R., Sauter, M., Hötzl, H., Köngeter, J., Teutsch, G. (Ed.), 2005. *Flow and Transport in Fractured Porous Media*. Springer-Verlag, Berlin.
- Dunne, T. (Ed.), 1978. *Field studies of hillslope flow processes*. Hillslope Hydrology. Wiley, Chichester, 227-293 pp.
- Freeze, R.A., Cherry, J.A., 1979. *Groundwater*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.
- Gabrielli, C.P., McDonnell, J.J., 2011. An inexpensive and portable drill rig for bedrock groundwater studies in headwater catchments. *Hydrol. Processes*.
- Graham, C.B., McDonnell, J.J., 2010. Hillslope threshold response to rainfall: (2) Development and use of a macroscale model. *J. Hydrol.*, 393(1-2): 77-93.
- Graham, C.B., van Verseveld, W., Barnard, H.R., McDonnell, J.J., 2010a. Estimating the deep seepage component of the hillslope and catchment water balance within a measurement uncertainty framework. *Hydrol. Processes*, 24(25): 3631-3647.
- Graham, C.B., Woods, R.A., McDonnell, J.J., 2010b. Hillslope threshold response to rainfall: (1) A field based forensic approach. *J. Hydrol.*, 393(1-2): 65-76.
- Haria, A.H., Shand, P., 2004. Evidence for deep sub-surface flow routing in forested upland Wales: implications for contaminant transport and stream flow generation. *Hydrol. Earth Syst. Sci.*
- Haria, A.H., Shand, P., 2006. Near-stream soil water-groundwater coupling in the headwaters of the Afon Hafren, Wales: Implications for surface water quality. *J. Hydrol.*, 331(3-4): 567-579.
- Harr, R.D., 1977. Water flux in soil and subsoil on a steep forested slope. *J. Hydrol.*, 33(1-2): 37-58.
- Harr, R.D., McCorison, F.M., 1979. Initial effects of clearcut logging on size and timing of peak flows in a small watershed in western Oregon. *Water Resour. Res.*, 15(1): 90-94.
- Harr, R.D., Ranken, D.W., 1972. *Movement of water through forested soils in steep topography*, University of Washington, Seattle.

- Hewlett, J., Hibbert, A., 1967. Factors affecting the response of small watersheds to precipitation in humid areas, In: Sopper WE, Lull HW (eds) *Procc Int Symp on Forest Hydrology*. Pergamon Press, Oxford, pp. 275-290.
- Hill, A.R., 2000. Stream chemistry and riparian zones. In: Jones, J., Mulholland, P. (Eds.), *Streams and Ground Waters*. Academic Press, London, pp. 83-110.
- Hopp, L., McDonnell, J.J., 2009. Connectivity at the hillslope scale: Identifying interactions between storm size, bedrock permeability, slope angle and soil depth. *J. Hydrol.*, 376(3-4): 378-391.
- Hursh, C., 1936. Storm-water and adsorption, AGU, 17. *Eos Trans*, pp. 301-302.
- Iwagami, S., Tsujimura, M., Onda, Y., Shimada, J., Tanaka, T., 2010. Role of bedrock groundwater in the rainfall–runoff process in a small headwater catchment underlain by volcanic rock. *Hydrol. Processes*, 24(19): 2771-2783.
- James, M., 1977. *Rock weathering in the Central Western Cascades.*, University of Oregon, Eugene.
- Katsura, S.y., Kosugi, K.i., Mizutani, T., Okunaka, S., Mizuyama, T., 2008. Effects of bedrock groundwater on spatial and temporal variations in soil mantle groundwater in a steep granitic headwater catchment. *Water Resour. Res.*, 44(9): W09430.
- Katsuyama, M., Ohte, N., Kabeya, N., 2005. Effects of bedrock permeability on hillslope and riparian groundwater dynamics in a weathered granite catchment. *Water Resour. Res.*, 41(1): W01010.
- Katsuyama, M., Tani, M., Nishimoto, S., 2010. Connection between streamwater mean residence time and bedrock groundwater recharge/discharge dynamics in weathered granite catchments. *Hydrol. Processes*, 24(16): 2287-2299.
- Kollet, S.J., Maxwell, R.M., 2006. Integrated surface–groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model. *Adv. Water Resour.*, 29(7): 945-958.
- Kosugi, K.i., Katsura, S.y., 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 Resour. Res.*, 44(1): W01407.
- Maxwell, R.M., Miller, N.L., 2005. Development of a Coupled Land Surface and Groundwater Model. *Journal of Hydrometeorology*, 6(3): 233-247.

- Mazurkiewicz, A.B., Callery, D.G., McDonnell, J.J., 2008. Assessing the controls of the snow energy balance and water available for runoff in a rain-on-snow environment. *J. Hydrol.*, 354: 1-14.
- McDonnell, J.J., 1990. A Rationale for Old Water Discharge Through Macropores in a Steep, Humid Catchment. *Water Resour. Res.*, 26(11): 2821-2832.
- McDonnell, J.J., 2003. Where does water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response. *Hydrol. Processes*, 17(9): 1869-1875.
- McDonnell, J.J., Tanaka, T., 2001. On the future of forest hydrology and biogeochemistry. *Hydrol. Processes*, 15(10): 2053-2055.
- McGlynn, B.L., McDonnell, J.J., Brammer, D.D., 2002. A review of the evolving perceptual model of hillslope flowpaths at the Maimai catchments, New Zealand. *J. Hydrol.*, 257(1-4): 1-26.
- McGlynn, B.L., McDonnell, J.J., Seibert, J., Kendall, C., 2004. Scale effects on headwater catchment runoff timing, flow sources, and groundwater-streamflow relations. *Water Resour. Res.*, 40(7): W07504.
- McGuire, K.J., McDonnell, J.J., 2010. Hydrological connectivity of hillslopes and streams: Characteristic time scales and nonlinearities. *Water Resour. Res.*, 46(10): W10543.
- McGuire, K.J. et al., 2005. The role of topography on catchment-scale water residence time. *Water Resour. Res.*, 41(5): W05002.
- McGuire, K.J., Weiler, M., McDonnell, J.J., 2007. Integrating tracer experiments with modeling to assess runoff processes and water transit times. *Adv. Water Resour.*, 30(4): 824-837.
- Montgomery, D.R., Dietrich, W.E., Heffner, J.T., 2002. Piezometric response in shallow bedrock at CB1: Implications for runoff generation and landsliding. *Water Resour. Res.*, 38(12): 1274.
- Montgomery, D.R. et al., 1997. Hydrologic response of a steep, unchanneled valley to natural and applied rainfall. *Water Resour. Res.*, 33(1): 91-109.
- Mosley, M.P., 1979. Streamflow generation in a forested watershed, New Zealand. *Water Resour. Res.*, 15(4): 795-806.

- O'Loughlin, C.L., Rowe, L.K., Pearce, A.J., 1978. Sediment yields from small forested catchments, north Westland, New Zealand. *Journal of Hydrology (NZ)*, 17(1): 1-15.
- Onda, Y., Komatsu, Y., Tsujimura, M., Fujihara, J.-i., 2001. The role of subsurface runoff through bedrock on storm flow generation. *Hydrol. Processes*, 15(10): 1693-1706.
- Pearce, A.J., Stewart, M.K., Sklash, M.G., 1986. Storm Runoff Generation in Humid Headwater Catchments: 1. Where Does the Water Come From? *Water Resour. Res.*, 22(8): 1263-1272.
- Rasmussen, T.C., Crawford, L.A., 1997. Identifying and Removing Barometric Pressure Effects in Confined and Unconfined Aquifers. *Ground Water*, 35(3): 502-511.
- Rowe, L.K., Pearce, A.J., 1994. Hydrology and related changes after harvesting native forest catchments and establishing *pinus radiata* plantations. Part 2. The native forest water balance and changes in streamflow after harvesting. *Hydrol. Processes*, 8(4): 281-297.
- Rowe, L.K., Pearce, A.J., O'Loughlin, C.L., 1994. Hydrology and related changes after harvesting native forest catchments and establishing *pinus radiata* plantations. Part 1. Introduction to study. *Hydrol. Processes*, 8(3): 263-279.
- Sayama, T., McDonnell, J.J., 2009. A new time-space accounting scheme to predict stream water residence time and hydrograph source components at the watershed scale. *Water Resour. Res.*, 45(7): W07401.
- Seibert, J., Bishop, K., Rodhe, A., McDonnell, J.J., 2003. Groundwater dynamics along a hillslope: A test of the steady state hypothesis. *Water Resour. Res.*, 39(1): 1014.
- Sklash, M.G., Stewart, M.K., Pearce, A.J., 1986. Storm Runoff Generation in Humid Headwater Catchments: 2. A Case Study of Hillslope and Low-Order Stream Response. *Water Resour. Res.*, 22(8): 1273-1282.
- Sollins, P., Cromack, K., Mc Corison, F.M., Waring, R.H., Harr, R.D., 1980. Changes in Nitrogen Cycling at an Old-Growth Douglas-fir Site After Disturbance. *J. Environ. Qual.*, 10(1): 37-42.
- Sollins, P., McCorison, F.M., 1981. Nitrogen and carbon solution chemistry of an old growth coniferous forest watershed before and after cutting. *Water Resour. Res.*, 17(5): 1409-1418.

- Stewart, M., Thomas, J., 2002. Moutere Valley groundwater: Nature and recharge from isotopes and chemistry, Institute of Geological and Nuclear Sciences science.
- Sudicky, E., Jones, J., Park, Y.-J., Brookfield, A., Colautti, D., 2008. Simulating complex flow and transport dynamics in an integrated surface-subsurface modeling framework. *Geosci. J.*, 12(2): 107-122.
- Swanson, F., James, M., 1975. Geology and geomorphology of the H.J. Andrews Experimental Forest, western Cascades, Oregon, Pac. Northwest For. and Range Exp. Stn., For. Serv., U.S. Dep. of Agric., Portland, OR.
- Tóth, J., 1962. A Theoretical Analysis of Groundwater Flow in Small Drainage Basins. *Journal of Geophysical Research*, 68: 4795.
- Triska, F.J., Sedell, J.R., Cromack, K.J., Gregory, S.V., Mccorison, F.M., 1984. Nitrogen budget for a small coniferous forest stream. *Ecol. Monogr.*, 54(1).
- Tromp-van Meerveld, H.J., Peters, N.E., McDonnell, J.J., 2007. Effect of bedrock permeability on subsurface stormflow and the water balance of a trenched hillslope at the Panola Mountain Research Watershed, Georgia, USA. *Hydrol. Processes*, 21(6): 750-769.
- Tsuboyama, Y., Sidle, R.C., Noguchi, S., Hosoda, I., 1994. Flow and solute transport through the soil matrix and macropores of a hillslope segment. *Water Resour. Res.*, 30(4): 879-890.
- Uchida, T., Asano, Y., Ohte, N., Mizuyama, T., 2003. Seepage area and rate of bedrock groundwater discharge at a granitic unchanneled hillslope. *Water Resour. Res.*, 39(1): 1018.
- Uchida, T., Kosugi, K.i., Mizuyama, T., 2002. Effects of pipe flow and bedrock groundwater on runoff generation in a steep headwater catchment in Ashiu, central Japan. *Water Resour. Res.*, 38(7): 1119.
- van Verseveld, W.J., McDonnell, J.J., Lajtha, K., 2009. The role of hillslope hydrology in controlling nutrient loss. *J. Hydrol.*, 367(3-4): 11.
- Weiler, M., McDonnell, J.J., Tromp-van Meerveld, I., Uchida, T., 2006. Subsurface Stormflow, *Encyclopedia of Hydrological Sciences*. John Wiley & Sons, Ltd.
- Wilson, C.J., Dietrich, W.E., 1987. The contribution of bedrock groundwater flow to storm runoff and high pore pressure development in hollows, *Erosion and Sedimentation in the Pacific Rim*. IAHS, Corvallis, OR.

Winter, T.C., 2007. The Role of Ground Water in Generating Streamflow in Headwater Areas and in Maintaining Base Flow¹. *Journal of the American Water Resources Association*, 43(1): 15-25.

Woods, R.A., Rowe, L., 1996. The changing spatial variability of subsurface flow across a hillside. *Journal of Hydrology (NZ)*, 35(1): 49-84.

Table 3.1 M8 and WS10 hillslope and catchment physical, meteorological and process characteristics. Source: Sayama and McDonnell (2009) as summarized from primary literature from the two sites.

Characteristic	M8, Maimai	WS10, HJ Andrews
Size (ha)	3.8*	10.2
Slope Angle (°)	34	29
Slope Length (m)	< 300	< 200
Local Relief (m)	100-150	60-130
Soil Type	Silt loams	Clay loams
Mean Soil Depth	0.7 (0.5 – 1.8)	3.0 (1.5-4.2)
Soil infiltration Capacity (mm/h)	6100	> 5000
Soil Ksat (mm/h)	250	275
Bedrock Type	Moderately weathered Pleistocene Conglomerate	Weathered and fractured pyroclastic Tuff and Breccias
Vegetation Cover	Mixed Evergreen forest	Second Growth Douglas-Fir
Avg Annual rainfall (mm)	2600	2350
Seasonality	Year round (Event every ~3 days)	80 % falls between Oct and Apr
Catchment Runoff Ratio (%)	60	56
Hillslope Runoff Ratio (%)	13	80
Runoff Characteristics	Very Responsive	Very Responsive
Pre-event water ratio	> 70	75-80
Stream water MRT	4 months	1.2 years
Bedrock Porosity Characteristics	Porous media	Dual Porosity

*M8 catchment size is calculated from the area upstream of a gauging weir located 50 m upstream of the instrumented hillslope we studied and therefore, actual area including the instrumented hillslope is slightly larger.

Table 3.2 Well characteristics at M8, Maimai and WS10, HJ Andrews.

Well	Distance from stream channel, m	Depth into bedrock, m	Screened Interval, m	Mid-Screen depth, m	Ksat, mm/d	Fracture density, fractures per m (upper most m/lower bedrock)	Average depth to water table, m	*Average water table response to precip, mm/mm	Spearman's Rank, Rho
M8, Maimai									
1	13.7	3.4	2.5	2.2	3.12	-	1.49	0.91	0.72
2	18.9	4.0	3.1	2.5	0.0012	-	3.61	1.69	0.45
3	23.4	5.3	4.4	3.1	0.0009	-	4.38	6.66	0.24
3a	24.6	4.9	4.0	2.9	0.0023	-	4.08	4.58	-
4	28.0	5.5	4.6	3.2	0.0005	-	4.61	3.59	0.28
5	32.5	5.2	4.3	3.0	0.0003	-	4.86	1.59	0.24
WS10, HJ Andrews									
A	3.2	3.4	3.4	1.7	-	26/6	1.48	8.59	0.63
B1	4.6	0.9	0.7	0.6	-	28/-	0.81	7.23	0.91
B2	4.6	3.5	2.0	2.5	-	29/7	1.45	1.92	0.43
B3	4.6	7.5	3.0	6.0	-	25/4	3.18	13.94	0.58
B4	4.6	1.0	0.3	0.9	-	27/-	0.91	-	-
C	6.2	4.6	2.0	3.6	-	18/9	1.49	1.28	0.48
D	6.4	3.8	2.2	2.7	-	21/6	1.91	21.80	0.88

*Note: Average was based on storm events greater than 20 mm total precipitation.

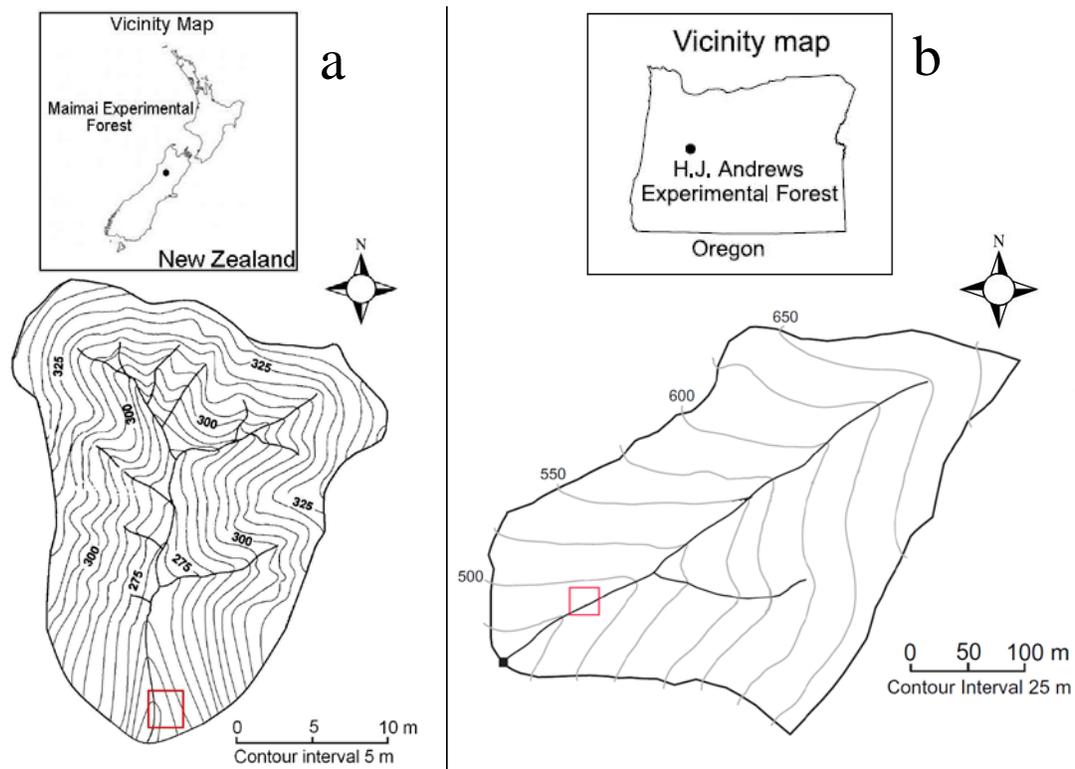


Figure 3.1 Vicinity and catchment map for (a) the M8 catchment at the Maimai Experimental Forest and (b) the WS10 catchment at the HJ Andrews Experimental Forest. Red squares represent the approximate location of the instrumented hillslopes. Note that the catchment boundary for M8 is larger than reported in previous studies. This is due to a weir replacement following a 1988 debris flow that destroyed the original weir for the 3.8 ha catchment. The new weir was constructed ~100 m downstream, resulting in an expanded catchment area as shown on this map. .

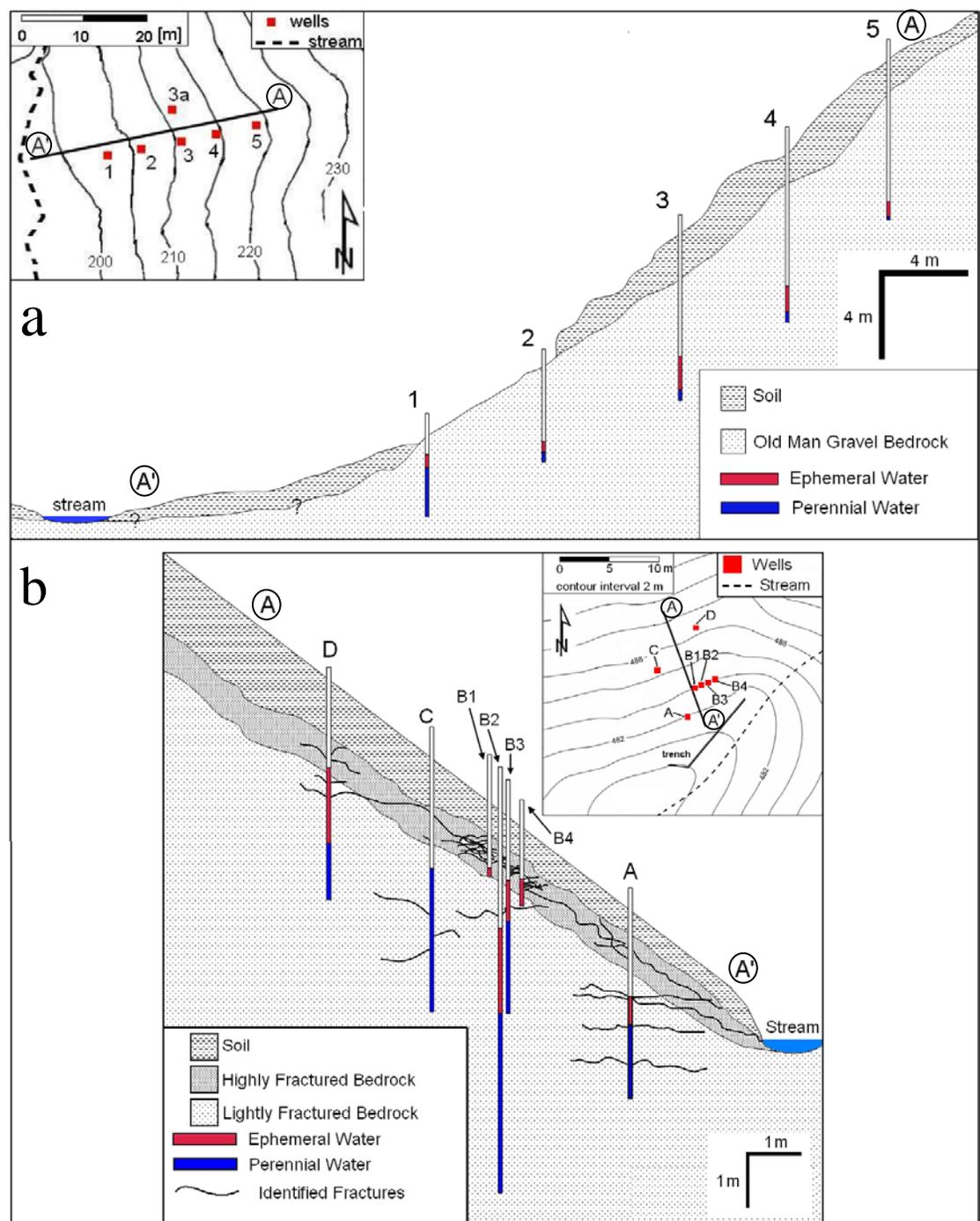


Figure 3.2

Figure 3.2 Profile of instrumented hillslopes at M8 (a) and WS10 (b) showing well depth, water level dynamics through the duration of the study period and geology. Inset map shows plan view of well location and transect line of profile. Core samples from wells were used to define the geological structure shown and to locate the water table in the bedrock. Note the missing soil in (a) due to the excavation work by Graham et al. (2010).

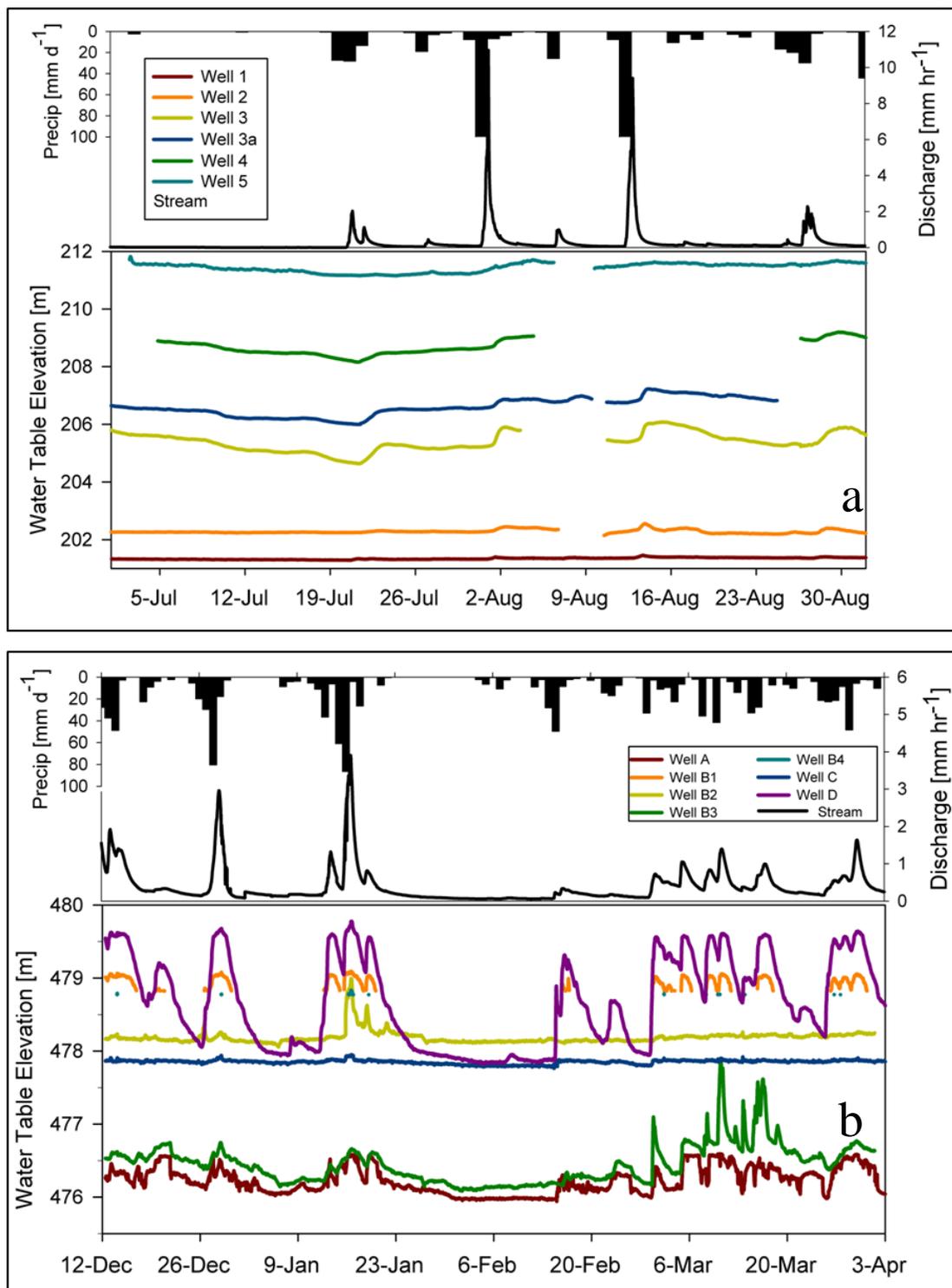


Figure 3.3

Figure 3.3 Water table elevation data from bedrock wells at M8 (a) and WS10(b) along with corresponding stream hydrograph and rainfall hyetograph. Note calculated M8 discharge values are uncertain and likely higher than actual values due to uncertainty in defining the “new” catchment area following the 1988 weir replacement, as noted in Figure 3.1. These runoff dynamics are used for illustrative purposes only to show their timing correspondence to measured well dynamics.

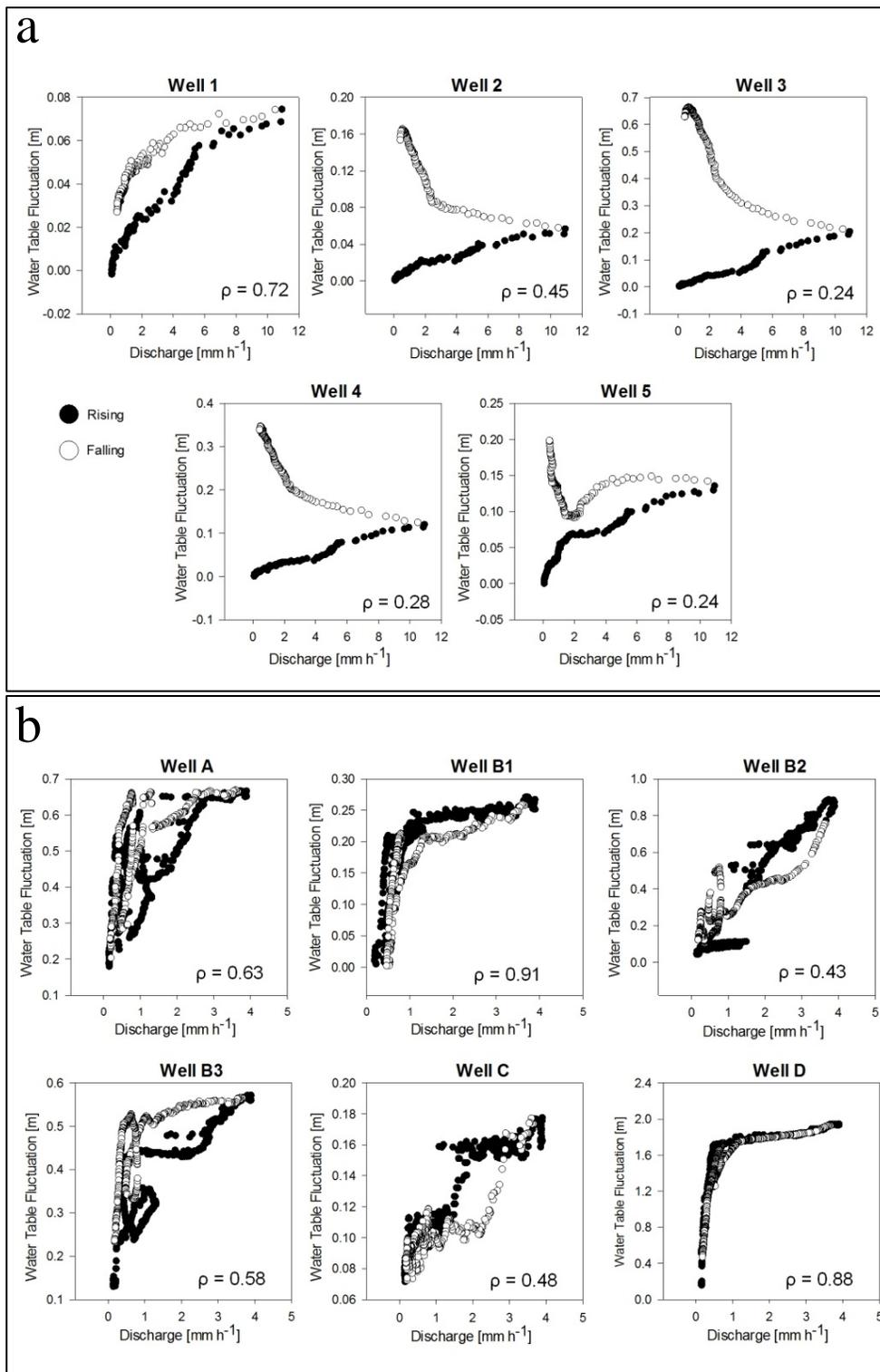


Figure 3.4

Figure 3.4 Relationship between runoff and change in water table for each well during the Aug 2 storm event at M8 (a) and the Dec 28 storm event at WS10 (b). Spearman's Rank Correlation Coefficient (ρ) is displayed for each well. Again, calculated runoff values (absolute amount in mm/hr) are uncertain and likely higher than actual values due to uncertainty in defining the "new" catchment area following the 1988 weir replacement, as noted in Figure 3.1. While the absolute value is uncertain, their timing and thus, hysteretic relations with water table, will not be affected by area-based offset.

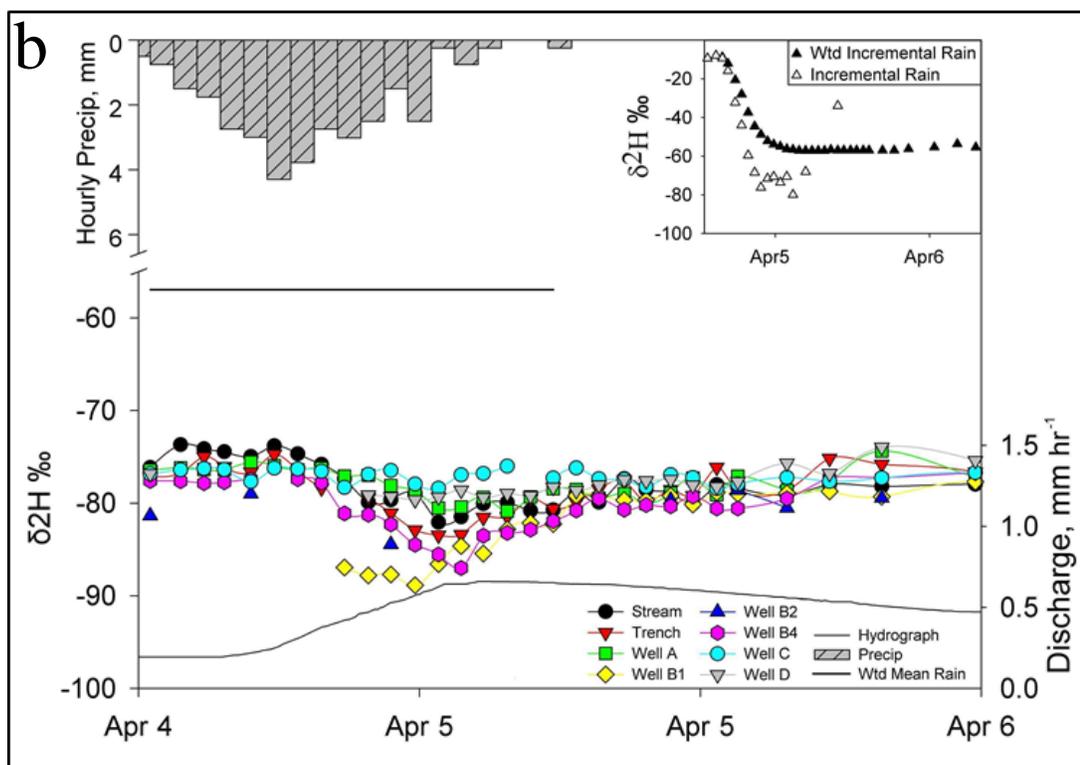
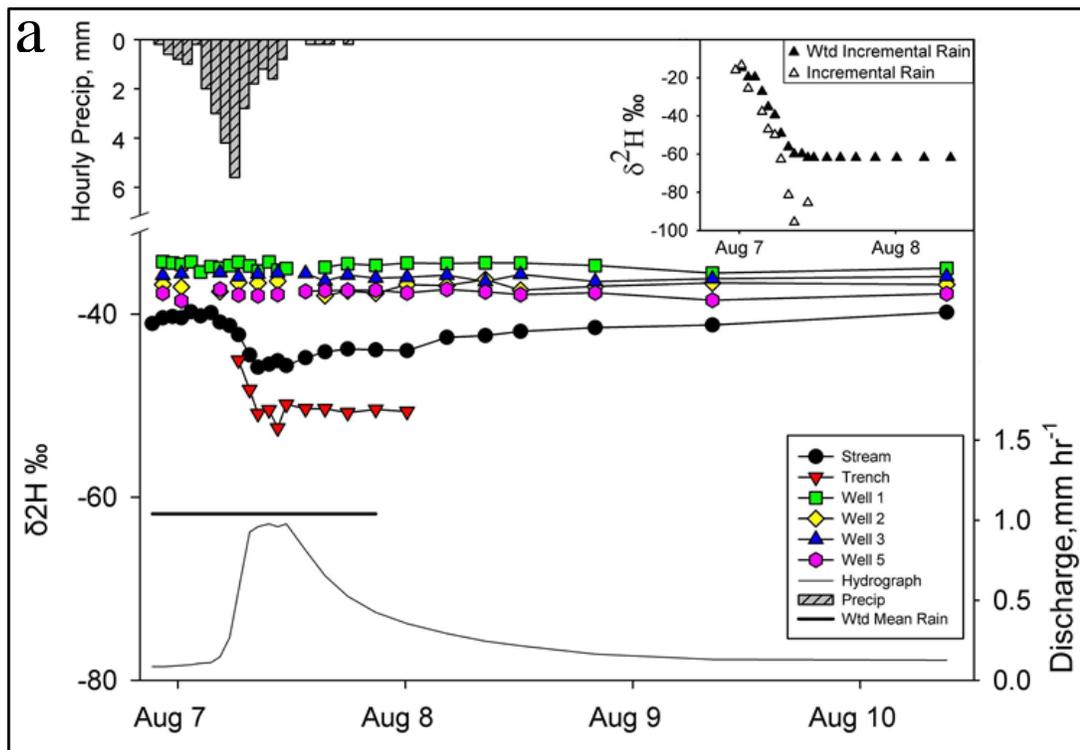


Figure 3.5

Figure 3.5 Isotopic time series data for sampled storm event at M8 (a) and WS10 (b) with hydrograph and hyetograph. Total storm precipitation was 36 mm at M8 and 34 mm at WS10. Horizontal black line represents total storm weighted mean rain deuterium value. The inset diagrams in each plot display the isotopic values of the sequential samples of rain water (with each dot representing a point sample taken at hourly increments) in the solid triangles and the calculated incremental mean of the time series during the storm progression shown in the open triangles.

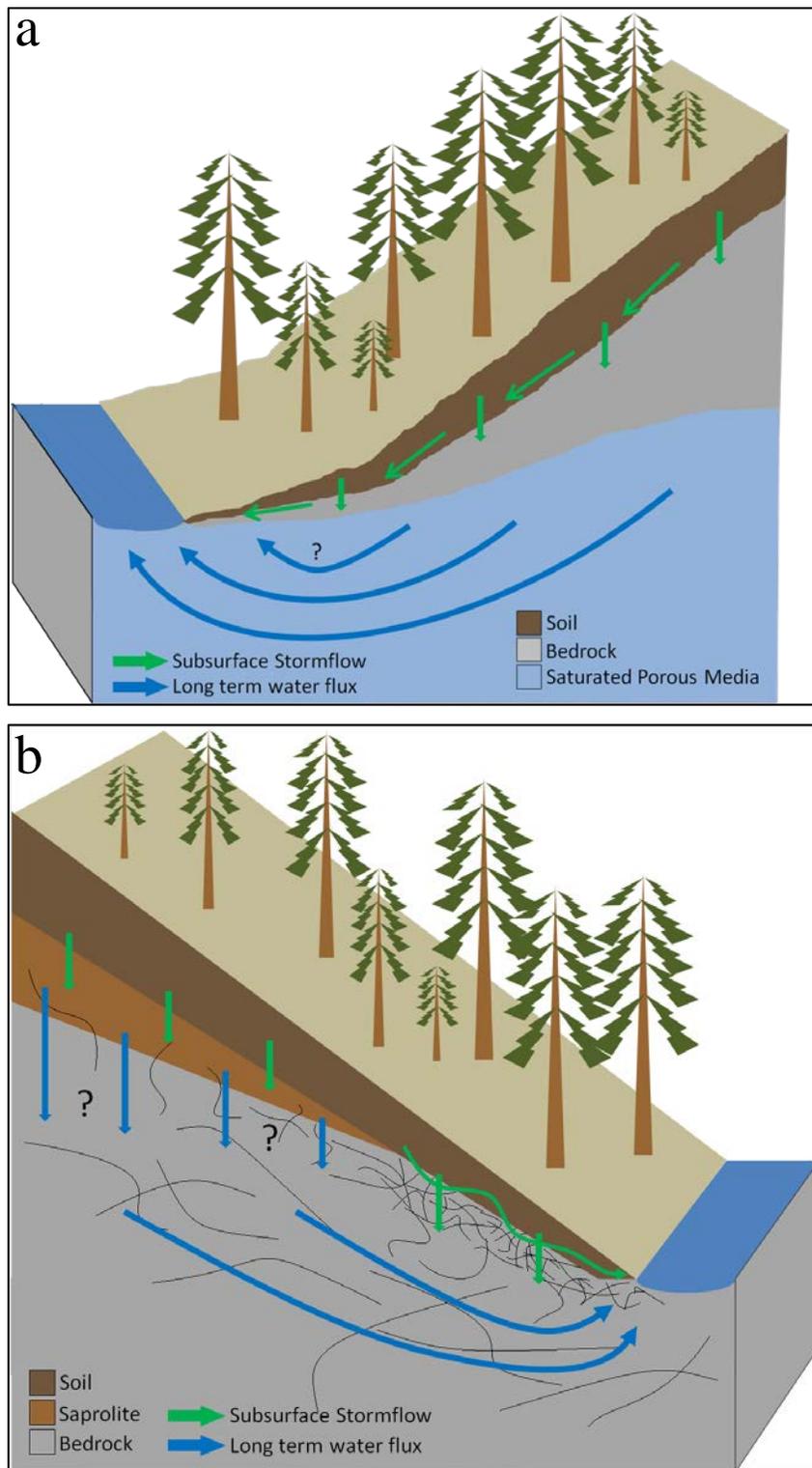


Figure 3.6

Figure 3.6 Perceptual models of water flow through (a) M8 hillslope and (b) WS10 hillslope. The M8 model highlights significant seepage into the bedrock that ultimately reemerges at the stream channel, while the WS10 model shows movement of water through fracture pathways resulting in lateral subsurface stormflow in the shallow highly fractured bedrock and deeper seepage returning as baseflow through longer more tortuous flowpaths in the deeper less fractured bedrock.

4 CONCLUSIONS

4.1 CONCLUSIONS

This thesis has presented results on the development of a portable bedrock drill system designed for drilling in head water catchments where terrain limits access of truck mounted drilling systems. We have also presented the results of bedrock groundwater monitoring at two benchmark headwater catchments and provided a comparative analysis of the influences of their respective bedrock structure on subsurface flow processes.

Chapter 1 presented a new bedrock drilling system designed for headwater studies where access prohibits the use of traditional truck mounted drill systems. We have responded to the need for a portable system capable of accessing bedrock groundwater in headwater catchments. Our work has resulted in a drilling system that has been proved capable of drilling boreholes up to 10 m deep in a variety of geologies. A detailed description of the drill system and a transparent comparison of our system to other previous and current portable drill designs were provided.

In Chapter 2 we utilized this new drilling system at two well known and well studied benchmark catchment that share many similar attributes but differ considerably in their bedrock geologies. Monitoring of bedrock groundwater dynamics at WS10 the HJ Andrews has shown that bedrock plays an important role in lateral subsurface flow on a storm event time scale. A highly fractured region of bedrock near the soil bedrock interface offers a highly transmissive preferential flow path for lateral subsurface flow during events. We have shown that the bedrock is capable of connecting the stream channel to upper regions of the hillslope. Bedrock groundwater

monitoring at the M8 catchment at Maimai has shown that the bedrock is not impermeable as was previously thought. The soft porous bedrock structure allows for significant loss to deeper groundwater bodies and a considerable portion of rainfall input is routed through the hillslope bedrock eventually reemerging in the stream channel.

4.2 FUTURE WORK

The recognition that bedrock structure has a significant influence on the mechanics of hillslope runoff, lateral subsurface flow and stream generation has existed for many decades. Continued work that focuses on bedrock characterization and direct hydrometric measurements of bedrock groundwater dynamics is needed. The innate heterogeneity of fracture flow which is so common to bedrock underlying headwater catchments provides a unique challenge to hillslope hydrologists trying to decipher data from point source measurements of bedrock wells. Future work should continue with field based exploration of bedrock controls on hillslope processes, but more importantly, it must begin to integrate this knowledge into modeling approaches to provide a tool that can better synthesize the myriad hillslope processes occurring simultaneously that produce the single common output, streamflow.

5 BIBLIOGRAPHY

- Anderson, S.P. et al., 1997. Subsurface flow paths in a steep, unchanneled catchment. *Water Resour. Res.*, 33(12): 2637-2653.
- Bachmair, S., Weiler, M., 2011. New Dimensions of Hillslope Hydrology Forest Hydrology and Biogeochemistry. In: Levia, D.F., Carlyle-Moses, D., Tanaka, T. (Eds.). *Ecological Studies*. Springer Netherlands, pp. 455-481.
- Banks, E. et al., 2009. Fractured bedrock and saprolite hydrogeologic controls on groundwater/surface-water interaction: a conceptual model (Australia). *Hydrogeol. J.*, 17(8): 1969-1989.
- Beven, K.J. (Ed.), 2006. Streamflow generation processes. *Benchmark papers in hydrology*, 1. International Association of Hydrological Sciences, Wallingford.
- Bonell, M., 1998. Selected challenges in runoff generation research in forests from the hillslope to headwater drainage basin scale. *Journal of the American Water Resources Association*, 34(4): 765-785.
- Brammer, D., 1996. Hillslope hydrology in a small forested catchment, Maimai, New Zealand, State University of New York, Syracuse, 153 pp.
- Buttle, J. (Ed.), 1998. Fundamentals of small catchment hydrology. *Isotope Tracers in Catchment Hydrology*. Elsevier, Amsterdam, 1-43 pp.
- Crouzet, E., Hubert, P., PH, O., Siwertz, E., Marce, A., 1970. Le Tritium dans les mesures d'hydrologie de surface. Détermination expérimentale du coefficient de ruissellement. *J. Hydrol.*, 11: 334-344.
- Dagan, G., 1978. A note on packer, slug, and recovery tests in unconfined aquifers. *Water Resour. Res.*, 14(5): 929-934.
- David R. Montgomery, W.E.D., Raymond Torres, Suzanne Prestrud Anderson, John T. Heffner, Keith Loague, 1997. Hydrologic response of a steep, unchanneled valley to natural and applied rainfall. *Water Resour. Res.*, 33(1): 91-109.
- Dietrich, P., Helmig, R., Sauter, M., Hötzl, H., Köngeter, J., Teutsch, G. (Ed.), 2005. *Flow and Transport in Fractured Porous Media*. Springer-Verlag, Berlin.
- Dunne, T. (Ed.), 1978. Field studies of hillslope flow processes. *Hillslope Hydrology*. Wiley, Chichester, 227-293 pp.

- Freeze, R.A., Cherry, J.A., 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.
- Gabrielli, C.P., McDonnell, J.J., 2011. An inexpensive and portable drill rig for bedrock groundwater studies in headwater catchments. *Hydrol. Processes*.
- Graham, C.B., McDonnell, J.J., 2010. Hillslope threshold response to rainfall: (2) Development and use of a macroscale model. *J. Hydrol.*, 393(1-2): 77-93.
- Graham, C.B., van Verseveld, W., Barnard, H.R., McDonnell, J.J., 2010a. Estimating the deep seepage component of the hillslope and catchment water balance within a measurement uncertainty framework. *Hydrol. Processes*, 24(25): 3631-3647.
- Graham, C.B., Woods, R.A., McDonnell, J.J., 2010b. Hillslope threshold response to rainfall: (1) A field based forensic approach. *J. Hydrol.*, 393(1-2): 65-76.
- Haria, A.H., Shand, P., 2004. Evidence for deep sub-surface flow routing in forested upland Wales: implications for contaminant transport and stream flow generation. *Hydrol. Earth Syst. Sci.*
- Haria, A.H., Shand, P., 2006. Near-stream soil water-groundwater coupling in the headwaters of the Afon Hafren, Wales: Implications for surface water quality. *J. Hydrol.*, 331(3-4): 567-579.
- Harr, R.D., 1977. Water flux in soil and subsoil on a steep forested slope. *J. Hydrol.*, 33(1-2): 37-58.
- Harr, R.D., McCorison, F.M., 1979. Initial effects of clearcut logging on size and timing of peak flows in a small watershed in western Oregon. *Water Resour. Res.*, 15(1): 90-94.
- Harr, R.D., Ranken, D.W., 1972. Movement of water through forested soils in steep topography, University of Washington, Seattle.
- Hewlett, J., Hibbert, A., 1967. Factors affecting the response of small watersheds to precipitation in humid areas, In: Sopper WE, Lull HW (eds) *Procc Int Symp on Forest Hydrology*. Pergamon Press, Oxford, pp. 275-290.
- Hill, A.R., 2000. Stream chemistry and riparian zones. In: Jones, J., Mulholland, P. (Eds.), *Streams and Ground Waters*. Academic Press, London, pp. 83-110.

- Hopp, L., McDonnell, J.J., 2009. Connectivity at the hillslope scale: Identifying interactions between storm size, bedrock permeability, slope angle and soil depth. *J. Hydrol.*, 376(3-4): 378-391.
- Hursh, C., 1936. Storm-water and adsorption, AGU, 17. *Eos Trans*, pp. 301-302.
- Ice, G., Schoenholtz, S., 2003. Understanding how extremes influence water quality: Experience from forest watersheds. *Hydrol. Sci. Technol.*, 19: 99 - 107.
- Iwagami, S., Tsujimura, M., Onda, Y., Shimada, J., Tanaka, T., 2010. Role of bedrock groundwater in the rainfall–runoff process in a small headwater catchment underlain by volcanic rock. *Hydrol. Processes*, 24(19): 2771-2783.
- James, M., 1977. *Rock weathering in the Central Western Cascades.*, University of Oregon, Eugene.
- Katsura, S.y., Kosugi, K.i., Mizutani, T., Okunaka, S., Mizuyama, T., 2008. Effects of bedrock groundwater on spatial and temporal variations in soil mantle groundwater in a steep granitic headwater catchment. *Water Resour. Res.*, 44(9): W09430.
- Katsuyama, M., Ohte, N., Kabeya, N., 2005. Effects of bedrock permeability on hillslope and riparian groundwater dynamics in a weathered granite catchment. *Water Resour. Res.*, 41(1): W01010.
- Katsuyama, M., Tani, M., Nishimoto, S., 2010. Connection between streamwater mean residence time and bedrock groundwater recharge/discharge dynamics in weathered granite catchments. *Hydrol. Processes*, 24(16): 2287-2299.
- Kollet, S.J., Maxwell, R.M., 2006. Integrated surface–groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model. *Adv. Water Resour.*, 29(7): 945-958.
- Kosugi, K.i., Katsura, S.y., Katsuyama, M., Mizuyama, T., 2006. Water flow processes in weathered granitic bedrock and their effects on runoff generation in a small headwater catchment. *Water Resour. Res.*, 42(2): W02414.
- Kosugi, K.i., Katsura, S.y., 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 Resour. Res.*, 44(1): W01407.

- Lovell, J., 1969. Tyee formation: Underformed turbidities and their lateral equivalents: Minerology and paleogeography. *Geol. Soc. Am. Bull.*, 80: 9-22.
- MacDonald, L.H., 1988. An Inexpensive, Portable System for Drilling into Subsurface Layers. *Soil Sci. Soc. Am. J.*, 52(6): 1817-1819.
- Maxwell, R.M., Miller, N.L., 2005. Development of a Coupled Land Surface and Groundwater Model. *Journal of Hydrometeorology*, 6(3): 233-247.
- Mazurkiewicz, A.B., Callery, D.G., McDonnell, J.J., 2008. Assessing the controls of the snow energy balance and water available for runoff in a rain-on-snow environment. *J. Hydrol.*, 354: 1-14.
- McDonnell, J. et al., 2007. Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology. *Water Resour. Res.*, 43: 359-389.
- McDonnell, J.J., 1990. A Rationale for Old Water Discharge Through Macropores in a Steep, Humid Catchment. *Water Resour. Res.*, 26(11): 2821-2832.
- McDonnell, J.J., 2003. Where does water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response. *Hydrol. Processes*, 17(9): 1869-1875.
- McDonnell, J.J., Tanaka, T., 2001. On the future of forest hydrology and biogeochemistry. *Hydrol. Processes*, 15(10): 2053-2055.
- McGlynn, B.L., McDonnell, J.J., Brammer, D.D., 2002. A review of the evolving perceptual model of hillslope flowpaths at the Maimai catchments, New Zealand. *J. Hydrol.*, 257(1-4): 1-26.
- McGlynn, B.L., McDonnell, J.J., Seibert, J., Kendall, C., 2004. Scale effects on headwater catchment runoff timing, flow sources, and groundwater-streamflow relations. *Water Resour. Res.*, 40(7): W07504.
- McGuire, K.J., McDonnell, J.J., 2010. Hydrological connectivity of hillslopes and streams: Characteristic time scales and nonlinearities. *Water Resour. Res.*, 46(10): W10543.
- McGuire, K.J. et al., 2005. The role of topography on catchment-scale water residence time. *Water Resour. Res.*, 41(5): W05002.

- McGuire, K.J., Weiler, M., McDonnell, J.J., 2007. Integrating tracer experiments with modeling to assess runoff processes and water transit times. *Adv. Water Resour.*, 30(4): 824-837.
- Montgomery, D.R., Dietrich, W.E., Heffner, J.T., 2002. Piezometric response in shallow bedrock at CB1: Implications for runoff generation and landsliding. *Water Resour. Res.*, 38(12): 1274.
- Montgomery, D.R. et al., 1997. Hydrologic response of a steep, unchanneled valley to natural and applied rainfall. *Water Resour. Res.*, 33(1): 91-109.
- Mosley, M.P., 1979. Streamflow generation in a forested watershed, New Zealand. *Water Resour. Res.*, 15(4): 795-806.
- Muñoz-Villers, L. et al., 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.
- O'Loughlin, C.L., Rowe, L.K., Pearce, A.J., 1978. Sediment yields from small forested catchments, north Westland, New Zealand. *Journal of Hydrology (NZ)*, 17(1): 1-15.
- Onda, Y., Komatsu, Y., Tsujimura, M., Fujihara, J.-i., 2001. The role of subsurface runoff through bedrock on storm flow generation. *Hydrol. Processes*, 15(10): 1693-1706.
- Pearce, A.J., Stewart, M.K., Sklash, M.G., 1986. Storm Runoff Generation in Humid Headwater Catchments: 1. Where Does the Water Come From? *Water Resour. Res.*, 22(8): 1263-1272.
- Rasmussen, T.C., Crawford, L.A., 1997. Identifying and Removing Barometric Pressure Effects in Confined and Unconfined Aquifers. *Ground Water*, 35(3): 502-511.
- Rowe, L.K., Pearce, A.J., 1994. Hydrology and related changes after harvesting native forest catchments and establishing *pinus radiata* plantations. Part 2. The native forest water balance and changes in streamflow after harvesting. *Hydrol. Processes*, 8(4): 281-297.
- Rowe, L.K., Pearce, A.J., O'Loughlin, C.L., 1994. Hydrology and related changes after harvesting native forest catchments and establishing *pinus radiata* plantations. Part 1. Introduction to study. *Hydrol. Processes*, 8(3): 263-279.

- Sayama, T., McDonnell, J.J., 2009. A new time-space accounting scheme to predict stream water residence time and hydrograph source components at the watershed scale. *Water Resour. Res.*, 45(7): W07401.
- Seibert, J., Bishop, K., Rodhe, A., McDonnell, J.J., 2003. Groundwater dynamics along a hillslope: A test of the steady state hypothesis. *Water Resour. Res.*, 39(1): 1014.
- Sklash, M., Farvolden, R., 1979. The role of groundwater in storm runoff. *J. Hydrol.*, 43: 45-65.
- Sklash, M.G., Stewart, M.K., Pearce, A.J., 1986. Storm Runoff Generation in Humid Headwater Catchments: 2. A Case Study of Hillslope and Low-Order Stream Response. *Water Resour. Res.*, 22(8): 1273-1282.
- Sollins, P., Cromack, K., Mc Corison, F.M., Waring, R.H., Harr, R.D., 1980. Changes in Nitrogen Cycling at an Old-Growth Douglas-fir Site After Disturbance1. *J. Environ. Qual.*, 10(1): 37-42.
- Sollins, P., McCorison, F.M., 1981. Nitrogen and carbon solution chemistry of an old growth coniferous forest watershed before and after cutting. *Water Resour. Res.*, 17(5): 1409-1418.
- Stewart, M., Thomas, J., 2002. Moutere Valley groundwater: Nature and recharge from isotopes and chemistry, Institute of Geological and Nuclear Sciences science.
- Sudicky, E., Jones, J., Park, Y.-J., Brookfield, A., Colautti, D., 2008. Simulating complex flow and transport dynamics in an integrated surface-subsurface modeling framework. *Geosci. J.*, 12(2): 107-122.
- Swanson, F., James, M., 1975. Geology and geomorphology of the H.J. Andrews Experimental Forest, western Cascades, Oregon, Pac. Northwest For. and Range Exp. Stn., For. Serv., U.S. Dep. of Agric., Portland, OR.
- Tóth, J., 1962. A Theoretical Analysis of Groundwater Flow in Small Drainage Basins. *Journal of Geophysical Research*, 68: 4795.
- Triska, F.J., Sedell, J.R., Cromack, K.J., Gregory, S.V., Mccorison, F.M., 1984. Nitrogen budget for a small coniferous forest stream. *Ecol. Monogr.*, 54(1).
- Tromp-van Meerveld, H.J., Peters, N.E., McDonnell, J.J., 2007. Effect of bedrock permeability on subsurface stormflow and the water balance of a trenched

- hillslope at the Panola Mountain Research Watershed, Georgia, USA. *Hydrol. Processes*, 21(6): 750-769.
- Tsuboyama, Y., Sidle, R.C., Noguchi, S., Hosoda, I., 1994. Flow and solute transport through the soil matrix and macropores of a hillslope segment. *Water Resour. Res.*, 30(4): 879-890.
- Uchida, T., Asano, Y., Ohte, N., Mizuyama, T., 2003. Seepage area and rate of bedrock groundwater discharge at a granitic unchanneled hillslope. *Water Resour. Res.*, 39(1): 1018.
- Uchida, T., Kosugi, K.i., Mizuyama, T., 2002. Effects of pipe flow and bedrock groundwater on runoff generation in a steep headwater catchment in Ashiu, central Japan. *Water Resour. Res.*, 38(7): 1119.
- van Verseveld, W.J., McDonnell, J.J., Lajtha, K., 2009. The role of hillslope hydrology in controlling nutrient loss. *J. Hydrol.*, 367(3-4): 11.
- Weiler, M., McDonnell, J.J., Tromp-van Meerveld, I., Uchida, T., 2006. Subsurface Stormflow, *Encyclopedia of Hydrological Sciences*. John Wiley & Sons, Ltd.
- Wilson, C.J., Dietrich, W.E., 1987. The contribution of bedrock groundwater flow to storm runoff and high pore pressure development in hollows, *Erosion and Sedimentation in the Pacific Rim*. IAHS, Corvallis, OR.
- Winter, T.C., 2007. The Role of Ground Water in Generating Streamflow in Headwater Areas and in Maintaining Base Flow1. *Journal of the American Water Resources Association*, 43(1): 15-25.
- Woods, R.A., Rowe, L., 1996. The changing spatial variability of subsurface flow across a hillside. *Journal of Hydrology (NZ)*, 35(1): 49-84.

