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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

WILEY

The Maimai M8 experimental catchment database: Forty years of process-based research on steep, wet hillslopes

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1 | INTRODUCTION

Many of our legacy research and observation catchments were developed during the First International Hydrological Decade (IHD) (1965–1974)—a period of intense catchment gauging/instrumentation and arguably the beginning of serious process hydrology. The IHD helped our science move beyond the era of infiltration (Beven, 2021) and towards an era that recognized subsurface contributions to runoff via subsurface stormflow.

The year the IHD ended the Maimai experimental catchment(s) were initiated in New Zealand (Figure 1). These studies investigated originally the hydrological effects of forest harvesting and radiata pine plantations in former native beech and podocarp forest but quickly morphed into a long sequence of runoff process investigations. Maimai has slopes that are short (<30 m) and steep (mean 34^{O}) with local relief on the order of 100–150 m. Maimai showed that subsurface stormflow was by far the major contributor to storm runoff with chronically wet soils, with 156 rain days per year (Rowe & Pearce, 1994). Pearce, Stewart, & Sklash et al. (1986, p.1266) notes that 'mean annual gross rainfall is approximately 2600 mm, producing approximately 1550 mm of runoff from 1950 mm of net rainfall

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[Rowe, 1979]. The catchments are highly responsive to storm rainfall: 1000 mm (65%) of the mean annual runoff is quick flow (QF) as defined by Hewlett and Hibbert's [1967] separation method [Pearce & McKerchar, 1979]. Quick flow is 39% of annual total rainfall (P)'.

Here we outline the data that underpins many of the studies from three main field instrumentation and sample collection phases: (a) early M8 catchment-scale research and observations (1974–1988), (b) hillslope scale trenching, forensic analysis and tracing (1993–2010) and (c) drilling the critical zone with a focus on bedrock groundwater dynamics, tritium age and its relation to streamflow and transport (2014–present). We describe the data series and provide a link to an online repository of these data in Hydroshare at https://www.hydroshare.org/resource/a292cb65a5d24a31a60978b2ab390266/.

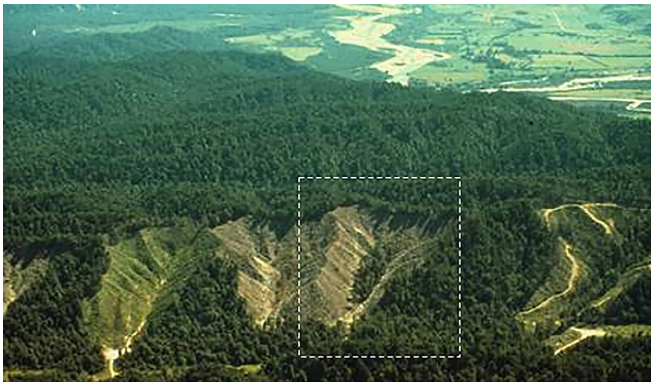

FIGURE 1 The Maimai catchments, aerial photo taken circa 1980. The M8 catchment is noted by the white dashed box, located to the left of the non-harvested catchment. Photo credit unknown

2 | MAIN PHASES OF EXPERIMENTAL OBSERVATIONS AT MAIMAI

2.1 | Phase 1: Early M8 catchment-scale research and observations (1974–1988)

Observations on the M8 catchment were first initiated as part of a paired watershed study together with several neighboring catchments down the greater Maimai valley (as shown in Figures 1 and 2). Stream gauging began in 1974 and continued until forest harvesting commenced in October 1978. This period immediately before logging was a time of exceptional data collection, as reported in Mosley (1979). Stream gauging of a 0.3 ha sub-watershed (called Site D) was added within the already small 3.8 ha M8 watershed. These hydrographs have been discussed extensively elsewhere (as reviewed by McGlynn,

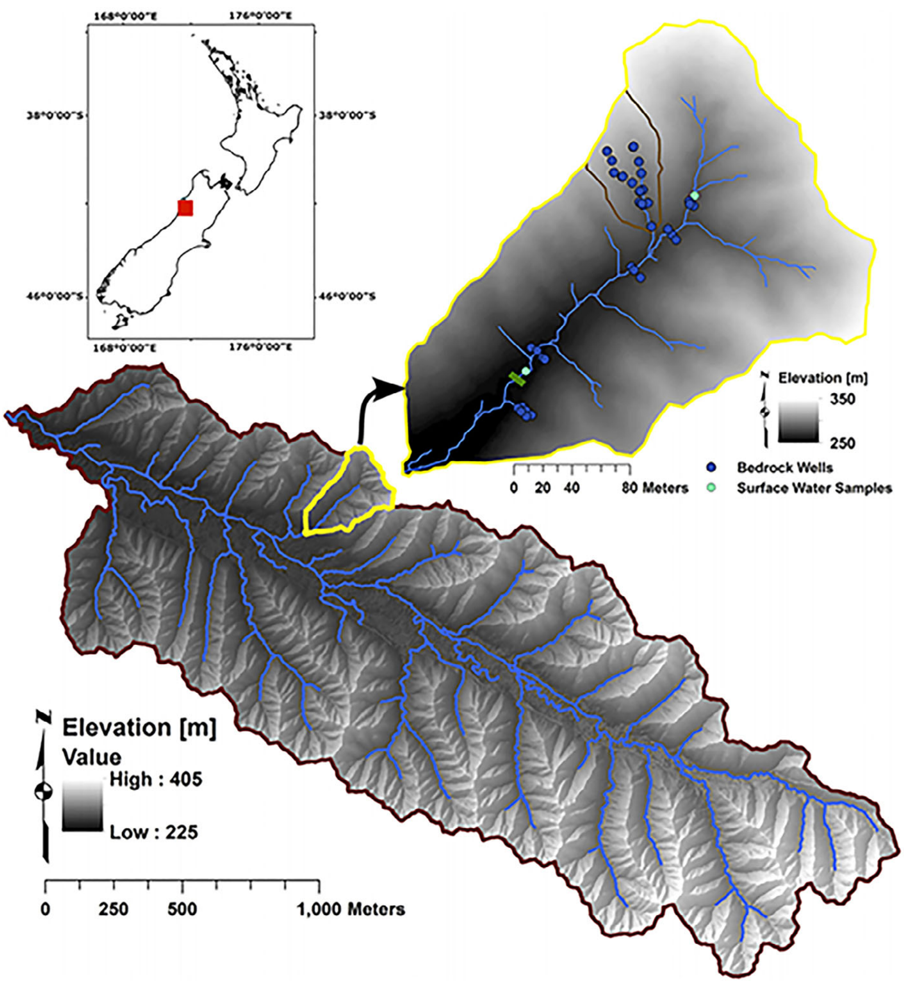

FIGURE 2 The Maimai experimental catchments showing the M8 catchment (in its 4.5 ha, post 1988 configuration) and general location within New Zealand and within the Maimai valley. The green bar shows the approximate location of the original weir (1974–1988). The brown outline within the M8 watershed is the 0.3 ha sub-watershed. From Gabrielli, Morgenstern, Stewart, and McDonnell (2018), used with permission

McDonnell, & Brammer, 2002) but Figure 3 shows their shape, coincident timing and remarkably steep recession curves. No overland flow was observed in any of these events outside of the narrow 2–3% riparian area in the incised valley bottom.

The M8 forest was logged using a 'downhill hauler' from October 1978 to March 1979. The neighboring watersheds were also harvested; each in different ways (with and without roads etc., as shown in Figure 1). The M8 catchment underwent a prescribed burn in February 1980 (following a first, unsuccessful attempt at burning in April 1979 when only 5% of the watershed was able to be ignited). The watershed was then re-planted with radiata pine in July 1980. The water balance, water chemistry and stream temperature results of these paired watershed studies are reported in Rowe and Fahey (1991) and Rowe and Taylor (1994).

From February 1977 to March 1980, stable isotope data were collected to compute streamwater transit time and nascent

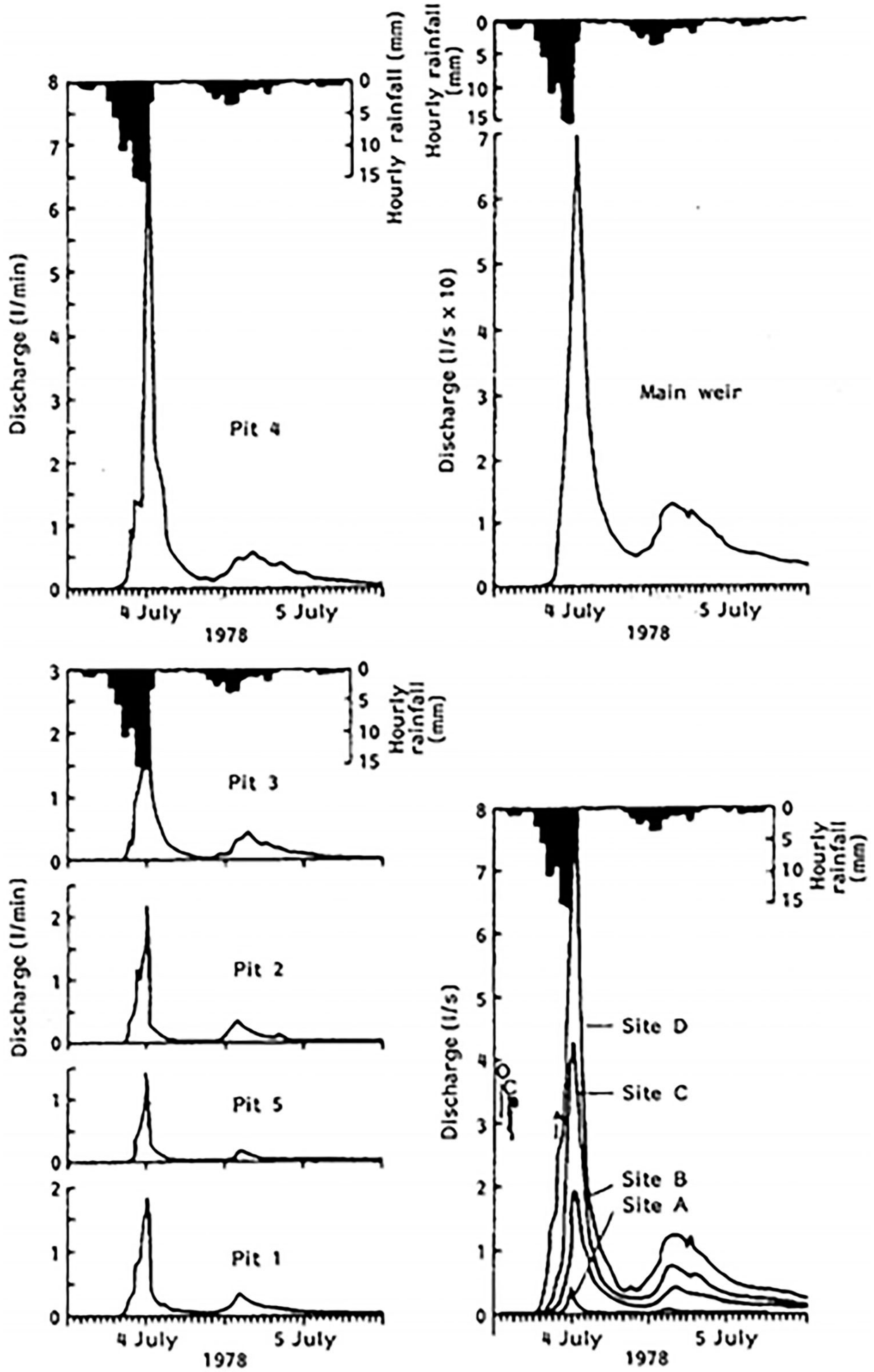

FIGURE 3 The flow data from the Mosley (1979) hydrometric analyses. These data are 4 years after the beginning of stream gauging in the native beech and podocarp forest and some months before clear-felling began in the M8 catchment. Note the extreme steepness of both the rising and falling limbs of the hydrographs; their synchronicity and apparent downslope increases in water volumes. The sites are all within a 0.3 ha sub-watershed of the M8 catchment. Space restrictions preclude descriptions of the measurement locations—the 'pits' were excavated approximately 1 m wide trenches at different positions on the hillslope, and the Sites A–C represent flow measurements at positions within the stream; all within the 0.3 ha sub-watershed. Site D defines the 0.3 ha outflow. From Mosley (1979), used with permission

hydrograph components (Pearce, Stewart, & Sklash, 1986). Follow-on fieldwork by Sklash et al. (1986) shed further light on the rapid effusion of old water. Following the Sklash field campaign came McDonnell's PhD fieldwork and combined hydrometric (tensiometer, well, trenchflow, rainfall-runoff) and isotope tracing. These data were collected throughout 1987 and reported in a series of papers that outlined how pipeflow of old water could occur (McDonnell, 1990a) and the nature of catchment-scale runoff generation as deduced from a combination of hydrometric, isotopic and geochemical analyses (McDonnell, Owens, & Stewart, 1991; McDonnell, Stewart, & Owens, 1991).

The end of Phase 1 was marked by the weir being destroyed in a debris flow May 19, 1988, as reported in McDonnell (1990b). About 1000 m^3 of soil and Old Man Gravel material (the underlying bedrock) were swept into the channel and down the valley to cover the weir, following a 160 mm rainfall event that occurred at the end of an 11-day low-intensity rainfall period totaling 250 mm. With the new gauging station placed downstream of the debris flow deposit in the channel, the catchment area increased to 4.5 ha at this juncture (Figure 2).

2.2 | Phase 2: Hillslope scale trenching, forensic analysis and tracing (1993–2010)

Beginning in 1993, a major trench study was undertaken, as reported in Woods and Rowe (1996). In what is today, still one of the most ambitious hillslope trenching studies ever completed, Woods and Rowe assembled a 110-day record of flow for 30 troughs of 1.7 m length in two groups across the base of hillslope section some 10s of meters down the valley from the current weir location (Figure 4). They found that subsurface flow per unit area drained was highly variable but became more spatially uniform during large storms with wet antecedent conditions. The role of subsurface topography in explaining these findings was also discussed in McDonnell (1997) and Woods and Rowe (1997). Based on these findings, a new topographic index was developed in an attempt to explain the time-varying spatial variability of subsurface flow (Woods & Rowe, 1997). Figure 5 shows an example of the complex space and time variability in trench flow observed at this site.

Following the completion of the gauging portion of the hillslope study, Brammer and McDonnell (1996) conducted a line source Br- tracer experiment from March 24, 1995 to May 10, 1995. Those data, further analyzed and modeled by Weiler and McDonnell (2007), showed how the tracer was conducted through soil pipes, activated during rainfall events. The hillslope focused work was extended to measurements and understanding of dissolved organic carbon transport by McGlynn and McDonnell (2003) and then extensive soil stripping and forensic analyses was made of the soil bedrock interface and its microtopography, as described by Graham, McDonnell, and Woods (2010) and Graham and McDonnell (2010). Drilling into that now-exposed approximately 4×8 m^2 bedrock surface was done during a 65-day drilling and tracing campaign between July 1, 2010, and September 3, 2010. These data were reported in Gabrielli, McDonnell, and Jarvis (2012).

2.3 | Phase 3: Drilling the critical zone: Bedrock groundwater dynamics, tritium age and its relation to streamflow and transport (2014–present)

The most recent phase of field data collection at Maimai was from December 11, 2014, to January 31, 2016, representing 416 days of monitoring. This period was marked by a drilling campaign using a custom field-portable drill rig specially designed for use at the Maimai site (Gabrielli & McDonnell, 2011). The 40 wells drilled to a maximum of 10 m showed how the low permeability Old Man Gravel, a weakly lithified conglomerate, regulated groundwater age, stream water mean transit time (MTT), and surface water- groundwater interaction (Gabrielli & McDonnell, 2018, 2020). Gabrielli and McDonnell (2018)

FIGURE 4 The Woods and Rowe (1996) trench with 30 troughs of 1.7 m length in two groups across the 60 m slope portion. Tipping buckets recorded flow. Subsequent studies on this slope section performed isotope tracing, line source breakthrough experiments and forensic analyses of the soil and bedrock surface above the trench. Photo credit unknown

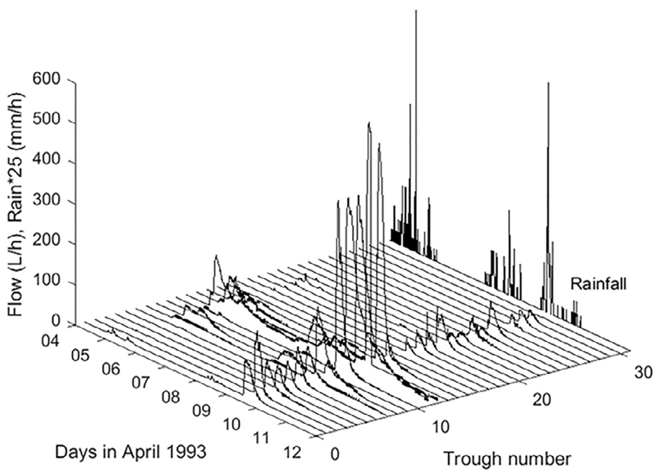

FIGURE 5 Spatial distribution of trough flows from the Woods and Rowe (1996) analysis (re-worked and re-drawn)

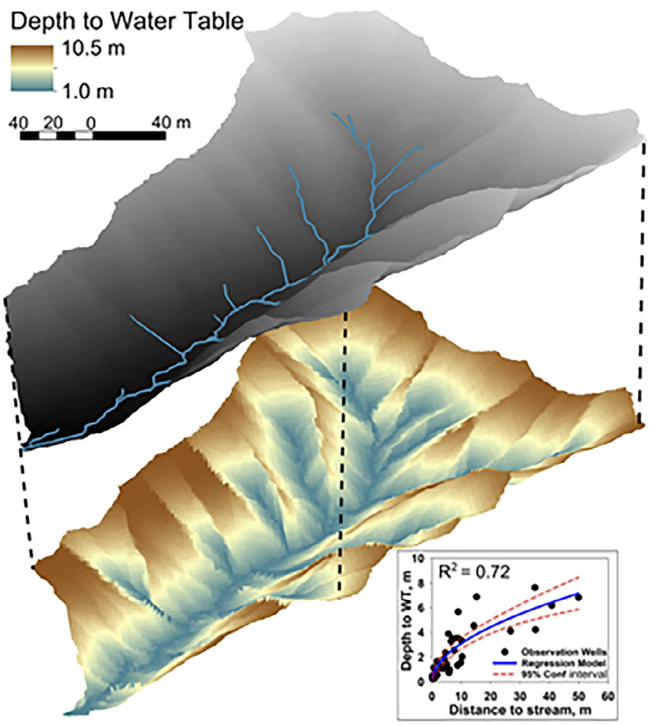

FIGURE 6 Water table depths for the M8 watershed based on 400 days of monitoring from 36 bedrock wells. The scatter plots on the inset diagram show the relationship between distance to stream and depth to water table. From Gabrielli et al. (2018), used with permission

found two distinctly different catchment storage units: (a) a young water storage compartment in the soil and (b) a much older water storage compartment in the bedrock. The Gabrielli and McDonnell (2018) paper and related papers (e.g., Gabrielli et al., 2018) observed groundwater ages up to 23 years compared to soil water ages that ranged from 0.1 to 0.5 years—like the early estimates of Stewart and McDonnell (1991). Figure 6 shows a 3D representation of the spatially varying groundwater depths.

3 | OBSERVATION METHODS

For Phase 1 data collection, a tipping bucket raingauge recorded 10 min precipitation totals throughout the period. Due to the passage of time, we lack information on the raingauge precision per tip. Streamflow was recorded at the M8 outflow at an hourly interval using a Forest Research Centre 90° degree v-notch weir and Leopold Stevens recorder fitted with a low-torque, 10-turn, 1 k-ohm potentiometer. Again, we lack information now exact gearing and precision. Environmental isotope analyses were conducted at the Institute of Nuclear Sciences, Lower Hutt. Deuterium samples were prepared by the zinc reduction method (Coleman, Shepherd, Durham, Rouse, & Moore, 1982) and analyses run on a V.G. Micromass 602 (South Manchester, UK) mass spectrometer.

Phase 2 tensiometric data were powered by a 24 V DC supply regulated to 12 V DC for all the devices. As noted by McDonnell (1993) this ensured supply of voltage to the tensiometer transducers that was precise and constant since sensor output was directly related to voltage output. The pressure sensors used for the tensiometers were Sensym Inc (Santa Barbara, CA) Model SCX15DN 0–1.02 × 10s Pa). They were temperature compensated with response times and calibration reported in McDonnell (1993). All were electronically multiplexed (Campbell AM32 multiplexer) and recorded by a Campbell CR21X micrologger (Logan, UT). The 22 other tensiometers were linked to a fluid wafer switch (Scanivalve Inc., San Diego, CA; Model W0602/1p-24T) and solenoid stepper drive (Model WS5-24) to timeshare 22 tensiometers and two water reference pressures to a single SCX15DN unit. Mini 10:1 v-notch weirs mounted directly on to 210 L storage drums were used to gauge the re-activated throughflow pits from the original Mosley, 1979 study. Ministry of Works N.Z. underwater pressure sensors (0–0.5 m absolute transducers) were used to monitor stage height in the drums for flow computation. Soil water and transient groundwater were sampled using standard Soil Moisture Corporation 40 mm diameter porous cup suction lysimeters. Electronically operated vacuum-type automatic 24 bottle liquid samplers (ALS Ltd., Brisbane Australia, Models 4BSEC and 3BSEC) were used to sample throughflow and streamflow at discrete intervals through the storm hydrographs.

Phase 3 well construction followed the design laid out in Gabrielli and McDonnell (2018). Wells were cased with PVC pipe screened along their lower lengths and backfilled with clean sand across the screen interval, followed by bentonite to the ground surface. Water levels were recorded with unvented pressure transducers (Heron Instruments. Dundas, Ontario, Canada. DipperLog Nano 10 m, accuracy 0.005 m; Onset Computer Corporation, Bourne, MA, Hobo U20 10 m, accuracy 0.005 m). Recorded absolute pressure was corrected with barometric pressure data collected onsite with an additional pressure transducer. Tritium analyses was conducted on water samples collected from wells and stream runoff. Concentrations were measured using electrolytic enrichment and liquid scintillation counting (Morgenstern & Taylor, 2009) at the New Zealand GNS Science Water Dating Laboratory. Groundwater and streamwater MTT estimates were made using a lumped parameter convolution approach following Małoszewski and Zuber (1982).

4 | APPLICATIONS OF THE MAIMAI DATASET

Klaus and Jackson (2018) compared the physical and hydrological characteristics of 17 hillslopes. They found that the Maimai site had the longest downslope travel distance for subsurface stormflow, due to its high soil to bedrock conductivity ratio and steep slope gradient (Figure 7). Further hillslope-scale contextualization of Maimai has been conducted by Freer et al. (1997) who compared the topographic controls on subsurface stormflow with the Panola site in Georgia, United States. Uchida, McDonnell, and Asano (2005) and Uchida, Tromp-van Meerveld, and McDonnell (2005) performed a functional intercomparison of water sources, flowpaths, and MTT of the Maimai site compared to several Japanese sites; and how lateral pipe flow compared to trenched Japanese hillslopes. Gabrielli et al. (2012) compared a Maimai slope with the HJ Andrews WS10 slope for runoff

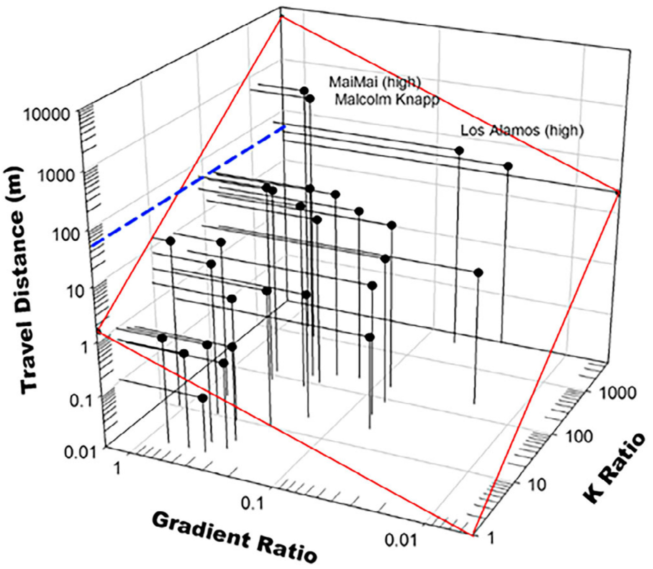

FIGURE 7 The Klaus and Jackson (2018) analysis of 17 hillslopes showing the position of the Maimai M8 relative to other studied hillslopes around the world. Note that the M8 catchment has the longest downslope travel distance of any of the studied hillslopes. The K Ratio is the ratio of saturated hydraulic conductivity of the overlying soil layer and to the saturated hydraulic conductivity of the underlying impeding layer. The Gradient Ratio as defined by Klaus and Jackson is the slope of the hillslope relative to the normal hydraulic gradient, From Klaus and Jackson (2018), used with permission

characteristics. Lastly, a modeling intercomparison by Sayama and McDonnell (2009) used a time–space accounting scheme to compare stream water residence time and hydrograph source components at the Maimai site vs WS10 at the HJ Andrews.

The data included in this data note have been used to develop new model evaluation approaches using 'soft data' (Seibert & McDonnell, 2002), 'virtual experiments' (Weiler & McDonnell, 2004) and MTT (Vaché & McDonnell, 2006). Furthermore, the data have been used to decide model rejection (Dunn, McDonnell, & Vaché, 2007; Fenicia et al., 2010; Fenicia, McDonnell, & Savenije, 2008). The work by Kavetski and Fenicia (2011) included M8 in a comparison of suitable model representations for different catchments and showed that hydrograph dynamics of the Maimai catchment were adequately captured by a single reservoir non-linear model, consistent with earlier model descriptions of the site that described the system, as 'strikingly simple' (Vaché & McDonnell, 2006). Uncertainty estimates in modeling streamflow (Beven & Freer, 2001) and water table data (Freer, McMillan, McDonnell, & Beven, 2004) have been based on M8 data. The more recent deep groundwater data also have been used in understanding how leaky headwaters subsidize flow to their downstream parent watersheds (Ameli, Gabrielli, Morgenstern, & McDonnell, 2018).

4.1 | Statement of funding origins

Maimai was set-up originally by the NZ Forest Service with funding coming from the Department of Scientific & Industrial Research (DSIR). In 1992, Crown Research Institutes were created from previous government-owned bodies, and thereafter Landcare Research funded the ongoing operations at Maimai. The development of the Phase 2 trenched slope was funded by New Zealand's National Institute for Water and Atmosphere Research and Landcare Research. Grants from the U.S. National Science Foundation in the United States funded much of the other Phase 2 work including M8 intercomparisons with U.S.-based watersheds at Sleepers River, Vermont and Panola Mountain, Georgia (not described here). AGU Horton Research Grants to McDonnell, McGlynn and Gabrielli helped fund their PhD study at Maimai. Phase 3 work was funded mostly by the Canadian NSERC Discovery Grant program.

4.2 | Contributors

Nearly 50 years of work described here means many people to thank. Long since retired but not forgotten are the team of Andy Pearce, Lindsay Rowe, Paul Mosley and Colin O'Loughlin who were the intrepid pioneers at the Maimai site. Their imagination, vision and hard work at the site have lasting value, and they set a high bar for future data collection. Similarly, Mike Sklash's sabbatical fieldwork in 1983 was remarkable in its efficiency and impact. Barry Fahey and Colin Taylor are thanked for their important contributions to the forest harvesting analysis. Similarly, Tim Moore and Breck Bowden are thanked for their insight and contributions to the biogeochemical understanding of the catchment over the past decades. Dean Brammer is thanked for his early field contributions. Countless technicians have worked at Maimai over the decades. The hero among them is John Payne whose tireless dedication to continuing the Maimai recording went well past the call of duty and long after the watershed was officially mothballed by Landcare Research New Zealand. John is an exemplar of fieldwork tenacity, inventiveness and imagination with an equal measure of wit and humor. Lastly, Jim Freer was supported for his time on this paper by the Global Water Futures program. Kim Janzen and Cody Millar are thanked for assistance with the final manuscript editing.

DATA AVAILABILITY STATEMENT

The Maimai M8 experimental catchment database is publically available at https://www.hydroshare.org/resource/a292cb65a5d24a31a60978b2ab390266/. With so many decades of data collection by so many groups, we had to adopt strict data inclusion rules on the Hydroshare site. Only data that have been described in journal papers are included. The data are arranged as per the three main phases of research, as described in this paper and in the following sections on the Hydroshare site:

- Rainfall and runoff from 1975 to 1988
- Potential evaporation for 1987
- Stable isotopes for rainfall and runoff in 1987
- Soil water matric potential for 40 days at multiple locations
- Trenched hillslope runoff data
- Trenched hillslope tracer data

- Rainfall runoff data for 2015
- Water table data for 40 soil and bedrock wells for 2015
- Tritium based soil, stream, and bedrock groundwater age estimates

Additional files containing Lidar topography for M8 and the larger Maimai valley are also included in a separate folder:

- 1 m Lidar-derived digital elevation model (DEM)

This legacy data cover the period 1973–2015. Given the passage of time, lack of original documentation, and changes of personnel, we have limited information on some instrumentation, methods, and measurement uncertainties. When known, we provide those details. All data are cleaned to the best of our ability with outliers removed, but a full provenance of the data is not provided (interested parties should refer to the information available in the published papers). We have tried our best to tie all the measurements to a standard netCDF format. This was difficult since many measurements were collected in the pre-GPS era. Uncertainties in these measurements are discussed where appropriate in the metadata reports in each directory. Some raw data files are included, and where present, some discussion of why they are useful and how they can be used is discussed. We aim to evolve the Hydroshare site to improve the metadata information as we gain feedback from users and will add comments to note new additions on the site. Some field notes are included where raw data appear. For more information on the available datasets, please contact the first author at jeffrey.mcdonnell@usask.ca.

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