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A Progress Report

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Abstract

Seven experiments were carried out on the Maimai Catchments, Westland, to test assumptions about the nature of unsaturated zone water flows in this humid environment. Hypotheses tested were: 1) that the deuterium (D) content of baseflow water sources in small streams are constant at any given time, 2) that different soil moisture sampling methods give the same D contents, 3) that throughfall has the same D content as rainfall, 4) that saturation overland flow is mainly composed of current event rainfall, 5) that macropores are not connected into pipe networks, 6) that the underlying substrate (Old Man Gravel conglomerate) does not deliver water to the stream during rainfall events, and 7) that different near-stream water sources have the same D contents at a given time. Over 570 samples were collected of which 300 were analysed for deuterium in 1992-1993. This report gives the background, rationale, methods and brief results of the experiments. The results will be integrated with other measurements and written up in one or more papers for journal publication.

Keywords

Runoff; Maimai Catchment; Unsaturated Zone; Deuterium; Groundwater Recharge

Introduction

Stable isotopes have been used increasingly in recent years to investigate the roles of "new" or storm water, and "old" or pre-storm water, in producing storm runoff in catchments [eg. *Sklash et al.*, 1976; *Rodhe*, 1981]. The results have indicated that "old" water, generally interpreted as groundwater, plays a surprisingly active and possibly even a dominant role in producing stormflow. This is in conflict with hydrometric studies, particularly as applied to hillslopes, which have emphasized the importance of processes allowing rapid flow of rainwater to channels [*Mosley*, 1982].

Studies in Maimai catchment, West Coast, New Zealand have illustrated this conflict. The catchments are steep and have shallow soils, and streamflow is very responsive to rainfall [*Pearce et al.*, 1976]. Hydrometric studies [*Mosley*, 1979] have shown that waterflows in the soil at all positions in the catchment (hillslopes and channel system) increase rapidly and simultaneously after rain. It was concluded that rapid flow of new water to the stream via "pipes" of connected macropores (pores greater than 1mm) was necessary to explain the rapid response of streamflow. On the other hand, tracer studies using deuterium showed that new water was not greatly involved in streamflow [*Pearce et al.*, 1986; *Sklash et al.*, 1986]. Streamflow following storms contained at most 20-30% new water, and much of that could be attributed to rainfall on channel and bottom slope areas. Deuterium analyses showed that old water was also dominant in flows within the soil mantle of the slopes and valley bottom. The old water contribution increased toward the bottom of slopes [*Sklash et al.*, 1986].

To resolve these differences, more detailed studies of the physical processes within the soil were undertaken. Detailed studies of the soil water status, soil water flows and their deuterium concentrations have been made at the Maimai catchment by *McDonnell* [1989]. The soil water content and flow measurements are described by *McDonnell* [1990]. Interpretation and modelling of the deuterium concentrations in soil water were discussed by *Stewart and McDonnell* [1991], who investigated the soil water residence times during stream base flow conditions.

The present work with J.J. McDonnell (Utah State University, Utah) was undertaken to test many of the assumptions of the isotopic method and its application to Maimai Catchment. The work consisted of a series of experiments to investigate the hypotheses: 1) that the deuterium (D) contents and temperatures of baseflow water sources in small streams are constant at any given time; 2) that different sampling methods have no effect on the D content of soil moisture samples; 3) that rainfall and throughfall D contents are the same during a given storm; 4) that saturation overland flow delivers mainly new water to the stream; 5) that macropores in the soil are not connected into "pipe" networks; 6) that the Old Man Gravel conglomerate does not influence stream response (apart from being effectively impermeable); and 7) that near-stream water sources (including groundwater) have the same D contents at a given time. Experiments 1 and 7 were funded by the Groundwater Programme (C05226), the remainder were funded by the Isotope Hydrology Programme (C05227).

During the field work in August 1992, over 570 samples were collected along with temperature, hydrometric and other measurements. This report gives the background, rationale, methods and discusses briefly the results obtained to date for each experiment.

Nature of Soil and Description of Catchment

The study was conducted in a steep, humid headwater catchment on the South Island of New Zealand (45°0.5'S, 171°48'E). The M8 catchment (Figure 1) has been monitored since 1974 [*Pearce et al.*, 1976]. Mean annual rainfall is 2600mm producing 1550mm of runoff from 1950mm of net rainfall [*Rowe*, 1979]. Slopes are short (30m) and steep (mean 34°), with local relief of the order of 100-150m. The soil is underlain by a firmly compacted, moderately weathered, early Pleistocene conglomerate, known as the Old Man Gravels. This unit has been described as "effectively impermeable" [*Mosley*, 1979, p. 795], and "poorly to moderately permeable" [*Pearce et al.*, 1976, p. 150].

Soils in the catchment have developed from the underlying soft, weathered conglomerate and colluvium and are broadly classified as Blackball Hill soils [*New Zealand Soil Bureau*, 1968;

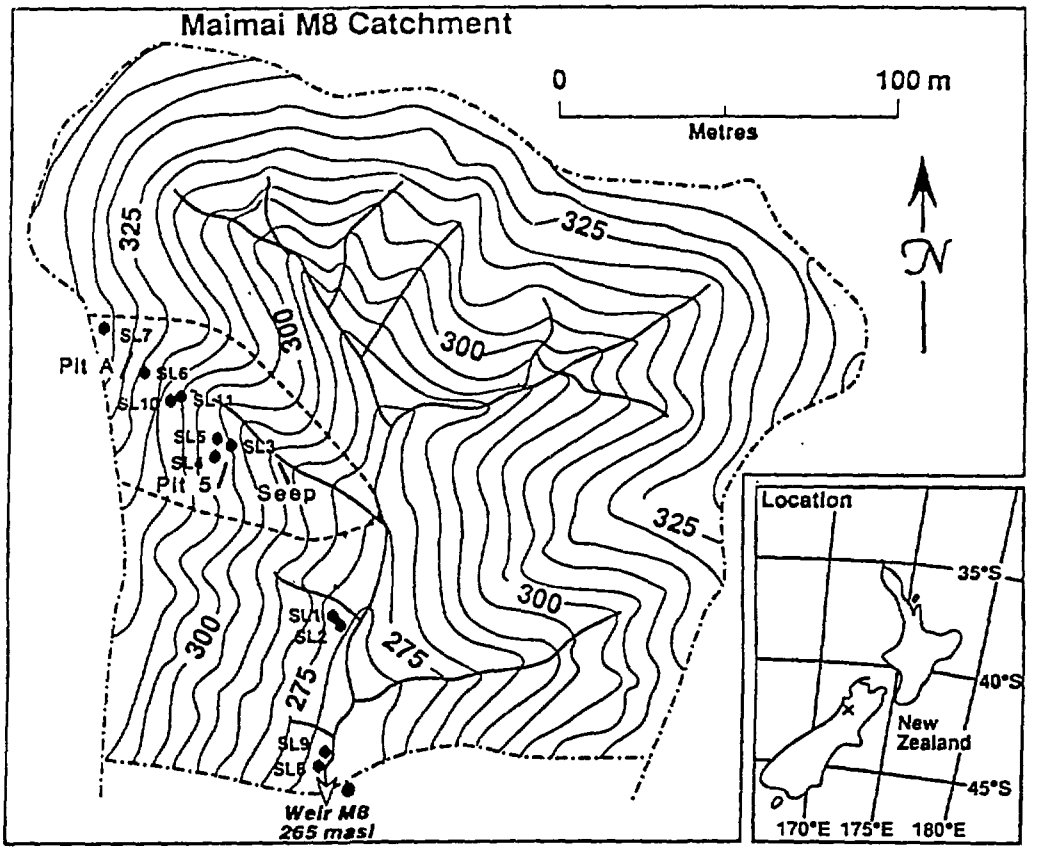

Fig. 1. Maimai 8 catchment showing suction lysimeter (SL) and pit locations.

TABLE 1. M8 Soil Profile Classes Compiled From Data of *McKie* [1978]

Class	Slope Position	Slope	Drainage
1. Shallow podzols	upper nose	15–30	well
2. Podzols	nose and sideslopes	30–40	well
3. Grey podzols	upper hollows	20–40	imperfect
4. Podzolized lowland YBE	sideslopes, upper nose	25–35 (70%); 36–50 (30%)	moderate
5. Mottled YBE	valley basin hollows	26–35 (70%); 10–26 (30%)	imperfect
6. Shallow gley	near-stream (limited)	15–35	poor
7. Gley	near-stream	15–35	very poor

Mew et al., 1975]. They show large spatial variability in depth (mean 0.6m, range 0.2-1.8m) and character (from podsolized yellow brown earth (YBE), to mottled YBE, to gley soils), and are dominantly stoney throughout their profiles. Mineral soil horizons are overlain by a thick (mean 170mm) well-developed upper humic horizon. *Webster*[1977] reported average saturated hydraulic conductivity of the upper humic layer and mineral soil of the order of 6100mm h^{-1} and 260mm h^{-1} respectively.

McKie [1978] separated the soils belonging to the Blackball Hill group into seven soil profile classes according to their parent material, slope angle, vegetation and drainage (Table 1). Generally, there is a strong relationship between soil type and slope position as they relate to drainage and soil development processes. The common profile features of the dominant soil profile classes (2, 4 and 5) were derived by McKie from a selection of most commonly occurring properties found in a number of described profiles, whereas the features of the less widespread classes (1, 3, 6 and 7) were based on a representative profile.

Description of Experiments

Experiment 1

Hypothesis: That there are no significant upstream/downstream δD or temperature differences in baseflow composition of main channel sections of small headwater catchments.

Background: Schiff, Hinton and others at University of Waterloo have found downstream trends in groundwater discharge positions along short sections of the Harp 4 catchment, Ontario. Kobayashi showed that stream temperature could be used to separate snowmelt hydrographs into melt and groundwater. Lars Bengtson and others in Sweden have used the technique for both melt and rain events. Stream ecologists at USU regularly use stream temperature to identify groundwater exfiltration zones in the channel, where certain fish and benthic species exist. DeWalle and Swistock related baseflow groundwater seepage zones along streams in Pennsylvania and correlated stream temperature/solute concentration/isotopic composition with fish health mortality.

Expectations: *McDonnell et al.* (1991) found significant spatial variability of soil water and groundwater δD in catchment M8. Much of this variation could be explained by topographic position. Since lateral flow into the main channels of the Maimai is controlled by hollow discharge with unique δD (as compared with nose slopes, etc.), downstream variation may be noticed. There should be some correlation between groundwater discharge zones and depressions in stream temperature.

Implications: If variation is large, what effect does sampler positioning have on old water estimates? Can this variation be reconciled with earlier Anderson and Burt (1979-82) work? Can this guide TOPMODEL-type simplification of the mixing process? Is temperature a good surrogate for δD work in the Maimai catchments?

Procedure: Channel surveys were carried out at 5m increments upstream from the weir during baseflow conditions (August 7). Catchments M14, M9, M6 were surveyed. Catchment M8 was surveyed on August 12 at baseflow at 5m intervals, including stream, air, soil water temperature.

Samples collected: HMD241-284 analysed; HMD 467-572 not analysed.

Results to date: The samples from M8 show little variation in D content, except for one part of the catchment (20 - 30m upstream of the weir) which had δD up to 13‰ less negative than the other samples.

Experiment 2

Hypothesis: That the amount of tension applied to low volume suction lysimeters has no effect on retrieved soil water δD.

Background: DeWalle (Penn State), Dowd (Georgia), Kendall (USGS Menlo Park) and Hooper (USGS Atlanta) and several others have expressed concern that suction lysimeters

versus zero tension and other techniques affect δD and $\delta^{18}O$ of soil composition of samples derived from suction lysimeters.

Expectations: Maimai soils remain within 10% of saturation through most of the year (Mosley, 1979). The influence of suction magnitude is likely to be correlated to soil saturation. Earlier work (McDonnell 1989; Stewart and McDonnell 1991) indicated that larger volume suction lysimeters and zero tension throughflow pit δD were not significantly different. Large pressure-related δD differences in Maimai near-saturation suction cup samples are not expected.

Implications: If effects of applied suction are large at Maimai, earlier work may have to be reconsidered. Implications for less humid sites could be a more major problem. What would the impact be on the design of automated suction lysimeters now in development stage by Williams (Plymouth Polytechnic), Dowd (Georgia) and Jackson (LandCare, NZ)?

Procedure: Four low volume Soil Moisture Corp. suction lysimeters were deployed at Hut and evacuated to 45, 60, 75 and 90 centibars. These values were chosen based on field test of the maximum applicable suction (90cb) and minimum suction-sample retrieval (45cb). Seven day experiment, samples collected daily, or at 24 hour intervals August 13-20 (inclusive).

Samples collected and analysed: HMD199-227

Results: δD values were almost constant for all of the 60,75 and 90 cb samples. The first four 45 cb samples were more negative in δD than either the later samples or the samples collected at higher suction (see results in Fig.2). This is presumably because the 45cb samples were from larger pores.

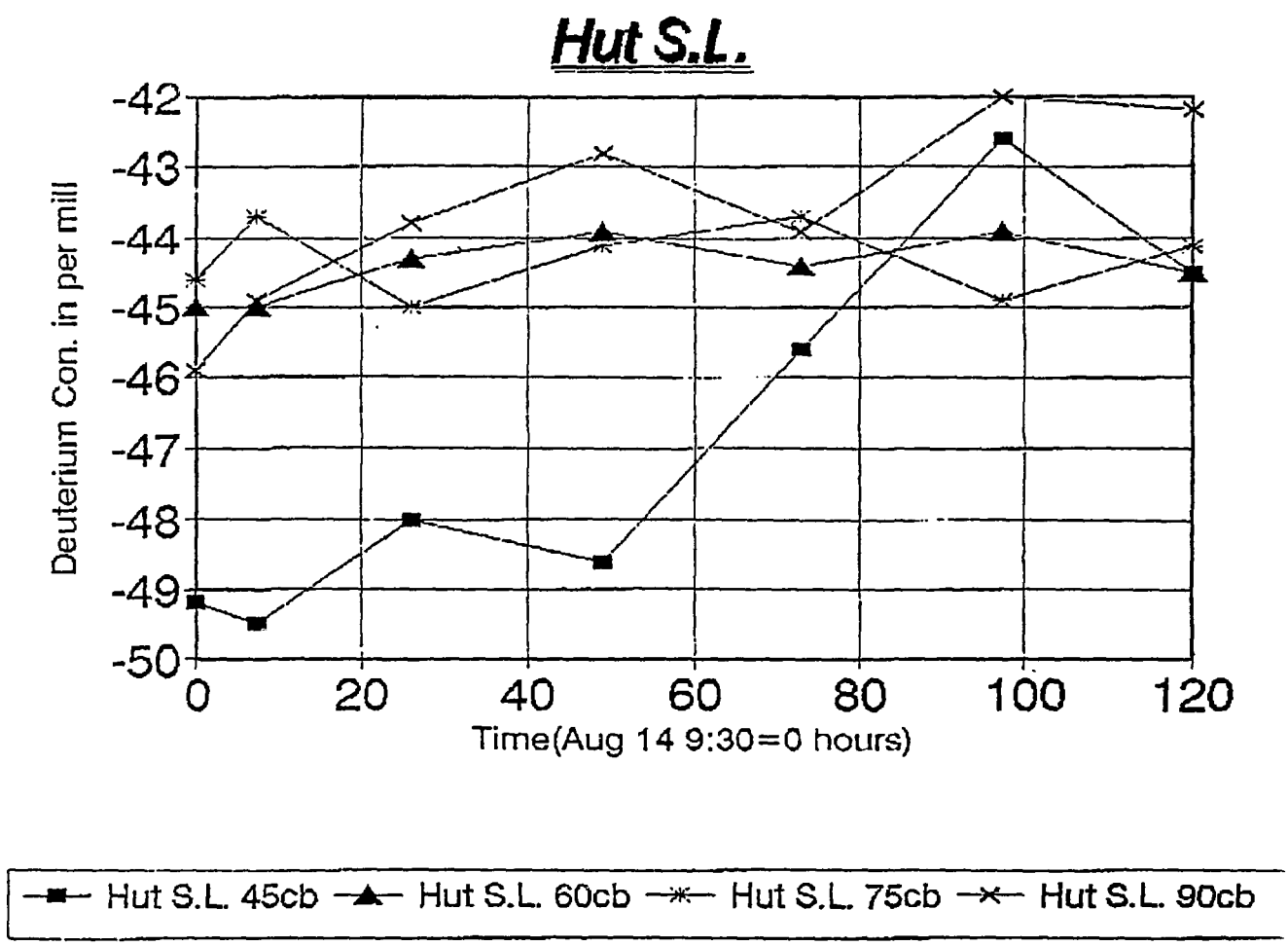

Fig. 2. Deuterium concentration in soil moisture sampled at different suctions. (Experiment 2; cb = centibars.)

Experiment 3

Hypothesis: That there is no difference between ambient rainfall δD and throughfall δD in Maimai catchments.

Background: *Swistock et al* (1989) showed no significant differences between rain and throughfall for Pennsylvania watersheds. Kendall (USGS) and others have shown large differences for Panola Mountain and Sleepers River catchments.

Expectations: During winter rainfall events at Maimai, canopy evaporation is likely to be very low (ie. there is typically little wind, low vapour pressure gradients, etc.), therefore large δD differences are not expected during this experiment. However, the same experiment during December/January may yield results consistent with *Kendall et al* in press.

Implications: Sequential rainfall samples reported in McDonnell (1990) should be re-examined. Old/new water ratios from Maimai and other forested catchments should be re-examined. Modelling should be initiated to investigate the evaporative effects within the ccanopy.

Procedure: A sequential rainfall sampler (392mm dia. funnel; 600ml bottle = ~5mm increments) was co-located with a sequential throughfall sampler (1200mm x 10mm trough; 600ml bottle = 5mm increments) at Hut. Three major events were sampled (August 8, 13, 19) during the 20 day Earthwatch experiment.

Samples collected: HMD106-142, 166-197 and 229-235 all analysed; HMD517-567 not analysed. The reasons for these differences are being considered.

Results: The δD values of the rainfall were more negative than those of the throughfall for the August 13 storm, and less negative for the August 19 storm (Fig.3). The reasons for these differences are being investigated.

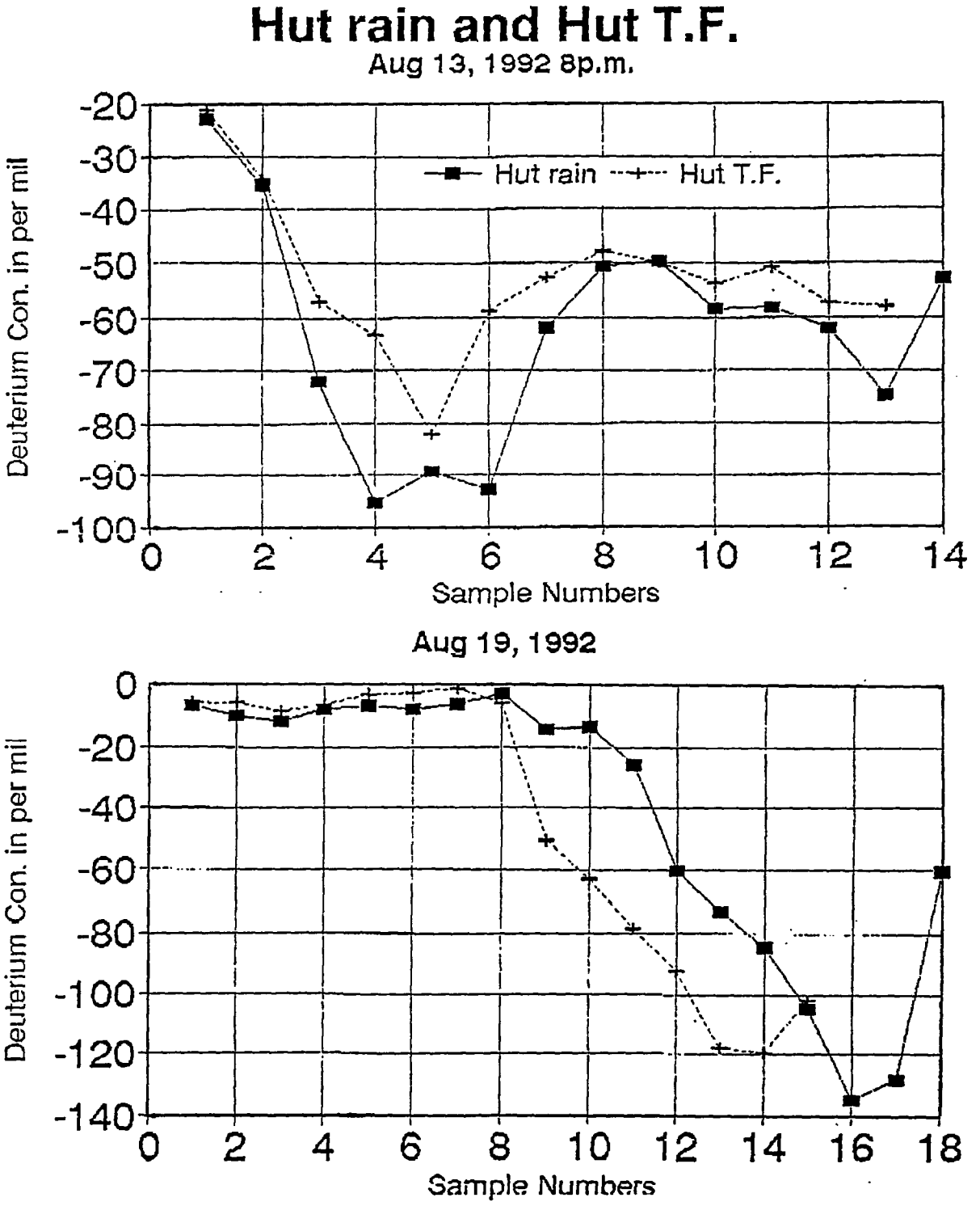

Fig. 3. Deuterium concentration in rainfall and throughfall during rain events on August 13 and 19. (Experiment 3.)

Experiment 4

Hypothesis: That rain falling onto near-stream saturated areas is incorporated into streamflow during that storm's hydrograph rising limb, following the Hewlett and Dunne hypothesis.

Background: Classical variable source area (VSA) theory would suggest that expansion and contraction of saturated areas and direct precipitation on them is directly related to quickflow volumes. *Waddington et al* (1993) recently found in a wetland catchment in Ontario that the VSA model does not hold for isotope/chemical tracing of return flow/exfiltrating groundwater signatures. Rodhe (Upsala) examined molecular diffusion of saturation overland flow and also identified problems with the VSA concept.

Expectations: From the near-stream tensiometer work in M8 (McDonnell 1990), soils become surface-saturated within a few hours after the onset of rainfall and maintain saturation for days following the event due to upslope discharge into valley bottoms. Mixing of saturation overland flow and return flow may be such that rain falling on Maimai catchment saturated areas does not in fact flow directly into the channel and participate in the storm hydrograph.

Implications: What does this mean for stream chemistry/acid deposition modelling? Can this explain Colin Neale's near-stream controls on water chemistry? Can this explain confusion between isotope community and hydrometric community for determining basic hydrologic response? What does this mean for old/new water ratios?

Procedure: A small near-stream $1m^2$ area, 5m upstream from M206 weir was identified, roughly similar to the 1987 M8 near-stream tensiometric site. 500g of sodium bromide 1x1m section was applied during a rainfall event. A sequential ALS sampler was located 5m downstream of an area of likely surface/subsurface runoff, collecting samples at 30 min intervals through rising limb of August 19 event, then at irregular intervals through recession.

Samples collected: HMD289-400 analysed; HMD401-465 not analysed.

Results: The bromide analyses are not available yet. The deuterium measurements gave very similar results between catchments.

Experiment 5

Hypothesis: That there is no or little connectedness or continuity of soil pipe networks in Maimai soils and that pipes vary randomly in space within undrained hollows.

Background: Work of Mosley (1979; 1982), Nieber, McDonnell (1990) and most of the original 1960's forest hydrologists (Whipkey, Aubertin, etc.) assumed downslope continuity of pipeflow/macropore networks, at least for 10's of meters (Mosley, 1979). FRI live tree root mapping by Rowe, Phillips, Watson and O'Loughlin support this hypothesis. The only true macropore/pipe mapping in natural catchments is JAA Jones (1970's) at Plynlimon. This work, although very good, is not widely applicable due to the uniqueness of his site (ie. man-size pipes!). Successful application of the Nieber model, interpretation of Taratoot's MS thesis, development of Yakashima's dissertation, etc. depend on some estimate of pipe connectedness, size and distribution within the profile.

Expectations: Sideslope draining into hollows may not show strong connection. Main axes of hollows should have largest soil Old Man Gravel (OMG) level pipes, enlarged though eluviation. Relationships should exist between clay content and crack/pipe development. Exposed pipes at faces should be able to be traced, following assumptions from previous Maimai and other research.

Implications: If not connected; how are rapid Maimai physical/chemical responses explained ... kinematic wave approximations? Have we been too naive in our assumptions about the simplistic nature of soil pipes?

Procedure: Pipes were difficult to find at newly excavated trenches in the study hollow due to extreme wetness of site. Good exposures were encountered along Powerline Road, 0.5km upstream from M15. A face 6m long was gridded into 0.5m cells, with detailed description, black and white photography and pipe measuring. A full block of the slope was isolated with side and headwall trenches down to the OMG surface, approximately 5m upslope from face. Pipes were traced upslope using orange smoke bombs, dye tracers and wire insertion and deuterium tracing.

Samples collected: HMD93-104 analysed

Results: Experiments using smoke bombs, dye tracers and wire insertions gave good results that are now being evaluated.

Experiment 6

Hypothesis: That Old Man Gravel conglomerate is effectively impermeable and does not affect catchment storm isotopic/hydrometric response.

Background: Thomas performed a hydrogeological survey of Moutere Gravels and concluded that they are hydrologically tight, with no gain or loss of streamflow along measured sections of channel. Estimates of loss to deep groundwater at Maimai by Pearce and others (1970's) are approximately 100mm of total water balance. All Maimai work assumes this formation is tight. Work by Dietrich and others at UC Berkeley found that in N. California catchments where bedrock was assumed to be tight, leakage/pressure on slopes had a large influence on catchment flow pathways.

Expectations: Along fresh exposures of OMG at Powerline Road there appears to be exfoliation features within gravel formation. This is also seen at the new M8 trough site and other exposures throughout the area. Although most certainly impermeable for timescales of storm events, some question exists whether or not loss/contribution from OMG waters affects previous physical/chemical/isotopic interpretations of Maimai.

Implications: Too horrible to mention.

Procedure: Expose fresh OMG surface by clearing away soil. Drill holes into rock and add dye. Problems: smearing of hole walls, representativeness of surface, absence of cracks/exfoliation. May inject in nearby cracks to see where the water goes.

Samples collected: HMD145-164 analysed.

Results: Not evaluated yet.

Experiment 7

Hypothesis: That there is no δD difference between near-stream groundwater, hyporheic water and channel flow through the hydrograph in a small catchment stream cross-section.

Background: USU ecologists, hydrologists at USGS and several conference participants at AGU Chapman were interested in the connectedness of surface water and groundwater. The degree of lateral mixing of these waters is very important from a hydrogeochemical mixing perspective, as well as for the life cycle of several benthic invertebrate species.

Expectations: During baseflow, no significant differences should be encountered. During the rising limb of the hydrograph, upslope input of isotopically different soil water (as per McDonnell, 1990) should change channel δD signatures. Near-stream discharging groundwater will likely not see this rising streamflow/changing stream δD and resident groundwater should not change.

Implications: How does one model stormflow and groundwater δD through an event? What does this mean for chemical/ecological modelling? Has groundwater-surface water interaction been over-emphasized?

Procedure: Six suction lysimeters were deployed at 0.5m intervals in a line normal to the channel, 10-15m upstream from M206 weir. Samples were taken daily for three days preceding the August 19 event, then every two hours during the rising limb of the hydrograph and irregularly through recession. Stream samples were taken concurrently.

Samples collected: HMD1-91 analysed.

Results: Plotted in Fig.4.

Concluding Remarks

It is expected that the results of these experiments will strengthen the conceptual foundations and lead to better methods in the application of environmental isotopes to the investigation of streamflow generation mechanisms in catchments. The experiments also have strong relevance to questions of infiltration and groundwater recharge, which are certainly among the most contentious areas in hydrology today.

During these experiments 570 samples were collected for deuterium analysis. 300 of these were analysed during 1992-93. The remainder will be measured in 1993-94. The results have been encouraging and are now being collated with other physical and chemical data to produce an integrated interpretation. Several papers are expected to result from this work.

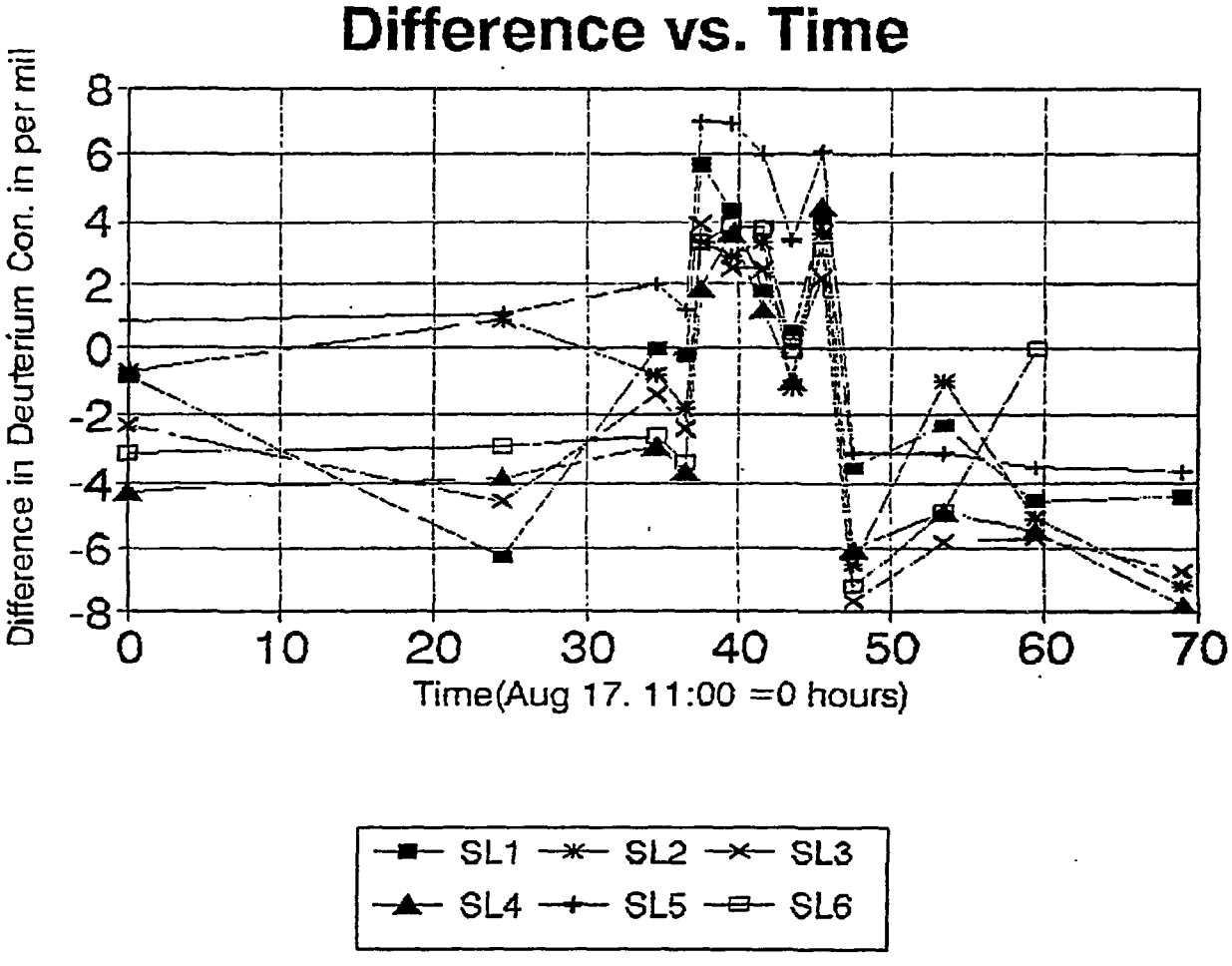

Fig. 4. Difference in deuterium concentrations of soil moisture and streamflow as functions of time. (Experiment 7.) The data are displaced by the change in streamflow concentration at the onset of rainfall at 37 hours.

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