Characterization of Groundwater Recharge and Flow in a Vermont Upland Watershed Using Stable Isotope Tracing Techniques

Master of Science Thesis Proposal

by

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Abstract

The project which I propose will use measurements of stable oxygen isotopes in precipitation (rain and snow) and groundwater (wells) to characterize groundwater recharge and flow in the upland portion of the Browns River basin in northwestern Vermont. The basin initiates on the steep western slopes of Mount Mansfield and consists of fractured metamorphic bedrock (schist) underlying glacial till of varying thickness. Due to the heterogeneous nature of groundwater flow in bedrock fractures, characterizing this type of hydrogeologic system via traditional means (i.e. pumping tests, injected tracer tests) is a complex effort. This study represents a new approach to the problem.

Since early July of 1995, I have collected precipitation samples on a weekly basis from 16 stations in the area in order to determine the spatial and temporal distribution of rain volume and to monitor the isotopic composition of recharge to groundwater. Air temperature information has also been collected at two of the locations. Water samples are measured for $\delta^{18}O$ composition at the University of Vermont isotope laboratory. We have observed a decrease in $\delta^{18}O$ composition with elevation in samples collected thusfar which we suspect to be a function of temperature gradients within the basin. The $\delta^{18}O$ composition at individual stations also appears to vary seasonally based on initial data.

In October of 1995, I began sampling and $\delta^{18}O$ analysis of groundwater from 8 wells within the uppermost portion of the basin (i.e. the western slopes of Mt. Mansfield above Underhill Center). Continued isotopic analysis of groundwater samples will provide a means for detecting the altitudinal and seasonal isotope signatures in the bedrock groundwater system to compare with precipitation signatures. This information will be used to identify upper elevation areas of recharge and determine travel rates from the recharge zones to the lower elevations.

Introduction

In a setting such as the upper Browns River basin, the highest elevations of the watershed are typically considered to be the "cleanest" recharge areas. This is due to the lack of development which translates to a minimized potential for contamination of recharging water. These upper elevation recharge areas may represent the best sources for future water supplies in the nearby developing towns in the Browns River valley, namely Underhill Center, Underhill and Jericho. Therefore, the focus of this study is on characterizing the dynamics of groundwater recharge and flow in the uppermost portion of the basin.

In settings with substantial topographical relief, the amount of precipitation increases with elevation (Friedman et al., 1964). At the top of Mount Mansfield, the highest mountain in Vermont (1339 m), approximately 250 cm of rain and snow/rain equivalent fall annually. It is assumed that a significant portion of precipitation travels to the lower valley as surface runoff (saturated overland flow) or shallow baseflow in the till cover, entering the Browns River or one of its several tributaries. However, a portion of the water infiltrating through the till eventually enters the fractured bedrock and is transported downgradient through the bedrock groundwater system. Several residents on the slopes of the mountain already take their water from shallow bedrock springs. Almost all of the drilled wells installed in the area are supplied by deeper bedrock fractures. At this point, the paths which groundwater takes through the fractured rock, as well as the residence time of water in the bedrock system, are unknown. In order to develop plans for future water supply development in this and other similar settings, it is necessary to have a more detailed description of groundwater movement in the bedrock.

Objectives

The specific objectives of this study are threefold:

1) Characterize the isotopic signature of precipitation and groundwater with elevation and time. This study will be a test for the usefulness of isotope tracing techniques in characterizing basin-scale upland groundwater flow in this type of geologic setting.

2) Use the collected data discussed above, along with the geometry of the bedrock aquifer and surficial cover, to determine groundwater recharge, storage, and transport characteristics in this type of setting.

3) Provide at least a preliminary understanding of groundwater recharge and flow characteristics necessary to develop plans for future water supply development in the towns of Underhill Center, Underhill and Jericho. This will include creating a groundwater flow model for predictive simulations.

Geologic Setting

The topography of the study area is controlled predominantly by bedrock. The bedrock consists almost exclusively of silver-green magnetite bearing chlorite-muscovite-quartz (-albite) schist of the Underhill formation. The schist has local layers and lenses of quartz-feldspar granulite and white quartzite and occasional greenstone horizons (Thompson and Thompson, 1991). This rock has undergone several progressive deformational/metamorphic events during the Taconic and perhaps the Acadian orogenies (Stanley and Ratcliffe, 1983). The resulting structure of the rock exhibits a folded north-south striking bedding schistosity which dips in general to the west away from the Green Mountain Anticlinorium. Garnet crystals observed at higher elevations indicate a more highly metamorphosed component of the rock which forms the apex of the anticlinal folding.

Three predominant joint directions have been measured on Mt. Mansfield. Two joint sets, one striking approximately N30E with a 75NW dip and a second vertical north-south striking set, are interpreted to be tension joints resulting from post-metamorphic adjustments. A third vertical set of cross joints strikes N80E (Christman, 1959; Christman and Secor, 1961). These relatively recent fractures may represent the most significant zones of water storage and transport in the bedrock flow system to the lower elevations. Identification of significantly jointed zones through photolineament examination is planned as part of this study.

Isotopes as Environmental Tracers

The oxygen isotopic composition of water in precipitation is dependent upon the conditions under which the water forms. Individual water molecules may form with three different oxygen isotopes (^{18}O , ^{17}O , and ^{16}O). Heavy (^{18}O) and light (^{16}O) oxygen isotopes have different masses and different vapor pressures. Therefore, the tendency of these isotopes to form water molecules condensing in a cloud varies with the temperature in the cloud, among other factors to be discussed below. This in turn affects the ratio of heavy to light isotopes in rainfall. Once water is formed, the oxygen isotopes exhibit conservative behavior (i.e. a stable ratio of heavy to light isotopes) in environments where evaporation is slight or nonexistent. The oxygen isotope ratio is typically reported as a ratio of $^{18}O/^{16}O$ relative to a standard (Standard Mean Ocean Water) and expressed in per mil (parts per thousand) as $\delta^{18}O$. Earlier studies (Dansgaard, 1964) found that vapor origin and rainout history were the primary factors influencing the $\delta^{18}O$ composition of local precipitation, with mixing in clouds and rain intensity causing a secondary fractionation. Fritz et al. (1987) found that seasonal effects may be due to both temperature change and the influence of arctic air masses. This study also showed a correlation between the seasonal $\delta^{18}O$ variations in shallow groundwater and precipitation.

Stable isotopes of oxygen in water have been used as environmental tracers for some time. Due to their conservative behavior in non-evaporative environments, oxygen isotopes can be efficient recorders of climatic changes (i.e. atmospheric temperature variations) in water systems. Oxygen isotopes have also been used in several hydrologic experiments to characterize stream flow and response to storm events. (Space et al., 1991; Busek et al., 1991; McDonnel et al, 1991). Recent use of oxygen isotopes in groundwater studies is discussed below:

Davisson and Criss (1993) observed seasonal $\delta^{18}O$ variation in groundwater extracted from a shallow aquifer in the southwestern Sacramento Valley, California. Sveinbjornsdottir and Johnsen (1992) identified recharge areas to springs through comparison of $\delta^{18}O$ in rain and spring discharge in Iceland. Ingraham et al. (1991) and Mazor and Vuataz (1990) also used $\delta^{18}O$ to characterize the hydrology of spring complexes. Evaluation of the evaporated condition of groundwaters (i.e. $\delta^{18}O$ vs. hydrogen composition, δD, in reference to the World Meteoric Water Line) has been used to determine recharge characteristics in arid regions (McKenna et al., 1992; Rosenthal et al., 1990; Adar and Long, 1987).

Recent studies in mountainous terrain have included Lizarazu et al. (1987) which used $\delta^{18}O$ variations to determine groundwater flow boundaries in the Bolivian Plateau. Febrillet et al. (1987) studied variations in the $\delta^{18}O$ composition of groundwater and precipitation with altitude in the Dominican Republic karstified limestone mountain ranges. Albero et al. (1987) were able to determine the contribution from separate watersheds supplying groundwater through stream infiltration in the Andes Cordillera.

Locally, the USGS has conducted oxygen isotope monitoring in precipitation, stream flow, and groundwater at the Sleepers River watershed. Data provided by the USGS show significant seasonal variation in the $\delta^{18}O$ composition of precipitation. Our initial data matches these findings. In the USGS study, groundwater samples from wells installed in overburden deposits responded only minimally to large snowmelt events. However, response in groundwater over longer time periods to seasonal changes was observed (Shanley, 1995).

Sampling and Measurement Techniques

Since July ,1995, I have gathered rain samples on a weekly basis from 16 collectors installed in my field area, including 6 in the uppermost portion of the watershed (Mt. Mansfield). The locations of collectors are shown in Figure 1. Collectors were installed downgradient of the Mt. Mansfied basin as well as to the north and south, to examine spatial distribution of $\delta^{18}O$ rainfall composition. Rain collectors were designed to capture rain during the one week monitoring period without allowing fractionation of isotope composition by evaporation to occur. This was accomplished through burial of the collection bottle in most locations. Above treeline on Mt. Mansfield, the collection bottles were placed in an insulating container. A diagram of the type of collector used in most of the locations is shown in Figure 2.

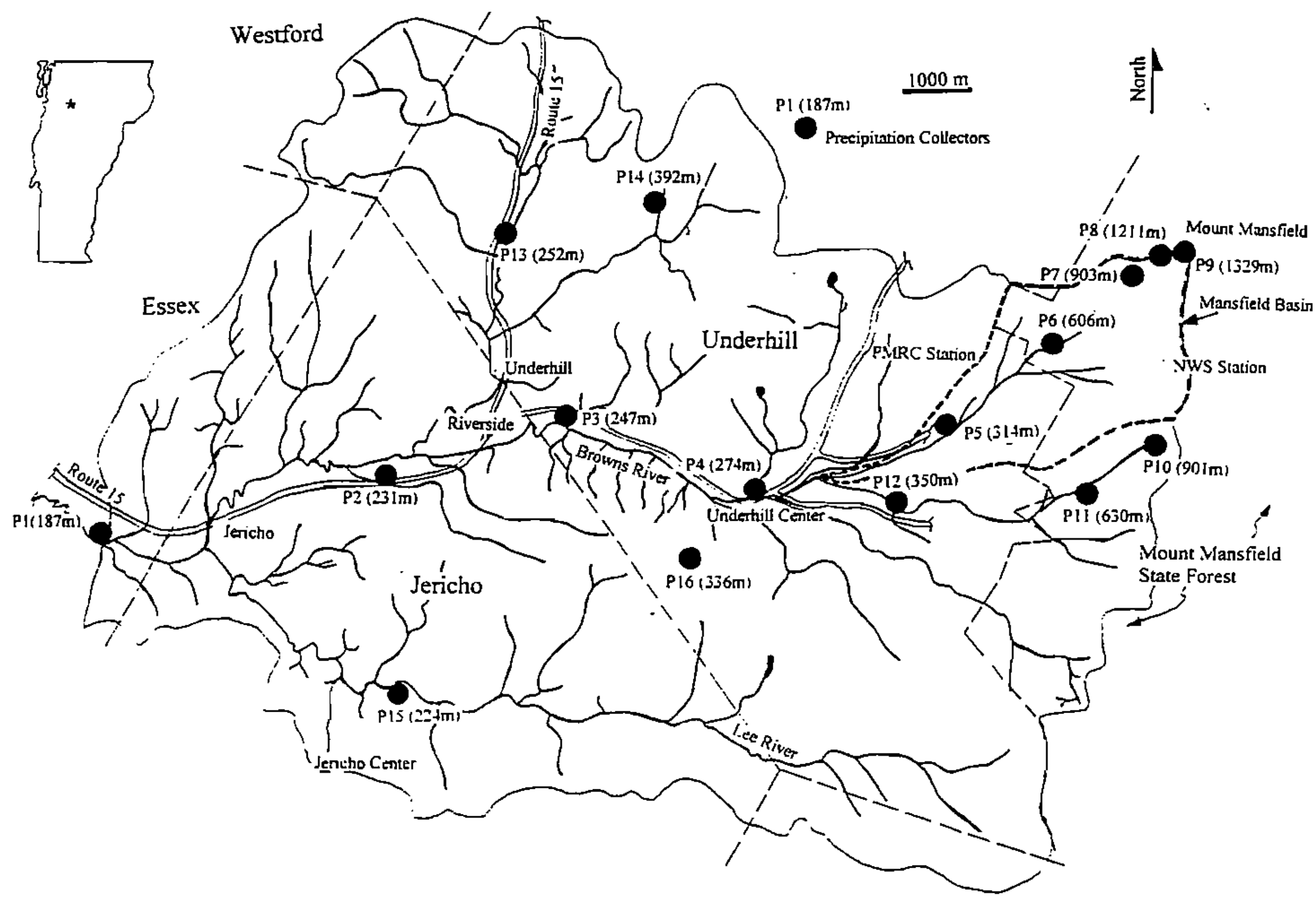

Figure 1
Precipitation Collector Locations
Upper Browns River, Including Mt. Mansfield Basin

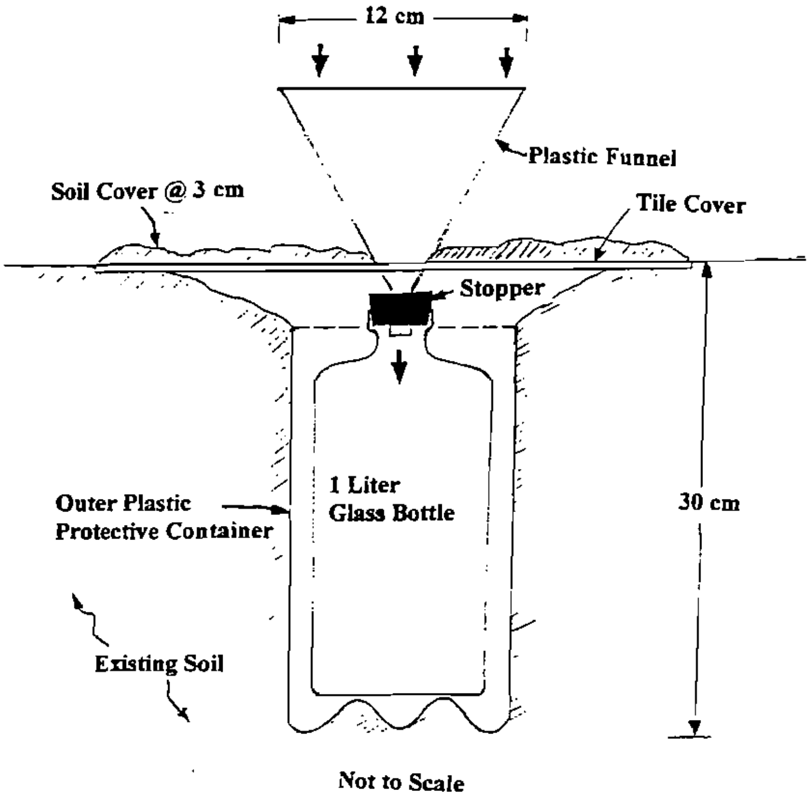

Figure 2
Diagram of Rain Collector

Temperature data-loggers have been installed at locations P1 (187 m) and P7 (903 m) since precipitation sampling was initiated. In addition, I obtain temperature and precipitation data from the National Weather Service summit station on Mount Mansfield as well as from the Proctor Maple Research Center in Underhill Center. My project is now part of the Vermont Monitoring Cooperative, an intensive forest ecosystem monitoring and research program in the Mount Mansfield State Forest.

I recently began groundwater sampling (October, 1995). Samples are collected on a weekly basis from 8 residential wells via outside faucets. The well locations are shown in Figure 3. Of the wells shown, 4 are installed in deep bedrock and 4 are fed by shallow bedrock springs. An additional sample is taken weekly from the Jericho public water supply system downgradient of the Mansfield basin. During the drought in June of 1995, 27 baseflow samples were collected from streams in the area. Results of analysis for these samples, when compared with groundwater $\delta^{18}O$ signatures, will be used to describe discharge of shallow bedrock groundwater to the streams.

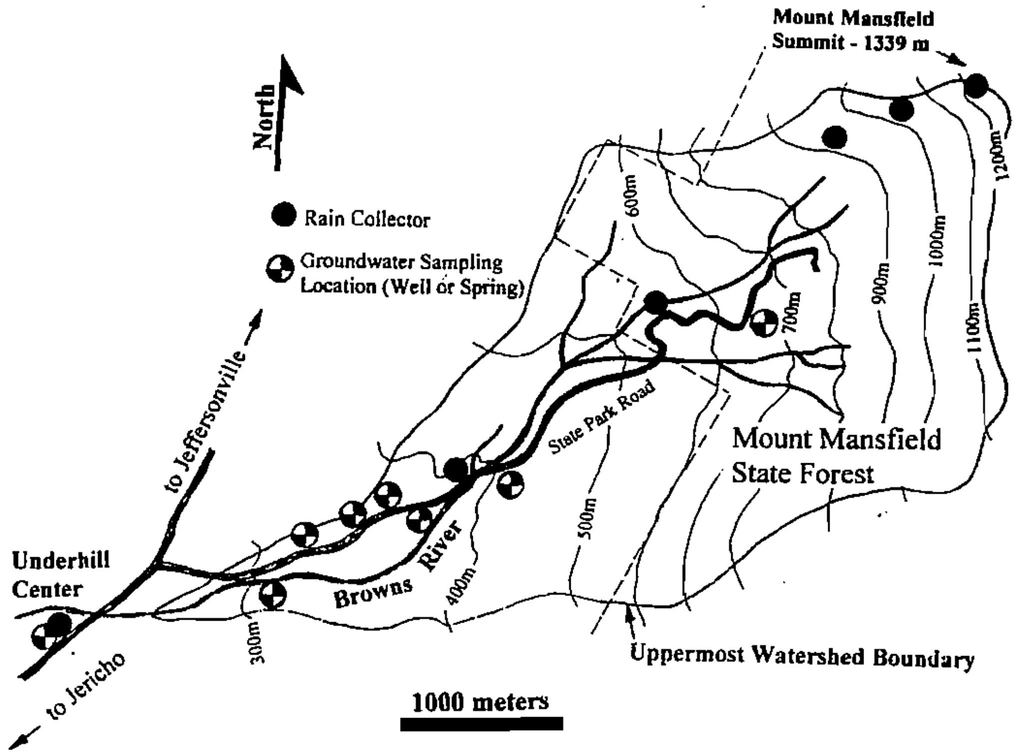

Figure 3
Monitoring Locations
Mt. Mansfield Basin

Currently, I am collecting snow via two methods. Snow lysimeters have been installed to collect melting snow on a weekly basis. In addition, samples are collected directly from the recent snow pack each week. Data from the two sample types will provide an assessment of the relationship between the $\delta^{18}O$ composition of winter precipitation and infiltrating water (i.e. snowmelt). Figure 4 presents a diagram of a snow lysimeter. This device may also be used to collect rain that may fall before or after the snow season.

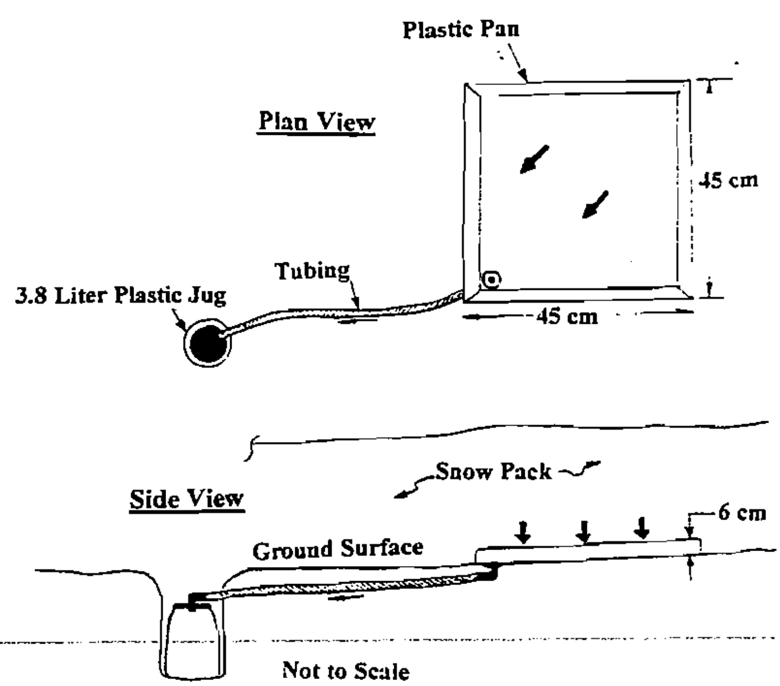

Figure 4
Diagram of Snow Collector

All $\delta^{18}O$ analysis of water samples is being conducted at the UVM isotope laboratory in the Department of Geology. We begin the analysis by evacuating (on the laboratory vacuum line) a glass sample container equipped with rubber stopper. Then carbon dioxide gas (CO_2) is injected into the container at a controlled pressure. A 2 ml portion of the water sample to be analyzed is injected through the stopper into the glass tube. Samples are kept in a water bath at 25°C for at least 4 hours to allow the CO_2 to equilibrate isotopically with the water sample. The CO_2 is then separated from the water using cryogenic techniques on the vacuum line. The $\delta^{18}O$ composition of each sample is measured on the SIRA Series II mass spectrometer. Data are reported relative to Standard Mean Ocean Water (SMOW).

Discussion of Initial Data

A total of approximately 70 precipitation samples and 16 groundwater samples have been analyzed for $\delta^{18}O$ composition. From these data, several relationships are evident. The $\delta^{18}O$ composition of precipitation becomes more negative (i.e. more depleted of heavy oxygen isotopes) with elevation in most weeks. This appears to be related to the variation of temperature with altitude. Figure 5 shows the variation of $\delta^{18}O$ for four collection stations over the first ten sample collection events. Figure 6 presents a plot of the variation in $\delta^{18}O$ at each of the four stations relative to the low elevation station. A regression line is plotted through the data. Based on the initial data, the approximate gradient of $\delta^{18}O$ with elevation is -2.3 per mil/1000 meters. The $\delta^{18}O$ composition of precipitation is also becoming more negative over time as seasonal temperatures cool. Figure 7a and 7b illustrate this relationship at two stations equipped with temperature loggers.

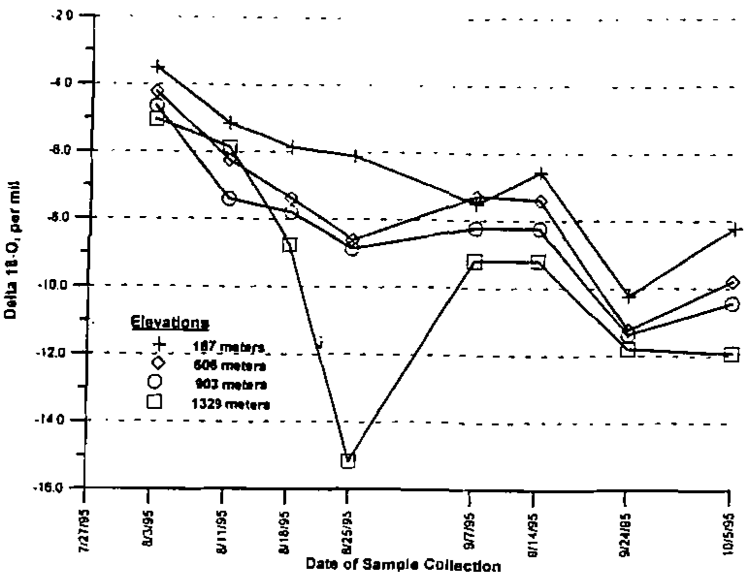

Figure 5
Oxygen Isotope Composition
of Rain vs. Time

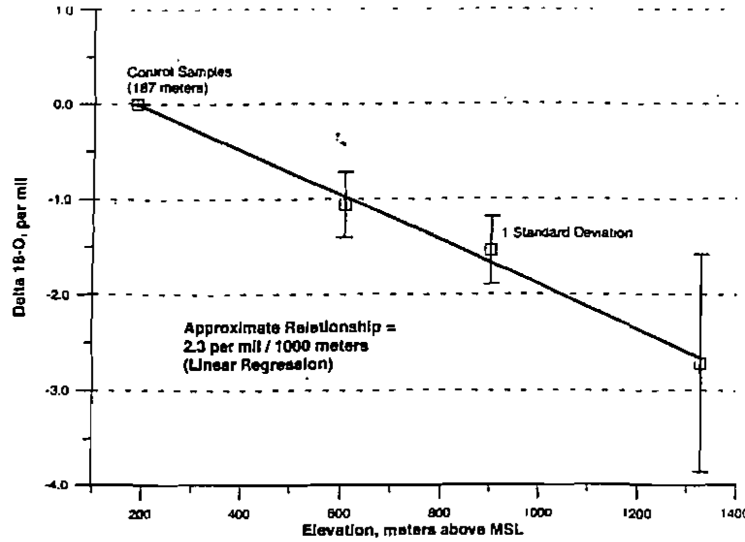

Figure 6
Average Offset of Weekly
Oxygen Isotope Composition
Relative to Samples at Elevation 187m

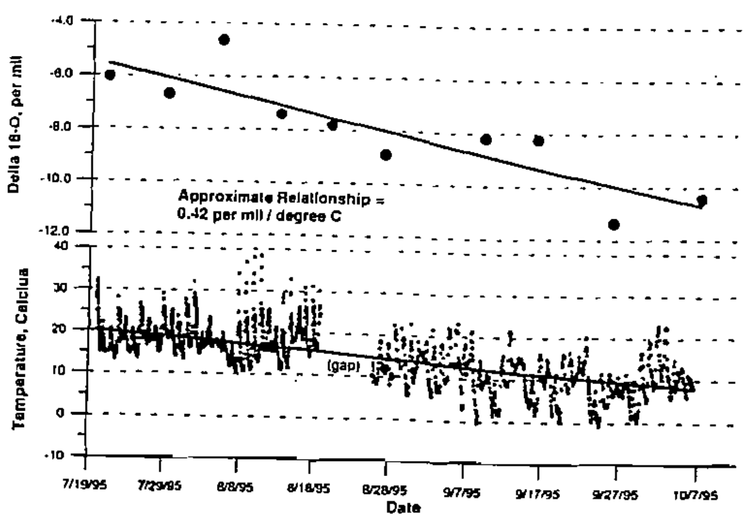

Figure 7a
Oxygen Isotope Composition
and Temperature vs. Time
Elevation 903m

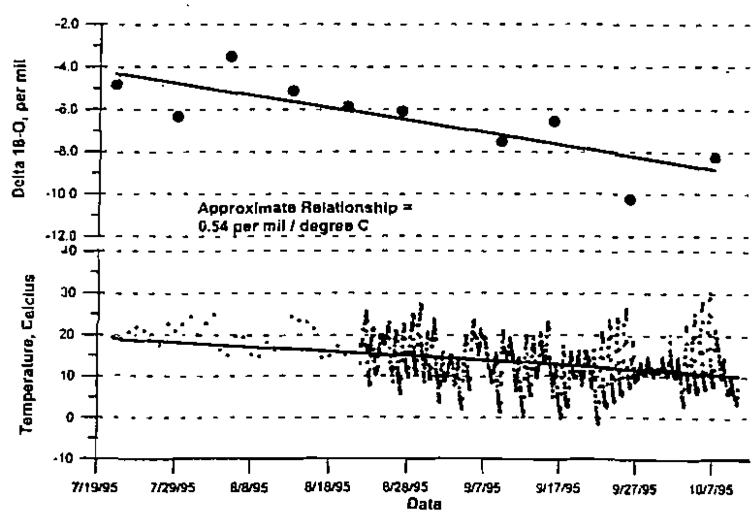

Figure 7b
Oxygen Isotope Composition
and Temperature vs. Time
Elevation 187 m

The $\delta^{18}O$ composition appears to vary with the type of storm (i.e. rain amount, wind direction, etc.). However, no consistent relationship between rain amount and $\delta^{18}O$ has been identified. I have observed that the amount of rain collected at each station varies according to the setting. Some collectors are located in open fields, some in forest, and some on the windswept summit of Mount Mansfield. This may be one reason a correlation between rainfall amount and $\delta^{18}O$ is difficult to see. It is also possible that there is no consistent relationship.

The initial results of groundwater $\delta^{18}O$ analysis indicate that there is significant variation in the $\delta^{18}O$ of groundwater with location. $\delta^{18}O$ in springs and wells varied from -8.9 to -12.5 per mil. The highest spring is adjacent to a stream and has approximately the same composition (-10.5 per mil) as rain collected in the same week. This suggests that the spring may be supplied by rapidly infiltrating shallow groundwater flow. Other springs and wells showed more positive or more negative $\delta^{18}O$ composition than the contemporary rain fall, suggesting that the water was recharged some time earlier. Additionally, infiltrating water may be mixed with pre-existing groundwater of different $\delta^{18}O$ composition. Continued sampling will help to explain the relationship between groundwater $\delta^{18}O$ and location.

Summary of Planned Activities

I will continue to sample and analyze rain/snow on a weekly basis for at least one year. This will allow me to develop a seasonal $\delta^{18}O$ record. Continued weekly sampling of the wells and springs will indicate whether and how $\delta^{18}O$ varies temporally in groundwater. If trends can be identified, it may be possible to link groundwater at each location to past recharge.

In addition to oxygen isotope tracing, major ion chemical analyses may be carried out on some of the groundwater samples. This will help to verify residence times estimated through $\delta^{18}O$ measurement. Unfractionated meteoric water exhibits a consistent relationship between $\delta^{18}O$ and δD composition. As part of this study, several groundwater samples will be analyzed for δD composition to determine if the water has been fractionated through evaporation or other mechanisms prior to entering the groundwater system.

As discussed earlier, photolineament examination is planned in order to identify significantly jointed zones in the bedrock, if present, as well as other geometric features. Combined with the results of isotopic analysis, this information will be used to characterize the bedrock aquifer. A groundwater model will be developed for use in predicting the effects of increased water extraction on the sustainability of the bedrock water supply.

References Cited

Adar and Long, *Oxygen-18 and Deuterium Distribution in Rainfall, Runoff and Groundwater in a Small Semi-Arid Basin: the Aravaipa Valley in the Sonora Desert, Arizona*, Isotope Techniques in Water Resources Development (proceedings), 1987, pgs. 257-273

Albero et al., Isotopic *Evidence for the Different Origins of the Tulum Valley Groundwaters (San Juan, Argentina)*, Isotope Techniques in Water Resources Development (proceedings), 1987, pgs. 287-299

Buzek et al., *Evaluation of the Runoff Components on the Slope of an Open-Cast Mine by Means of Environmental Isotopes 18O and T*, Journal of Hydrology, Vol. 127, No. 1/4, 1991, pgs. 23-36

Christman, *Geology of the Mount Mansfield Quadrangle Vermont*, Vermont Geological Survey Bulletin No. 12, 1959, pgs. 1-75

Christman and Secor, *Geology of the Camels Hump Quadrangle Vermont*, Vermont Geological Survey Bulletin No. 15, 1961, pgs. 1-70

Dansgaard, *Stable Isotopes in Precipitation*, Tellus, Vol. 16, 1964, pgs. 436-468

Davisson and Criss, *Stable Isotope Imaging of a Dynamic Groundwater System in the Southwestern Sacramento Valley, California, USA*, Journal of Hydrology, Vol. 144, No. 1-4, 1993, pgs. 213-246

Febrillet et al., *Isotopic and Hydrogeological Studies in the Southwest of the Dominican Republic*, Isotope Techniques in Water Resources Development (proceedings), 1987, pgs. 317-333

Friedman et al., *The Variation of the Deuterium Content of Natural Waters in the Hydrologic Cycle*, Review of Geophysics, Vol. 2, 1964, pgs. 1-124

Fritz et al., *Isotopic Composition of Precipitation and Groundwater in Canada*, Isotope Techniques in Water Resources Development (proceedings), 1987, pgs. 539-550

Ingraham et al., *Stable Isotopic Study of Precipitation and Spring Discharge in Southern Nevada*, Journal of Hydrology, Vol. 125, No. 3/4, 1991, pgs. 243-258

Lizarazu et al., *Isotope Study of the Oruro-Caracollo Basin (Bolivia)*, Isotope Techniques in Water Resources Development (proceedings), 1987, pgs. 301-315

Mazor and Vuataz, , *Hydrology of a Spring Complex, Studied by Geochemical Time-Series Data, Acquarossa, Switzerland*, Applied Geochemistry, Vol. 5, No. 5/6, 1990, pgs. 563-569

McDonnell et al, *Effect of Catchment-Scale Subsurface Mixing on Stream Isotopic Response*, Water Resources Research, Vol. 27, No. 12, 1991, pgs. 3065-3073

McKenna et al., *A Stable Isotope Study of Bank Storage Mechanisms in the Truckee River Basin*, Journal of Hydrology, Vol. 134, No. 1/4, 1992, pgs. 203-219

Rosenthal et al., *Definition of Groundwater Flow Patterns by Environmental Tracers in the Multiple Aquifer System of Southern Arava Valley, Israel*, Journal of Hydrology, Vol. 117, No. 1/4, 1990, pgs. 339-368

Shanley et al., *Chemical and Isotopic Evolution of a Layered Eastern U.S. Snowpack and its Relation to Streamwater Composition*, Biogeochemistry of Seasonally Snow-Covered Catchments (proceedings), 1995

Space et al., *The Use of Stable Isotopes in Quantifying Groundwater Discharge to a Partially Diverted Creek*, Journal of Hydrology, Vol. 129, No. 1/4, 1991, pgs. 175-193

Stanley and Ratcliffe, *Simplified Lithotectonic Synthesis of Pre-Silurian Rocks in Western New England*, Vermont Geological Survey Special Bulletin No. 5, 1983, pgs. 1-9

Sveinbjornsdottir and Johnsen , *Stable Isotope Study of the Thingvallavatn Area, Groundwater Origin, Age, and Evaporation Models*, OIKIS, Vol. 64, No. 1/2, 1992, pgs. 136-150

Thompson and Thompson, *Bedrock Geology of the Camels Hump-Bolton Mountain Area, North-Central Vermont*, Vermont Geological Survey Special Bulletin No. 12, 1991, pgs. 1-32