DEVELOPMENT OF A WATER BUDGET IN A TROPICAL SETTING

ACCOUNTING FOR MOUNTAIN FRONT RECHARGE:

TUTUILA, AMERICAN SAMOA

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By
Jeff A. Perreault

Dissertation Committee:

Aly I. El-Kadi, Chairperson
Ali Fares
Delwyn S. Oki

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Abstract

A threshold-style water budget for Tutuila, American Samoa was developed to estimate mean daily recharge over the west-central part of the island. The study focused on the Tafuna and Leone Plains, areas of low relief and deep soils that lie at the base of a steep mountain range. Mountain front recharge was observed occurring at the mountain/plain interface of the Tafuna Plain and was therefore included as a component part of the water budget.

The Tutuila budget was processed for the 30-year period of 1971 – 2000. The results indicate that, on average, the west-central area of the island receives an estimated recharge of 106 million gallons per day (Mgal/d). Mountain front recharge is estimated to contribute about 8 Mgal/d, or about 8 percent of total recharge. At the mountain/plain interface this percentage increases substantially, in places accounting for more than 50 percent of estimated mean daily recharge.

Different conditions were tested through sensitivity analyses, and generated recharge estimates in the range of 79 – 133 Mgal/d. Changes of plus or minus 15 percent to rainfall (the average annual variability for the period of record) generated changes to estimated recharge of about plus or minus 25 percent. Sensitivity of runoff-to-rainfall ratios was tested by using the minimum or maximum monthly basin value within a region rather than the regional mean monthly value. Using minimum values increases estimated recharge by 12 percent; using maximum values decreases estimated recharge by 14 percent. Use of alternative canopy interception values (canopy interception rate, free throughfall rate, and canopy storage limit) generated changes to estimates of recharge of plus 3 to minus 10 percent. Changes to other parameters generated changes to estimates of recharge no greater than plus or minus 5 percent relative to baseline results.

Sensitivity analyses showed little change in estimates of actual evapotranspiration, with no test producing a change larger than 9 percent, and most frequently less than 5 percent. This may be due to patterns of rainfall that provide frequent and abundant input to the

canopy and plant/soil systems at rates that exceed potential evapotranspiration. This finding may have negative implications if a trend develops towards locally drier conditions.

Introduction

Tutuila is the largest island within the nation of American Samoa, and lies just south of the equator and just east of the International Date Line (fig. 1). The island's volcanic origins are reflected in its current topography dominated by an east-west trending mountain range comprised of older volcanics, and by a much shorter north-south spur of younger volcanics extending southward from the east-west range on the western half of the island. This spur lies between two large, dominantly flat areas of the island where much of the population resides: the Leone Plain to the west of the spur and the Tafuna Plain to the east. These plains are the products of the same recent volcanism that created the spur, and overlie older reef and lagoon deposits. Located on these plains are the vast majority of the production well fields that serve the approximately 55,000 residents of the island (U.S. Census Bureau, 2000). While there are many active wells on the island, there are almost as many that have been abandoned due to high levels of chlorides. An improved understanding of the island's hydrology would enable more targeted and efficient development of critical water resources to occur.

Water budgets are used to quantify or refine some component of the hydrologic cycle. Recharge is one of the more difficult components to quantify as many of the critical processes are not directly observable. For assessing recharge, the water budget method is superior to more basic, single-variable regression equations such as is described in Shade and Nichols (1996). Some recharge, often referred to as mountain front recharge (MFR), occurs along a mountain/plain interface where areas of high relief and thin soils abut areas of low relief and deep soils. Although typically accounted for in arid to semi-arid continental montane settings (Wilson and Guan, 2004), MFR may be considerable in any locale where these types of conditions are present. MFR was observed occurring along the mountain/plain interface above the Tafuna Plain, and was therefore included as a

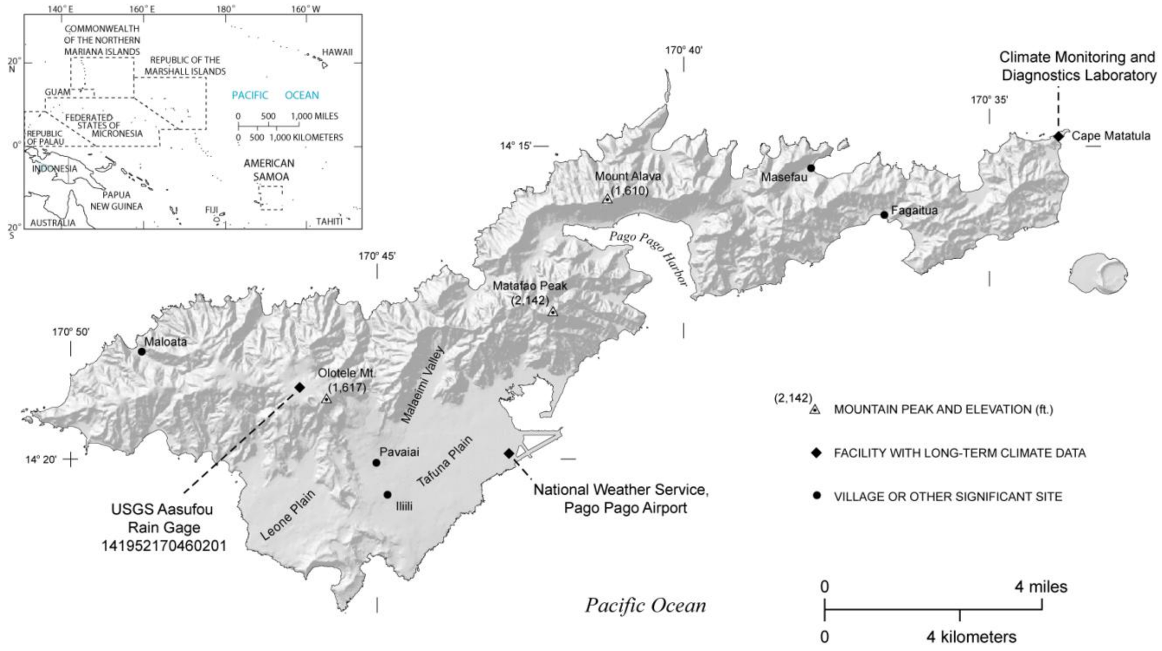

Figure 1. Location map for the island of Tutuila, American Samoa (modified from Izuka and others, 2005b).

critical element of the water budget using an approach that combined topographic relief with soil property types and locations.

Examples of recent study locales in the Pacific Basin that have featured or incorporated water budget assessments include the islands of Hawaii (Oki, 2002), Kauai (Izuka and others, 2005), and Maui (Engott and Vana, 2007). A study by Izuka and others (2007), funded by the United States Environmental Protection Agency (USEPA) served as the catalyst for the development of the water budget and defined scope with regard to study area. As a result the budget was developed for a 34.4 sq. mi. area of the island between longitudinal boundaries of W 170° 41’ 30” and W 170° 49’ 00”.

Data and Methods

“The Water Budget” is a seminal paper authored in 1955 by Thornthwaite and Mather, and the conceptual model they describe served as the basis for the Tutuila water budget (fig. 2). Water is introduced as input to an area, typically but not exclusively as direct rainfall. Some of the input is intercepted by vegetative canopy and evaporated before reaching the ground. Some is assigned as runoff which may be later re-introduced as recharge along mountain/plain interfaces or reaches of losing streams. The remainder infiltrates into the temporary storage reservoir of the soil. The soil profile is divided into layers based on common characteristics, such as available water capacity, and the input is distributed into the layers in a top-down manner adding to antecedent moisture. Evapotranspiration is accounted for and removed before the reservoir is checked for moisture content in excess of available water capacity (Oki, 2008). Excess moisture is removed from the soil profile and added to cumulative recharge for that specific spatial area. A budget is often processed for a predetermined period of time, and the results averaged to provide estimates of spatially discretized mean daily recharge.

Numerous components and processes are necessary to consider in developing a water budget, but they can be simplified to a few conceptual terms:

$$P - RO - E_{cnpy} - E_{plnt} - SM_{\Delta} - RC = 0 \tag{1}$$

where

P	is precipitation over some time step,
RO	is runoff resulting from rainfall,
E_{cnpy}	is evaporation from vegetative canopies,
E_{plnt}	is evapotranspiration from the plant/soil system,
SM_{Δ}	is a change in soil moisture storage, and
RC	is recharge driven by soil moisture in excess of storage capacity.

The Tutuila budget was developed with the assumption that the first 5 terms are either known or can be determined directly from the known terms, with recharge recognized as representing the amount necessary to bring the budget into balance.

A more detailed list of elements considered for the Tutuila budget include rainfall distribution, structural canopy components (canopy interception rate, free throughfall

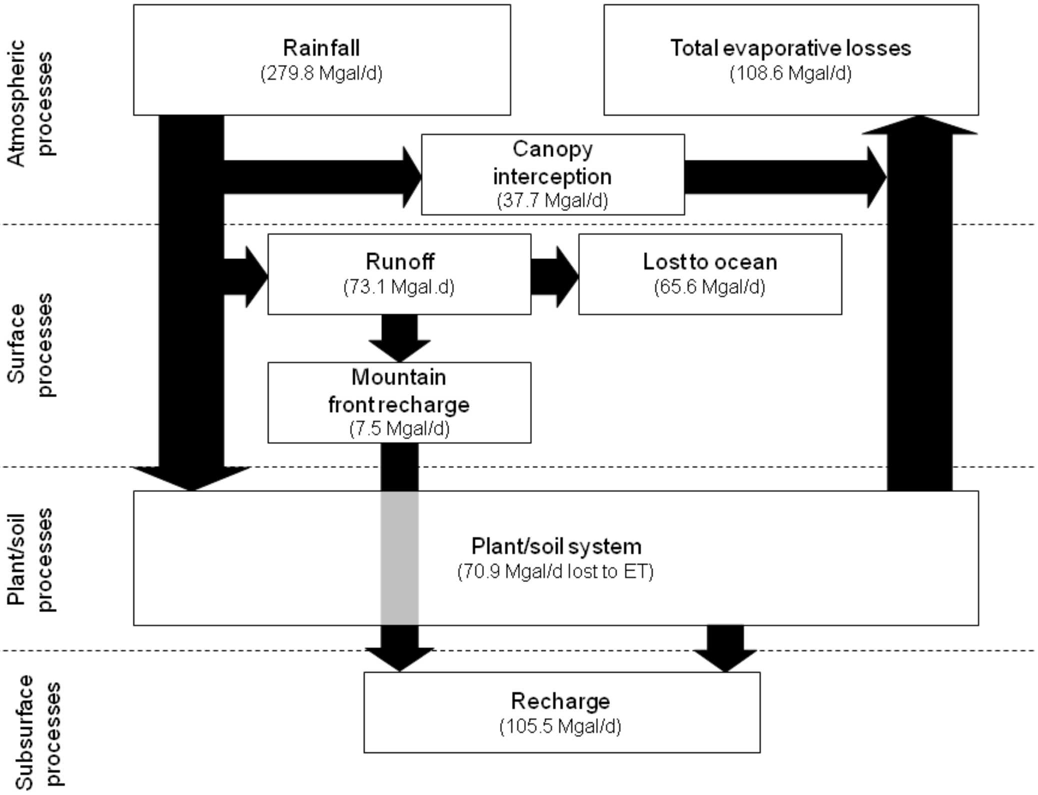

Figure 2. Conceptual model of process flow for Tutuila water budget. Results in parentheses reflect baseline estimates.

rate, and canopy storage limit), runoff as a fraction of rainfall, the final disposition of runoff, land use and cover, vegetation types and their effect on evapotranspiration, soil characteristics, and periods of record/model-run intervals. For the Tutuila budget the elements are processed in a spatially based manner in that all processing for the entire period of record is completed for one area before moving on to another. No effort is made to select areas in a particular order.

To prepare for budget processing, all spatial data, including those representing different temporal periods of similar data, were integrated using ArcGIS to produce polygons of common characteristics. A FORTRAN program, modified from prior efforts (e.g., Oki, 2002, and Izuka, 2005a), is used for soil moisture processing.

Preparation of Synthetic Daily Rainfall

Mean monthly rainfall is based on raster data published by the PRISM Climate Group (Daly and others, 2006) for the period of record 1971 – 2000 (table 1). The raster data were converted using ArcGIS into polygon shapefiles to establish isohyet-bound areas of equal rainfall (fig. 3). These polygons were intersected with polypoint shapefiles representing rain gages for which National Climate Data Center (NCDC) and/or U.S. Geological Survey (USGS) data are available (fig. 4). To account for inter-annual variability, daily data from the airport gage (NRDC gage 4690) were summed to monthly values for the years 1971 – 2000. Differences between actual rainfall and the mean monthly value from the PRISM dataset were used to modify rainfall throughout the study area for that month/year.

Modified mean monthly rainfall were disaggregated to a daily schedule in amounts synthetically derived from gage data (Oki, 2002; Izuka and others, 2005a) (fig. 5). Complete monthly rainfall records for stations within defined fragment zones were used as templates to enable the disaggregation to occur. The fragment zones were configured to provide a balance between diversity and relevance through the use of a sliding 4-in. isohyet “window” (table 2). Each month was dealt with individually and the pools became reservoirs from which disaggregation templates were randomly selected. Once selected the same template was used throughout budget processing for all polygons falling within the same fragment zone for that month/year.

[in/mo, inches per month; in/yr, inches per year)

Rainfall Gage			Mean montly rainfall[1] (in/mo)												Mean annual rainfall[1] (in/yr)
Name	USGS Identifier	NCDC Identifier	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Aasufou	141952170460201	4000	18	19	18	18	19	17	13	15	17	21	18	22	215
Airport ('57 - '66) Airport ('66 - '01)	 142038170430501	4869 4690	12	11	11	10	9	7	6	6	7	10	10	13	112
Atu'u		4060	19	16	15	15	16	12	11	10	11	17	16	19	177
Aua	141621170393401	4005b	17	16	15	15	15	12	11	12	12	16	17	18	176
Fagaalu Reservoir		4135	21	20	19	18	17	15	15	14	14	21	20	23	217
Fagaalu Stream		4138	20	19	18	16	18	13	12	13	11	19	18	18	195
Fagaitua	141621170370490		13	12	12	11	11	8	7	8	8	11	11	13	125
Fagatogo		4149	22	21	20	17	20	14	14	16	11	21	19	19	214
Leone		4397	16	15	16	12	13	9	9	9	9	15	14	18	155
Malaeimi	141921170441691		16	18	15	17	14	16	11	9	9	16	16	16	173
Malaeloa		4594	13	15	14	13	11	10	8	8	9	13	11	13	138
Pioa	141644170391701	4005a	16	16	15	15	15	12	11	12	12	16	17	18	175
Taputimo		4873	11	12	13	10	12	10	6	8	7	13	13	13	128
Vaipito		4902	21	15	16	21	16	13	14	11	14	17	17	17	192
Vaipito Dam	141732170422001		21	20	20	19	17	15	16	14	14	21	20	24	221
Vaipito Reservoir	141717170423390		18	18	24	21	15	13	16	12	13	15	18	23	206

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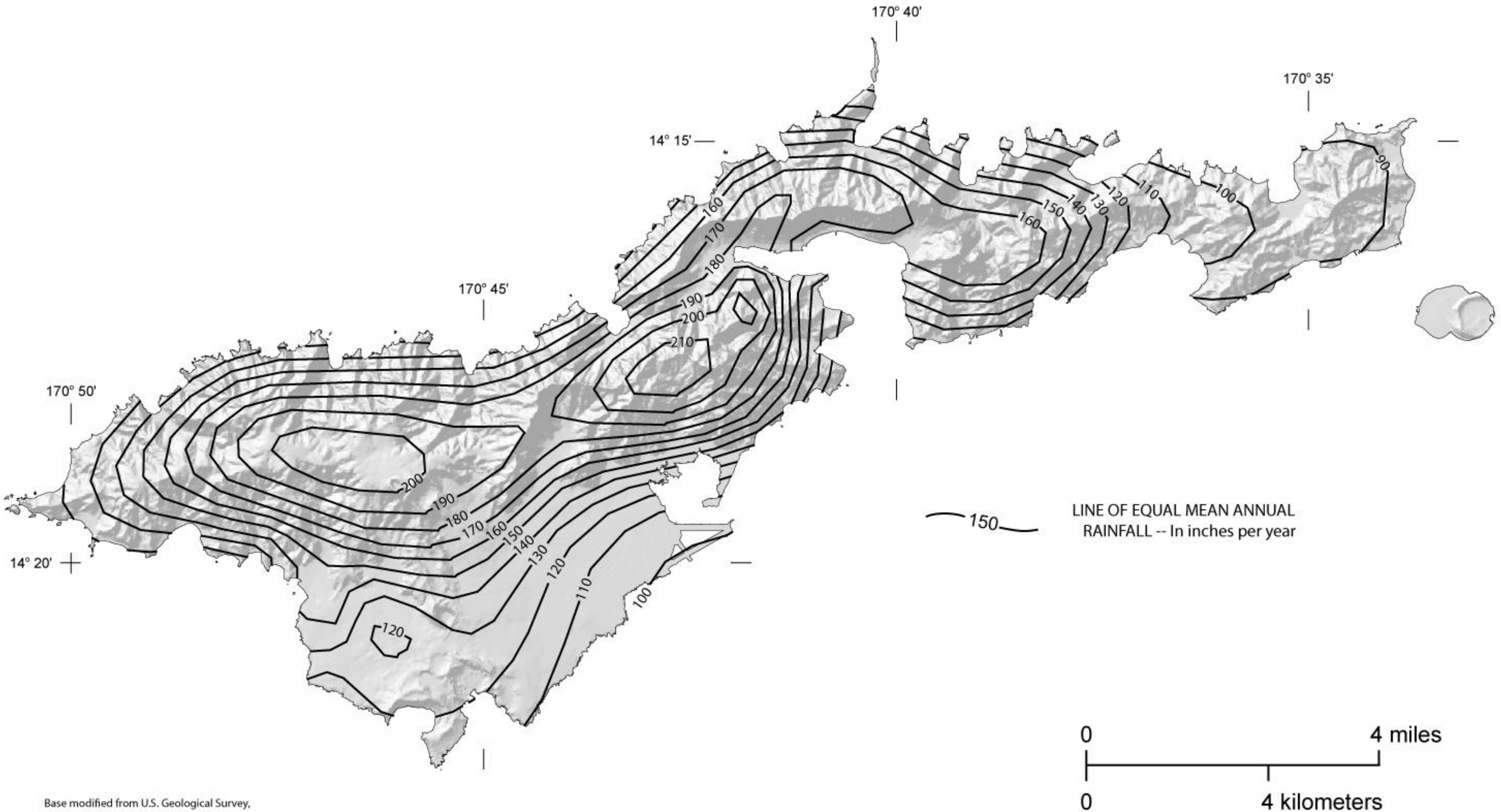
[1] All mean rainfall values are derived from PRISM data.

Table 1. Distribution of mean monthly rainfall on the island of Tutuila, American Samoa.

[in, inches]

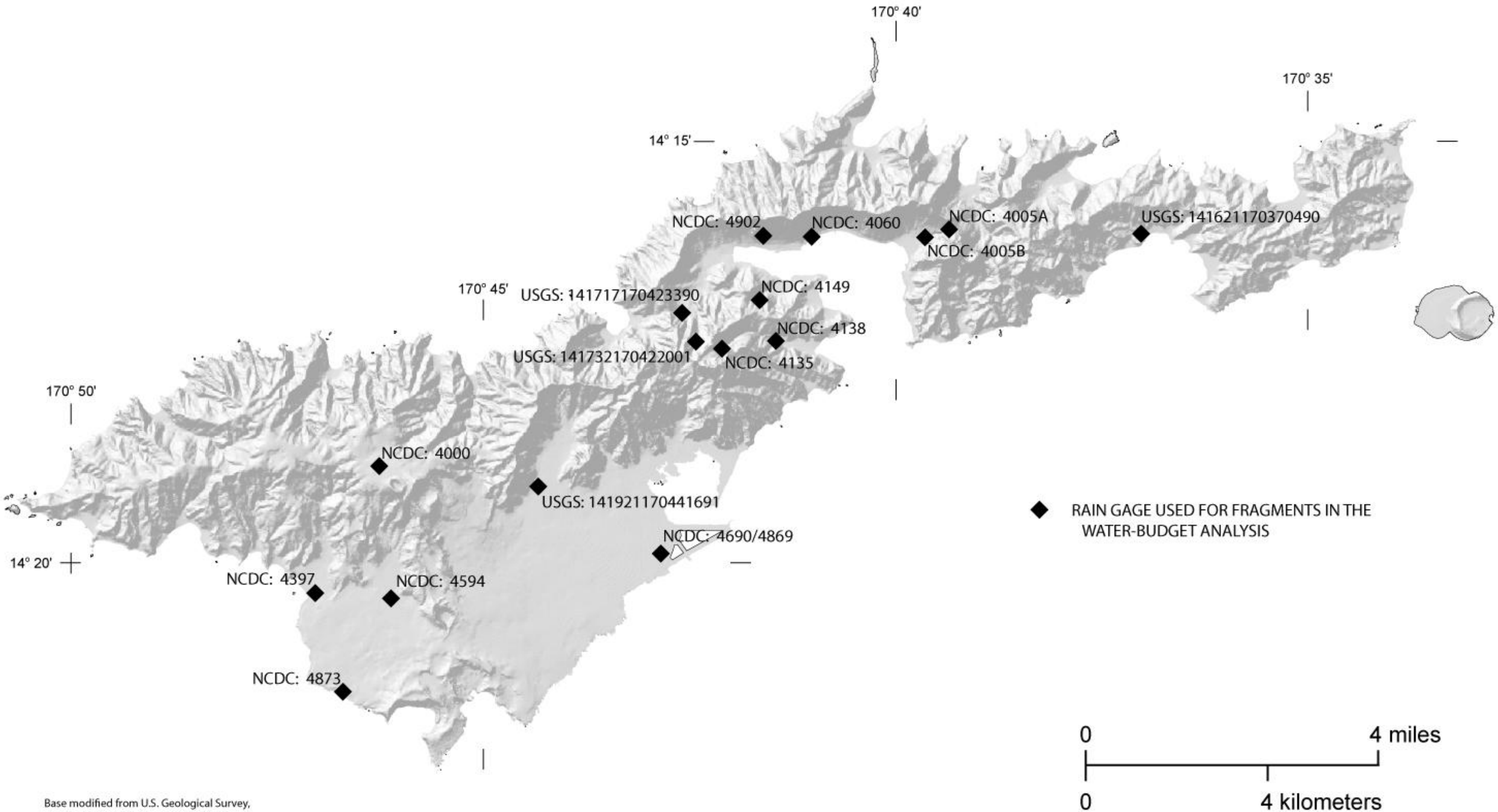
Month	Zone 1		Zone 2		Zone 3		Zone 4	
	Rainfall range (in)	Number of fragments	Rainfall range (in)	Number of fragments	Rainfall range (in)	Number of fragments	Rainfall range (in)	Number of fragments
January	9 to 13	57	13 to 17	45	17 to 21	47	21 to 25	38
February	8 to 12	53	12 to 16	27	16 to 20	83	20 to 24	34
March	8 to 12	54	12 to 16	48	16 to 20	65	20 to 24	24
April	7 to 11	58	11 to 15	14	15 to 19	88	19 to 23	31
May	7 to 11	52	11 to 15	33	15 to 19	79	19 to 23	36
June	5 to 9	54	9 to 13	38	13 to 17	64	17 to 21	27
July	4 to 8	62	8 to 12	48	12 to 16	60	16 to 20	27
August	3 to 7	53	7 to 11	27	11 to 15	83	15 to 19	39
September	5 to 9	60	9 to 13	59	13 to 17	48	17 to 21	35
October	8 to 12	55	12 to 16	23	16 to 20	50	20 to 24	70
November	7 to 11	52	11 to 15	20	15 to 19	87	19 to 23	39
December	11 to 15	61	15 to 19	53	19 to 23	34	23 to 27	36

Table 2. Grouped bands of mean monthly rainfall were used to define the boundaries of fragment zones (modified from Izuka and others, 2007).



Base modified from U.S. Geological Survey,
Tutuila East, Tutuila West, 1:24,000 scale,
Universal Transverse Mercator, zone 2, south,
World Geodetic System 1984,
Digital Line Graph and Digital Elevation Model data.

Figure 3. Mean annual rainfall for the period of record 1971 – 2000 (modified from Izuka and others, 2007).



Base modified from U.S. Geological Survey,
Tutuila East, Tutuila West, 1:24,000 scale,
Universal Transverse Mercator, zone 2, south,
World Geodetic System 1984,
Digital Line Graph and Digital Elevation Model data.

Figure 4. Gages where entire months of daily rainfall records were available from NRDC and/or USGS (modified from Izuka and others, 2007).

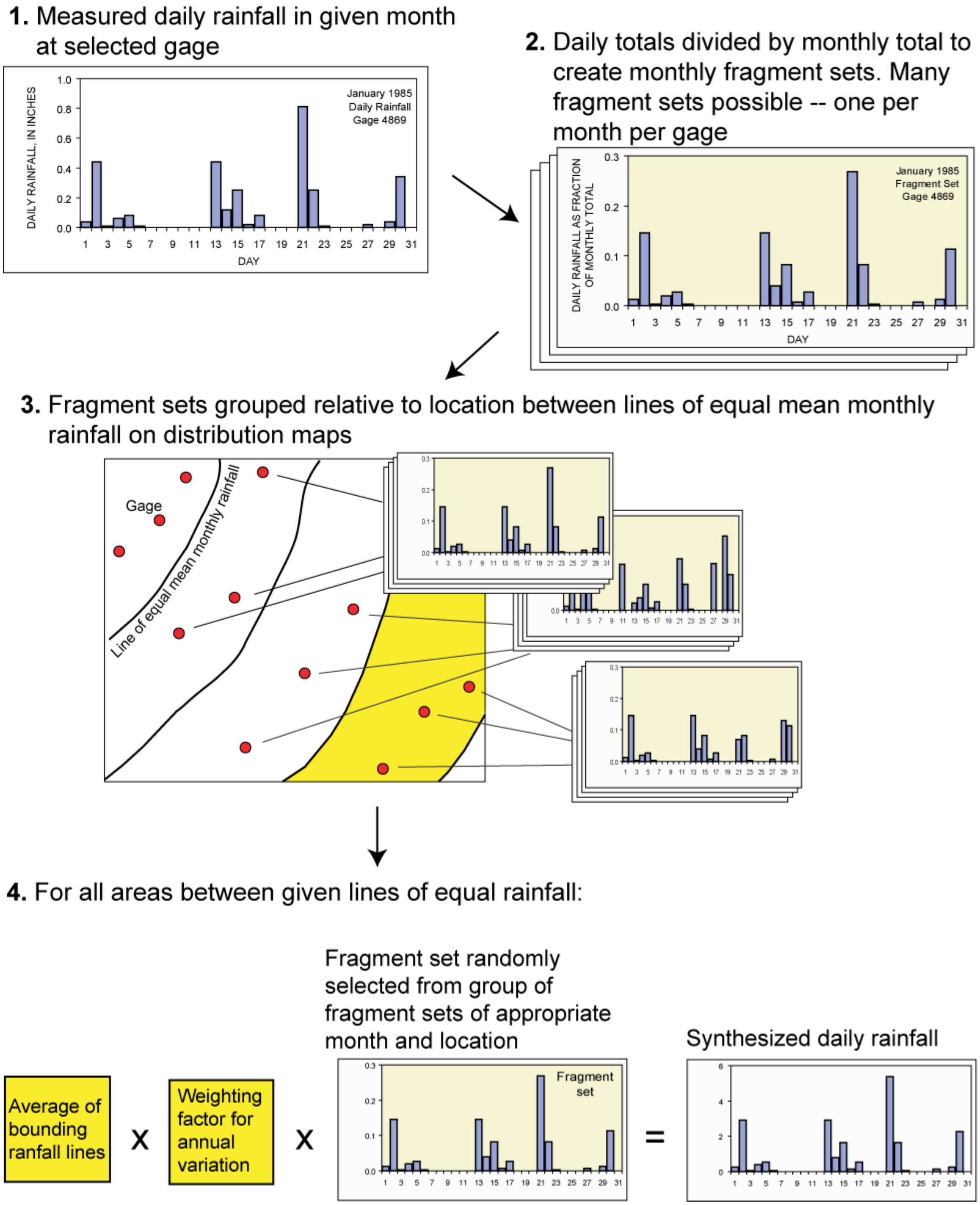


Figure 5. Mean monthly rainfall was disaggregated to a daily schedule using the method of fragments (modified from Izuka and others, 2007).

Canopy Interception in Forested Areas

Potential evapotranspiration rates are based on climate data gathered exclusively at grassy sites (Izuka and others, 2005b). They therefore represent reliable constraints on the amount of moisture than can evapotranspire from a grassy setting. However, the results of numerous studies have shown that substantial amounts of moisture can be intercepted by, and evaporated from, vegetative canopies, sometimes in amounts that are multiples of that attributed to the plant/soil system (e.g. Calder and others, 1986; Asdak and others, 1998; and McJannet and other, 2007). Since large areas of Tutuila are forested, and are areas that receive the highest rainfall, canopy interception was included in the Tutuila water budget. Median values from prior studies were used for mean canopy interception rate (CI = 18 percent), free throughfall rate (p = 25 percent) and canopy storage (S = 2 mm). Additional study values were used for sensitivity analyses (table 3).

Canopy interception rates are commonly listed as mean percentages of gross rainfall without regard for conditions such as inter-annual variability, seasonality, storm intensity or evolutionary wetting of a canopy (i.e. early in a storm when most surfaces are dry as opposed to later in a storm when much of the surface areas are partially to fully wetted). However, it's also commonly accepted that the highest rates of interception/evaporation occur when the canopy is dry, and that this rate declines as the canopy becomes more thoroughly wetted. The Tutuila water budget is designed to account for higher rates of interception early in the wetting process by allowing for interception of all gross rainfall less free throughfall up to the limit of canopy storage. After the limit of storage is reached a fixed rate of additional gross rainfall (again, less free throughfall) will continue to be lost to interception and evaporation. The amount intercepted and evaporated by the canopy is determined as follows:

$$E_{cnpy} = P_{gross} \ x \ (1 - p) \qquad (2)$$

when $[P_{gross} \ x \ (1 - p)] \leq S$, otherwise

$$E_{cnpy} = [P_{gross} \ x \ (1 - p) - S] \ x \ CI + S \qquad (3)$$

where

E_{cnpy} is evaporation from forested canopy associated with interception (L),

P_{gross} is gross rainfall (L),

p is the rate of free throughfall, or fraction of gross rainfall that bypasses the canopy (L/L),

S is canopy storage threshold (L), and

CI is the rate at which gross rainfall less free throughfall is intercepted by the canopy once canopy storage has been exceeded (L/L).

The amount of net rainfall reaching the forest floor is simply the difference between gross rainfall and losses to canopy interception:

$$P_{net} = P_{gross} - E_{cnpy} \tag{4}$$

where

P_{net} is net rainfall reaching the forest floor (L).

All values are expressed as being of equivalent depth over an equal area, and are therefore expressed as units of length (L). Rates are similarly expressed as length per length (L/L) over an equal area. Volumetric amounts (L^3) for reporting purposes are later calculated as length multiplied by polygon area.

Since canopy interception is commonly referred to as a mean percentage of gross rainfall and the Tutuila processing method allows for interception of as much as 100 percent of gross rainfall less free throughfall, it was necessary to run the budget numerous times to determine how different rates of interception would affect gross rainfall. An analysis of results indicated that once the canopy was wetted to the limit of its storage capacity, an interception rate of 15 percent of additional rainfall less free throughfall resulted in a mean annual canopy interception rate of 18 percent. Therefore the rate of canopy interception of gross rainfall less free throughfall above the threshold of canopy storage was set to 15 percent for baseline conditions.

[mm, millimeters]

Author(s), year	Canopy interception rate (% of gross rainfall)	Canopy storage (mm)	Free throughfall rate (% of gross rainfall)
Lloyd and others, 1988	9		8
Hutjes and others, 1990	9		
Shuttleworth, 1988	10		
Germer and others, 2006	11		
Asdak and others, 1998	11		
Bruijnzeel and Wiersum, 1987	13	0.8 - 1.2	36
Bruijnzeel and others, 1993	15		
Jetten, 1996	16 - 17		
Sinun and others, 1992	17		
Luvall, 1984	17		
Loescher and others, 2005	17 - 18		
Dykes, 1997[1]	18		
Waterloo and others, 1999	18 - 19		
Calder and others, 1986[2]	21	2	
Manokaran, 1979	22		
Wallace and McJannet, 2006	25	3.0 - 3.5	
McJannet and others, 2007	7, 26 - 29		
Cavelier and others, 1997	37		
Scatena, 1990	39		
Schellekens and others, 2000	39 - 48		
Schellekens and others, 1999	50	1.15	
Gash and Morton, 1978			10
Jackson, 1975[3]			25
Herwitz, 1985		2.2 - 8.3	

[1] Canopy interception rate of 18% from Dykes, 1997, used for Tutuila water budget.

[2] Canopy storage value of 2 mm from Calder and others, 1986, used for Tutuila water budget.

[3] Free throughfall rate of 25% from Jackson, 1975, used for Tutuila water budget.

Table 3. Canopy interception values for the Tutuila water budget were based on prior research of tropical forested areas. Boxed values were used for baseline processing.

Fog drip in a cloud forest setting is sometimes recognized as being an input separate from rainfall. However, it is more rigorously an aspect of canopy interception characterized by small droplet adherence or vapor condensation directly onto vegetative surfaces in excess of evaporation from those surfaces. There are areas in American Samoa identified as cloud forest, but none on the island of Tutuila (Fosberg and Mueller-Dombois, 1998). Therefore fog drip was not factored as participating in canopy interception.

Runoff-to-Rainfall Ratio

Runoff-to-rainfall ratios were calculated for all basins on the island for which stream discharge data are available for all or part of the period 1971 - 2000 (fig. 6). Runoff for the purpose of this study is defined as all streamflow in excess of baseflow, and is derived from data downloaded from the USGS National Water Information System (NWIS) database. Separation of baseflow from total flow was managed by version 4.12 of the BFI software package developed by Wahl and Wahl (1995) (fig. 7). All processing runs used the same method, “1 = STANDARD Institute of Hydrology method (N-day avg. recession test; uses "N" and "f")”, and set f = 0.9. Processing runs were made for “N” values of 1 through 9 inclusive, and the results were visually evaluated for changes in slope. A pronounced change in slope was interpreted as representative of a general transition from runoff to baseflow conditions for a particular stream, and the data generated by processing with that “N” value were used to calculate runoff (table 4).

Watershed boundaries above the gage sites were determined using the “Weasel” software package (Viger and Leavesley, 2007). Total rainfall for a watershed was determined by intersecting watershed boundaries with the PRISM mean monthly rainfall data sets. Daily discharge data at the gage sites were summed to monthly values and compared to integrated rainfall values, resulting in watershed-unique mean monthly runoff-to-rainfall ratios (table 4).

When comparing data types having high temporal variability but also high correlation, such as runoff and rainfall for a common area, it’s critical that the data be based on the

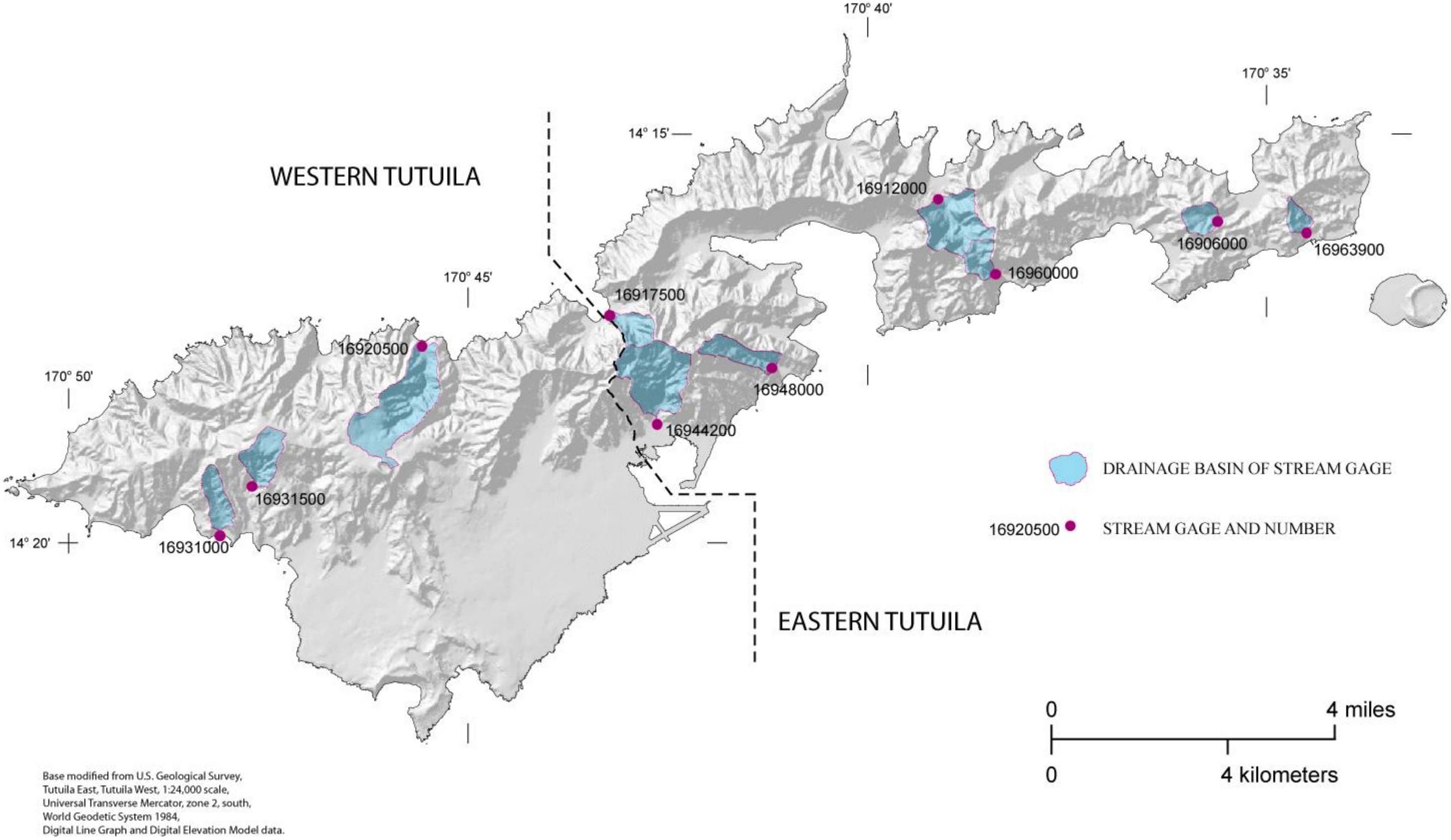


Figure 6. Stream discharge data from gaged watersheds were used to determine runoff-to-rainfall ratios (modified from Izuka and others, 2007).

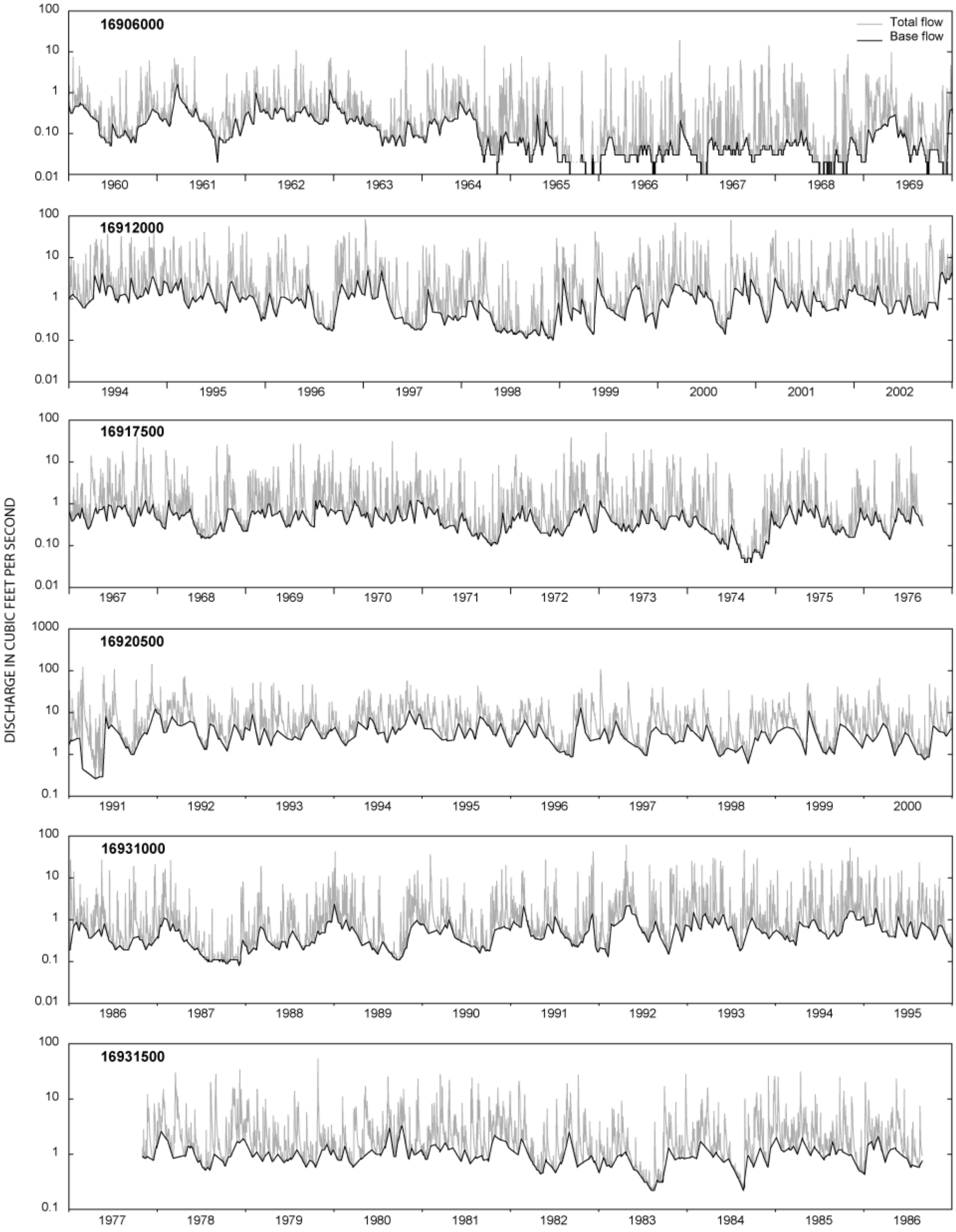


Figure 7. Examples of hydrograph separation of baseflow from total stream flow. Total flow less baseflow was considered runoff for the Tutuila water budget, and was compared to mean monthly rainfall to generate runoff-to-rainfall ratios (modified from Izuka and others, 2007).

[RO, runoff; RF, rainfall]

Stream data				Month											
Stream Name	**Identifier[1]**	**Index Station/ r^2 value**	**BFI "N" value**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Western															
Aasu	9205	N/A	5	0.2665	0.2588	0.2565	0.2146	0.2517	0.1696	0.2178	0.2855	0.2343	0.2758	0.2272	0.2799
Atauloma	9310	N/A	4	0.4182	0.3901	0.3354	0.3751	0.3940	0.2660	0.2949	0.3954	0.3084	0.4237	0.3187	0.4648
Asili	9315	9205 - 0.9486	5	0.3142	0.2206	0.5773	0.2568	0.2248	0.1243	0.1938	0.4751	0.2332	0.4453	0.4100	0.2729
Average				0.3330	0.2898	0.3897	0.2822	0.2902	0.1866	0.2355	0.3853	0.2586	0.3816	0.3186	0.3392
Eastern															
Vaitolu	9060	9480 - 0.7438	3	0.1213	0.2149	0.1735	0.1722	0.0928	0.2331	0.1475	0.1528	0.1409	0.1773	0.1065	0.2848
Pago	9120	N/A	3	0.3711	0.3491	0.3663	0.2994	0.2977	0.1981	0.2440	0.2505	0.2346	0.3562	0.2581	0.3639
Leele	9175	9480 - 0.6754	3	0.2761	0.2567	0.1018	0.2948	0.2446	0.2704	0.3954	0.3889	0.3550	0.4455	0.2507	0.2836
Papa	9442	9480 - 0.8100	4	0.3553	0.1660	0.1083	0.3583	0.3304	0.2420	0.3109	0.2811	0.2419	0.1655	0.1623	0.2724
Afuelo	9480	N/A	4	0.3378	0.3177	0.2713	0.2883	0.2937	0.2193	0.2348	0.2927	0.3019	0.3140	0.2661	0.3548
Alega	9600	9480 - 0.8054	4	0.2281	0.2572	0.1752	0.2384	0.1667	0.2397	0.2013	0.1878	0.1674	0.1867	0.1303	0.3011
Leafu	9639	9480 - 0.9339	3	0.3004	0.1785	0.2859	0.2536	0.5274	0.1031	0.1717	0.1984	0.2477	0.2507	0.3771	0.3819
Average				0.2843	0.2486	0.2118	0.2721	0.2790	0.2151	0.2437	0.2503	0.2413	0.2708	0.2216	0.3204

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[1] USGS identifers for Tutuila Stream gages are of the format 16xxxx00 where only xxxx is listed for brevity.

Table 4. Runoff-to-rainfall ratios (RO:RF) were based on runoff data from selected watersheds and rainfall data from PRISM (modified from Izuka and others, 2007).

same period of record. The 1971 – 2000 PRISM data set was used for the budget and therefore stream discharge data for the same period needed to be selected for processing. Complete records are available for 4 of the 10 watershed gaged basins (9120, 9205, 9310 and 9480), but only partial records are available for the other 6 (9060, 9175, 9315, 9442, 9600 and 9639). Record extension was used for the partial record sites by comparing their respective daily records to the corresponding data at each of the 4 full record sites. From this comparison it's possible to assess correlation, and to develop regression equations to lengthen the records at the partial sites. The 4 complete record sites are referred to as index sites, and the regression equations from the index site with the highest correlation to the partial record site was used to extend that site's record on a monthly basis. The same pairing of index station and partial record station was used for all months. Using this method made it possible to develop runoff-to-rainfall ratios for each of the 10 watershed basins for the entire 1971 – 2000 period of record. Perhaps not surprisingly, the best correlations for western sites was with other western sites, and similarly for the eastern sites. Additionally, one of the two potential index sites in both areas had the highest correlation with the other sites and was therefore used for all record extension. The western site is 16920500: Aasu, and the eastern site is 16948000: Afuelo.

A review of the results highlighted three important issues: 1) the total area of the 10 watersheds represents a small fraction of the island, 2) none of the 10 watersheds contribute to streams that flow through the key parts of the study area, the Tafuna and Leone Plains, and 3) there's high variability among watershed rates in general, and among rates for different months within the same watershed. Since some form of extrapolation was necessary to deal with areas for which no direct data are available, the island was patitioned into eastern and western regions, and an average of all the basin ratios within the region was used for baseline processing.

There's an inherent weakness in using a static ratio that's similar to the situation described earlier with regard to capturing 100 percent of gross rainfall less free throughfall without consideration of the wetting stage of the canopy. Both situations are likely simplifications of what's actually occurring. In the case of canopy interception it's likely that a smaller fraction of gross rainfall is being captured as the limit of canopy storage is approached and surpassed rather than a sharp interface that shifts interception from 100 percent to 15 percent. With regard to use of a single runoff ratio without consideration for rainfall intensity, the problem occurs because low intensity events are likely to produce little if any runoff, and therefore most if not all rainfall reaching the ground will add to soil moisture rather than being lost as runoff (or at least be stored in the layer of detritus and leaf litter overlying the soil). These types of problems are generally due to coarse resolution datasets. Our understanding of how these settings respond to events of varying intensity will evolve as finer resolution datasets become available.

Mountain Front Recharge

In 2005 I led a USGS team doing field work in support of the study by Izuka and others (2007) when a high-intensity (multi-inch/hour) rainfall event forced us to get our equipment under cover. The stoppage occurred in the village of Pavaiai which lies at the interface between the high-relief slopes of Olotele Mt. and the Tafuna Plain. Hortonian overland flow was prevalent in the area, halting traffic and carrying rocks and debris downslope. As soon as the rainfall stopped and we resumed work I was stunned to see that not only was there no standing water on any non-hardened surface, but also no surface runoff downgradient of the interface.

Later observations in other parts of the study area during a 3-week period showed conditions that were strikingly similar. A high-intensity storm near the Malaeimi Valley (to the east of Pavaiai) generated substantial overland flow, but just over 100 m downgradient of the interface this flow had completely infiltrated. A much higher-intensity, longer-duration event occurred to the southeast of Pavaiai at the base of the small spur ridge that separates the Tafuna and Leone Plains. This event was even more compelling in that it had caused widespread flooding on the Leone Plain. However, as soon we crested the short ridge and descended onto the Tafuna Plain we were stunned to see no sign of surface water. These events suggested that the conceptual model for mountain front recharge had relevant application with regard to the Tafuna Plain, but likely not its counterpart, the Leone Plain.

According to the Natural Resources Conservation Service (NRCS), the interface areas between the central mountain range and the Tafuna Plain are comprised of soils that are less consolidated than those upslope (Nakamura, 1984). There are numerous steep ravines on the upslope areas that terminate at the interface, and diminishing channelization beyond the interface. The NRCS soil coverage included a unit that hugged the base of the mountains: Map Unit 23 – Pavaiai stony clay loam, 6 – 12 percent slopes. It is described as a "moderately deep, well drained" soil where "permeability … is moderately" high. Existing within this soil unit's boundaries are the areas in Pavaiai and Malaeimi Valley where my team observed two of the rapid infiltration events. In consideration of these factors, this soil unit's boundaries were recognized as the area where upgradient runoff would be re-introduced as additional input in the form of MFR. A second capture/infiltration system, substantially smaller in area, was recognized on the ridge separating the plains where a cinder quarry was located, and from which no runoff is known to occur.

The task of delineating runoff source areas is similar to identifying a watershed boundary based on topography. The eastern boundary of the primary capture zone is defined along the same topographic profile used to bisect the island into regional runoff-to-rainfall basins. The topographic high of the crest is the northern boundary, while the topographic crest of the ridge separating the Tafuna and Leone Plains becomes as the western boundary. The southern boundary, defined as the upgradient edge of the infiltration corridor, completes the delineation of the primary capture zone, an area of about 3.4 sq. mi. As previously stated, the boundaries of Map Unit 23 describe the infiltration corridor for this capture zone comprising an area of about 0.8 sq. mi. A similar process is undertaken for the relatively minor secondary system near the cinder quarry and produces a capture zone and infiltration corridor of about 0.1 sq. mi. apiece (fig. 8).

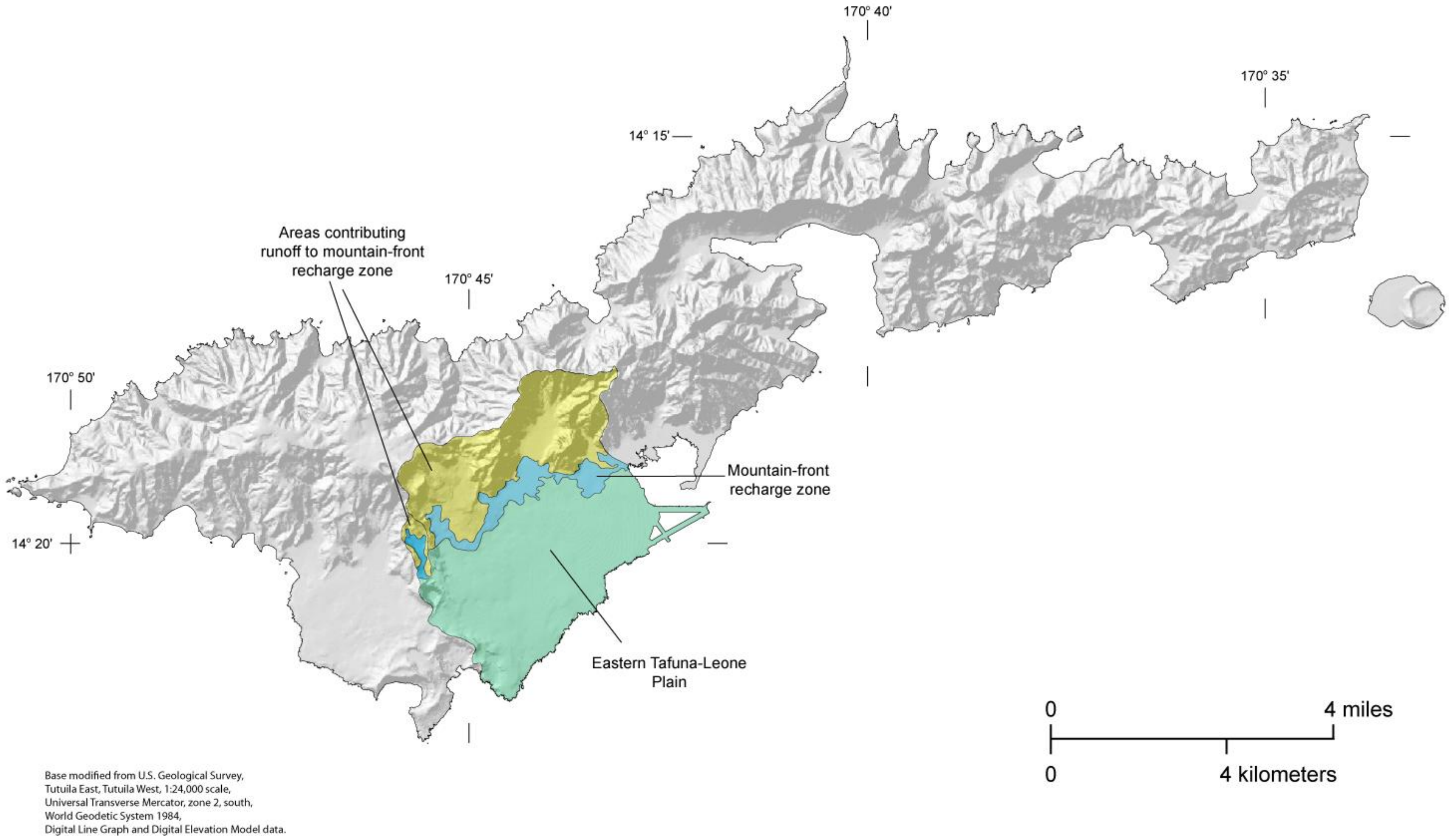


Figure 8. A fractional amount of runoff from mountainous areas overlying the Tafuna Plain was re-introduced as mountain front recharge at the mountain/plain interface. The runoff-to-rainfall ratio was substantially reduced for the Tafuna Plain (modified from Izuka and others, 2007).

Since the method of budget processing is spatially based, no allocations and/or accumulations of overland flow are tracked polygon to polygon, but are instead summed en masse for disposition at the end of processing. At that point the summed volumes of overland flow are added to the recharge accumulations for the polygons within the infiltration corridors on a time- and area-weighted basis. All soil moisture processing steps are bypassed, the rationale for which will be discussed in the Results and Discussion section.

Runoff from the Tafuna Plain

Runoff from the Tafuna Plain was not observed during the 3-week period of field work despite the high-intensity rainfall events described earlier. Further, the NRCS description of the primary soil unit for the plain, Map Unit 32 – Tafuna extremely stony muck, 3 to 15 percent slopes, is described with compelling characteristics with regard to runoff: "permeability … is very" high, "available water capacity is very low, runoff is very slow, and the hazard of water erosion is slight." Further, all the gaged sites used to determine runoff-to-rainfall ratios are located either at the mountain/coastal strand interface or within the steep gradient watersheds themselves (as sub-units of a larger watershed). Considering these data points it's likely that runoff from precipitation falling directly on the Tafuna Plain is occurring at a very low rate, and only during the highest-intensity events.

To better reflect what is more likely occurring with regard to runoff, the ratio used for the western half of the island (where the Tafuna Plain is located) is reduced for both baseline processing and sensitivity analyses. The baseline runoff ratio for the Tafuna Plain is reduced to 25 percent of the baseline western ratio, and is reduced to 50 percent and 0 percent for sensitivity analysis. For example, the baseline runoff-to-rainfall ratio for the western half of the island for the month of January is 33.3 percent. For the Tafuna Plain for the month of January the ratio is reduced to 25 percent of that amount, or 8.3 percent of gross rainfall. For sensitivity analysis the amount is reduced to 50 percent and 0 percent of baseline, or to 16.6 percent and 0.0 percent of gross rainfall respectively.

Soil Moisture Processing

Soil moisture processing is based on the premise that budget inputs (rainfall less canopy interception and runoff for the Tutuila budget) infiltrate into the plant/soil zone where they add to antecedent moisture. Some moisture is lost back to the atmosphere as evapotranspiration, while the remainder is retained to the extent of storage capacity. Moisture beyond this capacity percolates downward through the vadose zone until a phreatic zone is encountered, and recharge occurs

Potential evapotranspiration for the island of Tutuila was determined by Izuka and others (2005b) with the results published as mean monthly and mean annual maps (fig. 9). Given that the water budget is processed on a daily time step, the mean monthly map values are divided by the number of days in the month to estimate daily values.

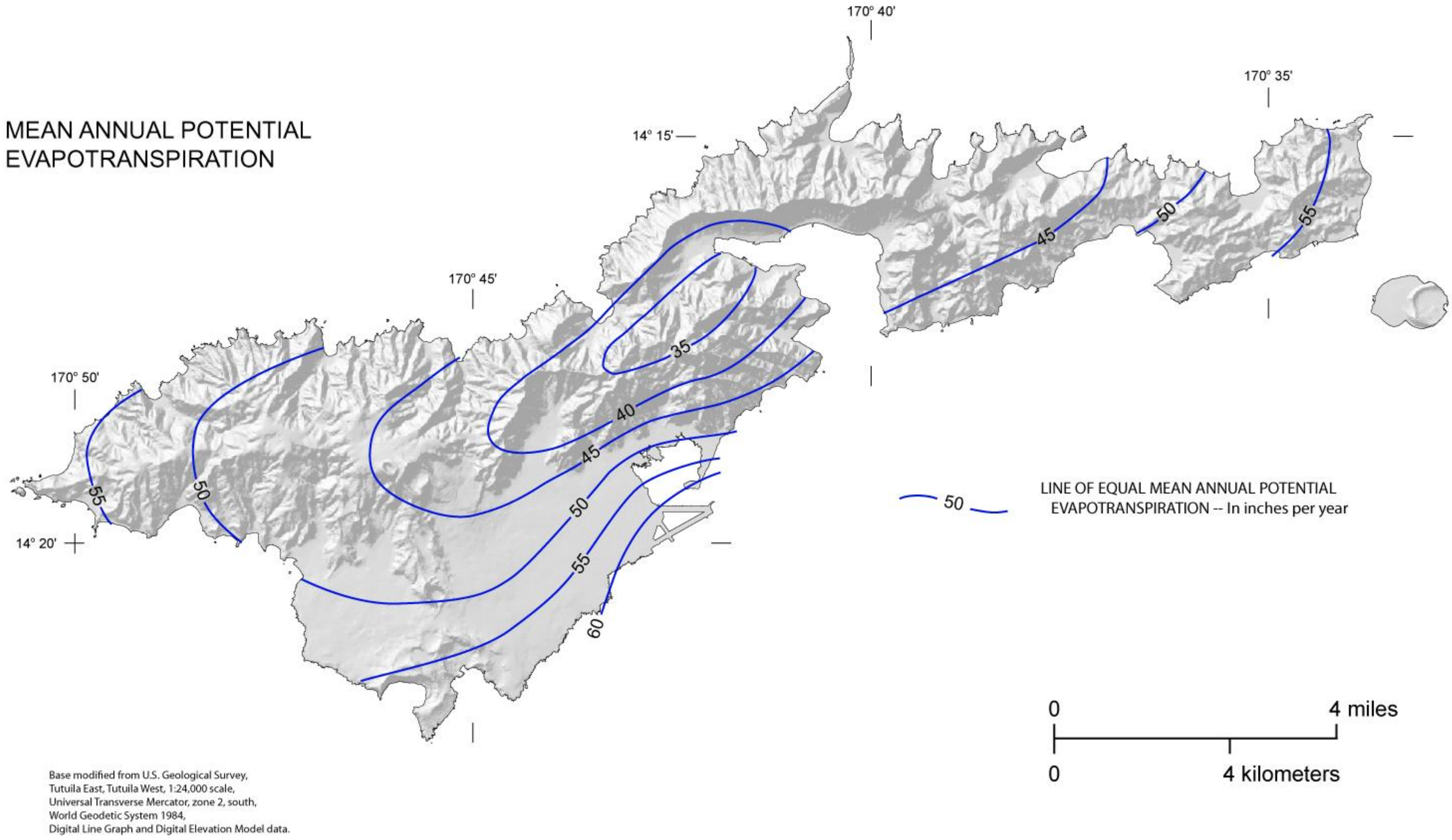
To determine maximum soil moisture available for actual evapotranspiration (SM_{max}), data were compiled from the NRCS (Foote and others, 1972; Nakamura, 1984; SoilDataMart, 2007) and the U.S. Forest Service (Cole and others, 1988; Donnegan and others, 2004). The NRCS data provided expected root depths by vegetation type in a tropical setting (table 5), a map of soil locations, and tabular data of layer thicknesses,

[in, inches; classification scheme based on Fosberg and Mueller-Dombois, 1998[1])

Vegetation type	Root depth (in)
Rain Forest	36
Modified Forest	36
Shrub and Grass	12
Developed Land	12
Sand Beach and Bare Rocks	6
Cleared Land	6
Mangrove	6

[1] Footnote: full reference is Fosberg, F.R. and Mueller-Dombois, D., 1998, Vegetation of the Tropical Pacific Islands, Ecological Studies V. 132, Springer Publications, 733 p.

Table 5. Vegetation types and root depths used for soil-moisture processing.



Base modified from U.S. Geological Survey,
Tutuila East, Tutuila West, 1:24,000 scale,
Universal Transverse Mercator, zone 2, south,
World Geodetic System 1984,
Digital Line Graph and Digital Elevation Model data.

Figure 9. Maps of potential evapotranspiration rates for the island of Tutuila, American Samoa, published as part of a prior study, were used to set maximum upper limits of actual evapotranspiration for the plant/soil system (from Izuka and others, 2005b).

composition, and available water capacity. The Forest Service data provided a spatial land use/land cover map, and tabular data of vegetation type to supplement the map. From these data, layers of equal depth and unique available water capacity are constructed for each polygon, with the number of layers based on the NRCS soil unit description.

The process of calculating soil moisture can be represented as a mass-balance equation taking into consideration the components previously discussed:

$$SM_i = SM_{i-1} + P_{net} - E_i , \tag{5}$$

where

i is a subscript designating current day, and therefore

SM_i is the soil moisture for the current day (L),

SM_{i-1} is antecedent soil moisture (L),

P_{net} is net rainfall falling onto the soil surface (L), and

E_i is actual evapotranspiration from the plant/soil system (L).

The process of determining actual evapotranspiration from the plant/soil system remained functionally unmodified from the precursor FORTRAN program developed for a Kauai water budget, and is fully described in Appendix A of Izuka and others (2005b). The process is based on a method described in Allen and others (1998) which involves a threshold soil moisture value above which evapotranspiration occurs at the potential rate, but below which evapotranspiration occurs at a rate that declines linearly with soil moisture. The threshold soil moisture calculation uses a depletion fraction that ranges from 0 to 1, and is defined as the fraction of soil moisture that can be removed from the soil before stress occurs and evapotranspiration is reduced. Depletion factors are provided in table 22 of Allen and others, with values for a number of tropical fuits and trees listed as ranging from 0.30 to 0.65. Since the majority of Tutuila is covered by a diversity of tropical plants, a median value of 0.50 is used for all types of vegetation.

After a daily cycle of soil moisture processing is completed, an end-of-day threshold test is performed to determine if calculated soil moisture is in excess of the maximum storage limit (as determined by the NRCS data). If calculated soil moisture is less than the storage limit then no further processing is performed. However, if soil moisture is in excess of the storage limit then the excess amount is allocated as recharge, and the end of day value (SM_{eod}) is set equal to the storage limit:

$$RC_i = SM_i - SM_{max}, \text{ and} \tag{6}$$

$$SM_{eod} = SM_{max} \tag{7}$$

where

RC_i is recharge (L),

SM_{max} is the soil moisture storage limit (L), and

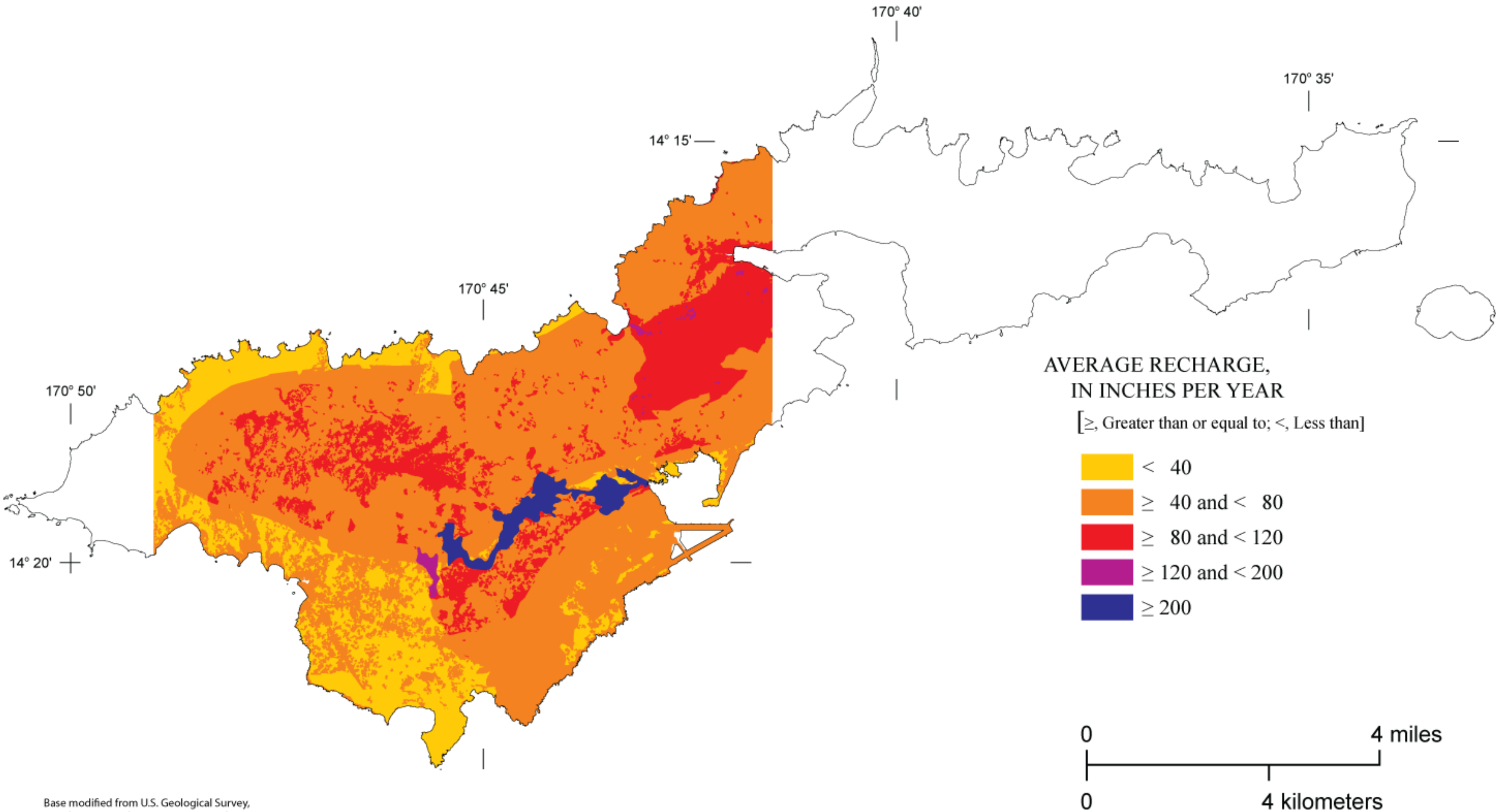
SM_{eod} is the end of day soil moisture (L).

The final step of daily processing is to set antecedent soil moisture (SM_{i-1}) equal to the end-of-day soil moisture value (SM_{eod}) in preparation for the next daily cycle:

$$SM_{i-1} = SM_{eod} \tag{8}$$

Results and Discussion

Budget results for the west-central area of Tutuila are based on mean daily input from direct rainfall for the 1971 – 2000 period of 280 Mgal/d. Of this amount, 38 Mgal/d is lost as forest canopy interception, a mean annual rate of 18 percent for these areas that receive 209 Mgal/d of rainfall. Direct runoff is estimated as 73 Mgal/d, of which 8 Mgal/d is captured and re-introduced as MFR. Soil moisture processing results in a loss of 71 Mgal/d to evapotranspiration from the plant/soil system, leaving the remaining amount, 98 Mgal/d, estimated as in-situ recharge. With the addition of the 8 Mgal/d contribution from MFR, total recharge is estimated to be 106 Mgal/d, or about 38 percent of input over the model area (fig. 10).



Base modified from U.S. Geological Survey,
Tutuila East, Tutuila West, 1:24,000 scale,
Universal Transverse Mercator, zone 2, south,
World Geodetic System 1984,
Digital Line Graph and Digital Elevation Model data.

Figure 10. Estimates of recharge for the west-central area of Tutuila, American Samoa were highest where MFR augmented normal inputs. Many of the water-supply wells are located downgradient on the Tafuna Plain downgradient of the mountain/plain interface.

The hypothesis for the Tafuna Plain is that a very small amount of runoff from the mountains is lost to the ocean as streamflow. However, incised channels do exist suggesting that rainfall events of sufficient intensity to produce runoff do occur. To reflect this hypothesis, baseline parameters are set to capture 75 percent of runoff above the Tafuna Plain for later reintroduction as MFR, and to use a runoff-to-rainfall ratio for the Tafuna Plain that is only 25 percent of the western region ratio. Runoff reaching the ocean via an incised channel crossing the plain would represent an integration of both the capture rate and the reduced rate of runoff for the Tafuna Plain. Since observations of very high-intensity rainfall events produced no runoff to the ocean it’s likely that both these arbitrarily selected values are overestimating runoff and therefore underestimating recharge, including MFR.

Sensitivity Analysis

Sensitivity analyses estimate the effects of changes to baseline parameter values (table 6). Since the primary budget input for Tutuila is rainfall, changes to this parameter have substantial effect on recharge. Changes to rainfall of plus or minus 15 percent (a value based on mean annual variability for the period 1971 – 2000 as measured at the airport rain gage) generated changes to estimates of recharge of 26 and -25 percent respectively.

Changes to runoff are expected to have substantial effect on estimates of recharge considering the direct relationship between rainfall and runoff. There were different sensitivity scenarios tested with regard to runoff, but the greatest effect was generated by using the minimum or maximum monthly basin ratio within a regional group as the regional value for that month’s processing. The results of these scenarios are changes to estimates of recharge of 12 and -14 percent respectively.

Changes to baseline values associated with canopy interception generated changes to estimates of recharge that are similar to, but slightly less than, those associated with runoff-to-rainfall ratios. Changes to the mean annual interception rate of plus or minus 5

(Mgal/d, million gallons per day; RF, rainfall; RO, runoff; AET, actual evapotranspiration; MFR, mountain front recharge; RCH, recharge)

Parameter	Baseline	Test	Water budget component (Mgal/d)					Percent difference in recharge
			RF	RO	AET	MFR	RCH	
Baseline results	-- --	-- --	279.8	65.6	108.6	7.5	105.5	-- --
Rainfall[1]	via PRISM	1.15 x baseline	321.8	75.5	113.5	8.6	132.8	26%
		0.85 x baseline	237.9	55.7	103.1	6.4	79.0	-25%
Runoff-to-rainfall ratio[2]	as calculated	minimum regional value	279.8	52.8	109.4	5.6	117.7	12%
		maximum regional value	279.8	81.8	107.1	9.8	90.9	-14%
Canopy interception rate	18% of annual rainfall	13% of annual rainfall	279.8	65.6	98.6	7.5	115.6	10%
		23% of annual rainfall	279.8	65.6	118.6	7.5	95.6	-9%
Canopy storage limit	2 mm	0.50 x baseline	279.8	65.6	100.7	7.5	113.5	8%
		1.50 x baseline	279.8	65.6	112.3	7.5	101.9	-3%
Free throughfall rate	25% of gross rainfall	36% of gross rainfall	279.8	65.6	105.2	7.5	109.0	3%
		8% of gross rainfall	279.8	65.6	113.8	7.5	100.4	-5%
Mountain front recharge - runoff retention rate	75%	100%	279.8	63.1	108.6	10.0	108.0	2%
		50%	279.8	68.1	108.6	5.0	103.0	-2%
Tafuna Plain - baseline runoff reduced to	25%	0%	279.8	62.3	107.0	7.5	110.4	5%
		50%	279.8	68.9	106.6	7.5	104.2	-1%
Available water content	via NRCS	0.50 x baseline	279.8	65.6	103.5	7.5	110.7	5%
		1.50 x baseline	279.8	65.6	110.6	7.5	103.5	-2%
Root depth	via USDA/FS	0.50 x baseline	279.8	65.6	106.0	7.5	108.2	3%
		1.50 x baseline	279.8	65.6	109.2	7.5	105.0	0%

[1] Annual rainfall varied by an average of plus or minus 15% per year over the 30 yr. period reflected by the water budget (1971 - 2000).

[2] Runoff-to-rainfall ratios were calculated for individual basins which were then regionally grouped. An average of the individual basin ratios within the region was used for baseline processing. Sensitivity analyses were based on the basin value that represented the minimum or maximum monthly value within the regional group.

Table 6. Water budget results for baseline and sensitivity scenarios for the west-central area of Tutuila, American Samoa.

percent (substantially less than the range of values reported in prior research) generated changes to estimates of recharge of 10 and -9 percent respectively. Changes to canopy storage and free throughfall rate using the minimum and maximum values reported from prior research generate changes to estimates of recharge that are all less than 10 percent of baseline, and often less than 5 percent.

All other sensitivity scenarios generated changes to estimates of recharge of 5 percent or less despite magnitudes of change to the baseline parameters greater than the 15 percent change to rainfall. For example, the baseline value for the capture of runoff on the slopes above the Tafuna Plain was set to 75 percent (meaning that only 25 percent of the runoff for this area is ultimately lost to the ocean). It's not likely that 100 percent of the runoff is captured for later infiltration, nor is it likely that as much as 50 percent is actually lost as direct runoff to the ocean; however, for the purposes of sensitivity analysis, the parameters were set to these values. Even at these values changes to estimates of recharge are only about 2 Mgal/d, or about 2 percent of the baseline result. Similarly, the baseline parameter for direct runoff from the Tafuna Plain (25 percent of the western value) was set to complete reduction (no runoff) and a 50 percent reduction for the purposes of sensitivity analysis. These values had slightly greater effect than changes to MFR capture rates, but still generated changes to estimates of recharge no greater than 5 percent.

An interesting aspect of the results of changes to rainfall is the muted response of evapotranspiration (plus or minus 5 percent for the same sensitivity scenarios) (fig. 11). Implicit in this is that shortages in rainfall (droughts) may, in general, have substantial negative affect on recharge in environmental settings where actual evapotranspiration (AE) is almost equal to potential evapotranspiration (PE). On Tutuila, AE from the plant/soil system is estimated to be about 92 percent of PE for the baseline scenario. Where AE is substantially less than PE, and assuming an episodic distribution of rainfall, a decrease in rainfall will result in a greater deficit of AE to PE, but may have a lesser negative affect on recharge relative to areas where AE is almost equal to PE.

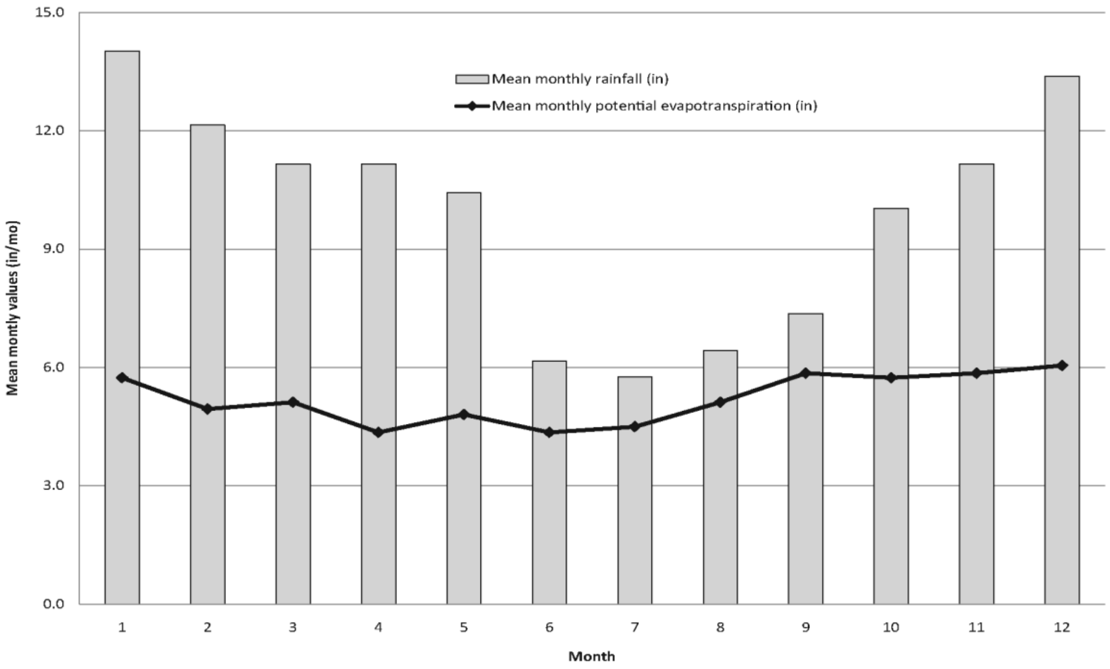


Figure 11. Comparison of mean monthly rainfall to mean monthly potential evapotranspiration at the airport may provide insights into why reductions to rainfall yielded muted responses in estimates of actual evapotranspiration from the plant/soil system on Tutuila, American Samoa.

As mentioned previously, MFR infiltration bypasses plant/soil processing. This method results in some over-estimate of recharge because some amount of MFR will likely be lost as AE. However, as described above, additional surface inputs on Tutuila result in very small estimates of additional AE. Use of baseline rainfall (280 Mgal/d) generates an estimate of 71 Mgal/d of AE lost from the plant/soil system. Increasing rainfall by 15 percent (to 322 Mgal/d, or an additional 42 Mgal/d) generates an estimate of 72 Mgal/d of AE, a 1 Mgal/d increase, almost exactly equal to the estimated increase in MFR. This is partly a result of more gross rainfall being intercepted by the canopy and being lost to runoff, but is also a reflection of the high effective rates of AE to PE on Tutuila. When rainfall is set equal to 115 percent of baseline, AE is estimated to be about 94 percent of PE compared to about 92 percent at baseline rainfall. The potential for substantial additional AE to occur from the plant/soil system is not plausible. Additionally, the conditions that generate MFR are at the wetter end of the rainfall continuum (analogous to the increased rainfall scenario). Soil moisture is therefore already high, likely exceeding available water capacity (field capacity) and putting the system into a recharging mode. Accounting for MFR input before reducing soil moisture for AE therefore has little practical advantage.

In summary, the results of the sensitivity analyses are, with few exceptions, intuitive. Given the ranges tested, changes to rainfall generate the largest changes to estimates of recharge. Changes to canopy interception and runoff ratios generate substantial changes to estimates of recharge, less than changes to rainfall but greater than changes to any of the other parameters. An interesting result of the sensitivity analyses is that changes to rainfall result in very small changes to estimates of AE (available soil moisture is often well in excess of PE) but much larger changes to estimates of recharge. This finding suggests that environmental settings like those modeled on Tutuila may experience greater deficits of recharge on a percentage basis during periods of drought than settings where AE is substantially less than PE under normal climatic conditions.

Future Research

Since the Tafuna Plain is the most important water supply area on the island of Tutuila, understanding the hydrologic dynamics of this area is crucial to maintaining a stable water supply. One aspect of this involves the interaction of surface runoff and groundwater recharge. There have been numerous stream gage sites on the island of Tutuila, but none on the Tafuna Plain. This is unusual since the slopes above the Plain receive the highest mean annual rainfall on the island at rates in excess of 200 in/yr. Such conditions often generate substantial runoff and become source areas for perennial streams. Additionally, gages often serve as flood warning mechanisms in locales where such hazards are considered a probable risk, something that would be appropriate for the relatively heavily populated Tafuna Plain. Further evidence that something interesting is occurring may be inferred from the numerous streams on the southeastern slopes of Olotele Mt. which transition from perennial to ephemeral near the boundary of NRCS soil units 23 and 32. The USGS-managed stream gage network on Tutuila was, unfortunately, idled in 2008 due to lack of funding. One or more continuous-record discharge sites, or even crest-gage sites, would provide significant clarification to the role of runoff and MFR in this critical geographic area.

The PRISM rainfall dataset is based on an extrapolation of point-source rain gage data. Precipitation in mountainous areas of the tropics is highly heterogeneous, and unadjusted, point-source data is often a moderately inaccurate reflection of areal distribution (Sevruk, 1982). Inaccuracies in areal assessments of rainfall may have been partially responsible for the highly variable results of the runoff–to-rainfall ratio processing, and may represent a significant uncertainty in the budget processing results. Installation of a well-calibrated WSR-88D radar station (Weather Surveillance Radar – 88 Doppler, commonly referred to as NEXRAD) would likely enhance understanding of the spatial and temporal distribution of rainfall on the island.

The budget results estimate that MFR contributes about 8 percent of total recharge for the study area. However, the distribution (directly upgradient of water-supply well fields on the Tafuna Plain) and localized intensity (estimated to contribute as much as 50 percent of localized recharge) of MFR may make it a critical component of the domestic water supply. Additionally, current and future wells are being located in the area where MFR is estimated to be infiltrating. Better understanding of the effects of this potentially key contributor to recharge could result in enhancements to water-supply management practices (e.g. dynamic load balancing of pumpage during periods of high-intensity rainfall).

Deployment of CTD probes (Conductivity, Temperature, and Depth) in one or more locations, perhaps in abandoned production wells, could provide valuable insights into aquifer development during high-intensity rainfall events. Given the high rates of horizontal hydraulic conductivity and proximity to the shore it’s possible that pulses of freshwater from the high-intensity rainfall events could be hard to discern from groundwater levels. CTD probes may be capable detecting these pulses, and thereby enhance our understanding of the local and regional effects of MFR.

Summary and Conclusions

Water budgets are commonly developed to estimate components of the hydrologic cycle that are difficult to directly measure such as recharge. A study designed to estimate the flow of water through surface areas and into developed aquifers on the island of Tutuila, American Samoa generated a need to understand more about recharge processes. In response, a threshold-style water budget has been developed to estimate the spatial distribution of recharge in the west-central area of the island. The results of the water budget estimate that the distribution of recharge is highly correlated with rainfall, but areas of significant divergence are estimated to occur at the upgradient edge of the Tafuna Plain. Results indicate that the rainfall correlation still exists, but is being overlain by a more powerful contributor: mountain front recharge.

MFR is a critical element of water budgets developed in continental montane and desert locales, but has not been considered in tropical island settings. Evidence of such recharge was observed on the Tafuna (but not the Leone) Plain as rain falling on upgradient slopes at rates in excess of local infiltration capacity developed into Hortonian flow. The mountain/plain interface presented conditions that were optimal for infiltration to occur because of three factors: higher infiltration capacity soil types, lower local rainfall rates, and a lower energy environment due to a lower surface gradient. The soils throughout much of the Tafuna Plain possess the highest infiltration rates on the island; an NRCS soil survey estimates their rates to be as high as 20 in/hr. Mean annual rainfall rates on the Plain, at 90 – 140 in/yr., are some of the lowest on the island. The abrupt change of gradient at the mountain/plain interface would have a commensurate kinetic effect, and this lowered energy state would create further opportunity for infiltration to occur at this boundary area rather than upslope of it.

Total recharge for the model area is estimated at 106 Mgal/d. MFR is estimated to contribute about 8 percent of total recharge for the model area, but greater than 50 percent in critical recharge areas directly upgradient of many of the island’s primary production well fields. Changes to rainfall generate substantially greater changes to estimates of recharge (15 percent compared to 25 percent). Similarly, changes to canopy interception and runoff-to-rainfall ratios generate substantial changes to estimates of recharge. Changes to other variables within the range of values tested generate little or no change to estimates of recharge, with the largest of these (modeling as though there is no runoff from the Tafuna Plain or reducing soil available water capacity by 50 percent) generating a 5 percent change in estimated recharge.

Future efforts to improve understanding of the hydrologic processes in this key locale would benefit from higher resolution datasets, including (but not limited to) rainfall data (both spatial and temporal), such as a NEXRAD site could supply, streamflow data, such as a continuous-record or even a crest-gage site could supply, and groundwater quality data, such as well-situated CTDs could supply.

References Cited

Asdak, C., Jarvis, P.G., van Gardingen, P., and Fraser, A., 1998. Rainfall interception loss in unlogged and logged forest areas of Central Kalimantan, Indonesia, Journal of Hydrology 206, 237 - 244

Allen, R.G., Pereira, L.S., Raes, Dirk, and Smith, Martin, 1998, Crop evapotranspiration; guidelines for computing crop water requirements; Food and Agriculture Organization of the United Nations, FAO Irrigation and Drainage Paper 56, 300 p.

Bruijnzeel, L.A., Wiersum, K.F., 1987. Rainfall interception by a young Acacia auriculiformis (A. Cumm) plantation forest in West Java, Indonesia: application of Gash's analytical model. Hydrological Processes 1, 309 - 319

Bruijnzeel, L.A., Waterloo, M.J., Proctor, J., Kuiters, A.T., and Kotterink, B., 1993, Hydrological observations in montane rain forests on Gunung Silam, Sabah, Malaysia, with special reference to the "Massenerhebung" effect: Journal of Ecology, v. 81, no. 1, p. 145-167.

Calder, I.R., Wright, I.R., and Murdiyarso, D., 1986. A study of evaporation from tropical rainforest, West Java, Journal of Hydrology 89, 13 - 31

Cavelier, J., Jaramillo, M., Solis, D., and de Leon, D., 1997, Water balance and nutrient inputs in bulk precipitation in tropical montane cloud forest in Panama: Journal of Hydrology, v. 193, p. 83-96.

Cole, T.G., Whitesell, C.D., Whistler, W.A., McKay, N., and Ambacher, A.H., 1988, Vegetation survey and forest inventory, American Samoa, Resource Bulletin PSWRB-25, Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, 14 p.

Daly, C., Halbleib, M., and Smith, J., 2006, Pacific Islands (Tutuila) Average Monthly and Annual Precipitation, 1971 – 2000: PRISM Group at Oregon State University [http://www.ocs.orst.edu/pub/prism/pacisl/grids/ppt/Normals/, accessed February 21, 2006].

Donnegan, J.A., Mann, S.S., Butler, S.L., and Hiserote, B.A., 2004, American Samoa's forest resources, 2001l, Resource Bulletin PNW-RB-244, Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 32 p.

Foote, D.E., Hill, E.L., Nakamura, S., and Stephens, F., 1972, Soil survey of the islands of Kauai, Oahu, Maui, Molokai, and Lanai, State of Hawaii: U.S. Department of Agriculture, Soil Conservation Service, 232 p.

Fosberg, F.R. and Mueller-Dombois, D., 1998, Vegetation of the Tropical Pacific Islands, Ecological Studies V. 132, Springer Publications, 733 p.

Gash, J.H.C., and Morton, A.J., 1978. An application of the Rutter model to the estimation of the interception loss from Thetford Forest, Journal of Hydrology 38, 49 - 58

Germer, S., Elsenbeer, H., and Moraes, J.M., 2006, Throughfall and temporal trends of rainfall redistribution in an open tropical rainforest, south-western Amazonia (Rondonia, Brazil): Hydrology and Earth System Sciences, v. 10, p. 383-393.

Giambelluca, T.W., 1983, Water balance of the Pearl Harbor-Honolulu basin, Hawaii, 1946 – 1975: University of Hawaii Water Resources Research Center Technical Report no. 151, 151 p.

Herwitz, S.R., 1985, Interception storage capacities of tropical rainforest canopy trees, Journal of Hydrology 77, 237 - 252

Hutjes, R.W.A., Wierda, A. and Veen, A.W.L., 1990. Rainfall interception in the Tai Forest, Ivory Coast: application of two simulation models to a humid tropical system. Journal of Hydrology 114, 259 - 275

Izuka, S. K., Oki, D. S., and Chen, C., 2005a, Effects of irrigation and rainfall reduction on ground-water recharge in the Lihue Basin, Kauai, Hawaii: U. S. Geological Survey Scientific Investigations Report 2005-5146, 48 p. [http://pubs.usgs.gov/sir/2005/5146/].

Izuka, S. K., Giambelluca, T. W., and Nullet, M. A., 2005b, Potential evapotranspiration on Tutuila, American Samoa: U.S. Geological Survey Scientific Investigations Report 2005-5200, 40 p. [http://pubs.usgs.gov/sir/2005/5200/].

Izuka, S. K., Perreault, J. A., and Presley, T. K., 2007, Areas contributing recharge to wells in the Tafuna-Leone Plain, Tutuila, American Samoa: U.S. Geological Survey Scientific Investigations Report 2007-5167, 52 p. [http://pubs.usgs.gov/sir/2007/5167/].

Jackson, I.J., 1975. Relationships between rainfall parameters and interception by tropical rainforest, Journal of Hydrology 24, 215 - 238

Jetten, V.G., 1996, Interception of tropical rain forest: performance of a canopy water balance model: Hydrological Processes, v. 10, p. 671-685.

Lloyd, C.R., Gash, J.H.C., Shuttleworth, W.J., and Marques, F.A. de O., 1988. The measurement and modeling of rainfall interception by Amazonian rainforest, Agriculture and Forestry Meteorology 42, 63 - 73

Loescher, H.W., Gholz, H.L., Jacobs, J.M., and Oberbauer, S.F., 2005, Energy dynamics and modeled evapotranspiration from a wet tropical forest: Journal of Hydrology, v. 315, p. 274-294.

Luvall, J.C., 1984, Tropical deforestation and recovery: the effects on evaporation processes. Athens, University of Georgia, PhD. Dissertation, 146 p.

Manokaran, N., 1979, Stemflow, throughfall and rainfall interception in a lowland tropical rain forest in peninsula Malaysia: Malays. For., v. 42, p. 174-201.

McJannet, D., Wallace, J., Fitch, P., Disher, M., and Reddell, P., 2007. Water balance of tropical rainforest canopies in north Queensland, Australia, Hydrological Processes 21, 3473 - 3484

Nakamura, S., 1984, Soil Survey of American Samoa: U.S. Department of Agriculture Soil Conservation Service, 95 p.

Oki, D. S., 2002, Reassessment of ground-water recharge and simulated ground-water availability for the Hawi area of North Kohala, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 02-4006, 61 p.

Oki, D. S., 2008, The significance of accounting order for evapotranspiration and recharge in monthly and daily threshold-type water budgets: U.S. Geological Survey Scientific Investigations Report 2008-5163, 11 p. [http://pubs.usgs.gov/sir/2008/5163/].

Scatena, F.N., 1990, Watershed scale rainfall interception on two forested watersheds in the Luquillo Mountains of Puerto Rico: Journal of Hydrology, v. 113, p. 89-102.

Schellekens, J., Bruijnzeel, L.A., Scatena, F.N., Bink, N.J., and Holwerda, F., 2000, Evaporation from a tropical rain forest, Luquillo Experimental Forest, eastern Puerto Rico: Water Resources Research, v. 36, no. 8, p. 2183-2196.

Schellekens, J., Scatena, F.N., Bruijnzeel, L.A., Wickel, A.J., 1999. Modeling rainfall interception by a lowland tropical rain forest in northeastern Puerto Rico, Journal of Hydrology 225, 168 - 184

Sevruk, B., 1982, Methods of correction for systematic error in point precipitation measurement for operational use, Operational Hydrology Report No. 21, World Meteorological Organization Report No. 589, p. 91.

Shuttleworth, W.J., 1988, Evaporation from Amazonian rainforest: Proceedings of the Royal Society of London: B. Biological Sciences, v. 233, no. 1272, p. 321-346.

Sinun, W., Meng, W.W., Douglas, I., and Spencer, T., 1992, Throughfall, stemflow, overland flow and throughflow in the Ula Segama rain forest, Sabah, Malaysia: Philosophical Transactions of the Royal Society of London B, v. 335, p. 389-395.

Thornthwaite, C.W. and Mather, J.R., 1955, The water balance: Publications in Climatology, v. 8, p. 1-104.

U.S. Census Bureau, 2000 Census of Population and Housing, Social, Economic, and Housing Characteristics PHC-4-AS, American Samoa Washington, DC, 2003

Viger, R.J., and Leavesley, G.H., 2007, The GIS Weasel user's manual: U.S. Geological Survey Techniques and Methods, book 6, chap. B4, 201 p. [http://pubs.usgs.gov/tm/2007/06B04/.]

Wahl, K.L. and Wahl, T.L., 1995, Determining the flow of Comal Springs at New Braunfels, Texas: Proceedings of Texas Water '95, A Component Conference of the First International Conference on Water Resources Engineering, American Society of Civil Engineers, San Antonio, Texas, August 16-17, 1995, p. 77-86.

Wallace, J.S. and McJannet, D.L., 2006. On interception modelling of a lowland coastal rainforest in northern Queensland, Australia, Journal of Hydrology 329, 477 - 488

Waterloo, M.J, Bruijnzeel, L.A., Vugts, H.F., and Rawaqa, T.T., 1999, Evaporation from Pinus caribaea plantations on former grassland soils under maritime tropical conditions: Water Resources Research, v. 35, no. 7, p. 2133-2144.

Wilson, J.L., and Guan, H., 2004, Mountain-block hydrology and mountain-front recharge, in Hogan, J.F., Phillips, F.M., and Scanlon, B.R., Groundwater recharge in a desert environment; the Southwestern United States: Washington, D.C., American Geophysical Union, Water Science and Application 9, p. 113-137