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# Influence of groundwater pumping and rainfall spatio-temporal variation on streamflow

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SUMMARY

Groundwater pumping and surface water management structures, i.e. dams and water flow diversions, have been raising serious concerns about the declines in groundwater levels and streamflow in different watersheds throughout the world. Small island watersheds with complex land use, and strong spatio-temporal climate and edaphic variability (e.g. Hawaiian watersheds) offer an ideal environment to help improve our understanding of groundwater–surface water interaction and the hydrological processes it involves. In this study, we investigate the spatio-temporal relationships between streamflow, rainfall, and groundwater using long-term (>40 years) data records from a small Hawaiian watershed. A suite of Mann–Kendall tests were used to evaluate trends and shifts in time series data. The impact of groundwater pumping in the valley on streamflow was also investigated; multiple linear regression analysis was used to quantify the effect of pumping on streamflow. Stream base flow and total flow have declined significantly since 1960, while rainfall showed no statistically significant trends since the 1960s. Groundwater pumping has significantly increased since 1960, and our findings indicate it is a significant contributing factor to streamflow decline. Watershed yield experienced two successive downward shifts: first around 1971–1972 and then again around 1991–1992. The first downward shift appears to be related to the pumping of groundwater from the mid-valley area which began in 1968. The second downward shift is the result of pumping in the upper valley, which began in 1991. Regression models and double mass curve analyses indicate that pumping may have captured significant amounts of groundwater that otherwise would have comprised stream base flow. Streamflow has been reduced by 19–22% since 1971 and as much as 36% since 1991.



## 1. Introduction

Water resource management has traditionally viewed surface water and groundwater as separate entities. Although surface water and groundwater are commonly hydraulically connected, their interactions are difficult to observe and measure, and have often been ignored in water-management considerations and policies (Winter et al., 1998). Policy makers commonly use natural recharge to balance groundwater use, a policy known as *safe yield* (Sophocleous, 2002). However, this policy ignores natural groundwater discharge, and eventually leads to the drying of springs, marshes, and riverine–riparian systems that comprise the natural discharge areas of groundwater systems, as observed in many parts of the world (Sophocleous, 1997, 1998, 2000a,b). Effective resource management requires a clear understanding of the linkages between groundwater and surface water. The tremendous variation in topography, climate, soils, geology, and land use/land cover makes the Hawaiian Islands uniquely suited for investigating surface water-groundwater relationships under a variety of conditions.

The Hawaiian Islands are the most isolated oceanic island group on earth and depend exclusively on precipitation for their fresh water resources. Consequently, fresh water is one of their most valuable natural resources with significant economic, agricultural, ecologic, cultural, and aesthetic importance. Infiltrating rainfall recharges groundwater aquifers that supply 99% of Hawai'i's drinking water and 50% of all fresh water used state-wide (Gingerich and Oki, 2000). Groundwater discharge to streams enables perennial flow that sustains habitat for native stream fauna and provides fresh water for irrigation during dry periods.

Mākaha valley on the island of O'ahu has long been a source of fresh water for agriculture and drinking. The ancient Hawaiians used water from Mākaha stream and plentiful springs in the valley for growing taro and other crops (Green, 1980). Since the late 19th century, numerous water supply wells, tunnels, and diversion ditches were constructed to tap fresh water aquifers and streams for large-scale sugar cane cultivation and growing municipal

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demands (Mink, 1978; Townscape, 2009). Sugar cane farming ceased in 1946 and fresh water extracted from the valley has since been used to supplement local municipal water supply and to irrigate two 18-hole golf courses completed in 1969 in the mid-valley area (Honolulu Board of Water Supply (HBWS), unpublished records; State of Hawai'i, unpublished records). Between 1968 and 1995, eight (8) municipal and irrigation water supply wells were brought online in the mid and upper valley areas (State of Hawaii, 1989, 1995). In 2006, the valley's fresh water resources supplied 3785 $m^3\ d^{-1}$ of high quality drinking water and as much as 5000 $m^3\ d^{-1}$ of irrigation water (HBWS, unpublished records; State of Hawai'i, 1995).

As late as 1880, Mākaha stream still flowed perennially all the way to the ocean (Hommon, 1970). However, diversion ditches and tunnels reduced the perennial portion of the stream to elevations above 180 m by 1940 (Takasaki, 1971). In 1945, a 1200 m long gravity-fed water supply tunnel (T1) was completed for the purpose of supplying fresh water for sugar cane (Mink, 1978). Tunnel T1 captured a substantial portion of stream base flow and reduced the perennial portion of the stream to elevations above 305 m (Takasaki, 1971). From 1940 to 1967, the groundwater level in the upper valley declined more than 10 m (Mink, 1978). By 1969, all of the springs in the upper valley were either dry or reduced to no more than a trickle (Hommon, 1970). Thus, the development of water resources dramatically reduced streamflow, groundwater levels, and spring discharges in the valley by the 1960s. One well in the upper valley (W4) was originally brought online in 1991 as an artesian well with static heads as high as 32 m above ground (HBWS, 1989; unpublished records). However, artesian flows in W4 ceased when upper valley well W3 began pumping in 1992, indicating an additional reduction in groundwater levels (HBWS, unpublished records). A permanent pump has never been installed in W4.

Recent studies have indicated further dramatic decline in stream base flow and total flow though the cause of the decline is not clear (Oki, 2004; Mair et al., 2007). Oki (2004) noted significant downward trends in Mākaha stream's annual mean base flow and mean total flow from 1960 to 2002 and from 1973 to 2002. Mair et al. (2007) noted a significant downward shift in annual mean total flow from 1991 to 2005, the period during which groundwater pumping began in the upper valley. They also reported a significant decline in annual watershed yield (i.e. ratio of total flow to rainfall) from 1991 to 2005. In 2000, concern over streamflow decline helped initiate the development of a watershed partnership between *Mohala I Ka Wai*, a Mākaha-based community group, and HBWS, the island's water purveyor. In response to their concerns, HBWS agreed to reduce pumping from all municipal wells in the upper valley for a 5-year period starting in 2002 (Townscape, 2009). The impact of groundwater withdrawals on Hawaiian streams state-wide is now receiving increased scrutiny (Izuka, 2006; Oki et al., 2006; Oki, 2007).

A decline in Hawai'i's rainfall and its negative effects on fresh water availability has been recently documented (Oki, 2004; Chu and Chen, 2005). Chu and Chen (2005) used a regional rainfall index to show that state-wide wet season precipitation (November–March) declined from 1905 to 2002. Oki (2004) also reported significant downward trends in annual rainfall at 17 locations state-wide from 1913 to 2001. As an apparent response to rainfall decline, annual mean total base flow declined from 1913 to 2002 in seven streams on four of the main Hawaiian Islands (Oki, 2004). The decline in base flow suggests that Hawai'i's rainfall decline is already impacting fresh water availability. While the long-term base flow trends are consistent with rainfall decline over parts of Hawai'i, the observed rainfall decline is not spatially uniform and does not account for all observed streamflow decline.

Analyses to date are inconclusive as to whether rainfall has declined in Mākaha valley because of missing records and data homogeneity problems (Mair et al., 2007; Mair and Fares, 2010). Oki (2004) analyzed four long-term rain gages within a 20 km radius of Mākaha valley over time periods ranging from 1893–2001 to 1973–2001. A significant downward trend in total annual rainfall was noted at only one gage (798) from 1953 to 2001, while no significant trends were noted for the other three gages. No significant trends in rainfall were noted at the four gages during all other time periods. Given the uncertainty in the rainfall data from Mākaha valley and lack of a consistent trend in the surrounding area, it is not known whether trends detected at other locations on the island or across the state are also occurring in the valley.

Identifying the cause(s) of recent streamflow decline and decreased fresh water availability is critical for the management of the upper Mākaha valley watershed. This study examines streamflow, rainfall, and groundwater data collected in Mākaha valley over the last 50 years. First, we adjust rainfall records and estimate missing data. We then investigate long-term rainfall data for trends and shifts, and compare them with stream base flow and total flow. Finally, we investigate the relationships between streamflow, rainfall, and groundwater.

## 2. Study area

Mākaha valley is located on the leeward coast of the island of O'ahu, Hawai'i, and encompasses a total area of 24.6 $km^2$ (Fig. 1). The area is comprised of a deeply eroded valley along the northwestern remnants of the extinct Wai'anae volcano with rugged topography that varies from sea level to the top of Mt. Ka'ala at 1226 m. Alluvium extends over much of the central portions of the valley, while Pliocene-age lava flows comprise most of the steep valley walls (Sherrod et al., 2007). Average annual rainfall varies from 600 mm near the coast to more than 2000 mm around Mt. Ka'ala (Fig. 1) (Giambelluca et al., 1986). Rainfall is largely dictated by topography of the Wai'anae mountains and the prevailing northeast trade winds.

The ancient Hawaiians distinguished the annual cycle into two 6-month seasons: *kau* (May–October) and *ho'oilo* (November–April) (Lau and Mink, 2006). Modern analysis now divides the annual cycle into a dry summer season of 5 months (May–September) and a wet winter season of 7 months (October–April) (Blumenstock and Price, 1967). During the summer season, when trade winds are dominant, areas of maximum rainfall are generally located on windward slopes where orographic effects are most pronounced (Chu and Chen, 2005). In leeward portions of the islands, the seasonal variation in rainfall tends to produce steeper rainfall gradients during the summer months. Diaz et al. (2005) identified 16 distinct seasonal rainfall regimes among the four major Hawaiian Islands. The leeward portion of O'ahu, including Mākaha valley, comprises one of the 16 rainfall regimes.

The principal rainfall-producing mechanism in Hawai'i is orographic lifting of moisture-laden northeast tradewinds up the windward slopes of each island (Giambelluca et al., 1986). Tradewinds prevail about 80–95% of the time during the summer months (May–September) and about 50–80% of the time during winter months (October–April) (Blumenstock and Price, 1967). On O'ahu, the second principal rainfall-producing mechanism is cyclonic rainfall produced by large-scale storm systems, which can account for more than 50% of annual rainfall in dry areas (Giambelluca, 1983). The pattern of rainfall on leeward slopes varies as a function of distance from the crest according to a geometric progression (Mink, 1962). Trade wind flow on O'ahu becomes partially desiccated after traversing the Ko'olau mountain range and produces less intense rainfall when lifted over the Wai'anae range,