ALAWAT: A Spatially Allocated Watershed Model for Approximating Stream, Sediment, and Pollutant Flows in Hawaii, USA

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ABSTRACT / The Ala Wai Canal Watershed Model (ALAWAT) is a planning-level watershed model for approximating direct runoff, streamflow, sediment loads, and loads for up to five pollutants. ALAWAT uses raster GIS data layers including land use, SCS soil hydrologic groups, annual rainfall, and subwatershed delineations as direct model parameter inputs and can use daily total rainfall from up to ten rain gauges and streamflow from up to ten stream gauges. ALAWAT uses a daily time step and can simulate flows for up to ten-year periods and for up to 50 subwatersheds. Pollutant loads are approximated using a user-defined combination of rating curve relationships, mean event concentrations, and loading/washoff parameters for specific subwatersheds, land uses, and times of year. Using ALAWAT, annual average streamflow and baseflow relationships and urban suspended sediment loads were approximated for the Ala Wai Canal watershed (about 10,400 acres) on the island of Oahu, Hawaii. Annual average urban suspended sediments were approximated using two methods: mean event concentrations and pollutant loading and washoff. Parameters for the pollutant loading and washoff method were then modified to simulate the effect of various street sweeping intervals on sediment loads.

Freshwater runoff, sediments, and various urban and rural contaminants often adversely affect aquatic wildlife, terrestrial life, and humans. Other researchers have reported on the relevance of GIS as a tool for evaluation of nonpoint source pollution (Morgan and Nalepa 1982, Pelletier 1985, Walsh 1985, Barry and Sailor 1987, Sivertun and others 1988, Stuebe and Johnston 1990, Sasowsky and Gardner 1991, Mertz 1993, Rifai and others 1993). In many locations, however, these models for analyzing basic watershed hydrology and nonpoint source pollution problems are difficult to use because of the amount of data they require and the need to run them on workstation and larger computers. Joao and Walsh (1992), for example, demonstrated the use of the Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS) model linked with a GIS to simulate nonpoint pollution in an urban area. Their model required a DEC Microvax II computer as well as data on total soil porosity, field capacity, steady-state infiltration rates, difference between steady state and maximum infiltration rate, etc.

Watershed models can be classified according to screening, planning, or design objectives. Screening models provide a preliminary assessment of runoff magnitude and indicate the need of further analysis (e.g., USDA SCS curve number method, USDA 1985). Planning models provide a computer-based assessment of runoff problems and are useful for initial analyses of rainfall–runoff processes [i.e., Precipitation Runoff Modeling System (PRMS), Leavesley and others 1983; simplified version of Storm Water Management Model (SWMM), Huber and Dickenson 1988; and Distributed Routing Rainfall Runoff Model (DR^{3}M), Alley and Smith 1982]. Design models offer detailed simulations generally focused on a single storm event and provide a complete description of flow and pollutant routing throughout the entire watershed (e.g., robust version of SWMM; Huber and Dickenson 1988).

The primary objective of the project was to develop a planning model for analyzing general watershed hydrology, as well as the effects of urbanization and watershed management measures on runoff, sedimentation, and pollutant loads. In addition, the project sought to make the model widely accessible to

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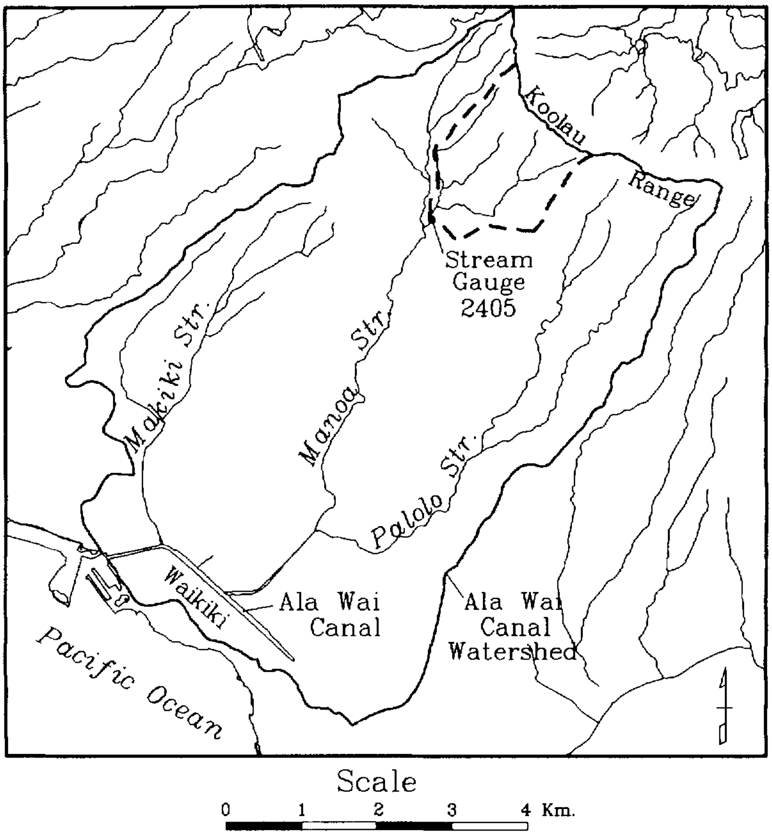

Figure 1. The Ala Wai Canal watershed.

planners by recognizing and accounting for limitations in the availability of data, as well as in computer hardware and software. This paper describes the model and some initial results.

Ala Wai Canal Watershed Model

The Ala Wai Canal Watershed Model (ALAWAT) derives its name from the Ala Wai Canal and associated watershed in Honolulu, Hawaii. The Ala Wai Canal is a man-made estuary that separates the predominantly tourist-oriented Waikiki area from the rest of Oahu.

The Ala Wai Canal is approximately 3100 m long, and water depth ranges between 1 and 3 m, averaging 2 m (Gonzalez 1971); when the canal is dredged, water depth ranges from 2 to 3 m. The boundaries of the watershed generally include all lands between Diamond Head and Punchbowl craters and extend to the crest of the Koolau Mountains (Figure 1). The Ala Wai drainage basin is characterized by diverse natural and developed features. Altitude ranges from sea level to over 800 m (2438 ft). Median annual rainfall varies from a semiarid 640 mm (25 in.) in Waikiki to over 4000 mm (158 in.) at the crest of the mountains. The upper reaches of the watershed form part of the Honolulu Watershed Forest Reserve. Almost 60% of the drainage basin is urban or built-up land. Industrial, commercial, and residential areas supply high levels of nutrients, suspended sediments, automobile contaminants, lawn and garden chemicals, and termiticides, among other pollutants. In 1989, the traffic count across the watershed was about 250,000 vehicles per day.

The Ala Wai Canal has long been known to have poor water quality, and investigations into options to alleviate the problem started over 20 years ago. Referring to the eutrophication of canal waters and the resulting algal growth, recent newspaper articles have described the canal as a "green smelly cesspool" and an "open sewer." Hawaii Department of Health analyses of water quality samples from the canal show that levels of many nutrient-related parameters and bacteria routinely exceed state water quality standards for estuaries (Department of Health 1991). Indeed, other studies of the Ala Wai Canal, both previous and current, report similar findings regarding bacteria and nutrient levels (Laws and others 1991, Kimura 1982, Cox and Miller 1976, and Ching 1972). Heavy metals and pesticides, which travel primarily on the high sed-

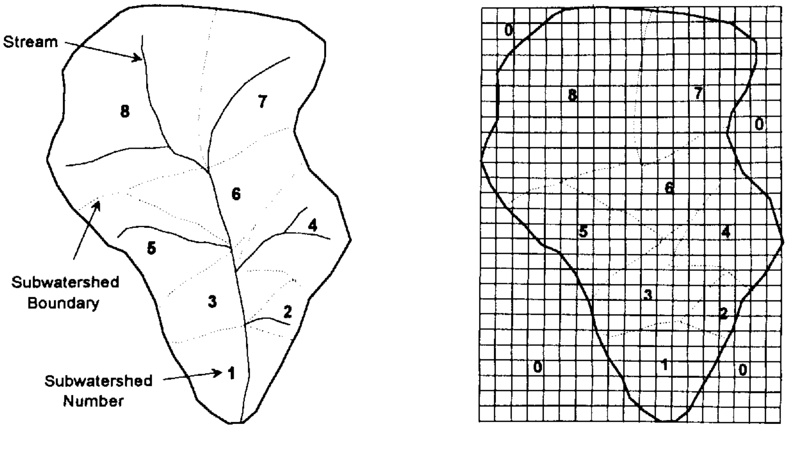

Figure 2. Subwatershed delineations and levels of spatial allocation using grid cells.

Digitized subwatershed delineations

Subwatersheds composed of hydrologically related grid cells ("0" grid cells are outside project area).

iment loads transported to the canal, are also present in substantial quantities in the canal (Department of Health 1991). US Fish and Wildlife studies of 127 US streams showed that fish from the principal stream in the watershed (Manoa stream) have by far the highest concentrations of dieldrin, chlordane, heptachlor epoxide, and lead in those studies (Schmitt and Brumbaugh 1990, Schmitt and others 1990) and have among the highest concentrations for other contaminants.

GIS and Spatial Organization

A geographic information system (GIS) is an organized collection of computer hardware, software, and geographic data designed to efficiently capture, store, update, retrieve, organize, manipulate, analyze, and display spatial information (Burrough 1986). A GIS organizes spatial data according to two types of structure, i.e., vector and raster. A vector structure organizes spatial data in points, lines, and polygons, while a raster structure uses rows and columns of square grid cells.

We chose to use a raster data structure because it provided a more simple and direct method for modeling system parameters, it was widely available in inexpensive software systems (i.e., IDRISI), and because data could be manually entered into the system (avoiding the need of a digitizer) by dividing maps into cells and entering the data into a standard spreadsheet program. From an hydrologic standpoint, a raster data structure is superior for capturing the extreme and complex rainfall gradients common in tropical areas. The parameterization of these complex gradients is critical for properly allocating rainfall over an entire watershed using data from rainfall stations. The GIS provides an efficient means for organizing map data collected at different spatial scales and times and mapped at different projections and to convert vector data to cell-based rasters for use in the model.

ALAWAT uses two levels of spatial organization to account for different types of calculations (Figure 2). Grid cells are used to approximate rainfall and direct runoff as well as for the storage of nonpoint source pollutants. Subwatersheds are composed of hydrologically related groups of grid cells. Direct runoff values from cells in a defined subwatershed are summed into daily runoff values for each subwatershed. These runoff values are adjusted with subwatershed-level hydrologic parameters to approximate long-term and short-term storage and streamflow for each subwatershed. Total daily streamflow for a subwatershed or a group of subwatersheds is then used to approximate sediment and pollutant loads using rating curves and other relationships.

Data Requirements

ALAWAT requires maps on subwatershed delineations (for aggregating subwatershed flows), annual rainfall (for approximating rainfall distribution over each subwatershed), and land use and soil hydrologic groups (for approximating initial direct runoff for each grid cell). The maps for this project were obtained in paper or digital form from commonly available sources. Watersheds were digitized from US Geological Survey 7.5-min topographic maps; annual median rainfall data were plotted on topographic maps and then digitized; soil hydrologic group maps were obtained as 7.5-min GIS coverages from the US Soil Conservation Service in Honolulu; and the land-use map was obtained as a GIS coverage from the US Geological Survey in Honolulu. All maps were originally processed as vector coverages and then converted to grid cells of 100 m × 100 m. (ALAWAT can accommodate a grid cell network of 350 × 350 cells with grid cells of any size.) The raster coverages were used as direct inputs to the model.

ALAWAT also requires daily data from at least one rain gauge and one stream gauge (the model can accommodate up to ten years of daily data from ten rain gauges and ten stream gauges). These data are easily obtained in paper form at many libraries through USGS annual reports and NOAA climate data reports. These data are also compiled on CD ROM disks for thousands of rainfall and stream gauge stations around the United States and are available through at least one commercial vendor (EarthInfo, Inc., Boulder, Colorado).

Hydrologic Components

Rainfall approximation. Daily rainfall data are known for only a few grid cells that have rain gauges. Therefore, ALAWAT uses the normal ratio method (Paulhus and Kohler 1952) to approximate daily rainfall values for other grid cells. Using an annual rainfall map, a normal ratio is defined for each grid cell by dividing the annual rainfall value for that grid cell by the annual rainfall at one of several close-by rain gauges. Daily rainfall is approximated for each cell by multiplying the daily rainfall at the appropriate rain gauge by the normal ratio calculated for the cell. ALAWAT handles the problem of missing data by assigning two representative rain gauges to each cell, a primary rain gauge and a secondary rain gauge. If the primary gauge is "missing data," the normal ratios from the secondary rain gauge are used to approximate rainfall distribution for that day.

Direct runoff approximation. ALAWAT uses a modified form of the USDA Soil Conservation Service curve number method to approximate direct runoff from each grid cell (USDA 1985). The method relies on previously determined statistical relationships between rainfall and runoff volumes, which are assumed to vary according to land use or land cover, four soil hydrological groups, and three antecedent soil moisture conditions (wet, normal, and dry). Each rainfall/runoff relationship is given in the form of a rainfall/runoff curve, defined with a number. For large storms, the curve number (CN) is roughly equivalent to the percent of total rainfall that will run off. Approximate curve numbers for various land-use/land-cover conditions are given in the SCS manual (USDA 1985). For each land use/land cover, 12 CN values are defined, one for each of the four soil hydrological groups and for the three soil moisture conditions. Total direct runoff for each subwatershed is calculated as the sum of the separate direct runoff values for all the cells in that subwatershed. Direct runoff from each grid cell is assumed to flow to the stream segment that drains that subwatershed.

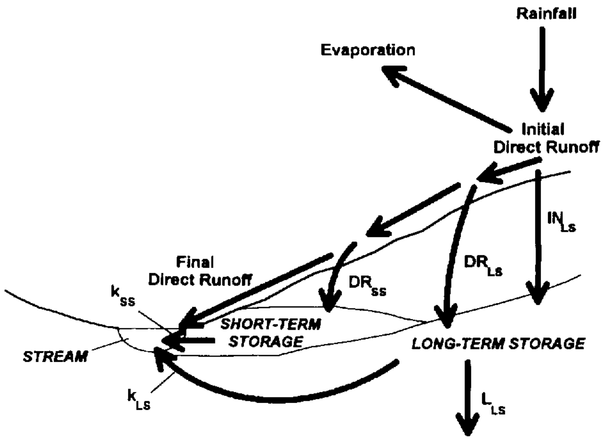

Figure 3. Runoff and storage components used in ALAWAT (terms defined in text).

Storage flow approximation. The SCS curve number approximates direct runoff and not streamflow, consequently approximations of total streamflow volumes require further adjustments for releases from short-term and long-term storage. Figure 3 shows the runoff and storage components of ALAWAT. The long-term and short-term storage parameters used by ALAWAT are defined below (for references see Dunne and Leopold 1978, Viessman and others 1989, Chow and others 1988, Lindsey and others 1988).

Short-term storage

1. Direct runoff to short-term storage partition coefficient (DR_{SS})
2. Initial short-term storage volume (I_{SS})
3. Short-term storage lost to streamflow release (k_{ss}).

Long-term storage

4. Rainfall to long-term storage (infiltration) coefficient (IN_{LS})
5. Direct runoff to long-term storage partition coefficient (DR_{LS})
6. Initial long-term storage volume (I_{LS})
7. Long-term storage release to streamflow (k_{LS})
8. Long-term storage loss rate (L_{LS}).

Adjustments to streamflow from short-term storage. A portion of direct runoff is stored or delayed for short periods of time as shallow subsurface flow (interflow) and perched groundwater. Some water leaks to deeper long-term storage (discussed below). The remaining direct runoff enters the stream course. More water is stored in the short-term as it is "pushed" into stream banks, resulting in elevated groundwater tables just adjacent to streams. All of these transfers to short- and long-term storage result in reducing streamflow volume for the first day of a storm. The stored water later reenters streams and adds to streamflow for days or weeks after the initial storm.

To account for these transfers, ALAWAT begins by using a "short-term storage partition," DR_{ss}, for each subwatershed, which defines the percentage of direct runoff that is transferred to short-term storage. The coefficient is assumed to be valid on average for all storms and all times of the year. ALAWAT then approximates the rereleases to streams from short-term storage for each subwatershed using a natural log-based decay function in the form of:

$$R_{ss(x)} = Q_{ss(x-1)}\,(1 - e^{-k_{ss}})$$

where $R_{ss(x)}$ is the water released from short-term storage for day x, $Q_{ss(x-1)}$ is the water in short-term storage for day $x-1$, and k_{ss} is the short-term storage release coefficient.

In this function, the release coefficient, k_{ss}, is roughly equivalent to the fraction of the water in short-term storage released during day x. ALAWAT assumes this coefficient represents the aggregate sum of the physical relationships in the subwatershed affecting short-term storage. Because values of k_{ss} are assumed to represent unchanging physical properties, k_{ss} remains constant for the duration of the model period. The k_{ss} values range from 0.005 to 0.05 for most subwatersheds. The k_{ss} value is set to 0.0 for urban subwatersheds (which have only storm drains). Short-term storage is initialized by specifying I_{ss} as a fraction of annual average rainfall.

Adjustments for long-term (groundwater) storage. A portion of rainfall infiltrates directly to long-term groundwater storage. ALAWAT specifies groundwater infiltration as a constant fraction (of rainfall/direct runoff) for each grid cell, IN_{LS}. A portion of direct runoff is also lost to long-term storage and is also defined as a simple fraction, DR_{LS}. Both values are assumed to be valid on average for all storms and all times of the year.

There are two types of losses from long-term storage—to streamflow and to deep groundwater. Long-term storage is rereleased to streams and lost to deep groundwater using natural log-decay functions similar to those used for short-term storage releases.

$$R_{ls(x)} = (Q_{ls(x-1)} - Q_{lsthr})(1 - e^{-k})$$

where $R_{ls(x)}$ is the water released from long-term storage for day x, $Q_{ls(x-1)}$ is the water in long-term storage at day $x-1$, Q_{lsthr} is the long-term storage threshold (below which streams become gaining instead of losing), and k is the release coefficients (k_{ls} for release to streams and k_{dgw} for release to deep groundwater).

Each subwatershed can also have a long-term storage threshold value assigned to it. When the quantity of water in long-term storage exceeds this value, the stream is gaining (water flows from long-term storage into the stream); when it is below this threshold, the stream is losing (stream water flows to long-term storage). The value for k_{dgw} can be negative for subwatersheds that have deep groundwater recharging the long-term storage (i.e., from an upstream subwatershed). Long-term storage is initialized by specifying I_{LS} as a fraction of annual rainfall.

Calibration of runoff and storage parameters. The runoff and storage parameters were generally calibrated in this order:

1. Peak streamflows are approximated by subtracting out infiltration (IN_{LS}), and direct runoff transfers to short-term (DR_{SS}) and long-term (DR_{LS}) storage.
2. Short-term patterns in streamflow are adjusted with the short-term release parameter (k_{ss}).
3. Broad long-term patterns in streamflow are adjusted with the long-term release (k_{LS}) and loss (L_{LS}) parameters.
4. The first part of the model run is adjusted using the storage initialization parameters (I_{SS} and I_{LS}).

Sediment and Pollutant Components

Sediment load approximations. Sediment loads are approximated using rating curves derived from known statistical relationships between streamflow rates and sediment concentrations or loads. Rating curves are produced by the US Geological Survey or the various state geological surveys for a limited number of streams using streamflow and sediment data for long time periods. Acceptable rating curves can also be constructed manually if daily average sediment concentration and streamflow records exist for a long time period (Glysson 1987). Rating curves of limited use can be constructed from short-term monitoring data from specific projects or from data from a recently installed monitoring station.

ALAWAT can use up to 100 sediment rating curves, each of which must be converted to a piecewise linear equation so that it can be represented as a set of up to four linear equation segments. These segments can be extracted from rating curves graphed using either linear–linear or log–log scales. Rating curves can represent either instantaneous curves (plotted as flow rate against sediment concentration) or daily load curves (usually plotted as flow rate against daily sediment load).

Pollutant load calculations. ALAWAT allows loads for up to five pollutants to be approximated using a combination of methods depending on data availability. Usually more than one method is required to account for all pollutant loads. These methods are described in more detail below.

Pollutant concentration and land-use relationships. Previous studies have determined mean pollutant concentrations with respect to direct runoff from specific land uses. These concentrations are stated as event mean concentrations (EMC). The EMC method assumes that pollutant concentrations are the same for all flow conditions and circumstances. This assumption may be more or less valid for calculating loads over extended periods of time, but is generally insufficient for approximating loads from specific storm events.

ALAWAT allows up to 100 land use/pollutant relationships to be defined. Each relationship can be defined as an EMC, as a series of constant concentrations each having a different applicable runoff range, or as a concentration–runoff relationship similar to the suspended sediment rating curve. As with the suspended sediment rating curve procedure, up to four linear equation segments can be defined for each relationship. Although the use of a single EMC concentration to approximate pollutant loads is useful, rating curve relationships are probably preferable if data are available.

Pollutant concentration in streamflow for subwatersheds. The process for using pollutant mean concentrations for subwatersheds is the same as using mean concentrations for land uses, except that the concentration value applies to streamflow from an entire subwatershed, which can be urban, rural, or mixed land use. This method assumes that the pollutant concentration is constant and takes into account all land-use, streamflow, and baseflow pollutant loading in the subwatershed. ALAWAT allows up to 250 pollutant subwatershed relationships to be defined.

Pollutant rating curve relationship with sediment loads. Some pollutants are transported primarily by the sediments to which they are attached and consequently have a more direct relationship to sediment loads than to streamflow. ALAWAT allows up to 100 pollutant/sediment load rating curve relationships, each of which must correspond to a particular sediment rating curve equation.

Mean pollutant concentration in spring flow/stream baseflow. As with other waters, spring flow and stream baseflow also contain pollutants (natural or via contamination). Rainfall itself can also have significant pollutant concentrations (El Swaify and Ahuja 1976). ALAWAT allows concentrations for up to five pollutants to be defined for each subwatershed.

Manual pollutant loading and removal. This method manually adds pollutants using user-defined loading rates and removes pollutants using user-defined criteria for management measures and wash-off rates.

Manual pollutant additions. Manual pollutant load additions can occur from three source types, each of which is added in a different way. Rainfall loads and other nonpoint source loads are added and stored at the grid cell level. Because streamflow in the model begins only after runoff from grid cells has been aggregated into subwatersheds, point source loads are added directly to stream water at the subwatershed level. Pollutants are considered to be conservative. That is, they neither degrade nor accrue on their own accord and are nonreactive with other substances or organisms in the environment. Rainfall sources of pollutants are specified as concentrations and are specified according to land use. Loads from rainfall concentrations are added "full-strength" directly to streams through direct runoff. Water that is taken from direct runoff and added to short-term storage is assumed to have the same concentrations as in the original rainfall. Because different land uses have different activities generating different types and amounts of pollutants, nonpoint source pollutant additions are specified according to land use. Running load totals are kept for each pollutant for each grid cell. Pollutant removals are made against these totals (see below). Point sources are specified as loads every x number of days and are added directly to streams at the subwatershed level. Complete dilution is assumed to occur within the subwatershed in which the load is added.

Manual pollutant withdrawals. Nonpoint source pollutants are removed from the land in two different ways: manual removal through management measures and naturally through washoff by rainfall. Both methods operate at the grid cell level. Management measures are user-defined measures to remove pollutants or permanently retain pollutants before they wash off the land as part of direct runoff. This method of pollutant removal was developed to simulate street sweeping, but can represent any manual

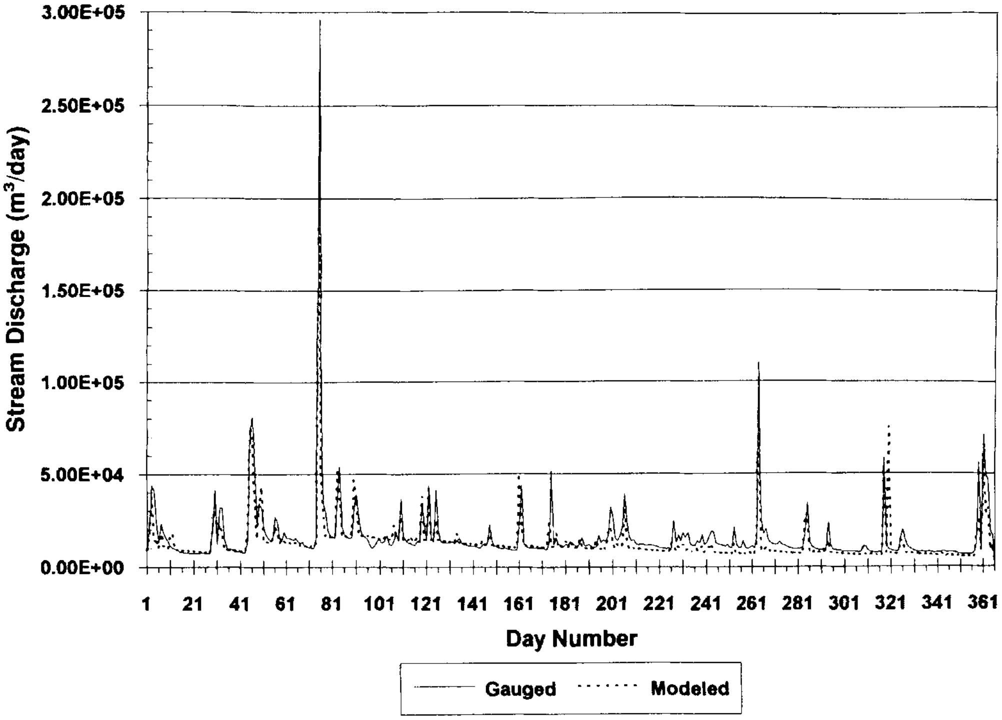

Figure 4. Modeled and measured streamflow for 1969 at stream gauge 2405.

measure that removes or permanently detains a pollutant. Pollutants are also removed when they are washed off the land and into storm drains and streams. Indirectly, pollutants are also removed from streams when stream water is lost. If a stream loses water, pollutants are lost in whatever concentration resulted after being completely mixed with the stream water in that stream segment.

Results

This study used ALAWAT to investigate several hydrologic and nonpoint source pollution problems on the island of Oahu, Hawaii. The study focused on a ten-year time period, 1967–1976, because this period had more hydrologic data available than any other time period. The three objectives of the study were:

1. Assess hydrology and rainfall/storage flow relationships for an undisturbed watershed on Waiakeakua Stream, a subwatershed of the Ala Wai Canal drainage area.
2. Calculate suspended sediment loads for urban areas draining into the Ala Wai Canal.
3. Simulate effects of various street sweeping intervals on urban suspended sediment loads. Simulations included street sweep intervals of 14, 7, 4, 2, and 1 day(s).

Rainfall/Storage Flow Relationship for Waiakeakua Stream

The study area is a 300-ha subwatershed located on Waiakeakua Stream (Figure 1). The area is completely undeveloped, extends to the crest of the Koolau Range, and has an average annual rainfall of about 3450 mm.

Streamflow time series plots show that the model successfully approximated day-to-day streamflows for the entire period (see Figure 4 for modeled versus measured streamflow in 1969). Linear regression statistics for the ten-year period are shown in Table 1. Seven of the ten R^2 values are over 0.70, two are above 0.80. The average R^2 for the time period is 0.68.

Most of the deviation in the regression statistics is due to at least two factors affecting modeled versus gauged peak flows. First, the normal ratio method used in ALAWAT to approximate daily rainfall is based on annual rainfall and can not account for the large spatial variation in daily rainfall. This deviation could be partly accounted for if monthly rainfall maps were used. Second, rainfall and stream gauge data were not recorded for the same 24-h period. Rain gauges were generally read in the early morning (8 a.m. to 10 a.m.), whereas stream gauge data were read from strip charts aggregated from midnight to midnight. Thus peak rainfall was occasionally recorded

Table 1. Regression statistics for relationships between modeled yearly streamflow and gauged yearly streamflow (at stream gauge 2405)

Year	Regression line	R^2	SEE (m^3/day)	Modeled gauged ratio
1967	Gauged = 1.286 × modeled + 1164	0.842	7669	0.719
1968	Gauged = 1.014 × modeled + 3653	0.644	14660	0.768
1969	Gauged = 1.185 × modeled + −187	0.844	7573	0.854
1970	Gauged = 1.135 × modeled + 1339	0.732	4826	0.776
1971	Gauged = 0.794 × modeled + 3907	0.652	7286	0.821
1972	Gauged = 0.682 × modeled + 1949	0.703	5033	1.091
1973	Gauged = 1.004 × modeled + 1135	0.712	5155	0.874
1974	Gauged = 1.278 × modeled + −668	0.785	6594	0.827
1975	Gauged = 0.667 × modeled + 2849	0.481	7452	1.011
1976	Gauged = 0.489 × modeled + 3200	0.354	6870	1.197
Avg.	**Gauged = 0.954 × modeled + 1834**	**0.675**	**7312**	**0.894**

Table 2. Regression statistics for relationships between total yearly short- + long-term storage releases to streams and gauged yearly streamflow and modeled annual rainfall

Regression line	R^2
Storage release = 0.350 × streamflow + 1.08E6	0.74
Storage release = 634.0 × rainfall + 3.10E5	0.55

for one day and peak streamflow recorded for another day.

Table 2 shows regression statistics comparing total modeled releases from storage (short term plus long term) with average watershed rainfall and with total streamflow. Both relationships show strong correlations with modeled storage releases. Figure 5 graphically shows the relationship between modeled releases from storage and gauged streamflow. Although measured data do not exist with which to compare the modeled results, the relative accuracy of the ten-year streamflow time series suggests that the modeled storage flow releases are sufficiently accurate for planning-level purposes.

In areas with distinct wet and dry seasons, releases from storage can supply a large amount of total streamflow. Thus ALAWAT provides an important tool for modeling the effects of land-use activities that either change the infiltration rate or affect the amount of water in storage and thus dry-season flow.

Urban Suspended Sediment Loads to Ala Wai Canal

ALAWAT approximated annual urban suspended sediment loads to the Ala Wai Canal using three separate scenarios. Each scenario used different sets of the event mean concentration values from separate research projects, and one scenario used simulated nonpoint source pollutant additions and withdrawals using simulated management measures.

Fujiwara (1973) conducted a storm drain study in urban Honolulu, for which flow-weighted mean event concentrations of suspended sediments (see Table 3) for three major land uses—residential, commercial, and industrial—were approximated.

Yamane and Lum (1985) evaluated pollutant data from two storm drains in Mililani, Oahu, Hawaii, between September 1980 and May 1984. Individual suspended sediment concentration observations were flow-weighted for each event and then converted to a log-normal average. The resulting EMCs for each storm drain and for both storm drains are shown in Table 4. The study area comprised mostly residential land uses.

Using the method described above in "pollutant concentration and land-use relationships," approximate annual suspended sediment loads were calculated using modeled daily urban runoff volumes and even mean concentration values from each of the two studies. Using the suspended sediment load results from these modeling runs, the loading and withdrawal parameters for the management measure method were calibrated to simulate street sweeping (assuming a 14-day interval with a removal efficiency of 70%). Table 5 shows the suspended sediment results of the three scenarios.

The annual average load results from the management measure simulations were generally close to the results using the standard mean concentration method for approximating total loads and concentrations from the two urban runoff studies.

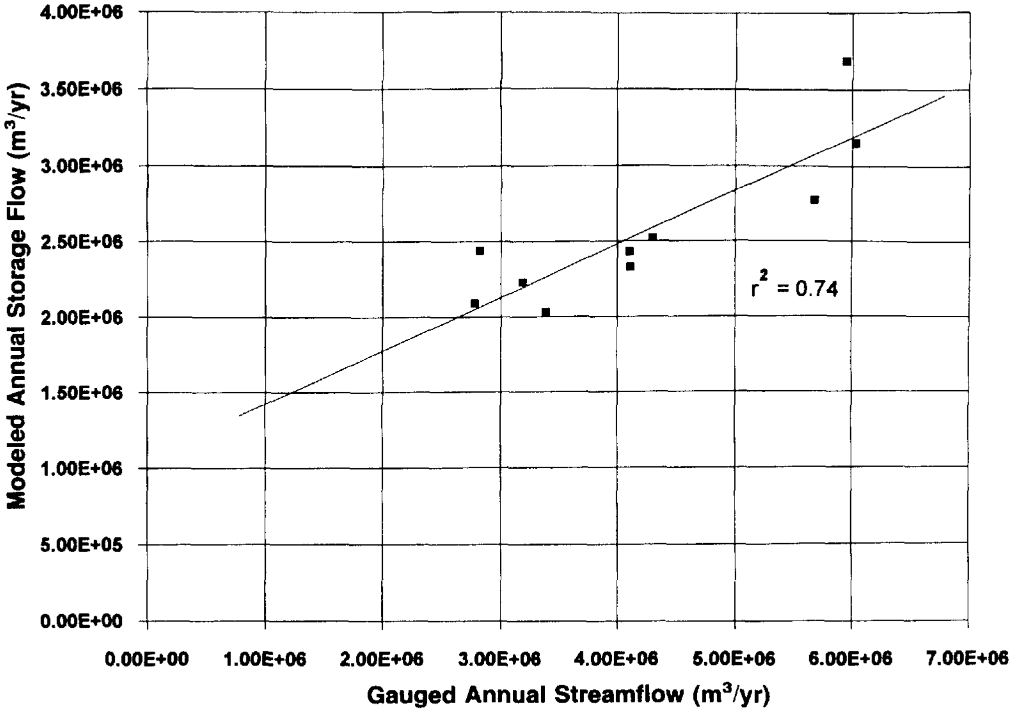

Figure 5. Total annual streamflow (gauged) and total annual storage flow (modeled) for years 1967–1976 at stream gauge 2405.

Table 3. Flow-weighted mean event concentrations for suspended sediment loads for three urban land uses (from Fujiwara 1973)

Land use	Suspended sediment concentration (mg/liter)
Residential	252
Commercial	142
Industrial	12

Table 4. Flow-weighted mean event concentrations for suspended sediment loads from Mililani storm-water runoff study (data from Yamane and Lum 1985)

Storm drain site	Suspended sediment concentration (mg/liter)
Station A	317
Station B	142
Stations A and B	268

Simulating Effects of Street Sweeping on Suspended Sediment Loads

Although the three scenarios for approximating suspended sediment loads generally agreed very well, only the method using simulated management measures provided the opportunity to simulate the potential effects of varying management parameters and intervals. Five different intervals of street sweeping were simulated, with 14, 7, 4, 2, and 1 day(s) between sweepings. The results are shown in Table 6.

These results suggest that street sweeping would have to be reduced from 14 days to two days to reduce suspended sediment loads to the Ala Wai Canal by half. This result is due to the inefficiency of street sweeping and the relative efficiency of rainfall. Street sweeping is assumed to be only 70% efficient, and large rainfall events will wash away all remaining loads. These results suggest that a cost–benefit analysis may provide additional information to derive an appropriate level of street sweeping.

Conclusions

ALAWAT uses commonly available hydrologic and GIS data to model long- and short-term storage and total streamflow. The model operates on any personal computer and requires the adjustment of only eight lumped-characteristic parameters. The model allows accurate planning-level approximations of basic stream hydrology and storage flow and investigations of watershed responses to various types of

Table 5. Urban suspended sediment load approximations for the Ala Wai Canal, Oahu, Hawaii, 1967–1976 (kg/yr)

	High	Low	Mean	Median	Range
Fujiwara (1973)	2.00E+06	8.09E+05	1.38E+06	1.41E+06	1.19E+06
Yamane and Lum (1985)	2.73E+06	9.92E+05	1.83E+06	1.88E+06	1.74E+06
ALAWAT management measure simulation	2.45E+06	1.06E+06	1.76E+06	1.85E+06	1.40E+06
Average	**2.39E+06**	**9.53E+05**	**1.65E+06**	**1.71E+06**	**1.44E+06**

Table 6. Simulations of street sweeping at 14-, 7-, 4-, 2-, and 1-day intervals to manage suspended sediment loads

Management interval (days)	Average suspended sediment load (kg/yr)
14	1.694×10^6
7	1.223×10^6
4	1.016×10^6
2	0.864×10^6
1	0.782×10^6

storms to be done economically and efficiently. ALAWAT is well suited for use in tropical areas by allowing the use of up to ten rain gauges to account for rainfall distributions in areas with high rainfall gradients and by requiring only basic daily hydrological data.

ALAWAT provides an efficient tool for exploring the effects of land-use changes and other activities that affect long-term storage and ultimately streamflow. Land-use changes such as deforestation or urbanization can affect infiltration rates and the overall relationship between rainfall and dry-season streamflows. Other activities, such as groundwater pumping, can affect long-term storage volumes. The maintenance of dry-season flows, which are dependent on storage volumes, is vitally important for irrigation for farmers and to sustain fish habitats and populations during low flow periods. All of these issues are especially relevant to rapidly developing tropical and subtropical areas.

ALAWAT can also approximate suspended sediment loads and pollutant loads using a combination of rating curve and mean–event concentration relationships derived from local literature and monitoring data. These approximations are invaluable for planning-level decision making and initial investigations. ALAWAT also makes it possible to simulate the effects of various management measures for controlling nonpoint source pollutants.

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