Allocations of Total Maximum Daily Loads of Total Suspended Solids, Nitrogen and Phosphorus for Kawa Stream, Kaneohe, Hawaii
TECHNICAL APPENDIX
June 21, 2005

A.1.0 Purpose.

The TMDL allocation process benefits from disaggregating watershed-scale observations of stream flow and stream quality to contributions from individual subbasins in the watershed and from identified land use areas, i.e., pollutant sources, in each subbasin during both dry weather and wet weather conditions. The elements of a systematic and technically consistent procedure for this disaggregation are described in this Appendix.

A.2.0 Rainfall Distribution.

Local climatic patterns are influenced by a number of local factors: topography, terrain features, and proximity to coastal moisture sources. Of these, the statistically most important factor is elevation. The governing equation for the PRISM system of climatic mapping is a linear regression function between climate parameters (temperature, precipitation) and elevation (Daly et al., 2002). Figure A1 displays 12-year annual averages for recorded rainfall (1986-1997) at four monitoring stations in the Kaneohe Bay area of windward Oahu. Rainfall data in this figure are displayed against station elevations.

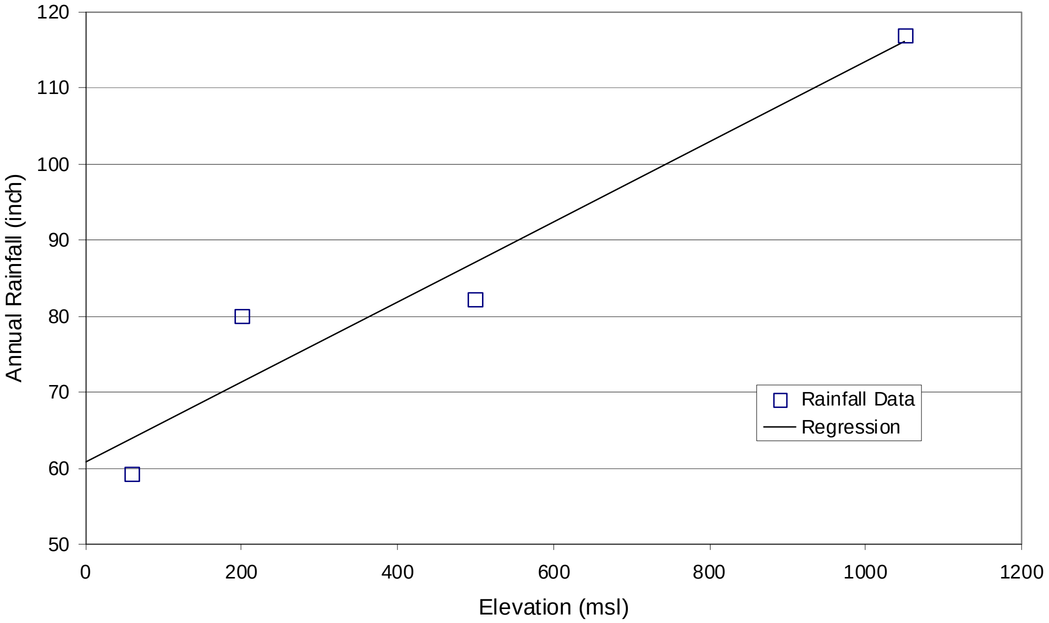

Figure A1. Correlation of Rainfall with Elevation, Windward Oahu

The regression equation in Figure A1, Y = 60.84 + 0.0526X ($r^2 = 0.93$), can be expressed:

$$P = P_0 (1 + eZ) \qquad (2\text{-}1)$$

Where:

P = mean annual rainfall, inch
P_0 = regression intercept, 60.84 inch
Z = station elevation, feet (MSL)
e = normalized regression slope, 0.0526/60.84 = 0.864×10^{-3} feet^{-1}

Equation (*2-1*) can be used to approximate the rainfall at any watershed location (j) based on reference rainfall data (P_R) from a monitoring station elsewhere in or closely near the watershed and the elevations of the two locations:

$$P_j = P_R \frac{(1 + eZ_j)}{(1 + eZ_R)} \qquad (2\text{-}2)$$

Mean watershed rainfall can similarly be approximated from the reference rainfall data and an expression of watershed topography:

$$\overline{P} = P_R \frac{\sum_j \frac{(1 + eZ_j)}{(1 + eZ_R)} A_j}{\sum_j A_j} \qquad (2\text{-}3)$$

Where:

A_j = area of individual subbasin or land use parcel j.

A.3.0 <u>Evaporation</u>.

Pan-evaporation data from Hawaii have been correlated inversely with annual rainfall (Takasaki et al., 1969). Rainfall can evidently be an effective surrogate for a combination of parameters (solar incidence, vapor pressure, cloud cover) normally found in calculations of evaporation and evapotranspiration. The form of the regression equation developed by Takasaki et al., $\log_{10}E = 1.9387 - 0.0035P$, is computationally awkward for TMDL disaggregation purposes. Figure A2 is a replotting of the Oahu evaporation data from Takasaki et al. (Table 4) in a more convenient linear form. The regression equation ($r^2 = 0.948$) for the evaporation data in this form is:

$$E_v = 78.39 - 0.341P \qquad (3\text{-}1)$$

Where:

E_v = median annual pan evaporation, inch
P = median annual precipitation, inch

Baseflow data for Kawa Stream (see section A.5.0) indicates that equation *3-1*, or at least its intercept, 78.39, may overstate actual evapotranspiration rates. Evapotranspiration, at least during conditions of limited soil moisture, is likely to be less than pan evaporation measurements.

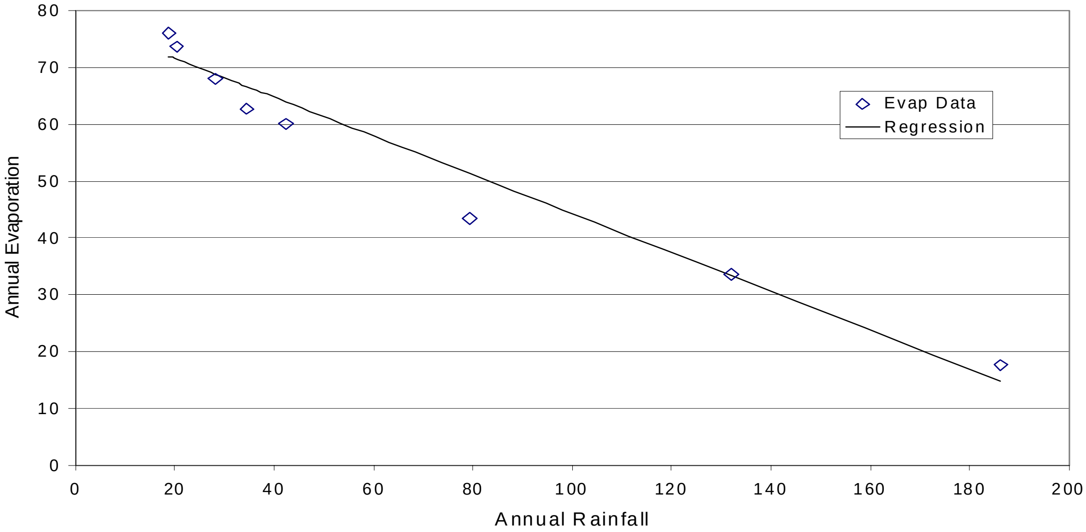

Figure A2. Correlation of Evaporation with Rainfall, Oahu Stations

A.4.0 Stormwater Runoff.

Of the several approaches used to simulate stormwater runoff, two relatively simple models are useful for the scale and purposes of TMDL development. For individual events, i.e., design storms, the SCS runoff formulation (USDA 1985, 1986) has found wide application:

$$R = \frac{(P - 0.2S)^2}{(P - 0.2S) + S} \tag{4-1a}$$

$$S = \frac{1000}{CN} - 10 \tag{4-1b}$$

Where:

R = event runoff, inch
P = event rainfall, inch
S = potential maximum retention after runoff begins, inch
CN = SCS curve number, $0 < CN < 100$.

The major factors that determine *CN* are the hydrologic soil group (*HSG*), land use, cover, and conservation practice. *CN* values are tabulated in the referenced TR-55 (USDA 1986). *HSG* classifications (Table K1) for Hawaii soils, along with detailed soil maps and other information, can be found in USDA soil survey reports (USDA nd, at http://www.ctahr.hawaii.edu/soilsurvey/soils.htm).

The runoff volume (ft^3) contributed by an individual land use parcel *j* is:

$$(V_R)_j = \frac{43{,}560}{12} \frac{(P_R \frac{(1+eZ_j)}{(1+eZ_R)} - 0.2S_j)^2}{P_R \frac{(1+eZ_j)}{(1+eZ_R)} + 0.8S_j} A_j \qquad (4\text{-}2)$$

For multiple event periods, e.g., seasonal or annual, a rational formula runoff expression has been commonly used. Estimates of annual pollutant loads in the Honolulu City & County of Honolulu MS4 permit application (CCH 1992) are based on such a runoff expression:

$$R = (P)(p_r)(R_v) \qquad (4\text{-}3a)$$

$$R_v = 0.05 + 0.9f_I \qquad (4\text{-}3b)$$

Where:

p_r = fraction of rainfall that produces runoff (0.9 used by Honolulu)
R_v = mean runoff coefficient
f_I = fraction of area that is effectively impervious.

Effective impervious area in equation *4-3* is that fraction of impervious area from which runoff flows directly to the storm sewer drainage system. In the application of equation *4-3*, *P* is the mean annual or seasonal rainfall and *R* is the corresponding mean annual or seasonal runoff.

The mean runoff calculated by the rational formula expression for the total watershed for a reference data rainfall event is:

$$\overline{R} = P_R \frac{\sum_j (1+eZ_j)(p_r R_v)_j A_j}{(1+eZ_R)\sum_j A_j} \qquad (4\text{-}4)$$

The runoff volume (ft^3) contributed by an individual land use parcel *j* is:

$$(V_R)_j = \frac{43{,}560}{12} P_R \frac{(1+eZ_j)}{(1+eZ_R)} (p_r R_v)_j A_j \qquad (4\text{-}5)$$

For either runoff expression, the load (kg) of pollutant *k* in the runoff from land parcel *j* is:

$$L_{jk} = \frac{28.32}{10^6} (V_R)_j C_{jk} \qquad (4\text{-}6)$$

Where:

C_{jk} = concentration of pollutant *k* in runoff from land use category *j*, mg/l.

A.5.0 Stream Baseflow.

A water balance developed for watershed soils connected hydraulically to the watershed surface streams will include recharge of soil water storage by infiltration (I) from rainfall events (and irrigation of agricultural soils) and depletion of the storage by evapotranspiration (E), other losses by percolation to underlying aquifers or at the watershed boundaries (L), and baseflow seepage to the watershed streams (Q_B). The dynamics of a monthly water balance is expressed.

$$\frac{\partial S_G}{\partial t} = (I - E - L)A_P - Q_B \qquad (5\text{-}1)$$

Where:

S_G = soil water storage, acre-inch
I = monthly infiltration, inch/month
E = monthly evapotranspiration, inch/month
L = other losses, inch/month
A_P = pervious watershed area, acres
Q_B = monthly baseflow volume, acre-inch/month

Infiltration and evapotranspiration are obviously connected to the pervious area of the watershed. Other water storage losses may not be so directly connected, but can certainly be expressed as a function of the pervious area.

Baseflow can be related to available soil water storage through a recession coefficient:

$$\alpha \equiv \frac{\partial Q_B}{\partial S_G} \qquad (5\text{-}2)$$

Net infiltration over a period of rainfall events can be related through the pervious area part of equation *4-3* to the total rainfall for the period.

$$I = (1 - 0.05\, p_r)(1 - f_I)P \qquad (5\text{-}3)$$

The above three equations can be combined to provide a dynamic baseflow function expressed in largely determinable terms of weather.

$$\frac{1}{\alpha}\frac{\partial Q_B}{\partial t} + Q_B = [(1 - 0.05 p_r)P - (E + L)](1 - f_I)A \qquad (5\text{-}4)$$

Where:

α = baseflow recession coefficient, month^{-1}
P = monthly rainfall, inch/month

The recession coefficient (α) is a technical function encompassing soil or aquifer hydraulic properties and watershed topography, stream density, and geology. A calculation of this recession coefficient may be developed from an appropriate expression of these watershed properties, i.e., through a mechanistic groundwater baseflow model. Alternatively, an operational value of the coefficient may be developed empirically, from available dry weather streamflow data, without committing to any particular groundwater model or mechanism beyond the thermodynamic demand of the water balance.

The integrated form of equation *5-4* expresses current baseflow in terms of its history.

$$(Q_B)_t = (Q_B)_0 \exp(-\alpha\Delta t) + A(1-f_I)[(1-0.05p_r)P-(E+L)]_{\Delta t}[1-\exp(-\alpha\Delta t)]d \tag{5-5a}$$

or

$$(Q_B)_t = (Q_B)_0(1-a) + ad[bP-c]_{\Delta t} \tag{5-5b}$$

for monthly mean flow,

$$(\overline{Q}_B)_{\Delta t} = (Q_B)_0(1-a') + a'd[bP-c]_{\Delta t} \tag{5-5c}$$

Where:

$a = [1 - \exp(-\alpha\Delta t)]$, if $\alpha < 0.2$, $a \approx \alpha\Delta t$
$a' = [1 - \exp(-\alpha\Delta t)]/\alpha\Delta t$, if $\alpha < 0.2$, $a' \approx \alpha\Delta t/2$
$b = A(1 - f_I)(1 - 0.05p_r)$
$c = A(1 - f_I)(E + L)$
d = units conversion to cfs, $(43{,}560/12)/(30 \times 86{,}400) = 1.4 \times 10^{-3}$.

The relative contribution to the watershed or subbasin area baseflow from an individual land use parcel *j* can be approximated through the *bP–c* term in equation (*5-5b*). Combining equations *2-2* and *3-1* with *5-5* yields the monthly *bP–c* expression for the individual land use parcel:

$$(bP-c)_j = \left(P_R \frac{(1+eZ_j)}{(1+eZ_R)}(1-0.05p_r+0.341) - \frac{78.39}{12} \right)(1-f_I)_j A_j \tag{5-6a}$$

This leaves *bP-c* in units of acre-inch/month. Converting these dimensions and replacing p_r with the Honolulu City & County value of 0.9 provides the individual parcel $d(bP\text{-}c)_j$ in units of cfs:

$$d(bP-c)_j = \frac{43{,}560}{(12)(30)(86{,}400)} \left(P_R \frac{(1+eZ_j)}{(1+eZ_R)}(1.296) - \frac{78.39}{12} \right)(1-f_I)_j A_j \tag{5-6b}$$

This baseflow model can be empirically tested against available rainfall and streamflow data. A regression-analysis fit of 1997-98 monthly mean baseflow measurements for Kawa Stream (Nance 1999) with initial monthly baseflow and contemporaneous local rainfall data (Kaneohe station 838.1) is shown in Figure A3. The regression equation in this figure,

$$Q_M = (0.781)Q_0 + (0.135)P - (0.223), \qquad r^2 = 0.956,$$

corresponds to values of 0.22, 0.76, and 1.25 for the parameters *a'*, *b*, and *c*, respectively, in equation *5-5c*, with 723 acres and 0.20 effective impervious fraction in the watershed area tributary to Nance's upper streamflow monitoring gauge. The regression value for *b* in this regression analysis is only about half the theoretically derived value of 1.296 in equation *5-6* and the value for *c* is only about 1/5 the pan evaporation intercept value of 6.5. This may be because 1998 was a very dry rainfall-year and a pan evaporation rate may overstate the actual evapotranspiration losses under extended dry conditions.

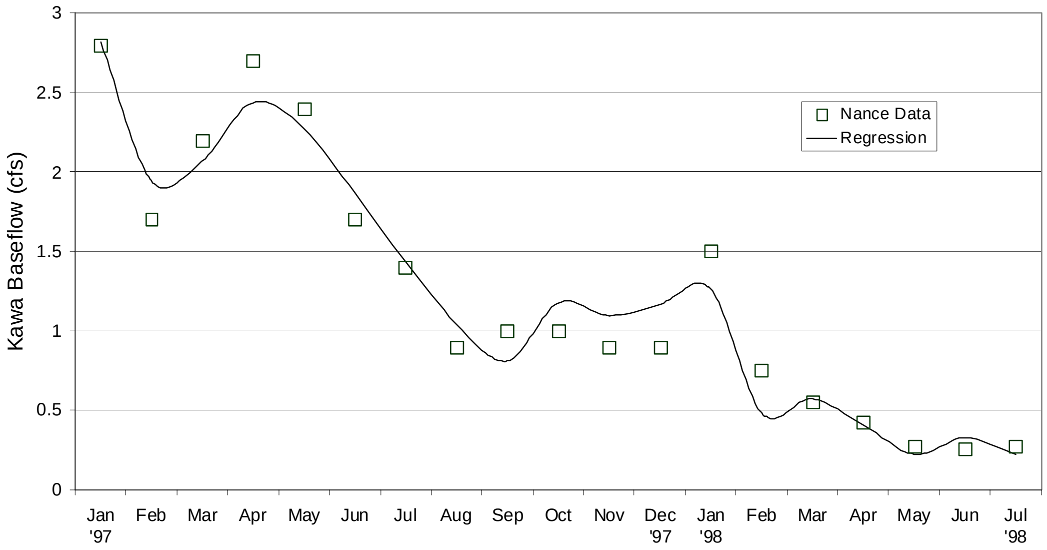

Figure A3. Kawa Stream Baseflow (1997-98)

Approximations for mean seasonal baseflows can be derived from the time-averaged integration of equation *5-5* with seasonal mean rainfall values:

$$\overline{Q}_W = B_D F_6 + B_W (1 - F_6) \tag{5-7a}$$

$$\overline{Q}_D = B_D (1 - F_6) + B_W F_6) \tag{5-7b}$$

Where:

$$F_6 = \frac{1 - \exp(-6\alpha)}{6\alpha(1 + \exp(-6\alpha))}$$

$$B_D = \frac{bP_D - c_D}{6}$$

$$B_W = \frac{bP_W - c_W}{6}$$

And:

P_D , P_W = respectively, dry and wet season rainfall totals, inch
c_D , c_W = respectively, dry and wet season evaporation and other losses, inch

This seasonal averaging model allows negative seasonal B_D values, i.e., wet season replenishing of dry season storage depletion, while still providing positive dry season baseflow. However, when the net seasonal Q_D or Q_W is negative for the subbasin or stream segment tributary area, this may indicate that the segment is losing rather than gaining streamflow. It may also mean that the constant evaporation loss term is overstated in the model; in reality, evaporation should decrease as soil moisture is depleted.

` The seasonal mean baseflow load contribution (kg/day) of pollutant *k* from land use parcel *j* is:

$$(L_B)_{jk} = 2.447\,(\overline{Q}_D \; or\, \overline{Q}_W)_j\,(C_B)_{jk}\,, \quad \overline{Q}_D \; or\, \overline{Q}_W \geq 0$$

$$(L_B)_{jk} = 0\,, \quad \overline{Q}_D \; or\, \overline{Q}_W < 0 \qquad (5\text{-}8)$$

Where:

$(C_B)_{jk}$ = baseflow concentration of pollutant *k* from land use category *j*, mg/l.

If the baseflow contribution from a land use parcel is not positive, no load is contributed from that parcel.

These expressions for volume and pollutant load contributions to baseflow are used in the Kawa Stream TMDL allocation process to disaggregate watershed baseflow volumes and loads to individual land use parcels.