J. ENVIRONMENTAL SYSTEMS, Vol. 6(2), 1976-77

# ENVIRONMENTAL IMPACTS OF LAND USE CHANGE*

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## ABSTRACT

Better measurement and analysis of environmental impacts are prerequisites to better land use planning. This paper develops an empirical matrix method for expressing the environmental impacts of land uses in a form compatible with economic evaluation techniques such as benefit-cost analysis. Impacts are first measured in standardized physical units, then converted to monetary value, modified by the locationally variable effects of several land characteristics, and finally summed into composite impact cost estimates. The presentation emphasizes the preparation of the kind of data required to operate the method. In a case study example from Hawaii, the method is applied to calculate the environmental impact costs of three alternative land uses at each of three proposed development sites.

Traditionally, land use decisions at the urban fringe of metropolitan areas have been made on economic and political rather than environmental grounds. However, today's society, with its increasing awareness of the impact of development on limited and irreplaceable land resources, is demanding that decision-makers also consider environmental factors in allocating land to various uses. This trend has created the impetus for research directed toward better measurement and analysis of the environmental impacts of land uses. This paper is one product of that research impetus.

In this paper, a method is developed to express quantitatively

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* The research on which this paper is based was supported by a grant from the U.S. Environmental Protection Agency.

doi: 10.2190/0EDX-Y0W9-CD3B-G0T5
http://baywood.com

the intensity of land use impacts and their modification by land characteristics at various locations. In addition, the method estimates an approximate monetary value of the land use impacts based on available data. The suitability of locations for land uses can then be explicitly indicated in terms of environmental costs. The emphasis of the paper is primarily empirical, with considerable attention paid to the development of data, in order to provide working information on the steps necessary to prepare for and "operate" the method.

The larger context of this research is that the social benefits of land development at a location are equal to the sum of the net private benefits (expressed as land value) and the public benefits and costs (expressed as fiscal and environmental impacts). This basic model provides a useful framework within which the calculation of many environmental impacts may proceed [1, 2]. By definition, "environmental impacts" here means adverse changes in the quality of the natural environment which result from a land use change. Not all environmental impacts (such as site preparation costs incurred by developers) are necessarily external to the calculation of land values, and many important ones are intangible (without measurable market value). For the present purposes, however, environmental impacts are defined as measurable costs external to the decision-making process of a landowner or land user. The most widely used measure for comparing and combining benefits and costs in commensurate units is monetary value. This constraint necessarily restricts the number and kind of impacts which may be analyzed to indicate the least-cost environmental suitability of locations for land uses.

## Environmental Impact Analysis

In order to calculate, compare, and combine the environmental impacts of various land uses in the framework suggested above, it is necessary to select the appropriate techniques for quantifying impacts. We require techniques which

1. permit impacts to be measured in standardized units which can be assigned some estimate of "cost" per unit impact per unit of time;
2. clearly express the spatial variation of impacts; and
3. enable the impacts to be manipulated systematically in a numerical framework.

Several recent studies have attempted to quantify some of the adverse impacts of urbanization on the natural environment. This may consist of describing the physical impacts of land use changes on selected environmental systems and characteristics (such as climate, watershed, soils, and vegetation), as well as identifying some of the interrelated factors contributing to the impacts [3, 4]. Berry *et al.* have compiled considerable data on air, water, solid waste, noise, pesticide, and radiation pollution and related this information to urban form, land use, and population density patterns at the interregional and intraregional scales [5]. There is also available a systematic compilation of the most important economic costs (capital and operating), environmental effects, and personal effects of prototype development patterns in various neighborhood and community types, with monetary values assigned to the economic cost variables [6]. With some exceptions, these studies do not express the environmental impacts of land uses in standardized physical units (i.e., units per acre per year), or attempt to estimate a monetary value for each impact. The available literature on monetary evaluation of environmental intangibles, usefully reviewed by Coomber and Biswas [7], focuses primarily on the measurement of benefits from various recreation activities at alternative destinations, through analysis of factors such as travel behavior and expenditures on facilities and services.

The spatial variation of land use impacts is most readily expressed by one of the numerous variations of McHarg's technique of overlay mapping used to compile an "ecosystem inventory" of a region [8]. In the McHarg approach, the incidence of each of a number of environmental factors occurring in a study area is mapped using a qualitative rating scale which expresses variation in the factor in terms of colors and tones in the map. In addition, each factor is ranked to show its relevance for specific land uses. Composite maps enable rapid visual assessment of the development suitability of locations within the study area in terms of minimizing disruption of the natural environment. In one application derived from McHarg's basic technique, computer mapping was used to analyze the congruity of proposed land uses in a new general plan with "land capability districts" based on the response to disturbance of the landscape's geomorphic characteristics [9]. The main limitation of these land suitability mapping techniques is that much of the ordinal information in the maps is subjectively determined and cannot be expressed and manipulated in numerical form.

Matrix methods offer a partial solution to the problem of numerical manipulation of environmental impact data. Initial applications, based on the technique of Leopold [10], used the matrix format essentially as a checklist relating the magnitude and importance of proposed actions to the environmental characteristics which would be affected. For the Arizona Economic and Environmental Trade-Off Model (ATOM), Battelle-Columbus Laboratories developed a matrix multiplication technique which quantifies the potential impacts of various land uses [11]. Impacts are expressed in commensurate environmental impact units obtained by multiplying impact parameter values (physical units of impact transformed to a 0 to 1 scale) by parameter importance factors. These importance factors are arbitrary weights and are not interpretable as "unit prices" of the parameter values. The ATOM technique requires separate analyses to derive the rates of impact of land uses and to determine the suitability of locations for land uses.

## The Matrix Multiplication Method

The method developed in this paper for analyzing land use impacts combines the strengths of the three kinds of techniques reviewed above. Land use impacts are measured as far as possible using objective data, and are "weighted" and combined using estimated monetary "prices" per unit impact. The spatial variation of impacts is made explicit by specifying the way in which the characteristics of each location affect the impacts. A modification of the matrix technique developed at Battelle-Columbus Laboratories [12] permits a number of impacts of a land use to be "priced", modified by characteristics unique to each location, and combined into a total environmental impact figure for that location in a simple three-step procedure.

The three steps of the method are illustrated in Figure 1. In Step One, a "unit price" is applied to each environmental impact's average rate of occurrence in physical units per acre, to give the average impact cost per acre by land use. This step is accomplished as Matrix A (Cost per Impact Unit by Impacts) is multiplied by Matrix B (Impacts by Land Use) to give Matrix C (Impact Costs by Land Use). In Step Two, a set of locational weighting factors is produced to adjust the average impact costs for the effects of the land characteristics at each location. This is the result of multiplying Matrix D (Locations by Land Characteristics) by Matrix E (Land Characteristics by Impact Costs) to give Matrix F (Locations by Impact Costs). In Step Three, the final matrix of composite impact costs for each land use at each location (Matrix G,

|  | MATRIX A |  | MATRIX B |  | MATRIX C |
|---|---|---|---|---|---|
| STEP ONE | Cost per Impact Unit by Impacts | X | Impacts by Land Use | = | Impact Costs by Land Use |
|  | MATRIX D |  | MATRIX E |  | MATRIX F |
| STEP TWO | Locations by Land Characteristics | X | Land Characteristics by Impact Costs | = | Locations by Impact Costs |
|  | MATRIX F' |  | MATRIX C |  | MATRIX G |
| STEP THREE | Locations by Impact Costs | X | Impact Costs by Land Use | = | Locations by Land Use |

Figure 1. Overview of matrix operations.

Locations by Land Use) is the result of multiplying the products of Step One (Matrix C) and Step Two (Matrix F). The data and operations required to fill out the matrices at each step are discussed in detail below.

A matrix multiplication procedure such as this has both advantages and disadvantages. The method allows for multiple comparisons of various land uses and their relative impacts on a number of locations. The numerical operations are clearly exposed and open to alteration by the user. The conversion of all impacts to common units of value (monetary cost) permits them to be combined unambiguously into totals. Like related multivariate techniques, however, the matrix method requires the assumption that the relationships among variables are linear and independent. For example, in applying the method we must assume that soil erosion is twice as great on a 20 per cent slope as on a 10 per cent slope, and that soil erodibility (a soil characteristic affecting the rate of erosion) is unrelated to the slope of the land. Another possible criticism of the method is that its requirement for "hard" numerical data may force quantification of subjective or unknown factors when this is inappropriate. But as this paper seeks to demonstrate, the method does yield useful order-of-magnitude estimates of average rates of land use impact as modified by locationally variable land characteristics.

## A Hawaiian Example

Under Hawaii's State Land Use Law, all land in the State is classified into districts designated for certain specific uses, the boundaries of which are clearly defined. Once established, district boundaries can be changed by the State Land Use Commission through an adversary-proceeding petition and hearing process [13]. For the City and County of Honolulu, which comprises the entire island of Oahu, there are three kinds of State land use districts: urban, agriculture, and conservation. Of Oahu's approximately 382,000 acres, roughly 20 per cent are classified as urban, with the remaining area about equally divided between agriculture and conservation districts. The major urban district land uses are residential, military, and streets; agriculture districts consist largely of sugarcane and pineapple plantations and pasture; and conservation districts are devoted principally to forested mountain watershed.

In common with many other American metropolitan areas, the City and County of Honolulu has seen substantial portions of land at its "urban fringe" converted in recent years from agricultural to urban uses. This conversion is reflected in the Land Use Commission reclassification of nearly 10,000 acres from the agriculture to the urban district during the period 1964 to late 1974. Three of the cases before the Commission in 1974, in which agriculture-to-urban land use district reclassification was requested by landowners and developers, form the case study examples analyzed in this paper. The first site, 4,560 acres in a flat coastal plain of low rainfall about eighteen miles from downtown Honolulu, is currently in heavily irrigated sugarcane plantation use and has been proposed to accommodate 25,000 to 26,000 dwelling units in a new-town configuration. The second site, 4,550 acres in a sloping ridgeline location of moderately heavy rainfall about thirteen miles from downtown Honolulu, is also in sugarcane cultivation and was proposed for nearly 27,000 dwelling units. The third site, 1,300 acres situated nineteen miles from Honolulu in a contained valley fronting on an ecologically threatened bay, is occupied by a low-income farming population who would be displaced by 6,700 new dwelling units. Land Use Commission action on these three cases was to approve 655 acres of the reclassification petition for the first site and to deny the petitions for the other two sites.

## Land Use Impacts

The method for analyzing the environmental impacts of land uses begins in Step One (see Figure 2) by estimating the average rates of impact and annual costs per acre for six exemplary environmental concerns: peak stream discharge (flooding), groundwater recharge loss, groundwater consumption, soil loss (erosion), sedimentation, and air pollution. The average environmental impacts are calculated for the three land uses which constitute the major use (by area) in each of the State land use districts on Oahu: forest reserve (conservation district), irrigated sugarcane plantation (agriculture district), and single family housing (urban district). The six environmental concerns represented by the impacts are those which, in the minds of many public decision-makers in Hawaii, are particularly critical to the process of land use planning. With the exception of air pollution, each of the land use impacts relates in some way to the interface between geologic and soil properties and the hydrologic cycle of rainfall, runoff, infiltration, and evapotranspiration. Other concerns might be more relevant and should be selected as impacts to be analyzed in other localities.

IMPACT COSTS BY LAND USE
(Dollars Per Acre)

| COST PER IMPACT UNIT | Peak Discharge | Groundwater Recharge Loss | Groundwater Consumption | Soil Loss | Sedimentation | Air Pollution |
|---|---|---|---|---|---|---|
| | $10 | | | | | |
| | | $.65 | | | | |
| | | | $.65 | | | |
| | | | | $30 | | |
| | | | | | $8 | |
| | | | | | | $75 |

MATRIX A: Costs per Impact Unit
("unit prices")

Peak Discharge (dollars per cfs per year)
Groundwater Recharge Loss (dollars per 1,000 gallons)
Groundwater Consumption (dollars per 1,000 gallons)
Soil Loss (dollars per ton)
Sedimentation (dollars per cubic yard)
Air Pollution (dollars per ton emitted)

X

| IMPACTS | Conservation | Agriculture | Urban |
|---|---|---|---|
| Peak Discharge | 1 | 2 | 4 |
| Groundwater Recharge Loss | 0 | 330 | 495 |
| Groundwater Consumption | 0 | 3465 | 1265 |
| Soil Loss | .4 | 5 | .2 |
| Sedimentation | .2 | 2.5 | .1 |
| Air Pollution | 0 | .16 | 10.4 |

MATRIX B: Average Rates of Impact
(in physical units)

Peak Discharge (net cfs per acre, 100-year storm)
Groundwater Recharge Loss (1,000 gallons per acre per year)
Groundwater Consumption (1,000 gallons per acre per year)
Soil Loss (tons per acre per year)
Sedimentation (cubic yards per acre per year)
Air Pollution (tons emitted per acre per year)

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| IMPACT COSTS | Conservation | Agriculture | Urban |
|---|---|---|---|
| Peak Discharge | $10 | $20 | $40 |
| Groundwater Recharge Loss | 0 | 214 | 321 |
| Groundwater Consumption | 0 | 2252 | 822 |
| Soil Loss | 12 | 150 | 6 |
| Sedimentation | 1.6 | 20 | .8 |
| Air Pollution | 0 | 12 | 780 |

MATRIX C: Average Value of Land Use Environmental Impacts
(in dollars per acre per year)

Figure 2. Step One of matrix method.

## MATRIX A

Matrix A (cost per impact unit by impacts) is a diagonal matrix which consists of the "unit prices" for each of the land use impacts. The "unit prices" represent estimates of the average monetary cost to society of the damage incurred or resources consumed per physical unit of impact. The intent in including this matrix in the method is primarily to provide a place for it in the overall framework of impact analysis. The actual impact cost data available at this time are too crude to be interpreted as more than order-of-magnitude values of the environmental costs involved. Definition and measurement of the impacts themselves are discussed later under Matrix B.

The "unit prices" in Matrix A were estimated as follows:

1. The impact cost per unit of peak discharge was calculated as the estimated annual value of damages which have been or would be incurred in a watershed experiencing a "100-year flood", divided by the net 100-year stream discharge for the stream watershed area. The average of these calculations for several Oahu watersheds is $10 per year per cubic feet per second (cfs) of discharge.
2. In calculating the impact cost per unit of groundwater recharge lost due to each land use analyzed, there were two possible approaches. One was to use the average price of delivered water for domestic uses on Oahu ($.37 per 1,000 gallons); the other was to use the locally estimated cost of desalinizing seawater ($.65 per 1,000 gallons), a technique not now in operation in Hawaii for supplying domestic water. The first approach represents the average user charge for water delivery infrastructure, while the second approach more nearly represents the opportunity cost of "producing" fresh water should the need ever arise. Thus the $.65 per 1,000 gallons potential desalinization cost was selected as a measure of the unit value of Oahu's groundwater resources.
3. For the reasons just discussed above, $.65 per 1,000 gallons was also selected as the unit impact cost of groundwater actually consumed by the land uses analyzed.
4. The impact cost of soil loss due to erosion in each of the land use alternatives was roughly estimated as the opportunity cost of topsoil which would hypothetically be required to "replace" the soil lost. The average delivered price of topsoil on Oahu is approximately $30 per ton.
5. The impact cost of sedimentation was based on the operating costs of estuarine dredging and ocean disposal operations for sediment loads of 5,000 cubic yards, without allowance for the

potential resale value of the dredged material. The unit price determined by the Corps of Engineers for these operations on Oahu is $8 per cubic yard of sediment.

6. The impact cost of air pollution was calculated from the total damages attributable to air pollution in Hawaii (roughly $61 million in 1970) divided by the total emissions (approximately 810,000 tons per year) from sources in the State land area in urban and agricultural uses. The resulting unit cost is $75 per ton of emissions.

## MATRIX B

Matrix B (impacts by land use) contains the basic data on the average rates of land use impact in physical units. As noted at the outset of this paper, the impacts are defined as adverse changes in the quality of the natural environment which can be measured, which are external to the decision-making process of landowners, and which can be said to be "social costs" affecting the general public. Each of the impacts therefore represents an amount of natural resources consumed (soil, groundwater, air) or damages incurred (through flooding, sedimentation, pollution) which are not normally charged as costs to owners and/or users of individual land parcels. Data for the impacts were derived from a number of locally done studies by the State Department of Land and Natural Resources, the Honolulu Board of Water Supply, the U.S. Department of Agriculture, and other agencies.[1] The three types of land uses analyzed (conservation, agriculture, urban) govern the average rates of impact through two primary variables not otherwise explicit in the method, namely degree of soil compaction and per cent of impervious cover. It is assumed that the natural condition of soil permeability and infiltration rate of undisturbed soils exists in the forested conservation areas and is reduced by half in cultivated agricultural and built-up urban areas. It is further assumed that 50 per cent of the ground surface in urban areas is impervious by virtue of being paved over or otherwise built upon. These assumptions are important for the calculation of rates of peak stream discharge and groundwater recharge by land use.

The average rates of land use impact in Matrix B were estimated as follows:

1. The rate of peak stream discharge from various areas within a

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[1] A more detailed discussion of the derivation of data on land use impacts, with references to the Hawaii source material, is contained in Joun and Schwind [1].

watershed was estimated from the total rate of discharge from the watershed in cubic feet per second (cfs) and the approximate distribution of land uses in the watershed. It is hypothesized that, on Oahu, (1) forested areas contribute the least runoff during a storm event, (2) agricultural area runoff rates are twice those of conservation areas, and (3) urban area rates are four times the conservation area rates. The estimated annual peak discharge from the watershed is subtracted from the projected peak discharge of the 100-year storm to obtain the net 100-year peak discharge, on the assumption that discharge in excess of the annual peak is apt to cause some overbank flow or flooding. The rate of net peak discharge for each land use is found from the following formula:

$$r(C) + 2r(A) + 4r(U) = PD_{100} - PD_1 \tag{1}$$

$$r = \frac{PD_{100} - PD_1}{C + 2A + 4U}$$

where r is the conservation area rate of stream discharge in cfs per acre; C, A, and U are the watershed areas in conservation, agriculture, and urban use, respectively; and $PD_i$ is the peak discharge for the $i^{th}$ year recurrence interval. By applying this formula to several watersheds on Oahu, an average rate of net peak discharge was derived for conservation use, and from this the rates for the other land uses. In cfs per acre, the rates are .98 for conservation, 1.96 for agriculture, and 3.92 for urban use.

2. Groundwater recharge occurs primarily in forested areas in Hawaii. A forested area in conservation use with 55 inches of rainfall annually (the Oahu average) would receive approximately 1.5 million gallons of rainfall per acre per year. Of this, roughly 44 per cent or 660,000 gallons infiltrates to the underground aquifer in such areas. Assuming groundwater recharge occurs in agricultural areas at approximately one-half the rate of recharge in forested areas of the same rainfall, 330,000 gallons per acre per year of potential groundwater would be lost in agricultural areas of 55-inch annual rainfall. If urbanization of these agricultural areas decreased infiltration again by one-half, an additional 165,000 gallons per acre per year would be lost to groundwater recharge, for a total loss of 495,000 gallons over conservation conditions.

3. Groundwater consumption for conservation areas was estimated at zero gallons per acre since no groundwater is withdrawn for consumption in these areas. Groundwater withdrawal averages 10,000 gallons per acre per day for sugarcane irrigation in Hawaii, which amounts to 3,650,000 gallons per acre per year. The

rate of groundwater consumption for residential areas was estimated at 3,465 gallons per acre per day (assuming an average density of 7.5 dwelling units per acre with 4 persons per unit, and water consumption at 115.5 gallons per capita per day), or 1,264,725 gallons per acre per year.

4. The soil loss rate for land in conservation use is based on the rate for forested areas (.4 ton per acre per year). The urban soil loss rate (.2 ton per acre per year) is based on established urban areas and does not account for the extremely high soil loss incurred during construction (19.3 tons per acre per year). Agricultural soil loss is a threshold figure (5 tons per acre per year) derived by evaluating the rates of soil loss from different portions of sugarcane plantation areas (gently and steeply sloping fields, access roads, etc.).

5. Sediment is a result of soil loss (erosion) and is transported in streams either in suspension or as bedload. The estuarine sedimentation was determined from the percentage of suspended sediment (approximately 50 per cent) contained in the total sediment load for a number of streams on Oahu. This percentage was applied to the soil loss rates for each land use to derive an estimated rate of estuarine sedimentation per acre. The rates in cubic yards are .2 for conservation, 2.5 for agriculture, and .1 for urban area.

6. Air pollutant emissions (sulfur dioxides, particulates, carbon monoxides, hydrocarbons, and nitrogen oxides) by point and movable sources on Oahu were summed by urban and agricultural land use source types, assuming that conservation areas do not contribute materially to air pollution. Dividing the total urban and agricultural emissions by the Oahu area in urban uses (54,465 acres) and agricultural uses (111,580 acres), respectively, yielded an estimate of air pollution rates by land use. The rates in tons per acre per year are .16 for agricultural areas and 10.4 for urban areas.

## MATRIX C

Matrix C (impact costs by land use) contains the results of multiplying Matrix A by Matrix B to give the average annual rates of environmental impact for each land use in dollar values. Agricultural use causes the greatest rates of groundwater consumption, soil loss, and sedimentation ($2,252, $150, and $20 per acre per year, respectively), while urban use causes the greatest rates of air pollution, groundwater recharge loss, and peak discharge ($780, $321, and $40 per acre per year, respectively). These impact costs by land use are subsequently modified by the locational weighting factors and combined into composite impact costs for each location.

## Modification by Land Characteristics

In Step Two of the matrix method (see Figure 3), locational weighting factors are derived which will be used in Step Three to modify the environmental impact costs for each land use by the effect of selected land characteristics. Land characteristics as defined here include five physical properties of the landscape (slope, rainfall, soil permeability, soil erodibility, and evaporation rate) as well as one locational variable (distance to downtown Honolulu). The land characteristics were selected with several perspectives in mind. First, they should be important variables which act relatively independently of each other in affecting the environmental processes which the land use impacts represent. Second, the land characteristics should be defined in such a way that they can readily be determined from available data sources. In most cases this requires some compromise between the way in which characteristics may be empirically measured and the way in which ideally they should be expressed in the semi-empirical equations available to predict surface runoff, peak stream discharge, soil loss, and related environmental processes.[2] Third, the land characteristics must be scaled in such a way as to be consistent in interpretation with respect to each land use impact. That is, the range of values for a land characteristic must lead to a positive or an inverse impact modification relationship with each impact affected by the characteristic. Fourth, the land characteristic values cannot be given additional interpretations beyond their direct effects on land use impacts. Thus, they are not general indicators of the amount and quality of resources which determine land use suitability, as in some of the resource base inventory and mapping approaches reviewed above.

### MATRIX D

Matrix D (locations by land characteristics) contains the basic land characteristic data for each project site. Sources for the data were locally available U.S. Geological Survey topographic maps, U.S. Weather Bureau rainfall maps, Soil Conservation Service soil survey maps and soil characteristic tables, and local pan evaporation data. The way in which information on each land characteristic is systematically scored for use in the matrix method is summarized in Table 1. The value of one implies an "average" value for any

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[2] Procedures examined include the "rational formula" for surface runoff, Soil Conservation Service formulas for estimating peak storm discharge, and the universal soil loss equation [14-16].

LOCATIONAL WEIGHTING FACTORS

LAND CHARACTERISTICS

| LOCATIONS | Slope | Rainfall | Permeability | Erodibility | Evaporation | Distance |
|---|---|---|---|---|---|---|
| 1 | .5 | .5 | 0 | .5 | 2 | 1 |
| 2 | 1 | 1 | 2 | .5 | 1 | .5 |
| 3 | 1 | 2 | 1 | 1 | .5 | 1 |

MATRIX D: Land Characteristic Scores

(See Table 1 for definition of score values.)

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IMPACT COSTS

| LAND CHARACTERISTICS | Peak Discharge | Groundwater Recharge Loss | Groundwater Consumption | Soil Loss | Sedimentation | Air Pollution |
|---|---|---|---|---|---|---|
| Slope | 1 | (0) | 0 | 1 | 1 | 0 |
| Rainfall | 1 | 1 | (0) | 1 | 1 | 0 |
| Permeability | (0) | 1 | 1 | 0 | 0 | 0 |
| Erodibility | 0 | 0 | 0 | 1 | 1 | 0 |
| Evaporation | 0 | (0) | 1 | 0 | 0 | 0 |
| Distance | 0 | 0 | 0 | 0 | 0 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| 2 | 2 | 2 | 3 | 3 | 1 |

MATRIX E: Impact Modification Relationships

(See text.)

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IMPACT COSTS

| LOCATIONS | Peak Discharge | Groundwater Recharge Loss | Groundwater Consumption | Soil Loss | Sedimentation | Air Pollution |
|---|---|---|---|---|---|---|
| 1 | 1 | .5 | 2 | 1.5 | 1.5 | 1 |
| 2 | 2 | 3 | 3 | 2.5 | 2.5 | .5 |
| 3 | 3 | 3 | 1.5 | 4 | 4 | 1 |

MATRIX F: Locational Weighting Factors

(for each impact at each location)

Figure 3. Step Two of matrix method.

Table 1. Land Characteristics Scoring

| | Score values | | |
|---|---|---|---|
| *Land Characteristics* | *.5* | *1* | *2* |
| Slope | 0-10 per cent | 10-30 per cent | 30 per cent and over |
| Rainfall | 0-30 inches | 30-50 inches | 50 inches and over |
| Permeability[a] | Slow | Moderate | Rapid |
| Erodibility | Slight | Moderate | Severe |
| Evaporation | 60 inches and under | 60-80 inches | 80 inches and over |
| Distance to C.B.D. | 0-15 miles | 15-25 miles | 25 miles and over |

[a] Score of 0 = impervious.

land characteristic, which does not increase or reduce the average rate of any environmental impact which the characteristic may affect. At locations with land characteristics scored .5, average impact rates affected by the characteristic are reduced by half; likewise, where land characteristic values of 2 appear, average impact rates are doubled. This method of scoring is intended to reflect the log-linear nature of some of the land characteristic/impact cost relationships in Matrix E, which in turn are based in part on the formulas referenced in footnote 2. Due to the nature of the matrix method, it is not possible to employ unique coefficient values which would relate change in each land characteristic accurately to change in each impact. This weakness is especially apparent when it would be desirable to show an inverse relationship between certain characteristics and impacts. However, the scoring system used is adequate to illustrate the method and probably appropriate to the accuracy of the data.

The land characteristics in Matrix D and Table 1 are defined as follows:

1. Slope—the proportion of vertical rise to horizontal distance over a given piece of land; for any site, the range of slope percentages.
2. Rainfall—average annual rainfall at the site.
3. Permeability—the relative rate of movement of water downward through undisturbed and uncompacted soil of the type occurring at the site.
4. Erodibility—the relative danger of accelerated erosion which would result from disturbance of the soil of the type occurring at the site.
5. Evaporation—pan evaporation rate per year, an approximate measure of the rate of evapotranspiration at the site

(combined evaporation rate from all ground surfaces and from transpiration of plants).

6. Distance—highway mileage from the site to downtown Honolulu.

## MATRIX E

Matrix E (land characteristics by impacts) contains the impact modification relationships between land characteristics and impact costs, indicating whether (1) or not (0) an impact is modified by a land characteristic. Due to the limitations of the matrix technique, all relationships are assumed to be either positive or non-existent. That is, negative values (-1) cannot be used here to indicate inverse relationships without giving false results in subsequent steps. (Correct results could be obtained in such cases by taking the inverse of the land characteristic values in Matrix D, but no way has been devised of expressing this in Matrix E.) Since negative values cannot be used, where an inverse relationship is thought to exist a zero had to be entered in the matrix (in parentheses). The column sums are retained in order to rescale the product values in Matrix F, as noted below.

The relationships between land characteristics and impact costs contained in Matrix E are as follows:

1. Peak discharge is a positive function of slope and rainfall, and an inverse function of soil permeability.
2. Groundwater recharge loss due to a land use is a positive function of rainfall and soil permeability (just as the total amount of groundwater infiltrated would be), and an inverse function of slope and evaporation rate.
3. Groundwater consumption is a positive function of soil permeability and evaporation rate, and an inverse function of rainfall.
4. Soil loss is a positive function of slope, rainfall, and soil erodibility.
5. Sedimentation, like soil loss, is a positive function of slope, rainfall, and soil erodibility.
6. Air pollution, essentially a human rather than a natural process, is here held to be a positive function of the distance from a project site to the urban center of the region. This relationship assumes, as is fairly well the case in Hawaii, that most air pollution is generated by automobile use and that such pollution increases with miles driven. No attempt has been made here to estimate the atmospheric and topographic effects on the distribution of air pollutants.

### MATRIX F

Matrix F (locations by impact costs) contains the results of multiplying Matrix D by Matrix E to give a set of locational weighting factors to modify each average impact at each location. Before Matrix F is used in Step Three, it is rescaled by dividing each column by the corresponding column sum from Matrix E. The effect of this operation is to standardize the impact values contained in Matrix F so that for an "average" location (one at which all the individual land characteristics have values of one), the composite impact modification score also becomes unity.

## Composite Impact Costs by Location

In Step Three of the matrix method (see Figure 4), Matrix F′ from Step Two (Figure 3), rescaled as noted just above, is multiplied by Matrix C from Step One (Figure 2) to give Matrix G (locations by land use). This final operation modifies the average dollar impact costs of each land use by the locational weighting factors based on land characteristics, and combines the separately modified impacts into composite impact cost figures for each land use at each location.

### MATRIX G

From Matrix G it is possible to determine the land use with the greatest environmental impact at each location, as well as the location at which each land use has its least adverse impact. Primarily because of the high rates of groundwater consumption, soil loss, and sedimentation due to irrigated sugarcane cultivation (see Figure 2), agricultural land use turns out to be the use with the greatest impact cost values at all three locations. Urban land use, with the highest rates of air pollution, groundwater recharge loss, and peak storm discharge (as well as significant groundwater consumption per acre), nonetheless has composite impact cost values of a lower order of magnitude than agriculture. Due to the land characteristics at each location and their modifying effects on impacts (see Figure 3), site 1 would be the best location for urban land use in terms of minimizing adverse impacts, while site 3 would be the best location for agriculture. This is in keeping with the land characteristics at each location. Site 1 (the flat coastal plain) has low rainfall and impervious subsoils which keep peak discharge and groundwater recharge at a minimum. Site 3 (in the valley fronting the bay) has much higher rainfall and a low evapotranspiration rate which holds down agricultural groundwater consumption.

COMPOSITE LAND USE IMPACT COSTS BY LOCATION

(Dollars per acre)

IMPACT COSTS

| LOCATIONS | Peak Discharge | Groundwater Recharge Loss | Groundwater Consumption | Soil Loss | Sedimentation | Air Pollution |
|---|---|---|---|---|---|---|
| 1 | .5 | .25 | 1.0 | .5 | .5 | 1.0 |
| 2 | 1.0 | 1.5 | 1.5 | .83 | .83 | .5 |
| 3 | 1.5 | 1.5 | .75 | 1.3 | 1.3 | 1.0 |

MATRIX F': Rescaled Matrix F

From Step Two (Figure 3)

X

LAND USE

| IMPACT COSTS | Conservation | Agriculture | Urban |
|---|---|---|---|
| Peak Discharge | $10 | $20 | $40 |
| Groundwater Recharge Loss | 0 | 214 | 321 |
| Groundwater Consumption | 0 | 2252 | 822 |
| Soil Loss | 12 | 150 | 6 |
| Sedimentation | 1.6 | 20 | .8 |
| Air Pollution | 0 | 12 | 780 |

MATRIX C

From Step One (Figure 2)

=

LAND USE

| LOCATIONS | Conservation | Agriculture | Urban |
|---|---|---|---|
| 1 | $12 | $2412 | $1706 |
| 2 | 21 | 3866 | 2150 |
| 3 | 33 | 2273 | 1947 |

MATRIX G: Land Use Impact Costs

Dollar value of environmental impacts per acre per year by land use at each location.

Figure 4. Step Three of matrix method.

To summarize from Matrix G, the baseline annual per acre environmental impact costs from conservation land use at each site are:

Site 1—$12. Site 2—$21. Site 3—$33.

The annual per acre environmental impact costs from agriculture at each site are:

Site 1—$2,412. Site 2—$3,866. Site 3—$2,273.

The annual per acre environmental impact costs from urban development at each site would be:

Site 1—$1,706. Site 2—$2,150. Site 3—$1,947.

## Conclusion

This paper has developed an empirical matrix method for analyzing the environmental impacts of alternative land uses at various locations. The method enables the user to:

1. express land use impacts in physical units of measurement,
2. convert the impacts to commensurate monetary values,
3. modify the impact costs based on the locational variation of land characteristics, and
4. combine the impacts into a composite total for each land use at each location.

Applying the method indicates the relative suitability of locations for alternative land uses in terms of environmental costs, although not necessarily in terms of the overall net social benefits to be derived from the land uses. Many of the data required to implement the method are partly hypothetical, but the assumptions are clearly stated and can be altered by other users to fit local conditions. The results of applying the method to three Hawaiian case study examples conform well to actual State Land Use Commission decisions. The site with greatest (least-cost) environmental suitability for residential development was the one partially approved by the Commission for conversion from agricultural to urban use. This indicates that the method gives "reasonable" results in cases in which the criteria for decision-making were fairly clear-cut, and suggests that the method will be useful in analyzing more complex situations in which intuitive evaluation would be less reliable.

## ACKNOWLEDGMENT

I am indebted to James Frierson, Jr., John Min, and Gerald Park for their assistance.

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