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Evaluating Erosion Susceptibility for Land-Use Planning in Coastal Watersheds

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Abstract This paper reports on research conducted in support of a coastal zone management effort to reduce erosion and sedimentation impacts in a wetland watershed, Elkhorn Slough, Monterey County, California. The research reviews methods of determining soil erosion susceptibility and relating it to land-use intensity within the watershed, measured by a land disturbance index. Erosion susceptibility is measured in three ways: by a combination of slope and the erosion factor of the Universal Soil Loss Equation; by field measurement of erosion and deposition on selected sites; and by computer-assisted terrain analysis of data from secondary sources. Land use is shown to be a more important factor than landform in influencing relative erosion susceptibility.

Introduction

Increasing development in California coastal watersheds is causing the loss and destruction of valuable wetland habitat. Direct dredging and filling are not the only reasons for degradation—

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accelerated erosion caused by intensified land-use practices has dramatically increased sedimentation of adjacent wetland areas (Dickert and Tuttle, 1981; Zedler, 1982). Accelerated sediment transport results in an increased load of suspended solids and bottom deposition, which have been shown to affect a wide range of wetland habitat values (Darnell, 1976).

Legislation at the federal and state levels has recognized the importance of wetland protection. Most programs, such as the federal Coastal Zone Management Act (CZMA) Estuarine Sanctuary Program, and CZMA-related state legislation, have been aimed at direct acquisition and conservation of wetland areas. These programs have not generally addressed the impacts of land uses from adjacent watershed areas and have failed to develop methods to integrate soil erodibility into coastal land-use planning.

Addressing this problem, our work looks at methods to incorporate soil erosion information into coastal zone management programs. Our goal was to determine the best means to rate the erosion susceptibility of various soils, in order that land development can be directed to the least sensitive areas. A key ingredient in this approach is the identification and testing of natural resource-based measures that describe changes in land characteristics in terms usable by local governments. This paper concentrates on evaluating the relative erosion susceptibility of watershed soils, examining the following methods: (1) Universal Soil Loss Equation *k* factor method; (2) field measurement of erosion and deposition; and (3) techniques derived from terrain analysis.

Planning Rationale

In the state–local collaborative arrangement, common in many coastal states, the land-use plan is the primary means to determine the compliance of local plans with state-mandated policies. This approach has placed increased emphasis on the extent to which broader resource policies, such as wetland protection, can be quantitatively related to land-use descriptors normally contained in a local government land-use plan. These descriptors typically include the designation of land-use type, location, and intensity in the form of a land-use-map. Thus, if such broader policies are to be incorporated in land-use plans, local governments need means to portray the variation in landscape characteristics in ways that can be related to the impacts of different types of land use.

Many local planning efforts have ignored these measurement problems, instead relying on the use of simplistic rules of thumb in making land-use designations. One such rule is the assumption that lower density development will result in generally lower levels of impact. Here parcel size, as a measure of density, may be used incorrectly to establish a linkage to physical processes.[1] In the case of sedimentation processes, for example, this oversimplification does not account for the wide range of land disturbance that may occur on large rural residential parcels. Similarly, local plans frequently ignore areawide processes that encompass entire watersheds or other coastal systems. For example, land uses in all the parts of a wetland watershed affect the water quality of the wetland. Regulations that apply to only a part of the watershed, or create linear buffer zones, introduce arbitrary limits that do not correspond to physical processes.

Therefore, measures are needed that can be related to land-use intensity. The measures must have a valid scientific basis in physical processes affecting the environment. Published results from other areas and generalized methods must be used with caution in specifying development review criteria that reflect local conditions. Such an approach demands both the analysis of existing localized data and focused field data collection to assess causal relationships.

Coastal Zone Management Context

California Coastal Act. The California Coastal Zone Conservation Act, approved by the state's voters in 1972, established an interim permitting system for all new developments in the coastal zone. The program was coordinated by a statewide Coastal Commission, and development permits were granted by six regional commissions.

The California Coastal Act of 1976, legislation growing out of the 1972 voter initiative, established a state–local collaborative planning arrangement, in which local jurisdictions would prepare "local coastal programs" (LCPs) according to statewide policies. The LCP consists of the land-use and zoning maps, as well as implementing ordinances for sensitive resource areas. This legislation provided for the phasing out of the regional commissions and transferred the development permit functions to local governments upon approval of their LCP. Once an LCP is approved, the Coastal Commission maintains an appellate and monitoring function.

The Coastal Act contains a broad range of policies for the protection and restoration of wetlands,[2] and for the siting of coastal development "where it will not have significant adverse effects, either individually or cumulatively, on coastal resources" (Section 30250). The state-local collaborative arrangement emphasizes the role of the local land-use plan in controlling these impacts (Dickert and Sorensen, 1978).

North Monterey County Local Coastal Program. This paper reports on research conducted in support of development of the North Monterey County Local Coastal Program (LCP). The goal of the project was to develop an approach that relates the intensity of land use to erosion susceptibility in the watershed of Elkhorn Slough, a large coastal wetland located at central Monterey Bay, California (Figure 1). All but the upper portions of this watershed are included within the coastal zone management area defined in the California Coastal Act.

The purpose of the planning system was to direct development away from the most erosive areas, and to identify and control the most damaging land uses. The approach departs from earlier efforts, such as the many non-point source pollution studies funded under the Federal Clean Water Act, in that it has been adopted in a land-use regulatory system at the local government level—the North Monterey County LCP (Monterey County, Board of Supervisors, 1982). The approach also differs from most soil conservation and local regulatory efforts in that it does not focus on the development of erosion control programs on a site-

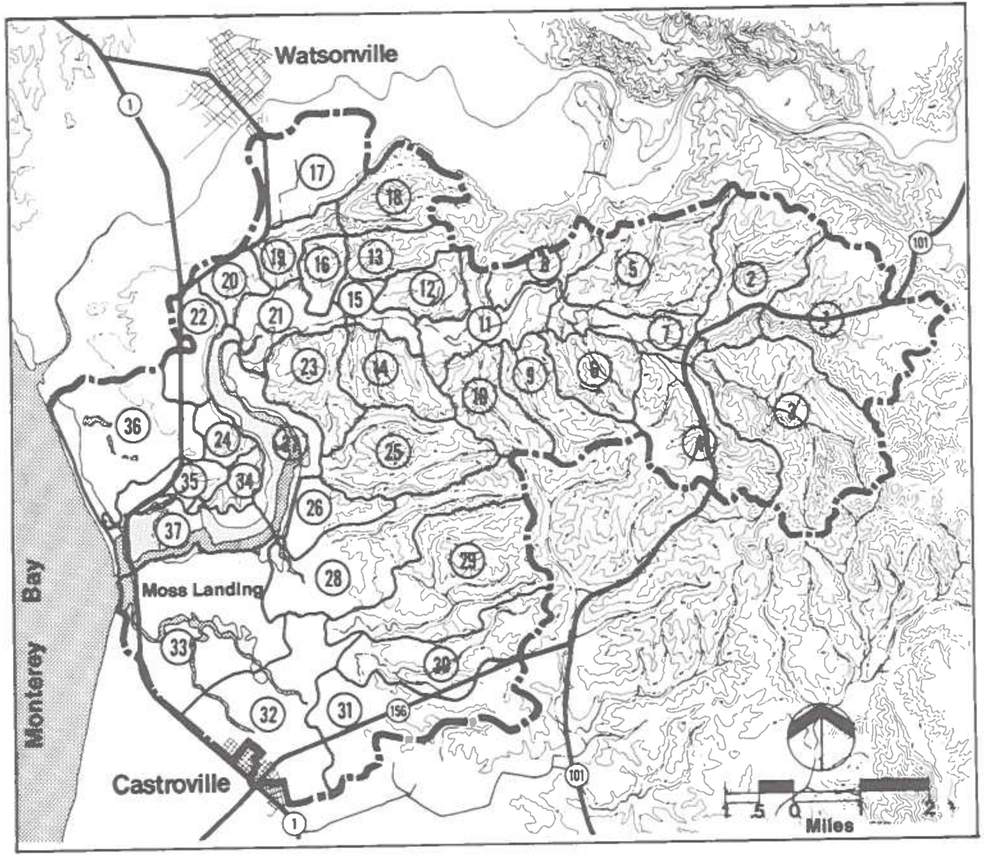


FIGURE 1. Elkhorn Slough watershed and subwatershed boundaries.

by-site basis, but accounts for the cumulative effects of development within an entire watershed.

The planning system for the 182-square-kilometer Elkhorn Slough watershed consists of two components: land disturbance targets (Figure 2, and as explained in the following paragraph) developed for 37 sub-units of the watershed, and an erosion susceptibility map portraying the relative erodibility of lands within the watershed. The intent of the erosion susceptibility map and land disturbance targets is to account for the cumulative effect of both urban and agricultural development within the entire watershed system. Using these analytical tools, it will then be possible to review on a project-by-project basis the contribution of a single development to cumulative effects within the entire watershed area. A detailed description of the planning system is presented in Dickert and Tuttle (1985).

Figure 2 illustrates the existing and potential land disturbance within the watershed area. The diagram shows subwatersheds on the *x* axis and the amount of land disturbance (as a percent of subwatershed area) on the *y* axis. The amount of land disturbance is estimated by summation of the products of the bare ground multiplier (Table 1) and the acreage of each land use. The land disturbance target is the maximum amount of bare ground present in the subwatersheds at any point within the period 1931–1981.[3] The amount of bare ground was measured from six sets of aerial photographs covering the years 1931, 1949, 1956, 1966, 1971, and 1980. Land disturbance is estimated for three conditions: (1) existing land uses; (2) full buildout to existing zoning;[4] and (3) land disturbance under the proposed Monterey County Local Coastal Program. As can be seen, the development levels initially proposed by the Monterey County LCP would exceed the land disturbance targets in 25 of the 37 subwatersheds. As a result of this analysis, the LCP was later revised to conform to the land disturbance targets illustrated in Figure 2.

Methods for Assessment of Erodibility

Erosion of the landscape is a function of variation in natural landscape and land use. Characteristics of the landscape, such as

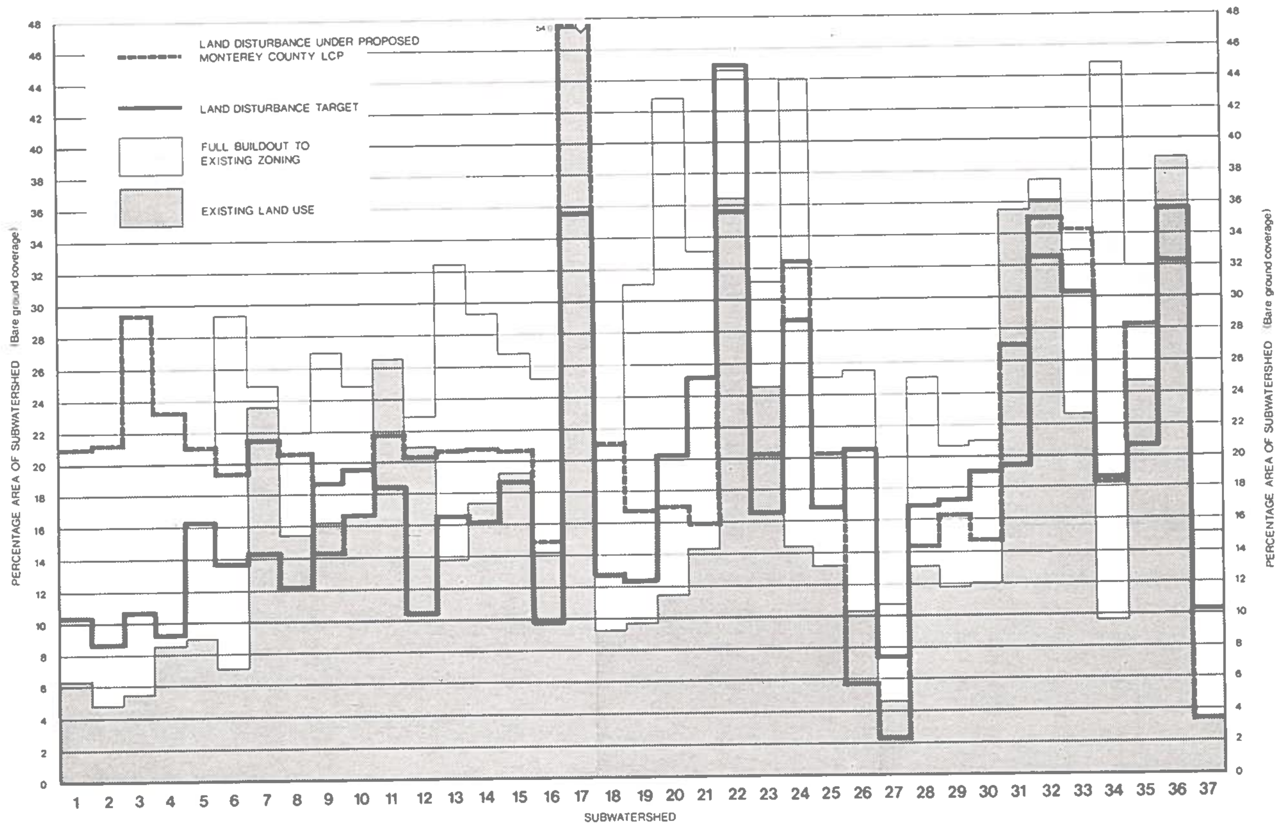


FIGURE 2. Land disturbance targets. Subwatershed and percentage bare ground coverage.

Table 1
Bare Ground Index for Land Uses in the Elkhorn Slough Watershed

Land Use	Bare Ground Exposure Mean (Standard Deviation) % of Parcel Area
Brush	6.0 (8.7)
Oak Woodland	1.1 (1.1)
Eucalyptus	3.2 (4.8)
Pasture; Grassland	6.5 (6.5)
Rowcrops; Artichokes	63.1 (19.2)
Strawberries	69.5 (13.6)
Orchards	93.2 (2.5)
Commercial	51.4 (28.5)
Industrial	48.2 (42.0)
Residential Uses:	
51 acre parcel and greater	9.6 (5.3)
31 to 50 acre parcel	7.9 (6.0)
15.5 to 30 acre parcel	13.2 (6.3)
10 to 15.4 acre parcel	8.1 (4.8)
5 to 9.9 acre parcel	9.9 (10.6)
2.4 to 4.9 acre parcel	3.8 (4.1)
1 to 2.3 acre parcel	14.7 (9.1)
0.5 to 0.9 acre parcel	19.5 (19.0)
0.2 to 0.4 acre parcel	10.8 (1.1)
0.1 acre lots	11.4 (7.1)
Less than 0.1 acre parcel	51.4 (12.8)

Source: Dickert and Tuttle, 1981.

soil, slope, and bedrock, define the susceptibility of the land to erosion. Surface disturbance, from human land uses, instigates accelerated erosion. The purpose of our analytic work was to examine the relative effects of land use and natural landscape on erosion in the Elkhorn Slough watershed, and to develop an index of erosion susceptibility of the natural landscape. Ideally, the approach would account for the relative erosion resulting from each combination of land use and landscape type.

Land Use. The most widely used method to predict soil erosion rates is the Universal Soil Loss Equation (Wischemeier and

Smith, 1978).[5] Land use is represented in this method by the cropping factor (C factor). This factor expresses the expected soil loss under a vegetation cover type as a percentage of the expected soil loss when unvegetated. Although some work has been done to derive C values for the western states (Evans and Kalkanis, 1977), the work has focused primarily on agricultural uses and not on many of the land uses present within urbanizing watersheds. In urbanizing areas, parcel size is most often the major criterion used by local governments in establishing land-use categories and developing zoning ordinances. Therefore, we chose to devise a method that reflects both cover characteristics (similar to the C factor of the USLE) and parcel size for determining the disturbance effects of various land uses in the Elkhorn Slough watershed.

We measured the effect of land use with a "land disturbance index." This index is designed to describe the impact of a land use on the natural hydrologic processes of the watershed. The most obvious such disturbances are creation of impervious surfaces by pavement and structures, and exposure of bare ground (see Dickert and Tuttle, 1985). Each disturbs the downstream sediment balance: the former by increasing the erosive power of stormflows, and the latter by directly exposing erodible soils. Bare ground exposure is the best measure of land disturbance in the Elkhorn Slough watershed since it is a rural area with a mix of urban and agricultural land uses (Bean, 1981). Bare ground was measured through stratified random sampling of land uses from aerial photographs. This approach does not account for seasonal variation in vegetation cover but measures the worst case represented by the October–April rainfall period. Table 1 shows mean percent bare ground exposure for each land use category.[6]

Erosion Susceptibility. We examined three ways of measuring erosion susceptibility. The first method is the easiest to apply, being based on existing data from the Soil Conservation Service. This index is based on a combination of slope classes and the soil erodibility factor (k factor) of the Universal Soil Loss Equation (Wischmeier and Smith, 1978), and is shown in Figure 3. The k factor is an expression of the inherent erodibility of the soil, and is measured in the field on nine percent, fallow slopes. The classes of our index range from A through J, with A being the least erodible. Given limited field data, this is the most practical method for planning agencies to use, as it depends only on having a slope map and an existing soil survey. This is the method used in the Monterey County Local Coastal Program; classes D, G, H, I, and J are classified as "critical erosion areas" in which further land conversion will be controlled.

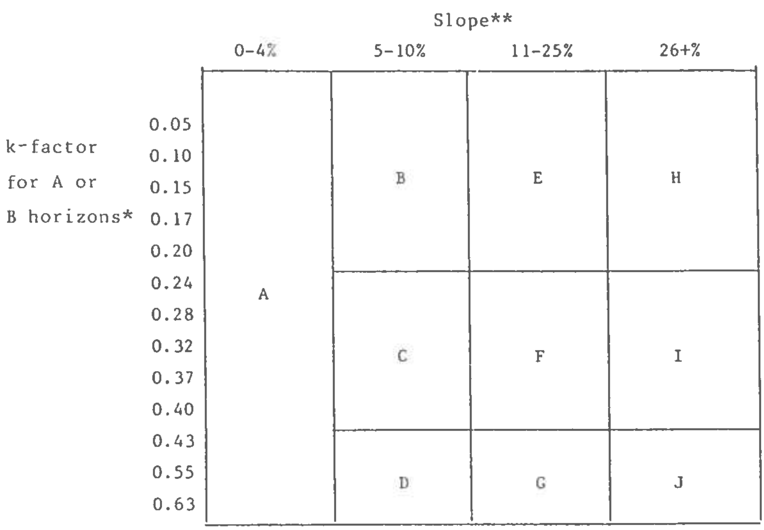
Although the erosion susceptibility index is a practical measure that can be computed with usually available data, it has limitations (Wischmeier, 1976). The USLE is based primarily on work done in the agricultural Midwest. For most soils in other areas, such as California, *k* factors are not determined in the field, but rather by a nomograph.[7] Wischmeier (1976) warns against extrapolating factor relationships far beyond the range of the data from which they were derived. Thus, caution should be used in applying nomograph values to soils that occur primarily on steep slopes, such as those in the canyon areas of Elkhorn Slough watershed. There is also some field evidence that values derived directly from the *k* factor nomograph may not be well suited to California upland soils (Trott and Singer, 1983).[8]

The second method involved field measurement of erosion and deposition on 30 selected sites in the watershed. These sites were selected to represent the various combinations of slope, soils, vegetation, and land uses present in the Elkhorn Slough watershed. The field data confirmed that land use is the most important determinant of erosion (discussed below); this effect was so large that it obscured the relative contribution of natural landscape characteristics.

The third method consisted of a watershed-wide analysis of data from secondary sources. Using the concept of terrain analysis, the landscape was classified into discrete "landform types" (Stewart, 1968; Hills, Love, and Lacate, 1970; Ellen, Peterson, and Reid, 1983). This classification assumes that areas of similar landform are created by similar geologic processes. Therefore, in terrain analysis, each terrain class represents a unique assemblage of geomorphic processes. The simplest type of terrain analysis divides the landscape into erosional and depositional landforms (Brown and Jackson, 1974). More complex classifications would further subdivide these erosional and depositional characteristics. Thus, landform types can serve as erosion susceptibility units in the Elkhorn Slough watershed. Our classification was performed using factor and cluster analysis of geographically-based data on soils, slope, and geology (Gordon, 1978). Although the initial analysis is complex, the resulting map of landform types can easily be incorporated in a planning system.

Data Analysis of Erosion Susceptibility

Our research on the erosion susceptibility assessment methods consisted of analysis of a combination of field and geographic data. The analysis consisted of four major components: (1) tabulation and analysis of field measurements of erosion/deposition; (2) compilation and aggregation of geographic-based data from secondary sources; (3) computer-aided analysis of the geographic data and classification of the landscape into landform



*Both the A and B horizons were rated individually, in order to account for grading or soil removal operations which may invalidate the rating for the A horizon alone.

**Slope categories were defined on the basis of typical cross-sectional areas in Monterey County ordinances for residential access roads and streets.

FIGURE 3. Erosion susceptibility index, based on slope and *k* factor.

types; and (4) ranking of landform types based on field measurement.

Field Measurement. Dickert and Tuttle (1981) reported field evidence of upland erosion in the Elkhorn Slough watershed, primarily as a result of poor agricultural practices. Significant amounts of sediment are being transported in the major streams, which ultimately deposit this material in the upper margins of the Slough.

Erosion was measured using the method of erosion pins (Gleason, 1957; Leopold, Emmett, and Myrick, 1966).[9] Erosion pins were placed in 52 transect lines at 30 selected sites near the slough margin and in other locations throughout the watershed. Some sites were selected to measure sheet and rill erosion activity on slopes, while others measured deposition and erosion activity at the base of slopes. The field sites compared erosion from undisturbed "natural" sites with that from localized effects of disturbance by machinery, cultivation, or urban development.

Measurements of annual total erosion and deposition were taken in late spring and early summer of both 1979 and 1980, following the winter storm cycle of each year. Mean erosion and deposition for each site were summed to create an "activity value"; a site with high erosion and later redeposition would show a high "activity," although only minimal net erosion.

For analysis, sites were divided into three slope categories (0–10 percent, 11–45 percent, and 46–100 percent) and three textural soil types (type 1 includes clay loams, clays, and silty clays; type 2, loams and sandy clay loams; type 3, loamy sands). Mean sediment activities of transects are arranged by slope and soil types in Table 2 to show the effects of slope and soil on erosion and deposition. They are broken down by slope and soil type of both the site and the primary upslope source of the sediment. Among low slope sites, those with steeper sources show much greater activity (primarily depositional) than do those with sediment sources of low slope. The high slope sites show lower activity than the low slope sites; this may be partly because many of the high slope sites are also the least disturbed by development. Our data are more effective at predicting deposition than

Table 2

Erosion, Deposition, and Sediment Activity as a Function of Slope, Soil Type, and Land Influence

Site Slope	Source Slope	No. of Sites	Erosion (cm) (std. dev.)	Deposition (cm)	Activity (cm) (Erosion + Deposition)
Low	Low	3	0.04 (0.07)	0.00 (0.00)	0.04 (0.07)
Low	Moderate	5	1.14 (2.21)	1.52 (2.51)	2.66 (4.72)
Low	High	7	0.81 (0.48)	3.43 (2.59)	4.24 (2.90)
Moderate	Moderate	5	0.79 (0.66)	0.38 (0.25)	1.17 (0.74)
High	Moderate	1	0.99	0.25	1.24
High	High	12	0.69 (0.56)	0.58 (0.89)	1.27 (1.04)

Site Soil	Source Soil	No. of Sites	Erosion (cm) (std. dev.)	Deposition (cm)	Activity (cm)
Type 3*	Type 3	11	0.30 (0.36)	0.51 (0.86)	0.81 (0.84)
Type 2	Type 2	13	0.79 (0.63)	0.71 (1.12)	1.50 (1.30)
Type 1	Type 1	1	0.66	0.96	1.62
Type 1	Type 2	4	1.73 (2.31)	2.56 (2.69)	4.29 (4.93)
Type 1	Type 3	4	0.89 (0.38)	3.66 (3.63)	4.55 (4.01)

Influence Type	No. of Sites	Activity (cm) (std. dev.)
Natural vegetation	6	0.53 (0.61)
Agriculture, pasture	6	0.38 (0.28)
Agriculture, cultivated**	6	3.40 (3.84)
Agriculture, other disturbed**	3	6.50 (3.33)
Urban, vegetated	2	0.69 (0.79)
Urban, disturbed**	10	1.96 (1.14)

*Soil types are based on texture. Type 3 being the coarsest.

**"Disturbed" influence types.

erosion, probably reflecting a bias in the original selection of sites; it was easier to gain access to a location below a disturbed field than to the eroding field itself. The data are not conclusive about the effect of soil type in influencing erosion/deposition activity.

Land influence type (Table 2) describes the land use that most influences the sediment regime on each site. In general, the results support the conclusion that sediment activity is much greater at sites with disturbed rather than undisturbed ground surfaces. However, the numbers are only relative measures of sediment activity as they do not account for size of sediment source area. In our field data the significance of soil type and slope has been masked by the stronger effects of the land-use influence types. Development activity affects erosion to a much greater extent than does variation in the natural landscape.

Regression Analysis of Field Measurements. We then performed linear regression analyses with the erosion pin data, in an attempt to determine the effects of the natural factors (soil, slope) on erosion and deposition. In our model, erosion and deposition were the dependent variables; and slope, soil, land use (expressed as dummy variables of land influence type), and erosion susceptibility class (an ordinal variable, treated as intervally scaled) were independent variables. Slope and soil type were not statistically significant predictors of erosion or deposition; partial correlations of these variables, controlling for land use, were not significant.[10]

The regression results did not add much information to the analysis shown in Table 2. It merely confirmed several limitations of the field data: (1) the low correlations suggest that a large part of the variance in the data is due to the small-scale variations of slope, soil texture, and vegetation within each transect; (2) natural factors such as soil and slope are correlated with each other, so it is difficult to separate the effects of these variables; and (3) the analysis was limited because it could not include the full range of soil types in the watershed.

Geographic Data Base Aggregation. The Elkhorn Slough watershed geographic data base consists of 17,994 hectare-size grid cells. Each cell contains such information as bedrock geology, soil type, soil *k* factor, slope, overland flow distance, and land use. The data were compiled from existing geologic reports, soil surveys, topographic maps, and aerial photography.

The geologic and soil units were initially aggregated into fewer categories to simplify the quantitative land classification. They were then ordinally ranked, based on inherent erodibility.[11] Twenty-six geologic units (Dupre, 1975; Tinsley, 1975) were reduced to 13 units, primarily by combining similar bedrock types. They were ranked, based on relative degree of consolidation and silt content (Table 3). Fifty-three soil units (U.S. Soil Conservation Service, 1978) were grouped into 22 units and ranked, in order of importance, according to: (1) Soil Conservation Service erosion hazard rating; (2) drainage class; (3) physiographic location; and (4) texture (Table 4).

Computer-Assisted Terrain Analysis. Factor analysis, using the FACTOR routine of the SAS (Statistical Analysis System) package, was performed on four variables in the geographic data base: ranked soil units, ranked geologic units, *k* factor, and slope. After rotation of the factor pattern matrix by the varimax method, three factors explained 88.5 percent of the variance of the data. Standardized factor scores were computed for all the 17,994 data cells, and these three new variables, each having equal weight, became inputs for the subsequent clustering procedure.

Cluster analysis was applied to the factor scores, using the FASTCLUS procedure of SAS, to find groups of similar data cells. Hartigan's mean square ratio test (Hartigan, 1975) was used as a guide, in conjunction with our judgment, to find the optimal number of clusters (MacQueen, 1967). Using a 672-cell sample of the data, we found that the optimal number of clusters was twelve. Because the clustering algorithm in FASTCLUS is sensitive to the sorting of the data, the clustering procedure was applied to the entire data set for 13 different sortings of the data. Among the results of the 13 sortings, we selected the partition that minimized the sum of distances of points from their cluster centers. The 12 clusters in this partition defined the landform units.

Analysis of the results showed that the procedure differenti-

Table 3
Geologic Units—Aggregated and Ranked*

Rank**	Name	% of Watershed
1	Igneous/metamorphic rock	3.0
2	Sandstones	5.0
3	Terrace deposits of Antioch	6.5
4	Older eolian deposits	6.3
5	Aromas sand	26.7
6	Terrace deposits	13.6
7	Eolian deposit of Manresa Beach	4.4
8	Dunes	1.4
9	Basin deposits	11.1
10	Alluvium	6.4
11	Floodplain deposits	1.7
12	Colluvium	10.3

*Geologic units were ranked based primarily upon degree of consolidation. Similarly consolidated units were distinguished by silt content (i.e., more silt rich units are assumed to be more erodible).

**Units ranked and listed from least to most erosive.

ated the landform units based on all four original variables. Each of the 12 landform units is a unique and significant combination of the variables, representing a specific land type that has surficial characteristics different from any other land type (Table 5). This method effectively deals with the problem of interrelated variables; minor distinctions are subsumed into a more significant global variable.

Landform Ranking. Nine of the twelve landform units had erosion pins located within them. Erosion and deposition on each site are a function of both landform and land use. The effect of land use is measured by the bare ground index (Table 1). If we assume that exposed bare ground area is linearly related to erosion, the relative erosion and deposition of a given land use on a specific landform unit can be estimated by

$$(1)\ \text{erosion susceptibility of landform} = \frac{\text{measured erosion}}{\%\ \text{bare ground}}$$

$$(2)\ \text{deposition susceptibility} = \frac{\text{deposition}}{\%\ \text{bare ground of sediment source}}$$

These quantities are tabulated in Table 5 for the nine landforms represented by field data sites. The data appear to confirm that the field observations are biased toward the measurement of deposition rather than erosion. For example, depositional landforms, such as basins and low slope alluvial areas, are not as "erosive" as the table suggests; erosion was measured on them because the sediment that was being deposited was extremely mobile.

The field data, together with the SCS erosion hazard ratings, suggest a ranking of the landforms by susceptibility to erosion (Table 6).[12] Thus, this analysis demonstrates a method of developing erosion susceptibility maps. The landforms, ranked with the aid of field data, can be used as erosion susceptibility units in a land-use planning system.

Conclusion

Coastal land-use programs must develop better means for relating the intensity and location of land use to impacts on wetland areas, since many wetlands are becoming degraded because of erosion from the watershed. The difficult problem investigated in this paper is the use of analytical means to define indicators that can express potential impacts in terms of easily measured quantities. Such indicators must be expressed in a way that can be linked directly to land-use intensity measures normally used in local government development review (e.g., units/acre, land coverage, etc.). As a result of our analysis, the concepts of bare ground exposure and critical erosion areas have been adopted in Monterey County's Local Coastal Program (LCP). Since the field data collection was limited by the legislatively defined plan preparation deadline, the planning system was designed to be revised as additional data become available.

Land use and natural landform are the two prime determinants of relative erosion in coastal watersheds. We found that land-use intensity, irrespective of its physiographic location, is the most important factor causing erosion in the Elkhorn Slough watershed. We examined three ways of mapping erosion susceptibility in ways that reflect land-use intensity:

Table 4
Soil Types, Aggregated and Ranked*

Rank**	Description	% of Watershed
1	Clay, clay loam; poorly drained, floodplains or basins	3.0
2	Silty clay loam; very poorly drained; basins and tidal flats	8.2
3	Sandy loam; well-drained; on hills and mountains	1.1
4	Clay; well-drained; uplands	2.2
5	Clay loam; well-drained; hilly uplands	1.5
6	Loamy sand; excessively drained; on fans or old dunes	1.7
7	Loamy sand; well-drained; uplands	3.8
8	Loam, sandy loam, silt loam, sandy clay loam, gravelly loam; well-drained; alluvium, fans, river terraces	2.0
9	Silty clay; well-drained; terraces, fans, floodplains	1.0
10	Fine sandy loam; moderately well-drained; terraces, alluvium	16.1
10	Fine sandy loam; well-drained; marine terraces, sandy sediments	12.6

- *Universal soil loss equation* k *factor*. This is the simplest and least expensive method. It depends only on the availability of a soil survey for the area. Use of the nomograph-derived k factor values in steep watersheds in western coastal states is problematic. The method does, however, provide one means to proceed where it is not possible to collect field data.
- *Field measurements of erosion and deposition*. Measurement of selected sites can document the actual erosion characteristics of local soils, slopes, and land uses. In West Coast watersheds with irregular topography and steep terrain, these measurements are potentially more revealing than nomograph-derived k factors. Ideally, one would systematically establish long-term soil plots, but the associated time and expense are inappropriate for land-use plans with legislative deadlines. However, without a field program, it is diffi-

Table 4 *(continued)*

Rank**	Description	% of Watershed
10	Loamy sand, sandy loam; moderately well to excessively drained; terrace remnants, hilltops	3.0
13	Silt loam, silty clay loam, clay loam, fine sandy loam; well-drained; uplands	1.9
13	Loamy sand; excessively drained; hills and uplands	30.0
15	Acquic xerofluvents; poorly drained, stratified; alluvium, floodplains	0.9
15	Sedimentary rock land; thin soils	0.8
17	Shaly loam, shaly clay loam; excessively drained; uplands	0.4
18	Clay loam; well-drained; steep uplands	4.2
19	Loam; moderately well-drained; alluvial terraces	2.1
20	Rocky clay loam, sandy loam; well-drained; uplands, hills, and mountains	1.3
—	Dunes; well-drained	0.1
—	Xerorthents; well-drained; steep bluffs or river banks	0.1

*Soil types were ranked based upon SCS erosion hazard rating, drainage class, physiographic location, and soil texture.

**Units ranked and listed from least to most erosive.

cult to predict site-specific results reflecting the relative erosion rates for every combination of slope, soils, vegetation, geology, and physiographic location. The predictive ability of this method improves when used together with knowledge of the geomorphic characteristics of the landscape.

- *Terrain analysis.* This approach has the same advantage as the field measurement method, in that it is based on local conditions. Using this method the landscape is classified into characteristic landform types, according to erodibility. Landform types can then be a basis for describing relative erosion susceptibility of the natural landscape. We used a computer-aided technique of terrain analysis. One limitation of this method is that the classification is sensitive to initial assump-

Table 5
Erosion and Deposition, Adjusted for Land Use, Measured on Each Landform Type

	Landform*	Watershed %	Number of Transects	i: Erosion ÷ Site bare ground (cm)	ii: Deposition ÷ Source bare ground (cm)	Activity (cm) (Columns i + ii)
A	Aromas sands, terraces, uplands; moderate slopes, *k* factors, and textures	10.8	9	14.02 (3)**	10.69 (6)**	24.71 (5)**
B	Steep upland sandstones, shales, plus some Aromas sand	5.4	none			
C	Basins, bluffs, riverbanks, terraces; high *k* factor, low slope	0.5	1	0.00 (9)	0.00 (9)	0.00 (9)
D	Low slope, low *k* factor, dunes or basins	2.3	2	28.14 (1)	46.53 (3)	74.67 (2)
E	Santa Ynez fine sandy loam, terraces, low to moderate slope	16.4	8	11.73 (5)	2.46 (8)	14.19 (7)
F	Aromas sand, Arnold loamy sand, steep	8.8	7	14.05 (2)	11.33 (5)	25.38 (4)
G	Very steep loamy sands, shaly loam	0.6	none			
H	Basins and floodplains, clay loams, poorly drained, moderate to high *k* factor	10.9	2	3.56 (7)	48.39 (2)	51.95 (3)
I	Low slope, Elkhorn fine sandy loan and Santa Ynez fine sandy loam	13.1	7	6.93 (6)	11.40 (4)	18.33 (6)
J	Steep igneous and metamorphic outcrop areas	0.2	none			
K	Aromas sand, Arnold loamy sand, moderate slopes	18.2	4	0.76 (8)	4.17 (7)	4.93 (8)
L	Arnold loamy sand on colluvium and alluvium, moderate slopes	12.7	12	13.46 (4)	212.50 (1)	225.96 (1)

*Landforms were defined by cluster analysis of slopes, soils, and geologic units in the watershed.
**Rank within column.

Table 6
Suggested Erosion Susceptibility Ranking of Landform Units, Elkhorn Slough Watershed

	Landform	Rank*
C	Bluffs, terraces, high *k* factor	1
H	Basins, floodplains, clay	1
D	Low slope, low *k* factor, basins	1
I	Low slope, fine sandy loam, depositional	4
E	Fine sandy loam, terraces, low slope	5
K	Aromas sand, Arnold soil, med. slope	6
L	Arnold soil, colluvium, med. slope	6
A	Upland sands, terraces, med. slope	6
F	Aromas sand, Arnold soil, steep	9
J	Steep igneous/metamorphic	10
B	Steep upland sandstones, shales	10
G	Aromas sand, Arnold soil, very steep	12

*Units ranked and listed from least to most erosive.

tions of relative weight of the variables. Furthermore, this method can not stand alone; landform definition and ranking are aided by the results of field measurements.

A watershed-wide land-use planning system is the most effective way to mitigate wetland sedimentation. To implement such a system, planners must have some means of evaluating the relative erodibility of the landscape linked to the hydrologic impacts of land uses. The North Monterey County plan uses a simplified method based on slope and *k* factor. Future studies could use a combination of terrain analysis and field measurements, as described in this paper. These methods would be particularly appropriate in areas of complex geomorphic processes where the USLE may be of limited applicability. Terrain analysis should be used to initially classify the landscape; then, field sites should be selected based on this classification. Field measurements over at least one full season can then be used to assess the relative erosion rates of the land uses and landforms in the watershed. With this information local governments can implement plans that would direct erosive land uses to the least sensitive parts of the watershed.

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Notes

1. Where the predominant land use is rural residential, planning studies have commonly used a one to ten acre minimum parcel size based upon the assumption that this parcel size would mitigate the effects of increased intensity of development.

2. The Coastal Act requires "special protection be given to areas and species of special biological significance" (Sec. 30230), and requires maintaining "the biological productivity and quality of coastal waters, streams, wetlands, estuaries, and lakes appropriate to maintain optimum populations of marine organisms and for the protection of human health . . ." (Sec. 30231).

3. The maximum amount of bare ground present during the time series period was used as the target value because of the lack of quantitative biological data. With such data a threshold value could be based upon a predicted level of resource loss.

4. Estimation of full buildout assumes that all parcels will be developed to the maximum intensity allowed by existing zoning. Although it may not reflect the level of development which will result from present or future market conditions, it is an important concept in establishing a baseline for cumulative impact assessment.

5. The Universal Soil Loss Equation is: A = RKLSCP; where A = soil loss (in tons/acre); R = rainfall erosivity index; K = soil erodibility index; L = hillslope length factor; S = hillslope gradient factor; C = cropping management factor; and P = erosion control practice factor.

6. Although extensive work has been done over the years to compile estimates of impervious surface area for various land-use types (for example, see Tourbier, 1973), bare ground values have generally been compiled only for agricultural land-use categories.

7. The nomograph is a graphical method for determining *k* factor based on particular soil characteristics including: silt and sand content, percent organic matter, soil structure, and permeability. Typical *k* values are: .28–.69 for silt loams, .26–.32 for clay and clay loams, .22–

.28 for sandy loams, and .08–.10 for loamy sands (Wischmeier and Smith, 1978).

8. In general, caution must be used in extrapolating values to other terrains that may be dominated by different geomorphic processes. The USLE was developed for agricultural areas dominated by sheet wash and rill erosion. Steep western watersheds are often dominated more by gully erosion which is not addressed by the USLE. Some researchers have further suggested that the dominant hillslope evolution process in the Pacific Northwest may be landslides in thick colluvial deposits (Dietrich and Dorn, 1984).

9. This method involves placing pins into the soil so that they are flush with the ground surface. Erosion and deposition can later be measured over any time interval as the difference between the top of the pin and the present ground surface.

10. Several of the dummy variables representing land influence type were statistically significant, producing the following equations:

$$\text{erosion} = f\,(\text{agriculture-pasture, natural vegetation})\ R^2 = .178$$

$$\text{deposition} = f\,(\text{agriculture-disturbed, agriculture-cultivated})\ R^2 = .418$$

$$\text{activity} = f\,(\text{agriculture-disturbed, agriculture-cultivated, urban-disturbed})\ R^2 = .442$$

11. The reason for the ranking was to ensure that units with similar erosion characteristics would be grouped together. The classification method is based on Euclidian distances and treats ordinal-scaled data as if they were intervally scaled. Thus, every landform type created by this method will be composed of several closely-related soil and geologic units.

12. The limited field data cannot in themselves be used as a basis for ranking erodibility of the landform units. Table 6 was derived in part from the erosion rankings in column i of Table 5; however, the erosion hazard ratings as well as common sense suggest that the low slope depositional landforms, D, E, I, and H, have unrealistically high "erosion" measurements. For these four landforms the suggested rankings are based on the SCS erosion hazard ratings for the dominant soil type of each. This method was also used to rank landforms G, B, and J, for which we had no field measurements. Only the rankings of landforms F, A, L, K, and C could be based primarily on the field measurements.

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