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A Coastal Wetland Watershed Example

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CUMULATIVE IMPACT ASSESSMENT IN ENVIRONMENTAL PLANNING

A COASTAL WETLAND WATERSHED EXAMPLE

THOMAS G. DICKERT AND ANDREA E. TUTTLE

Several theoretical, analytical, and institutional difficulties have impeded the development and application of the assessment of cumulative environmental impacts. Watershed development on coastal wetlands offers an ideal context for evaluating the land disturbance target approach to cumulative impact assessment. A model land use planning system involving a time series approach was developed for Elkhorn Slough in California. The approach included four major components: evaluation of erosion susceptibility, measurement of land disturbance, establishment of a land disturbance target, and a comparison of existing and target land disturbance values. Further research is needed to test the transferability of the approach in a wide range of coastal watersheds and to verify the applicability of the methods to other cumulative impact problems.

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During the past decade, the major portion of environmental assessment practice has consisted of the case-by-case appraisal of the impacts of separate development actions. In focusing on case-by-case impact assessment, we have lost sight of

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the broader and often more critical cumulative impacts of these individual projects. Planning programs, such as those begun under the Coastal Zone Management Act and related state legislation, offered new opportunities to use plan making as a means to consider cumulative effects.

The effective management of cumulative impacts is a complex problem that is frustrated by many theoretical, analytical, and institutional difficulties. Certain aspects of this topic have been discussed in the literature under the various headings of "carrying capacity analysis" (Conservation Foundation 1975; Godschalk 1977; ULI 1977), "environmental impact assessment" (Schaenman and Muller 1974; Jain et al. 1981), and evaluations of land use and environmental planning programs (Healy 1978; Scott 1981). However, there has been no comprehensive treatment of the topic in the literature. In reviewing more than 25 texts concerning methods for environmental impact assessment, we noted that only three included the term "cumulative impact" in the index, and of these only one discussed the question beyond the definition stated in the National Environmental Policy Act (NEPA) guidelines.[1]

The specific problems of cumulative impact assessment are described here in the context of planning for the land use related impacts of watershed development on coastal wetlands. This context is ideal for understanding the strengths and assumptions inherent in the land disturbance target approach as implemented in the Elkhorn Slough watershed, Monterey County, California.

The Elkhorn Slough case study illustrates methods for assessing the cumulative effects of erosion and sediment deposition in a wetland watershed system. Hydrologic processes of streamflow and sediment movement are perhaps the single most significant processes linking uplands to wetlands, and are processes that are influenced in a local planning program through the designation of land use type, location, and intensity. A method is presented to incorporate this information into a planning approach that local governments can use to assess the potential cumulative impact of upland development on a watershed basis, and to review on a project-by-project basis the contribution of each development project in relation to its cumulative effect on the entire watershed. The planning method uses a modified threshold approach in which the threshold is based on an assumed acceptable amount of land use change over time, as measured by historic rates of land use change, rather than an intrinsic ecosystem tolerance.[2]

[1]The 25 texts were purported by their titles to be manuals, handbooks, primers, or reviews of "environmental assessment." Bendix and Graham (1978) and Corwin and Heffernan (1975) limited discussion to NEPA guideline language in defining cumulative impact. Jain et al. (1981) contains a two paragraph discussion about the complexities of dealing with cumulative impacts (pp. 69–70).

[2]The concept of relating land use to intrinsic ecosystem tolerance originates with the work on land suitability and capability analysis. See, for example, Christian and Stewart (1953), McHarg (1968), Hills (1970).

DEFINITION OF CUMULATIVE IMPACTS

The use of the term "cumulative effect" dates from as early as 1928 in the hydrologic literature (Shephard 1928). In NEPA and similar state legislative guidelines, cumulative impacts are generally defined as the effect of a specific action when added to past, present, and proposed actions.[3] Thus, cumulative impacts are those that result from the interactions of many incremental activities, each of which may have an insignificant effect when viewed alone, but which become cumulatively significant when seen in the aggregate. Cumulative effects may interact in an additive or a synergistic way, may occur onsite or offsite, may have short-term or long-term effects, and may appear soon after disturbance or be delayed. An often important characteristic is the nonlinear rate of response to a linear increase in stress. This particularly holds true for hydrologic processes, where a change in land surface condition, such as paving, can result in a nonlinear increase in peak flow transporting sediment downstream at a geometrically increasing rate (Leopold 1981).

A key attribute characterizing cumulative impacts is the concept of the threshold (Kozlowski and Hughes 1972). Although the effect of an individual project is negligible, or can be made negligible through mitigation, it is when the combined effects of several projects exceed a threshold that significant environmental damage may become evident. Either an incremental or comprehensive approach to development review may be used to maintain cumulative effects below the threshold level.

In the incremental approach, projects are reviewed on a case-by-case basis on their merits without reference to other projects and without a priori knowledge of the system capacity. Case-by-case review continues until some impact becomes evident. At this point the options are to halt further projects, ignore the impact and continue project approvals, or in some way modify additional projects to avoid the impact.

The alternative strategy is a comprehensive approach where extensive field testing establishes the capacity of the system before project approvals are given. The rate or total amount of development is managed to stay below prestated threshold levels, and halted when such thresholds are reached. While this represents a logical approach, it is fraught with the technical difficulties of establishing system thresholds.

[3]Guidelines for the National Environmental Policy Act define cumulative as: "The impact on the environment which results from the incremental impact of the action when added to other past, present and reasonably foreseeable future actions regardless of what agency (Federal and non-Federal) or person undertakes such other actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time." (40 CFR §1508.7). Similarly, guidelines for the California Environmental Quality Act define cumulative impacts as: ". . . two or more individual effects which, when considered together, are considerable or which compound or increase other environmental impacts." (14 Cal. Admin. Code §15023.5; 5 Cal. Pub. Res. Code, §21083)

CUMULATIVE IMPACTS WITHIN NATURAL SYSTEMS

The documentation of cumulative impacts occurring within ecological systems is frustrated by four recurrent fundamental issues: defining the relevant system and its spatial boundaries; identifying system thresholds; capturing the episodic event in the historic record; and separating natural from human-induced impacts.

Identifying the Relevant System and Its Boundaries

The assessment of cumulative impacts requires that the system of cause and effect linkages be identified and the appropriate geographical boundaries used in defining the planning zone. For example, the logical analytical unit for assessment of hydrologic processes is the watershed. More arbitrary criteria are needed for systems that do not have clear physical boundaries, such as air basins, or service areas for public access to coastal resources. Here boundary identification may be an iterative process, requiring adjustment as new information on cause–effect interactions is obtained.

A well-recognized institutional albatross is the usual lack of conformance between the boundaries of natural systems and governmental jurisdictions (Clark 1977; Dickert and Sorensen 1978). This frustrates both data gathering and plan implementation. Implicit in federal and state coastal zone legislation was the intent to plan for coastal resources that often span local jurisdictions.[4] These programs provided a new opportunity to design coastal planning units that reflect the appropriate boundaries for cumulative impact assessment, such as the watershed, viewshed, or public facility service areas. Unfortunately, in most cases, coastal zone management boundaries simply added one more jurisdictional overlay that failed to reflect relevant physical systems. Planning zones were established according to arbitrary criteria of distance from a tideline (Michigan, Maine), entire coastal counties (Texas, Virginia), land subject to marine influences (Florida), or sometimes whatever was politically expedient (Robbins and Hershman 1974). For example, California's coastal zone generally stretches 1,000 yards inland, but it has "bumps" reaching farther inland to encompass some critical wetlands and estuaries and "dents" shrinking the zone in built-up urban areas (Healy 1978). The bumps, however, still do not incorporate the entire watersheds of those critical areas, being limited by a five-mile inland extent originally defined in the citizen initiative.[5]

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[4]The California Coastal Act contains a broad mandate to plan for coastal resources including: environmentally sensitive habitat areas (§30240), wetlands and intertidal habitats (§30231), agricultural lands (§30241, 30242), and the scenic and visual qualities (§30251).

[5]The citizen initiative on the ballot in November 1972 established the California Coastal Commission. The planning area established in the initiative included the area between the three-mile limit and the ridge of the first inland mountain range or five miles, whichever was less. The initiative defined a much smaller permit zone extending from three miles at sea to 1,000 yards inland from the mean high tide line.

While a coastal strip may be satisfactory for linear integration of shoreline facilities, the arbitrarily defined strip still frustrates planning for physical and natural systems that extend inland beyond the coastal zone management area. Subregional planning, based on the physical extent of cumulative impact boundaries (e.g., watersheds, viewsheds, public facility service areas, etc.) that span local jurisdictions, would provide one means to consider cumulative impacts (Dickert and Sorensen 1978).

Determining System Thresholds

A second problem concerns the difficulty of an a priori determination of system thresholds. In theory, a cumulative impact becomes evident only when the accumulation of individually insignificant effects crosses some threshold. The carrying capacity approach to cumulative impact management identifies system threshold levels before they are reached, and manages impacts to stay below the point at which significant adverse change occurs.[6]

The carrying capacity approach may be appropriate when thresholds can be identified ahead of time. The determination of system capacity is straighforward when dealing with such engineered public facility systems as water supply, sewage treatment, or traffic capacity (Dickert et al. 1976; CEQ 1976; ULI 1977). Here pipe sizes or road widths are known, and capacities can be computed within acceptable levels of accuracy. When capacities are known, decisions can be made regarding allocation of remaining capacity and system expansion. This was the rationale behind many early growth management programs, such as those for the cities of Petaluma, California (Gray 1974), and Ramapo, New York (Scott 1975).

In contrast, although it has been the focus of many modeling efforts [e.g., Delaware River Estuary (Ackerman 1974); Chesapeake Bay (Correll 1977a); Botany Bay, Australia (State Pollution Control Commission 1980)], the prediction of thresholds in natural ecosystems is still in its infancy. The measurement of natural threshold levels is made difficult by the masking effects of interactions between biotic and abiotic factors, compensatory responses, natural variance, and problems of field measurement. Although natural factors have been analyzed as part of many regional planning studies (Nassau-Suffolk Regional Planning Board 1976; Tahoe Regional Planning Agency 1982), other factors have often been found to be more limiting. For example, in the well-known environmental study of Sanibel Island in Florida (Clark 1976), the evacuation potential of the

[6]Carrying capacity refers to the size of a population that can be sustained in a given habitat over the long term. The concept stems from the range and game management literature (Wooten 1916; Leopold 1933; Stoddart et al. 1975) to express sustainable limits for livestock and game. Its use has since been expanded to include the carrying capacity for human use and resources, such as the carrying capacity of wildlands (Wagar 1974), of the nation (House 1976), and of the globe (Meadows 1972).

causeway bridge was the overriding factor limiting the level of urban development—even though extensive analysis of natural systems was undertaken.

Unlike engineered systems, thresholds in natural systems usually do not exist as discrete points but should be expressed in terms of the statistical probability of a set of events. One cannot point, for example, to the particular upstream housing project or logging operation that will suddenly trigger the "demise" of a downstream wetland; one can only estimate, and usually with hesitation, the probability of system response to the aggregate of disturbance within the entire watershed area.

Attempts to set numerical threshold limits for regulatory purposes usually engenders intense scientific debate. It is difficult enough for scientists to agree on ambient exposure levels for materials demonstrated in the laboratory to be toxic.[7] Even more difficult is the establishment of acceptable limits for such naturally occurring materials as sediment or degradable organics. In a recent California example, the lack of scientific consensus regarding the detrimental cumulative effects of logging in northcoastal watersheds led to dismissal of proposals for watershed-based regulation. These proposals would have established an upper limit on the rate or acreage of allowable harvest within a basin. Because the linkage between the extent of logging and resulting water quality impacts could not be sufficiently quantified, a watershed-based approach to limiting the harvest rate has been abandoned. The system continues to rely on adherence to prespecified forest practice rules and case-by-case onsite mitigation (California Board of Forestry 1982).

Because of the difficulty in prestating system limits, incrementalism has become the management approach to many cumulative impact problems. Land development projects, for example, are generally approved on a case-by-case basis following negotiation regarding onsite mitigation of direct impacts. Mitigation is the primary approach of most local planning agencies, coastal zone management programs and many other program areas in urban land use, water resources, and public lands management. A significant effect of the Clean Water Act 208 nonpoint source program in many states was the preparation by local governments of manuals for onsite erosion control.[8] The implicit assumption in these management programs is that onsite mitigation alone will be enough to avoid later cumulative effects. That is, if mitigation eliminates project impacts, the sum of the zero impact projects should cumulatively be zero.

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[7]Incomplete scientific evidence, conflicting test results, and uncertainty in assigning safety factors to convert animal test data to safe human exposure levels, complicates regulatory standard setting for hazardous substances (Kates 1978; Lave 1982). For example, although Dioxin (2,3,7,8 TCDD), identified in the Times Beach, Missouri, contamination, is recognized as extremely toxic to rats, linkages to human health defects and cancer are still unproved (Bumb et al. 1980; Kriebel 1981).

[8]Erosion manuals review the types of mitigation methods appropriate for a range of site conditions, typically including methods for slope stabilization, sediment retention, and means to slow rates of surface runoff. See, for example, State of California (1978) and State of Oregon (1978).

The incremental approach can be made to work if someone is watching the system for signs of stress. Unfortunately, except for a few large-scale research programs [e.g., Columbia River Estuary Program (CREST 1979)], systematic monitoring of most natural systems is not occurring. A more significant danger to this approach is the risk of irreversibility—the point at which the cumulative impact finally becomes evident through monitoring may come too late to bring about system recovery. At the same time, reliance on mitigation depends on postconstruction enforcement of permit conditions with continued monitoring of performance. In an era of budgetary cutbacks, such monitoring is low on the priority list. Yet without monitoring, mitigation is a hollow drum that will not provide the assurance that cumulative effects are being addressed.

Capturing the Episodic Event in the Historic Record

As noted, it is difficult to identify ecosystem thresholds before they are reached. At best, present models and available data provide only a broad estimate of ecosystem tolerances. It is difficult to develop justifiable management plans for natural systems using a carrying capacity approach.

An alternative approach to impact prediction involves the extrapolation of past events into the future. If present ecosystem conditions can be correlated with a documented series of past events, it may be valid to assume that the system will respond in a similar way to a continuation of those events. For example, if we can relate historic wetland change with past changes in upstream land use, we may be able to estimate what future wetland change will be if the same rate of upstream development continues.[9] Of course, the success of this approach in dealing with other types of cumulative impact problems (e.g., water quality) will be dependent on the availability of relevant historical data.

It must not be assumed that cumulative effects necessarily occur at a constant rate. Certain kinds of cumulative impacts, such as those related to flooding, coastal bluff erosion, fire, and sedimentation may become evident only as a result of the large-scale, low-frequency (i.e., episodic) event. In a sense, these cumulative impacts lie dormant until the "big one" (e.g., storm, earthquake, or flood) hits. For example, the effects of accelerated erosion from soil exposed in agricultural or construction grading may not become evident under average winter storm conditions, but may produce serious downstream sedimentation during a

[9]Similar analysis of land use change has been the basis for forecasts in transportation planning, public facility location studies, and energy policy studies. Probably one of the most intensive current efforts is the use of agricultural land use change detection as a basis for forecasting water demands by the California Department of Water Resources in the Central Valley.

larger, less frequently occurring type of storm. The effects of major episodic events have been documented in several California wetlands, including upper Newport Bay (Orange County Board of Supervisors 1980), Tijuana estuary (Zedler 1982), and Goleta Slough (Lohmar et al. 1980), where large amounts of sediment were suddenly deposited in the wetlands following a single set of major storms.[10]

The validity of the impact projection rests on the length of the historic record and the inclusion of the episodic event of record within the data base. In the wetland example, prediction of potential impact based on data from a series of average weather years would not only be wrong, but would be dangerous, as it would give false confidence that new development would pose no threat to downstream natural systems. While local governments, in recent years, have recognized the importance of gathering and processing large amounts of physical and socioeconomic information, manual or automated data bases generally contain only recent data. Historic information must be obtained from disparate sources such as assessor's and title records, early maps, survey notes, tideland grants, nautical charts, and aerial photographs. Common problems in using historical data from many sources and time periods include differences in scale, resolution, poor accessibility, spotty coverage, and breaks in the historic record.

Separating Natural from Human-Induced Impacts

The fourth difficulty concerns the ability to prove the causal connection between a human activity and the alleged effect. Natural systems may respond in the same way to the effects of accelerated erosion, landslides, or fires irrespective of whether they were humanly induced or naturally occurring. Any proposal to regulate land use in the name of cumulative impact management must be firmly based on a demonstration that the effect being regulated is caused or related to the land use activity in question.

In theory, determining that an impact is humanly induced requires that a comparison be made between the type, rate, and variance of system responses before and after the suspected human intervention. This procedure is complicated because the variance in natural processes is typically large, making it difficult to separate the response to a suspected human-induced effect from natural back-

[10]Similar results obtain to east coast wetland/watershed research; for an extensive overview of work on watersheds in the Eastern United States see Correll (1977b). For example, the upper Chesapeake Bay aged approximately 30 years in ten days as a result of a single major storm event, Hurricane Agnes, in June 1972 (Schubel and Hirshberg 1978).

[11]Some geologists have argued that because wetlands are ephemeral features with a short life span related to a geologic time scale (Schubel and Hirshberg 1978), we should not be concerned with the ecological impacts of short term wetland loss. However, because of the broad range of competing wetland values and generally short-plan preparation periods, most planning programs can not reasonably use a 10,000-year frame of reference when working in a public forum.

ground variation. In the wetland context, a determination that land use activities are accelerating the deposition of sediment is made difficult because sedimentation is an ongoing natural process.[11]

The bane of ecological research, including work on wetlands, is the lack of long term baseline data on conditions before disturbance. Where available, data from undisturbed systems elsewhere can be used for comparison, but they can easily be challenged as conclusions drawn from a different system may not be transferable. A related question concerns the significance of the additional increment of impact contributed by the land development activity. For example, is the magnitude of natural sediment discharge from a major storm event so large that the share of additional effects attributable to human-caused erosion is insignificant?

Another aspect concerns the identification of which of many land use activities in a watershed is the culprit. Silviculture, recreation, agriculture, urbanization, and road building can all contribute to downstream sediment problems, and the regulatory authority may be spread over many agencies. As noted by Fairfax (1981), we may lack the data to be able to ascribe the proper amount of blame to each activity; if causes cannot be clearly identified, one can neither regulate nor punish effectively. Therefore, if the regulatory system is to be effective, the data must be translated into indicators that measure the magnitude of individual responsibility.

METHODS FOR CUMULATIVE IMPACT ASSESSMENT

Although the assessment of cumulative impacts presents data gathering and analytical problems, the critical importance of wetland protection justifies efforts to improve methods of wetland watershed management. To be compatible with existing coastal zone programs and realistic levels of funding, management techniques should be usable by local governments and based on available or easily obtainable data. Because cumulative impacts must be assessed as cause–effect systems, the interjurisdictional questions of data gathering and plan implementation must be resolved.

In California, the Coastal Act established a state–local collaborative arrangement where local governments prepare plans to be reviewed and certified for compliance with a set of statewide policies. This legislation sets out a broad mandate for wetland protection, as well as for the consideration of cumulative effects.[12] The institutional arrangement of county–state collaboration, coupled

[12]The California Coastal Act declares a broad mandate for cumulative impact management in the definition of development, as follows: "New development . . . shall be located within, contiguous with, or in close proximity to, existing developed areas able to accommodate it, or where such areas are not able to accommodate it, in other areas with adequate public services and where it will not have significant adverse effects, either individually or *cumulatively* [emphasis added] on coastal resources . . ." [Calif. Public Res. Code §30250(a)]

with a planning boundary that included most of the watershed, provided one of the few opportunities to test the extent to which cumulative impacts could be assessed in local government land use planning. In addition, because of the general failure of previous efforts to plan for cumulative impacts, a demonstration of the workability of the approach was needed to ensure its application in other coastal watersheds.

ELKHORN SLOUGH WATERSHED

The work was conducted in the Elkhorn Slough watershed located on the central California coast. Although not large by east coast standards, the Slough is the second largest remaining estuarine system in California, and in 1981 it was designated as an Estuarine Sanctuary under Section 315 of the federal Coastal Zone Management Act, representing the Californian biogeographic province. The estuarine sanctuary program is typical of many federal and state programs aimed primarily at wetland acquisition, with little recognition of proposed land use changes and related impacts from the adjacent watershed areas. In Elkhorn Slough, however, the designation as an Estuarine Sanctuary, coupled with the ongoing planning effort for the local coastal program, did provide an opportunity to link the acquisition process with a regulatory activity.

The watershed encompasses 70.2 square miles, is typical of the central California coast, and extends inland from the coast about eight miles. Although the California Coastal Zone boundary reaches its furthest extent inland adjacent to the Elkhorn Slough, the legislatively defined management zone still excludes about one-third of the estuary's watershed area. Vegetation in the watershed consists of mixed oak woodland, chaparral, and grassland. Predominant existing land uses are rural residential and cultivated agriculture (Table 1). A major portion of the watershed consists of soils that are highly erosive when vegetation is removed. Serious erosion has occurred as the result of soil disturbance associated with recent increases in cultivated agriculture and rural residential uses within the watershed. An extensive biological information base for the wetland has been compiled over the years beginning with early species inventories (MacGinitie 1935). More recent biological research has established a quantitative data base, including species variation over time, for benthic invertebrates, fishes, and zooplankton (Nybakken et al. 1977).

The analytical work supporting the approach to cumulative impact assessment consists of four components: hydrologic assessment of runoff and sediment transport; field measurements of erosion and deposition resulting from various land uses throughout the basin; photogrammetric analysis of wetland and upland change spanning a 50-year time period; and measurements of site disturbance associated with dominant land uses. The work has emphasized the use of field measurements to provide primary data, supplemented in the hydrologic analysis by simple predictive models.

TABLE 1. Upland Land Use Change 1931–1981 in Elkhorn Slough Watershed

Photointerpretation category[a]	1931 Acreage	1931 Percentage of watershed[b]	1981 Acreage	1981 Percentage of watershed	Percent change	Change as percentage of watershed
Brush	5,765	12.8	3,395	7.6	−41	−5.3
Pasture	24,334	54.2	20,674	46.0	−15	−8.2
Oak woodland	4,838	10.76	6,280	13.9	30	3.2
Row crops	1,975	9.40	5,194	11.6	163	7.2
Strawberries	0	0	2,358	5.2	—	5.3
Orchards	2,556	5.69	182	0.4	−93	−5.3
Tree plantations	794	1.77	1,609	3.6	103	1.8
Urban	45	0.10	572	1.3	1,171	1.1
Industrial	123	0.27	300	0.7	144	0.39
Commercial	10	0.02	517	1.2	5,070	1.1

[a]The photointerpretative categories represent level I and II in the standard classification for land use and land cover data (Anderson 1976). More detailed categories were used for the wetland units and for the range of residential parcels shown in Table 2.
[b]The total area of the Watershed is 70.2 square miles.

Hydrologic Analysis

The watershed boundary of the Slough was delineated by ridgeline topography and corrected to include interbasin transfers. As a first step in the planning approach, the watershed area was subdivided into 37 smaller subwatershed units, each of similar slope, soil or land use characteristics (Figure 1). The subwatersheds were used both as the analytical units for data aggregation in the time series analysis as well as the planning units for assignment of the land disturbance targets.

Establishing the relationship between rainfall and resultant runoff is central to understanding the potential hydrologic effects of future development. There are two common hydrologic effects of urbanization caused by increases in impervious surface (paving, roads, rooftops): 1) increase of peak discharge for an equivalent size storm, and 2) shortening of lag time as rainfall reaches channels more quickly (Dunne and Leopold 1978). Both can produce downstream flooding if channel capacity is exceeded. Increased peak discharges also accelerate channel erosion and potential sediment transport.

For the Elkhorn Slough study area, only limited rainfall and runoff data were available. Daily, monthly, and annual rainfall values for the watershed were computed by the Thiessen method (Lindsley et al. 1958) with data from a network of gauging stations in the region. Field measurements of stream runoff in the two main tributaries to the Slough were made over several winter seasons. Synthetic hydrographs were also constructed for comparison with the field data.

The storms for which runoff data were collected had recurrence intervals of less than 1.5 years and thus represented typical annual runoff responses to the

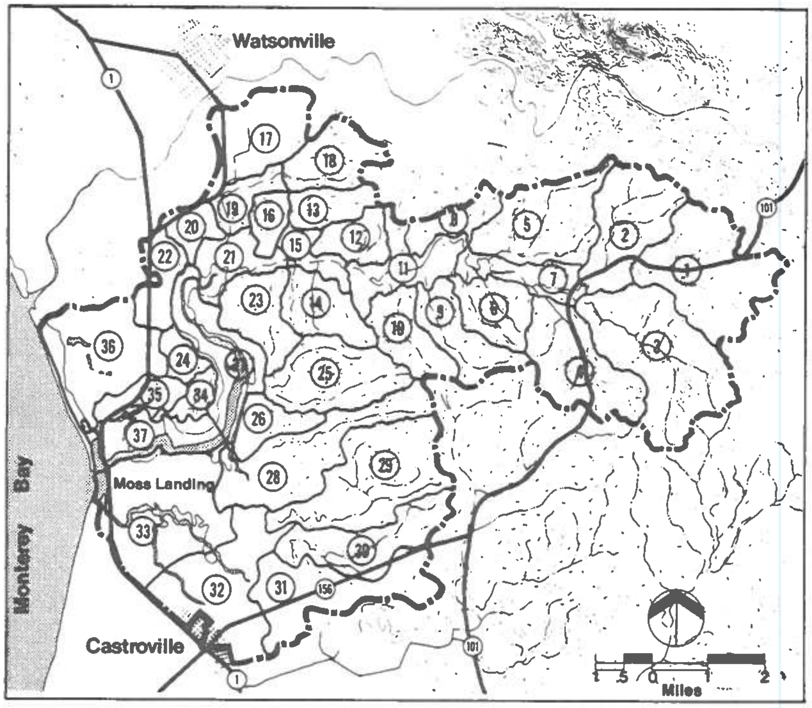

FIGURE 1. Elkhorn Slough watershed and subwatershed boundaries.

existing level of development. By using the synthetic hydrographs, computations were made of discharge under conditions of full buildout to existing zoning. The analysis showed that peak discharge, even under full buildout, would only increase about 5 percent for the storm of a two year recurrence interval. This amount is small and can be attributed to the limited impervious surfaces associated with rural residential and agricultural uses planned for the region. Runoff would be significantly affected only in two specific subwatersheds designated for development to urban density.

Limited investigation of sediment transport was also made in the main tributary stream. Because of the many measurement problems involved in the sediment budget approach, the aim of the sediment work was not to quantify total sediment load, but to establish that sediment was transported in the channel and to characterize the size and composition of material moved.[13] Measurements of sus-

[13]The problems in sediment budgeting are of several types. The first is establishing the relationship between sediment production and sediment yield (Dietrich and Dunne 1978). The second is tracing the sediment to its origin (Nelson and Coakley 1974). A third concerns quantifying the storage of sediment within the watershed system (Swanson et al. 1982). The sediment budget approach was not appropriate here because we were interested in the relative contribution of various land uses at the site rather than precise measurement of the amount of material transported in the channel.

pended load, bedload, and particle size were made for several storms. In addition, bedload transport was documented by bedload chains (Leopold et al. 1966) placed in the bed of the channel before winter and monitored at the end of the runoff seasons (1978–1980).

The field research demonstrated that large amounts of sand are moved along and deposited in the stream channel during normal winter flows. Although quantitative assessment of sediment delivery and deposition within the Slough was not a part of this work, it is evident that portions of the material moving in the channel are transported to the Slough and deposited on the tidal flats.

Upland Erosion and Deposition

A second research component investigated soil erosion occurring on over 30 sites in the watershed representing a range of soil, slope, and land use conditions. Erosion pin transects (Gleason 1957), consisting of spikes and washers placed at 5- to 10-foot intervals, were monitored following 1978–1980 winter storm seasons.

Sites selected for measurement included the range of land uses present in the watershed, such as cultivated agricultural fields, driveways, and road cuts associated with residential uses, pasture, chaparral, and forested lands. Slopes ranged from less than 2% to over 100%; soils were classified according to Soil Convervation Service hydrologic groups,[14] and each group was represented in the sample. Several transects were located along deltaic sand deposits that are forming on the wetland margin at the mouth of creeks draining upstream slopes. Irrespective of slope or soil type, erosional and depositional activity was highest on sites where natural cover had been removed and soil disturbed. Cultivated agriculture in general produced more than twice as much land disturbance as rural residential or urban uses.

Time Series Analysis

Sequential aerial photo analysis was used in the third component of the research to assess the change in land use over the past 50 years in the upland and wetland portions of the Elkhorn Slough watershed. The sequential photo analysis technique has been used successfully in many coastal applications, including measurements of bluffline retreat (Horikawa and Sunamura 1977; Drexhage 1978), barrier island movement (Baker 1976), beach erosion and accretion (Langefelder et al. 1972), and wetlands loss (Levin and Cronan 1972).

The use of historic aerial photography to establish rates of change is limited by variations in quality, scale, and resolution from one photo set to the next. It

[14]Four hydrologic groups define the relative runoff characteristics of soils after rainfall. Soil properties that influence the minimum rate of soil infiltration include the depth to water table, water intake rate, and permeability, and depth to layers of slowly permeable soil (USDA 1972).

is also limited by the short period of historic aerial coverage available (comprehensive aerial coverage of the United States was not begun until the 1930s (Fischer 1975; El-Ashry 1977)) and the inability to establish ground truth for an old photograph. However, historic aerial photographs provide the best and often the only source of detailed information on land use, soil disturbance, and vegetative cover that is necessary for historic analysis of site disturbance.

Six sets of aerial photographs, dating from 1931 to 1981, were used to make detailed measurements of vegetative cover, agricultural and urban development, and wetland morphology in the Elkhorn Slough watershed. All photography except 1981 was black and white at a scale of 1:24,000. Color infrared photography, at a scale of 1:12,000, was used in 1981 to provide better discrimination of wetland and upland units. Photointerpretation units were delineated and measured by subwatershed for each time interval.

The most dramatic change over the 50-year period has been the loss of almost half of the wetland habitat area, primarily caused by diking and draining for agricultural use (Figure 2). A portion has reverted to wetland following the breakdown of unmaintained dikes. Although we were specifically looking for evidence of sedimentation at the mouth of the main Slough tributary, precise measurement was hampered, mostly because of differences in photo resolution and tidal stage between sets of photographs. We did, however, measure significant conversion of wetland habitat at the head of the Slough caused by channelization of the creek and dredging of additional drainage channels.

Also significant is the development of over thirty sand and mud fans at the mouth of creeks draining the slopes above the Slough (Figure 3). The fans smother existing tidal communities, and owing to their slightly higher elevation and freshwater influence are dominated by upland or freshwater marsh species. Over time, wetland is converted to terrestrial habitat.

In the upland portions of the watershed, land use change is characterized by intensification in urban, rural residential, and agricultural uses with associated road networks. Previous pasture and woodland sites have been cleared for intensive specialty crop cultivation.

Measurement of Impervious Surface and Bare Ground

The alteration of the soil surface by grading and paving during site development affects the runoff and erosion potential of the parcel. The extent of alteration in the hydrologic characteristics of the site is dependent on the type and intensity of land use. Relevant measures of the hydrologic impact of a given land use are: 1) the area of impervious surfaces that contribute to runoff; and 2) the area of unvegetated surfaces that contribute to erosion.

In the fourth component of the research, impervious surface and bare soil exposure were measured for the dominant land uses occurring in the watershed. Measurements taken from 1981 color infrared photography and verified by field

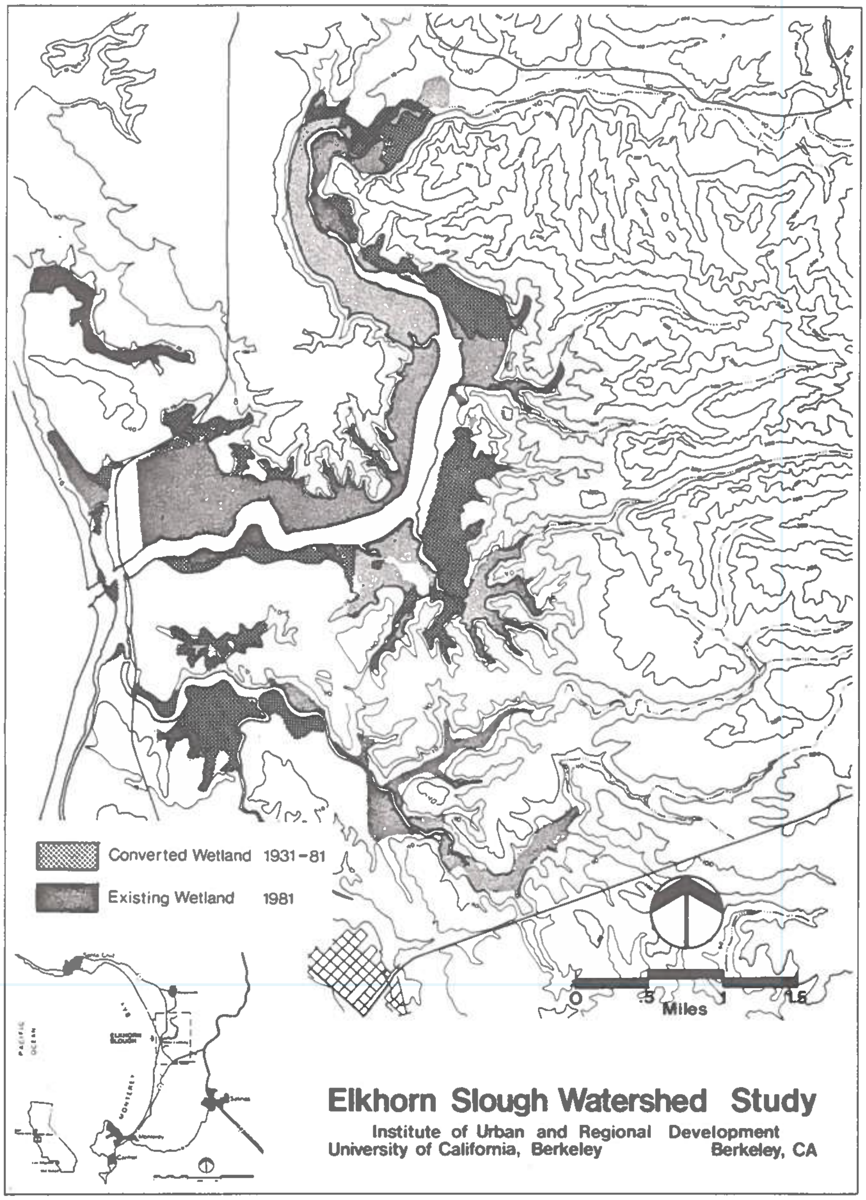

FIGURE 2. Area converted from Salicornia to upland habitat, 1931–1981.

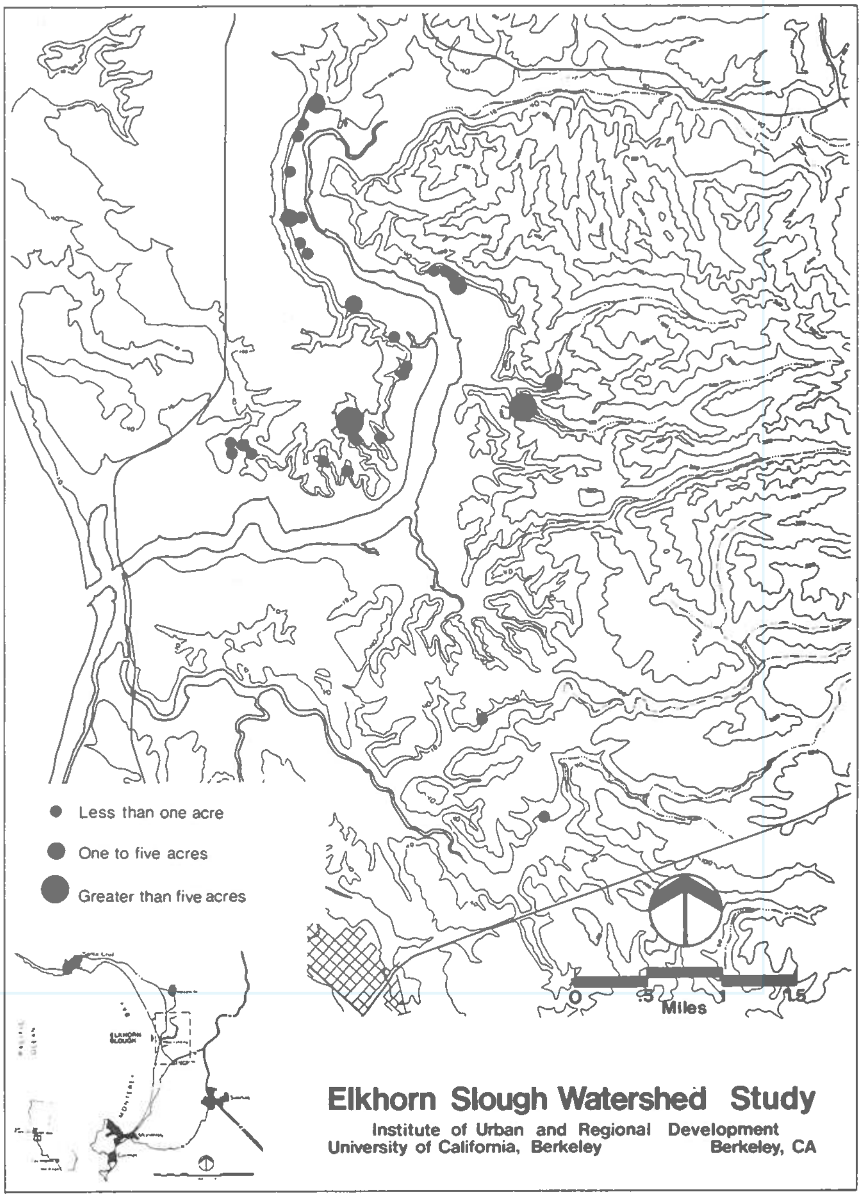

FIGURE 3. Location of alluvial and colluvial fans.

sampling are shown in Table 2. Impervious surface measurements included roofs and paved surfaces. In general, the values for impervious surface coverage for land uses in the Elkhorn Slough watershed are higher than comparable values found in the literature (Rantz 1971; Tourbier 1973; Rice Center 1974; and Nassau-Suffolk Regional Planning Board 1976). A wide variation exists in impervious surface values used in planning studies around the country. This variability is apparently attributable to differences in local development standards or other regional characteristics, and illustrates the problem with using site disturbance values from published studies without field verification.

Bare ground measurements included the extent of bare cut and fill slopes, unpaved roads and trails, soil exposed between crop rows, and other areas where vegetative cover was absent. Land use samples were stratified by exising use, zoning classification, and vegetative type. In contrast with the information available on impervious surfaces, no comparable measures of bare soil exposure for rural residential and urban uses could be found in the literature.

TABLE 2. Site Disturbance by Land Use Type

	Impervious surface coverage[a]	Bare ground exposure[a]
Land Use		
chaparral	0.0	6.0
oak woodland	0.3	1.1
eucalyptus	0.0	3.2
pasture; grassland	1.3	6.5
rowcrops; artichokes	0.2	63.1
strawberries	0.2	69.5
orchards	0.3	93.2
commercial	33.1	51.4
industrial	22.3	48.2
Residential Use		
51-acre parcel and greater	0.6	9.6
31- to 50-acre parcel	0.6	7.9
15.5- to 30-acre parcel	2.9	13.2
10- to 15.4 acre parcel	0.5	8.1
5- to 9.9-acre parcel	1.9	9.9
2.4- to 4.9-acre parcel	9.2	3.8
1- to 2.3-acre parcel	9.6	14.7
0.5- to 0.9-acre parcel	15.7	19.5
0.2- to 0.4-acre parcel	24.8	0.8
0.1-acre parcel	30.7	11.4
Less than 0.1-acre parcel	59.1	51.4

[a]All impervious surface coverage and bare ground exposure values are expressed as the mean percentage of the parcel area.

THE PLANNING APPROACH

The Elkhorn Slough watershed was used to develop a model land use planning system that could be transferred to other coastal wetland watersheds.[15] The planning approach consists of a set of land disturbance targets for subunits within the watershed; and an erosion-susceptibility map portraying the relative erodibility of lands within the watershed. The assumptions made in developing the planning system were that development should be located within areas of lowest erosion potential, and sedimentation rates from land use in the watershed should not exceed the rate of filling that has prevailed during the past 50-year period. The 50-year period was selected as a baseline because it represented the time period for which quantitative data could be acquired, and the era over which most land use changes in the watershed had occurred. The approach involves four major components:

Evaluation of Erosion Susceptibility

An Erosion Susceptibility Map was developed for the watershed representing a composite of slope, soils, and other geological factors that contribute to soil erodibility. The map was produced using a computerized geographic data base containing about 18,000 one hectare grid cells, with each cell containing information on bedrock geology, soil type, soil K-factor for the A and B soil horizons,[16] slope, overland flow distance, and land use. The data base was constructed in rastor format in order that LANDSAT data, particularly from the LANDSAT-4 thematic mapper,[17] could be used for on-going monitoring of land disturbance.

The geologic and soil units were aggregated into ten ordinally scaled classes, ranging from low to high erosion susceptibility.[18] Land falling into each of the erosion susceptibility classes was measured by subwatershed. Lands within the five lowest erosion classes were defined as "land available" for development; that is, that development could best be accommodated on those sites.

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[15]The transferability of the approach is being tested in Jacoby Creek watershed tributary to Humboldt Bay, and Penasquitos Lagoon watershed in San Diego County. Together with Elkhorn Slough these areas will demonstrate the utility of the approach over the range of climatic regimes present in northern, central, and southern California. Application of the method in estuarine systems larger than the California sites (i.e., larger than 400 square miles), such as Chesapeake Bay or San Francisco Bay, is limited by the intensive nature and subsequent cost of the analytical work required.

[16]The K-factor is a measure of inherent soil erodibility used by the Soil Conservation Service and available in published soil surveys (Wischmeier and Smith 1978).

[17]The LANDSAT-4 thematic mapper data, with a resolution of 30 meters, may be a less costly alternative to low-altitude conventional photography. The digital format also permits easy comparison of measured land use change with other variables in the data base. For a summary comparison of LANDSAT MSS and thematic mapper data characteristics, see Anuta et al. (1984).

[18]For a complete discussion of the scaling methods used in the erosion susceptibility measure, and evaluation of the use of the measure in coastal watershed planning, see Dickert and Olshansky (1985).

Measurement of Land Disturbance

Mean values from the measurements of impervious surface and bare ground associated with each land use were used as indices of land disturbance. The indices were used in combination with the amount of each land use found under historic, present, and future development conditions, to ascertain the aggregate amount of disturbed soil that had existed or would exist during each development period.

The acreages of historic and present land uses were determined from the time series analysis for the period 1931–1981. Acreages of future development were obtained both from the existing general plan for the region and from proposed designations in the local coastal program. Because land use plans tend to portray general rather than specific land use designations, three scenarios were developed assuming a range in the mix of future agricultural and residential land use intensities.

The hydrologic and time series analysis revealed that the cumulative impacts of impervious surface coverage for present land uses are low and will continue to be so even under full buildout to existing zoning. In contrast, the bare soil disturbance associated with present land uses is high, and it can be expected to increase with clearing for rural residential and intensive agriculture uses. Because of this projected trend in site disturbance, the bare ground values for past and future land uses became the basis for setting the land use targets.

Establishment of the Land Disturbance Target

The land disturbance target represents the recommended value for allowable land disturbance, expressed as a percentage of the subwatershed area. This value represents either the land available target or the historical trend target, whichever was lower. As noted above, the "land available" target is the amount of land in the subwatershed falling within the five lower erosion classes shown on the Erosion Susceptiblity map. The historical trend target is the maximum amount of bare ground present in the subwatershed at any point within the time period 1931–1981. Figure 4 illustrates the historical trend target and shows the three alternative target level choices (minimum, mean, or maximum bare ground disturbance) of which the maximum was selected.

Comparison of Existing and Target Land Disturbance Values

Subwatersheds were evaluated according to whether the existing development exceeded or fell below the land development target. As adopted in the Monterey County local coastal plan, additional development can be permitted in subwatersheds where existing use falls below target levels. Where existing use exceeds target levels, additional development will not be permitted until the overall level of bare ground in the subwatershed is reduced. Reduction can be accomplished

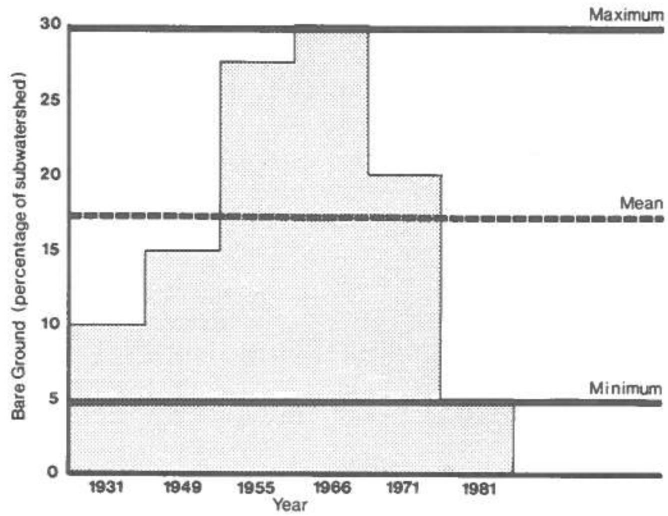

FIGURE 4. Historic trend target—illustrative subwatershed.

through revegetation programs and with the incorporation of mitigation measures (e.g., grading and erosion controls) which reduce the bare ground associated with the proposed land use.

LAND DISTURBANCE TARGETS IN ELKHORN SLOUGH

Figure 5 illustrates the percentage of bare ground exposed in each of the 37 subwatershed units under existing, planned, and recommended target conditions. The diagram can be viewed as a histogram for each subwatershed, or as a curve for the entire watershed. The shaded and lined elements contained in the figure are as follows:

- Bare ground from existing land use in the subwatershed (dark shaded area).
- Future bare ground under two conditions: full buildout to existing zoning designations[19] (light shaded area), and full buildout to the initial Monterey County local coastal plan (dashed line). (The local coastal plan was later revised to conform to the land disturbance targets, but it is included here to illustrate the use of this approach for plan testing and analysis.)

[19]Full buildout to existing zoning is the level of use that would result if all parcels were developed to the maximum intensity permitted in the zoning ordinance. It represents a worst case, but a realistic assumption of hydrologic intensity for a permitted use.

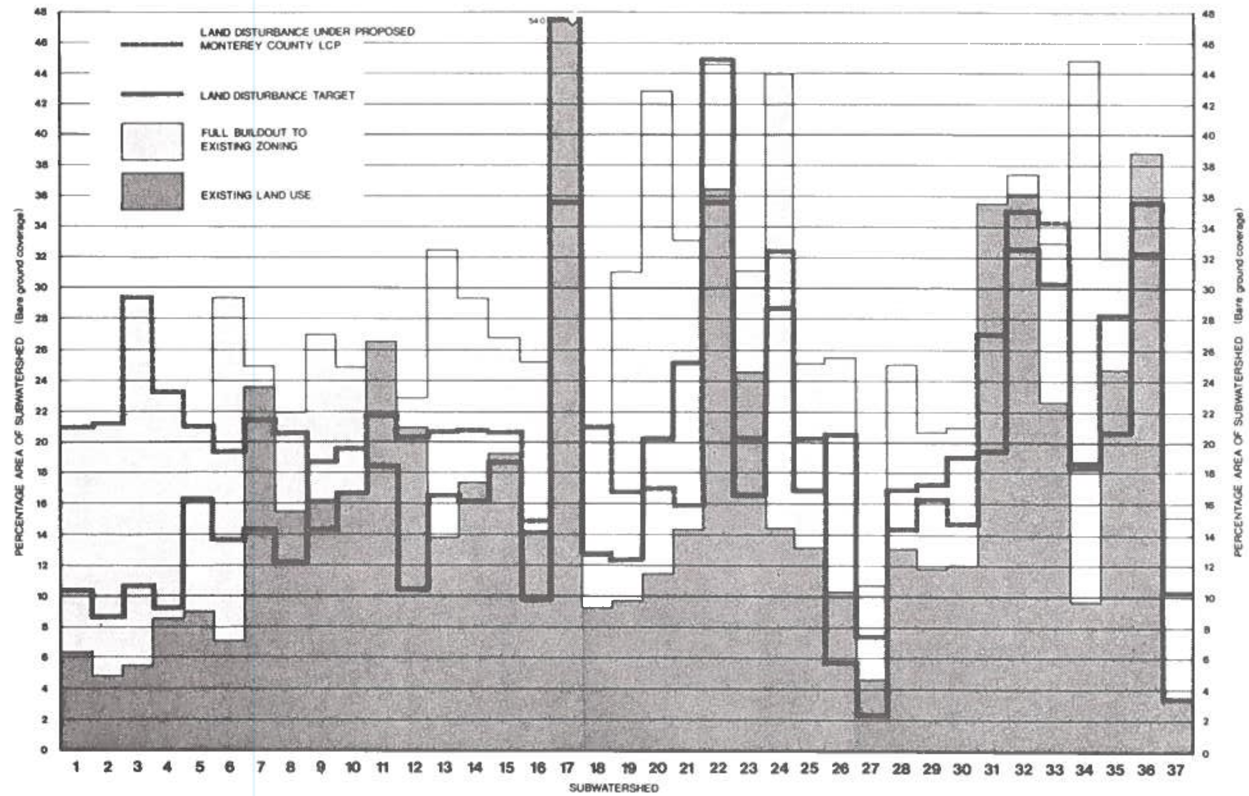

FIGURE 5. Land disturbance targets

- The recommended land disturbance target, chosen as the lower of the historic or land available target values (solid dark line).

For example, in subwatershed 6, existing bare ground exposure is about seven percent of the subwatershed area; future bare ground under full buildout to existing zoning would be about 29 percent; future bare ground under the initial local coastal plan would be 19.5 percent; and the recommended (and adopted) target level determined in this research is 13.5 percent.

The ability to evaluate the potential cumulative impact of both proposed plan changes and specific project proposals is an important benefit of the target approach. Once land disturbance targets and disturbance multipliers have been determined, disturbance resulting from alternative land use proposals can be easily computed. Similarly, the land disturbance associated with a specific project proposal can be computed and related to the target level for the subwatershed in which it is located. For example, further development in subwatersheds 1–6 would not be constrained since existing site disturbance falls below target levels.[20] In contrast, existing use exceeds target levels in subwatersheds 7 and 8, and additional development would be constrained until overall soil disturbance in the subwatershed was reduced, or adequate erosion control measures included in the proposal.

CONCLUSION

Protection of coastal resources, such as wetlands, requires better methods for assessing the cumulative impacts of land development. The reliance on mitigation measures or direct acquisition programs will not, by themselves, be enough to ensure long-term wetland protection. Similarly, project-by-project impact assessment does not provide a basis for estimating the watershed wide impacts of land development.

As illustrated in the Elkhorn Slough case, cumulative impact assessment methods must account for variation in both the spatial and temporal characteristics of the natural environment and land use. To be useful in the time frames available for local government planning and review, indicators such as land disturbance are needed that can express potential impacts in easily measurable terms. The use of focused field data collection, in combination with secondary data, offers an effective approach when land use plans must be prepared within a statutory deadline. The indicators must be expressed in terms that can be directly related to land use intensity measures (e.g., units/acre, land coverage, etc.) normally used in local government development review.

The planning method for Elkhorn Slough accounts for the four problems

[20]In the Elkhorn Slough, existing use falls below the land disturbance target levels in subwatersheds 1–6, 9, 10, 13, 18–22, 24–30, 33, 34, and 37. Existing use exceeds the land available target set by erosion susceptibility in subwatersheds 7, 8, 11, 12, 14–17, 23, 31, 32, 35, and 36.

identified concerning the assessment of cumulative impacts in natural systems. First, the approach uses boundaries defined by the watershed and subwatershed as the planning and analysis units most obviously relevant to hydrologic-processes.

Second, the method avoids the problems inherent in deriving intrinsic ecosystem thresholds by substituting a historic trend target based on extrapolation of known levels of land use impact. This method of threshold setting assumes that if other conditions (e.g., climate, sea level) remain the same, similar rates of watershed change will result in similar impacts on the wetland.

The threshold is data-limited in that it depends on the length of the historic record available. However, comprehensive aerial coverage for most of the United States was begun in the 1930s, and most coastal sites now have at least a 50-year record available. Although the longest possible historic record should be used, the approach in theory could use any period of record. The 50-year record is appropriate when it captures a major episodic event (e.g., 100-year recurrence interval storm) and reflects the period over which most intensive development has occurred. Alternatively, sedimentation rates over a longer geologic time period could be used for threshold setting. This approach would imply the intent to control natural sedimentation, as well as the portion attributable to development and would present significant analytical and data collection problems.

In computing the historical trend target, the maximum bare ground exposure (Figure 4) was selected as the threshold value rather than the more limiting minimum or mean values for the 50-year time series period. Although any of these three values could be selected, the maximum was used here because the change in the wetland attributable to sedimentation was small compared to other California wetlands (Mudie and Byrne 1979), and it would be difficult to support a threshold more stringent than warranted by the data. In addition, the choice of the maximum value is conservative in that it acts to compensate for measurement errors inherent in the interpretation of the photographic data. A further refinement of the method would weight the measurements of bare ground by the erodibility of the site. This approach was not practical here due to the small sample size for each land use when stratified by zoning and land cover class, and further stratification would reduce some sampling categories to zero. In Elkhorn Slough, the lack of weighting is in part compensated for by limiting future development to low erosion class sites defined in the erosion susceptibilty analysis.

Third, the method accounts for the occurrence of the episodic event to the extent that such events are captured within the historic data base. In Elkhorn Slough, a 100-year rainfall event had occurred within the 50-year period of available photography.[21] Thus the sedimentation effects of at least that size event

[21]Based upon the annual rainfall data for three stations (Watsonville, Watsonville Junction, and Watsonville Waterworks), close to a 100-year recurrence interval event of 41.79 inches was recorded at the Watsonville Junction station for the water-year 1941. On the basis of the monthly data, close to the 100-year recurrence interval event was recorded in 1937 (March), 1940 (January), and 1956 (December).

are reflected in the wetland system. We cannot predict the effects of longer recurrence interval rainfall/runoff events which would presumably be larger than those found for the 50-year time interval. Differences in wetland response may also occur from a different sequencing of future wet and dry years. However, some of these effects would be buffered by the storage components within the sediment transport process, and may not be significant when averaged over the 50-year period.

Finally, the historical trend method does not depend on the separation of natural from human-induced change. The method recognizes that wetland changes reflect an aggregate response to many causes. By assuming that natural processes will continue at the same rate as over the historical period, the changes attributable to human activities are left as dependent variables which can be adjusted through the land use plan.

The focus of this paper has been to identify the issues that must be addressed in developing a planning system that incorporates cumulative impact assessment and to demonstrate this approach using a case study of a coastal wetland watershed. Further research is needed on questions involved in the allocation of development rights under such a planning system, particularly for areas where development pressures are greater than in the predominately rural Elkhorn Slough watershed. In Elkhorn Slough, a "first come, first served" approach was adopted. Other approaches to allocation that may be applicable in other situations include: offsets and bubbles, distribution based on an acreage or per capita basis, or the establishment of markets in land development rights.[22]

The value of the time series approach used here is that it provides an alternative basis of threshold setting in cases where it is not otherwise possible to identify thresholds based on criteria such as toxicity or physical constraints. Thresholds based on intrinsic ecological limits require extensive ecosystem modeling in order to identify limiting factors and process thresholds. Although many estuarine ecosystem models have been presented in the literature, they are generally unproved, do not discriminate well between different types of land use as causal elements, and are largely unworkable in local planning programs. An important limitation in the transferability of this approach is that the cumulative impact problem must be visible on aerial photographs. Other types of cumulative impacts, such as groundwater/surface water exchange or toxic chemical accumulation will obviously require other data sources. However, it is important to recognize that the approach will be transferable to many cumulative impact problems where land use intensity is an important independent variable. Such problems include assessment of wildlife habitat, agricultural land conversion, visual quality, and geologic hazards. Ongoing research will identify the appli-

[22]For a review of the economic issues associated with the various allocation alternatives, see Joeres and David (eds.), 1983.

cability of the planning method to other geographic areas and types of cumulative impact problems.

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