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Origins, Management, and Measurement of Stress on the Coast of Southern Spain

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For political reasons Spain's Costa del Sol had until recently presented a classic example of reactive coastal management. The 1988 Coasts Act introduced a more proactive approach, but its management still lacks a scientific classification of the coastline upon which to base coastal policy. Such an overgeneralized delineation of the coastal domain generally ignores the variations in physical and socioeconomic variables and is likely to lead to oversimplified management practices. Against the background of the policies adopted over the past 50 years, this article presents an index that delineates different degrees of sensitivity of the coastline of the Costa del Sol. A geographical information system (GIS) approach is adopted in the construction of the index that recognizes that coastal vulnerability is equally a function of physical processes and human activities. Four physical (lithology, landforms, river discharge, marine processes) and two anthropomorphic (population growth, urbanization) components are incorporated, and the results are applied to produce a broadly based measure for policy making in southern Spain that also has applicability in other coastal situations.

Keywords coastal stress, Costa del Sol, sensitivity index

Introduction

One of the fastest rates of urban development in a coastal environment has occurred along Spain's Mediterranean littoral over the past 40 years. Nowhere is this better illustrated than in the Costa del Sol (Figure 1), where population has risen by over 10% per annum between 1950 and 1991, a figure that closely matches the growth of visitor traffic to Spain over the same period. A construction boom has paralleled this dramatic

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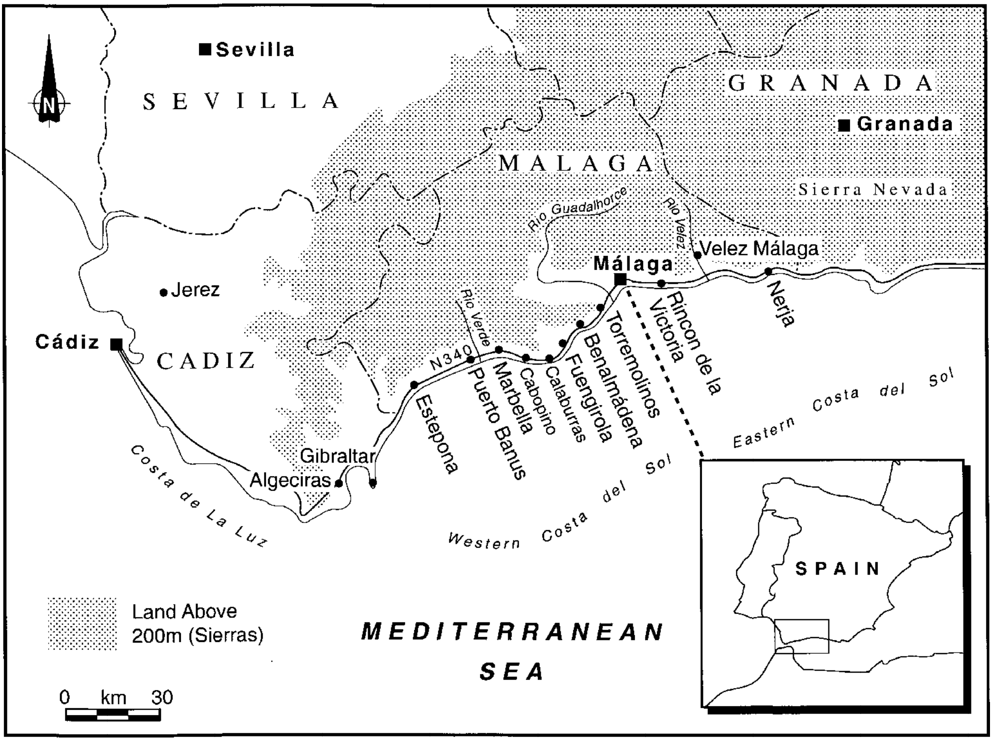


Figure 1. The Costa del Sol, southern Spain.

expansion of the resident and transient populations, resulting in considerable stress on the coast and demanding a management response to safeguard the coastal, and specifically beach, resources upon which the region's economy is based.

Unfortunately, a broadly based management response has only been implemented in the latter stages of the 20th century, the major part of postwar development of the Costa del Sol having taken place under Franco's extreme laissez-faire politicoeconomic regime and its aftermath. In consequence, those with an interest in coastal management, including engineers, have had to fight a rearguard battle, reacting to stresses induced by the absence of a strong environmental thrust in official decision making. Thus, until the 1980s, official actions were strictly limited to practical measures safeguarding vulnerable sections of the coastline or the sponsorship of construction projects (particularly marina developments) offering commercial gain. Even in those situations engineers lacked a complete understanding of the physical consequences of protective and commercial coastal building, as subsequent siltation and erosion processes brought about many unforeseen and unwanted effects.

In more recent years Spanish engineers have learned from previous experience, while legislators and planners have made concerted efforts to set out the basis for a more effective and comprehensive system of coastal management. However, although progress has undoubtedly been made, it has taken place without full knowledge of the variation in coastal vulnerability that exists along the Costa del Sol. Proper analysis of vulnerability is now required to provide an essential underpinning to planning in the region. This is now a practical possibility, with the improvements in the understanding of marine processes and the construction of high-powered computer models that have been developed to produce stress indicators that can highlight sensitive stretches of the coast. Until recently, these measures have been dominated by physical components, although there has been growing recognition that coastal vulnerability is equally a function of human activities.

The principal aims of this article are thus to examine the development of coastal management on the Costa del Sol in recent years and to construct a scientific tool based on a holistic sensitivity index that characterizes coastal stress and has the potential for applicability in similar situations where human pressures are profound.

Coastal Protection and Management

Attempts to protect the more highly stressed sections of the coast against erosion and flooding have a long history, but have assumed added importance with the recent reliance of the regional economy upon the visitor trade and the physical need to protect the fast-growing urban communities. Earlier, hard-engineering coastal defense based upon sea-walls and hammer-head groynes neither permanently solved erosion problems nor maintained beaches. However, the absence of planning coupled with the desire for short-term solutions meant that such measures were used extensively. The unsatisfactory results, highlighted by severe storm damage at the end of the 1980s, together with concern for the tourist industry then suffering stagnation and broader unease over the irreversible transformation of the coast through human activities, all coalesced to prompt the implementation of planning controls and new protective measures. This section examines both the changes in thinking with respect to coastal protection and the broader management policies within which the engineering solutions are now couched.

The Engineering Response

Most coastal engineering work on the Costa del Sol has taken place in the last 30 years and relates to local municipal demands for protective measures to be taken. The previous economic emphasis that characterized planning during the major part of the Franco era ensured that little or no attention was paid to coastal concerns, so that by 1970, Spain effectively lagged 20 years behind other leading nations in terms of coastal management and protection policy (Losada et al., 1996).

Notwithstanding that, some early developments did pre-date the 1970s. Fishing communities occupied sites immediately adjacent to beaches, and *salazones* (locations for the salting of fish) were located close to, and sometimes on, the beach itself. As early tourism developments occurred, *paseos* (promenades) were constructed in front of existing houses, encroaching on to the back-beach. Although the *paseos* did not obstruct littoral processes in fair weather conditions, they were subjected to inundation from both the sea and nearby streams during storm conditions, which led to concerns from local councils for further protection or strengthening of the new promenades.

At most locations, the occupation of the back-beach by infrastructural work affected the littoral dynamics in a predictable way. The back-beach, which had previously been effective as a coastal defense feature through the provision of protection in rare severe wave conditions, became fixed by vegetation during relatively long periods of inactivity. Once the back-beach had become superficially indistinguishable from the rest of the hinterland's landscape in terms of vegetation and apparent inactivity, development pressures and the absence of strict planning controls led to its urbanization in a number of prime locations. In the most highly urbanized sections of the coastal fringe, the complete elimination of the back-beach as a morphological feature has occurred. This is clearly evident in many sites along Costa del Sol, where fishermen's cottages and vegetable gardens had given way to promenades, restaurants, apartments, and hotel blocks by the 1970s (Figure 2).

Figure 2. Examples of urbanization along the Costa del Sol.

Promenades and Seawalls. Major commercial and residential concerns were instrumental in the development of protective measures to defend valuable real estate from marine attack. Promenades became important for their protective and recreational roles, while they also enabled access to the *chiringuitos,* or restaurants and bars, that were located on the beach itself. The nature of the problem to be solved, combined with the technology available at the time, suggested the construction of seawalls fronting improved promenades as the most feasible and appropriate policy.

The utilization of the seawall was encouraged by its perceived advantage of reflecting wave energy seaward. Although this does occur, the regenerated wave fields become short-crested and induce an off-shore-directed circulation (Van de Graff & Bijker, 1988; Silvester & Hsu, 1991), which, when combined with the prevailing oblique approach of waves on the Costa del Sol, cause changes in deposition patterns. Despite the fact that the coast experiences a relatively low-energy regime, reflected waves at the seawall front do produce erosion at the bed, inducing at best the removal of large quantities of sediment and, at worst (following storm conditions), collapse of the structure.

The western Costa del Sol began to experience increasing erosion problem in the 1970s after the configuration of most of the seawalled promenades in their present form. One of the most serious cases was at Estepona where, following the building in the 1960s of a promenade backing the then-extensive beach of La Rada, erosion was so serious that the beach narrowed and suffered a height reduction, so that the promenade itself was threatened with total destruction (Fernandez-Ranada, 1989).

Groynes and Marinas. In an attempt to solve the problem, groyne fields were constructed by the municipality in 1973 (Fernandez-Ranada, 1989). Five straight structures, built normal to the beach, were deployed in an attempt to protect the promenade and stabilize the eroding shoreline. However, the process causing the erosion of the beach was not tackled because, although the groynes were efficient in controlling longshore drift, they failed to stop off-shore-directed sediment transport, the main feature that induces losses of subaerial material (Bijker & de Graff, 1983).

This led to the subsequent use of hammer-head groynes designed to cope with orthogonal as well as longshore movement. Such groynes became a common feature not only at Estepona, but also to the east of Málaga (at Pedregalejo) and later at Benalmádena and Marbella.

Groyne fields have also been deployed in an attempt to minimize erosion and control deposition around the new marinas that have sprung up in abundance along the coast since the 1970s. No fewer than 24 marinas are managed by EPPA (Empresa Pública de Puertos de Andalucía) along the full length of the Costa del Sol between the Bay of Algeciras and Almería. This provides a mean distance of 12 km between each, which, although very convenient for sailors, presents a regular obstacle to longshore processes.

The issue of littoral drift along the Costa del Sol is not well understood given the nearly bidirectional wave climate of the region, where east-to-west and west-to-east wind and wave approaches are dominant. As a result, some classic problems exist concerning all local marinas, given the general exposure of Costa del Sol toward the south/southeast. One such is that eddies associated with the effect of the abrupt interruption of the longshore drift, in conjunction with the lack of wave energy immediately after the structure, leads to sediment deposition. The location of this deposition is, in most examples, close to the harbor mouth, so that navigational difficulties require the use of a semipermanent dredge, as was provided at Marina Cabopino soon after its construction. Groynes were added in order to alleviate this problem and the associated problem of lee-side erosion, both here and elsewhere along the coast. These are designed both to minimize erosion and to halt the siltation of the entrance caused by the effect of the *ponientes* (westerly winds and swell waves) that push fine sand into the harbor.

The largest marina on the Costa del Sol is that constructed at Puerto Banus in 1970. Mooring and servicing facilities for 915 boats were provided as well as a shopping center and other recreational features (EMOISA, 1989). Puerto Banus is located immediately to the west of the mouth of the Rio Verde (see Figure 1). Its exposure to winds and waves from the east dictated an entrance facing the downdrift direction, i.e., west, in order to prevent rapid siltation. As the marina presented a fixed barrier to the predominant littoral drift of sediment from the mouth of the Rio Verde, a field of hammer-head groynes was constructed to prevent erosion on the lee-side of the harbor. Pressure from owners of expensive properties located along this portion of the coast prompted a rapid response to concerns of imminent erosion. At the same time, the groynes provided the condominiums close to the marina with permanent beaches.

Groyne Removal and Beach Nourishment. Other examples of groyne fields associated with marinas and/or the development of promenades for the combined purpose of protection against erosion and containment of beach sand occurred elsewhere along the Costa del Sol, notably at Marbella and Benalmádena. However, despite the large investment, such fields were removed in the 1990s because of their lack of efficacy and a growing problem of sea-water pollution in the artificial embayments. The example of Benalmádena is a case in point. There, hammer-head groynes spaced at 200 m intervals and reinforced with large rock and tetrapod armoring were damaged by severe storms in the 1989/1990 winter. The inadequate design, mainly caused by poor groyne spacing, contributed to further damage to the seawall and occasional collapsing of the promenade (Carter et al., 1991).

A new approach to protection was introduced with the application of beach nourishment. However, as local hydrodynamics are responsible for the achievement of equilibrium profile and planform, the success of beach nourishment in terms of the longevity of the beach and its consequent economic viability is very site specific. Projection of outcomes of schemes is very much dependent upon knowledge of local conditions, and particularly an understanding of processes operating when modal conditions are exceeded. Experiences on the Costa del Sol show that the application of beach fill has not been entirely satisfactory partly because of difficulties in solving a fundamental problem of sediment starvation in the coastal system. Inland sources of sediments are constrained by river flows that have been much reduced by dam building, leaving offshore sediment deposits as the only realistic alternative despite the fact that they are not always sufficient or of ideal composition. In the latter case a reasonably resilient beach has been built, but only because the material that was pumped onto the beach was so coarse or had such a high component of cement that it became highly consolidated. In other cases off-shore material has been excessively shelly, making it unpleasant for recreational purposes. First attempts at Marbella failed partly through use of sands drawn from the mouth of the Guadalhorce. These sands suffered from uncomfortable encrustation in the upper levels, and thus provided an abrasive surface for recreational use.

In Marbella's case, the beach also failed the durability test, as it was subjected to subsurface erosion. In contrast, sediments utilized for nourishment of Málaga's beach were of ideal characteristics, although it was still prone to sand loss due to the effects of recurrent storms after beach fill. The failure to achieve a reasonable life span is strongly influenced by the distortion that beach nourishment introduces into the littoral system. The sudden addition of large volumes of beach material creates a significant shift in the hydrodynamics of shoaling waves, well beyond the expectations of the design phase (Dixon & Pilkey, 1989). This seems to have been the case on beaches such as Marbella and Málaga, where replenishment has had to be repeated soon after the first fill. The reason for this could be the entrainment of large volumes of sediment in a littoral cell whose dynamics have been distorted into a more effective transport machine. In this respect, no less than 7,167,000 m^3 of sand were pumped onto 27 km of beaches along the Costa del Sol in 1992 alone.

The shift from semidissipative to a fully reflective wave energy dispersal environment (given the increase in nearshore steepness) translates into exacerbated rates of transport in the cross-shore and longshore directions. As a result much beach material is dispersed out of the regions that required the material in the first place. Moreover, the presence of numerous marinas and harbors has led to significant accumulations of beach material on the upper drift side of the construction, while the low energy environment generated in the lee of the construction has become a deposition area. The resulting siltation problem is still unresolved for many small harbors and marinas along the Costa del Sol. Thus the extent to which coastal protection methods have been successful over the past 50 years is very much an open question despite complete reversal of techniques from hard to soft structures.

Coastal Management Policies

Present protection policies reflect the change in strategy that began to emerge from the mid-1980s in response to the high levels of urbanization by then present and the susceptibility of the region to any adverse trends in the vital tourist industry. Moreover, a coordinated official approach served to fill the vacuum in integrated and applied environmental planning policy inherited from the Franco era. Economic interests were paramount following the Spanish Civil War, and accordingly physical planning exhibited few restraints on the locational preferences of developers. Thus, urban development along the Costa del Sol was subject to little building restriction based upon environmental or other controls (Pollard & Domínguez-Rodríguez, 1995). Little or no attention was paid to general environmental matters or specific coastal concerns until the end of the Franco era despite the fact that a *Ley de Costas* (Coasts Act) had been passed in 1969. Its scope had concentrated on the establishment and distribution of executive power rather than the implementation of actual measures to manage the coastal fringe, and any potential value was quickly lost in the rapidity of coastal development (MOPU, 1989).

Thus the first effective national coastal management plan dates back only to 1982. Its main innovation lay in the treatment of the coastal fringe as a distinctive unit for the first time in a national context, recognizing the need for specifically directed investment and legislation. Investment in coastal management then increased dramatically so that outlays in 1993 were almost 40 times the levels of 1982 (MOPTMA, 1993).

The changes were introduced under a new legislative framework whose priorities were to update and introduce new laws for coastal environments and to assign responsibility for decision making between the national, regional, and municipal administrative levels. The new *Ley de Costas* performing these functions was passed in 1988.

The *Ley de Costas* encouraged the conservation of natural coastal environments and the establishment of buffer zones through set-back policies (MOPU, 1989). Wherever possible, public jurisdiction was extended throughout the coast to incorporate beaches, dunes, marshes, lowlands, and cliffs as well as a 6-m belt to permit access to the public domain. Behind this 6-m belt extended a protection zone of a further 100 m before any new building was to be permitted. Even then controls upon the type of building were established to ensure that new developments should be related to the coast providing such things as golf or other sports facilities, restaurants, or showering facilities with restrictions too on the height of buildings.

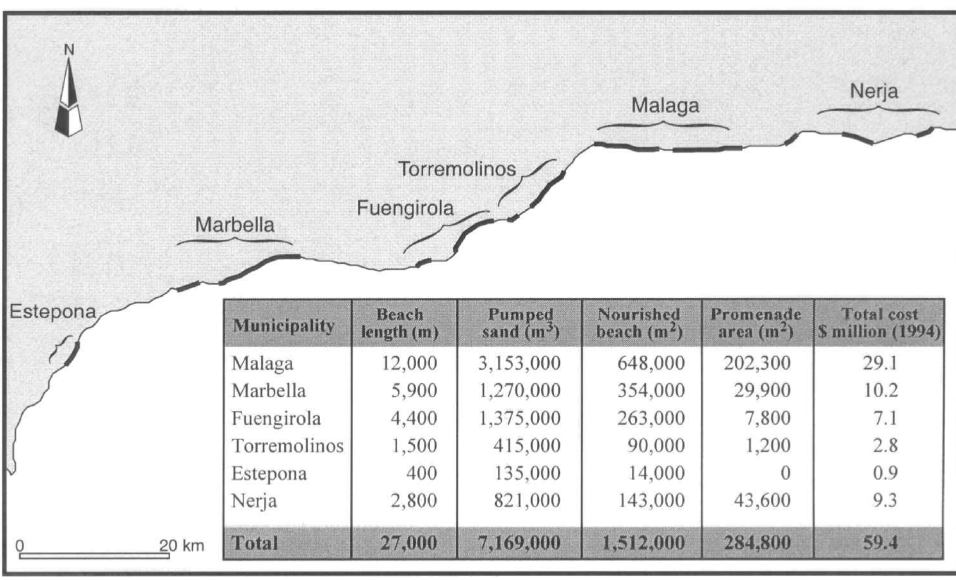
However, the belated introduction of such legislation restricted its applicability on the Costa del Sol, as past development policies had allowed private commercial interests to effectively urbanize long stretches of the coast to the neglect of environmental, conservation, or social concerns that fell within the wider public domain (Pollard & Domínguez-Rodríguez, 1995). As a result very few sections of the coastal fringe to Málaga province provide natural conditions in which the new legislative framework could operate. In a similar vein, the Natural Environment Agency (AMA) was able to designate only one nature reserve along the entire length of the Costa del Sol, viz. the Cliffs of Maro near

Nerja. Other previously existing fragile ecosystems that might have been candidates for such designation had already been destroyed in the rush to urbanize the coast.

New responsibilities were laid down and divided between the three tiers of the central government, the regions (Junta de Andalucía in this case), and the municipalities, and broad-based feasibility studies have been adopted for the assessment of the suitability of coastal protection works. In the latter, financial elements (expenditure, predicted income flows from additional users of facilities, tax revenues generated) are complemented by an evaluation of some social effects (employment generation, income redistribution) and the environmental impact of the proposal.

These methods were applied to three beaches, viz. Magalluf (Majorca), Maresme (Catalonia), and the Costa del Sol example of Pedregalejo (Málaga). At Pedregalejo the calculations were used to justify the expenditure of approximately $63 million at the national level. Substantially increased tax flows, together with additional income both actual and imputed totaling over $20 million, underpinned the investment on a stretch of coastline that was previously impoverished and yet had required physical protection.

The high benefit/cost ratio associated with beach investment was also used to justify beach regeneration at many locations along the Costa del Sol (Figure 3). Meanwhile many other significant changes followed in the wake of the *Ley de Costas,* including the removal of restaurants and bars (*chiringuitos*) and other recreational structures from the beach itself, as well as the destruction of some hard-engineering features, in particular many of the groyne fields noted earlier. At the same time, new constructions that flouts the law renders their builders liable to meeting the costs of demolition as well as payment of fines. Such fines exceed $300 per annum on average and have involved sums of up to 300 mn. ptas. ($2 million) on the Costa del Sol (Luis Lopez Pelaez, personal communication). While it is not possible to demolish constructions that predate the Act, controls are such that no increase in size is possible. If a building within the controlled zones is removed, no rebuilding or alternative construction is permitted. Unfortunately, much building activity took place in the 18-month intervening period between knowledge of the Act coming into the public domain and its implementation, thus reducing somewhat the efficacy of its impact and circumscribing future management.



Municipality	Beach length (m)	Pumped sand (m^3)	Nourished beach (m^2)	Promenade area (m^2)	Total cost $ million (1994)
Malaga	12,000	3,153,000	648,000	202,300	29.1
Marbella	5,900	1,270,000	354,000	29,900	10.2
Fuengirola	4,400	1,375,000	263,000	7,800	7.1
Torremolinos	1,500	415,000	90,000	1,200	2.8
Estepona	400	135,000	14,000	0	0.9
Nerja	2,800	821,000	143,000	43,600	9.3
Total	**27,000**	**7,169,000**	**1,512,000**	**284,800**	**59.4**

Figure 3. Coastal nourishment on the Costa del Sol (the heavy line marks nourished beaches).

Despite these problems, the dramatic improvement in coastal management is to be welcomed. At the same time, there remain significant possibilities for further improvement in management, particularly if a more efficacious system were in place to define areas that are most subject to stress. Marine processes have been investigated only for very limited sections of the Costa del Sol, while human actions that both affect those processes and act independently to exert pressures on the coast remain completely unmodelled. From the engineering standpoint, some classification of the coast has been done but this is too much based upon a cost/benefit analytical approach to beach nourishment or site-specific reports prior to coastal protection work, while coastal subdivisions derived from physical factors are too broad and do not take account of sources of energy and landform type in determining the engineering response. It is thus considered that the development and application of a broadly based sensitivity index, combining the influences of both a physical and a human nature, would offer a vital tool to improve decision making along this stretch of the Spanish coast.

The Measurement of Coastal Sensitivity

The Costa del Sol presents a classic example of coastal management based upon reactive procedures. The Spanish Ministry of Environment has, however, demonstrated its concern for changing this approach and adopting a more proactive policy aimed at the conservation of the coastal environment. However, their activities illustrated in the previous section lack the holistic scientific background that would enable any classification of the coastline that could provide a basis for the implementation of coastal policy. For instance, the width of the buffer zone to which the *Ley de Costas* applies varies between 20 and 500 meters, but is based upon planning criteria rather than any variation in local physical attributes of the coast. Policies based upon an overgeneralized delineation of the coastal domain will generally ignore the physical and socioeconomic variables acting on the coast, while the treatment of the coast as an undifferentiated unit is likely to lead to oversimplified management practices. Consequently, there is an urgent need to recognize variability in coastal sensitivity in order to implement policies more selectively. The development of an index capable of delineating different degrees of sensitivity of the coastline of the Costa del Sol represents an important step in providing a sound basis for policy making.

The presence of a combination of human and physical processes applying pressure to coastal areas demands an holistic approach to any assessment of sensitivity. While decisions as to which parameters should be used in delineating risk factors are not always clear cut, an attempt has been made in this case to avoid too site-specific an approach, so that the procedure might have a more general applicability.

This study adopts a meso-scale approach in an attempt to balance the vast demands for data in a fine resolution study of the 147 km length of the Costa del Sol, and the overgeneralization inherent in studies at the country or continental level as, for example, used in Gornitz's (1990) work on the east coast of the United States. Within that scale framework a geographical information system (GIS) approach provides the mechanism through which variables of a heterogeneous nature can be georeferenced and combined. The variables used are derived from Gornitz and are summarized in Table 1. They include four physical elements (lithology, morphology, fluvial sediment supply, and wave-induced marine processes), and the two anthropogenic impacts (population and urbanization) to which reference has already been made.

The method employed for the construction of the sensitivity index database is built on the retrieval of the relevant parameters from maps, published data series, and preprocessed data derived from wave and sedimentation models constructed by the authors. The

Table 1
Coastal risk variables and classifications

	Score within Index				
Variables	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
Exposure to wave energy and wave-generated processes	Sheltered, low-surf-zone activity	⟷	⟷	⟷	High concentration of wave energy dissipation on surf-zone; strong longshore/on-offshore current activity; exposure to prevailing wind-wave approach
Lithology	Plutonic, highly metamorphized rocks	Sandstones, conglomerates, low-metamorphic gravel	Most sedimentary rocks	Coarse unconsolidated sediment	Sands (fine unconsolidated sediment)
Morphology	High cliffs	Low cliffs	Rock platform	Wide beach with dune	Narrow beach
River discharge	Permanent	Intermittent	Frequent yields with partial regulation	Sparse yields with partial regulation	Permanent or sparse yields Heavily engineered
Population	Decreasing	Stable (effectively decreasing)	Growing at average Málaga's rate	Above average but not exponential	Rapid exponential growth (>average rate)
Urbanization	No urban infrastructure present	Basic infrastructure, very little housing	Scattered urban development	Low-density urban settlement	Totally urbanized

separate information layers are combined into a geographically referenced environment so that longitudinal segmentation of the coast can be defined in terms of relatively homogeneous sections determined by discontinuities in the strength of contributing variables.

Certain underlying principles have been adopted in the selection of these variables. Of particular importance is the consideration that the sensitivity index should reflect dynamic processes acting in the coastal environment and thus measure the presence of increasing stress wherever it exists, rather than merely quantifying the static situation. As an instance, anthropogenic impacts, including economic or urbanization phenomena, are most appropriately considered in terms of growth of the stress-inducing factor.

It is also important that physical processes should be analyzed through their actions rather than their effects. This contrasts with the approach adopted by Fleming and Townend (1989), which assumed that erosion was the criterion by which to assess vulnerability. On the contrary, marine agents in particular need to be included in the assessment as causal factors, while the littoral morphology reflects coastal adaptation to these active processes. It is therefore crucial to describe both the primary source of littoral energy through a comprehensive hydrodynamic and morphodynamic study and the availability of sediments to the marine system. Along an active, morphodynamic coastline in the midterm (1–10 years), those two parameters may be regarded as responsible for maintaining cellular circulation and are the primary source, when disturbed, of induced instability, erosion, and vulnerability. Only through a detailed recognition of littoral processes can a better understanding be obtained of the response of the coastal system to both modal and storm conditions. The application of wave propagation numerical modeling provides a valuable tool for the understanding and estimation of energy levels in different locations under a variety of conditions. This is one of the means of improvement of early indices, where the simplicity of the method is accompanied by an increasingly complex description of the dynamic variables (Dal Cin & Simeoni, 1989).

Lee et al. (1991) considered beach erosion, sedimentation, and accretion in their regional scale model of coastal vulnerability. However, their approach does not allow forecasts to be made of coastal behavior over the mid- to long term, as erosion or accretion can be a short-term (seasonal) event, or reflect a long-term tendency (shoreline change or sea-level rise). It is therefore important to know why erosion is taking place if any index is to be used for forecasting and management purposes.

It is also of note that coastal sensitivity/vulnerability studies commonly exclude analyses of sediment availability. It is probably no coincidence that the application of coastal stress indicators has been largely in the open ocean situations of the Atlantic and Pacific, where sediment supply has marine rather than terrigenous origin. However, in the Mediterranean, the source of sediment derives from rivers whose flows are subject to extreme variability and have been subject to major human interference. Sediment supply is both intermittent and much more restricted, and thus it assumes a fundamental significance in the evolution of the morphology and stability of the coastline. Consequently, sediment supply is an essential element in any calculation of coastal vulnerability in these conditions.

Nevertheless, the inclusion of a variable to characterize fluvial sediment supply to the coast does introduce a number of methodological complications related to the lack of quantitative models available on a regional scale that can provide a good indication of the sediment budget for the section of coast under investigation. At times some sectors can be studied relatively easily since gauged rivers can be monitored for sediment yield. Both modal and storm conditions can then be extrapolated to provide estimates of sediment inputs to the littoral system. However, the availability of reliable data from this source is uncommon in many locations, including the Spanish Mediterranean coast. No regional scale models covering all rivers exist for the Costa del Sol. Thus, in this study, a number of individual basins have been examined and data for sediment supply have been extrapolated for the region.

A GIS is the most appropriate methodological platform for the calculation and mapping of the sensitivity index derived from a combination of variables, each of which displays a distinctive spatial distribution pattern. Individual distributions can be input directly into the index following identification and mapping. The management of quantitative and qualitative data provided by index variables in the GIS enables input of data of varied nature, including different scales and units of measurement. However, a prior requisite step is the indexation of categories in the input variables. In this case, each variable for each coastal segment is ranked between 1 and 5 according to its level of vulnerability. (The maximum score is given to a highly vulnerable/sensitive condition.) Table 1 shows the variables and rankings used in this study. The ranges of the morphological and lithological variables allow for scenarios that are not found on the Costa del Sol and are included to permit the universal application of the index. Maximum and minimum scores for the physical-process-related and anthropogenic variables are, however, those found in the local system. Thus in this study the index has been customized to analyze the increased stress on the coastal fringe of the Costa del Sol over the last 50 years.

Consideration of previous applications of sensitivity indices led to the conclusion that the final cumulative index is best obtained via simple arithmetic procedures given the simplified nature of the quantifying of its component parts. The index results from the unweighted addition of its six elements. It is thus relatively free from possible statistical misinterpretation, but it still remains open to improvement by others who may recognize better procedures for combining variables, or those who can establish a sufficiently better understanding of the dynamic variables involved to permit a credible weighting procedure.

The six variables contributing to the sensitivity index and their derivations are listed below.

Coastal Lithology

The vital consideration is the effect of geology upon rates of marine erosion, so that the principal distinctions drawn are between the various lower erosion hard-rock types and the high-erosion environments of unconsolidated sediments. Information was extracted from the 1:50,000 series geological maps (IGME, various dates), providing a classification into five classes ranging from the most resistant highly metamorphosed rocks to fine unconsolidated sands.

Landforms

A similar five-point classification for coastal morphology distinguishes high cliffs, low cliffs, and platforms, which on the Costa del Sol are generally composed of metamorphic rocks, wide beaches backed by dunes, and narrow beaches without a wide back-beach or dune system. Narrow beaches are considered the most sensitive because their morphology provides extremely limited protection in storm events.

River Discharge

The direct consequence of tourism growth and urban development has been a massive increase in demand for water, a demand that has been met with damming of the water courses flowing into the Mediterranean, thus strongly reducing the supply of sediment to the coast. The classification of this variable is based upon the potential sediment yield calculated from natural discharge subject to engineering regulation. High sensitivity was assigned to sections of the coast that are either subject to ephemeral river supply or under severe watershed regulation schemes, whereas a minimal sensitivity score is allocated where discharge is permanent and largely unengineered.

Exposure to Marine Processes

A group of complex variables was synthesized and combined into a single process-related variable. In indices of the Gornitz type, marine variables are represented by waves and tides as dynamic processes, and trends in relative sea-level rise as long-term process. Given the short timescale of this study, sea-level rise has been omitted and, as tidal regimes are negligible along the Costa del Sol, they have also been suppressed. Thus, the variable has been calculated solely on the basis of modeling wave hydrodynamics and morphodynamics through numerical simulation of wave propagation from deep to coastal waters.

The methodological approach followed is based on the recognition of (i) circulatory cells and (ii) the identification of exposure to wave energy. These two elements are amalgamated in a unique "exposure to marine agents" variable that is then ranked and incorporated in the GIS database. The basis of these two elements is as follows.

Cells. The long-term development of morphodynamic processes is portrayed by the effects of coastal cellular circulations. After waves are refracted in the region of the nearshore, zones of concentration and divergence can be identified. Driven by topographic discontinuities and variations in wave crest dimensions, wave energy tends to concentrate or diverge around coastal features such as canyons or headlands. This dichotomy of concentration-divergence can be mapped along the coastline in the context of these cellular circulations. Such "cells" represent the fundamental units of study for nearshore evolutions (Carter, 1988) and, within them, system inputs and outputs (i.e., erosion and deposition areas in the nearshore area) can be defined and monitored. In the index cells are delineated from calculations of circulation based on forces defined as the derivative of the radiation stresses at each point of the surf-zone for which there is wave energy dissipation. This is performed in the HISWA model as described by Booij and Holthuijsen (1995).

Exposure to Wave Energy and Related Coastal Types. The Costa del Sol, like many open coasts, experiences differential exposure to the main wind and wave approaches and therefore shows different types of coastal adjustment. Classification of energy levels along the coast thus shows regions that are subject to higher stress levels. The HISWA numerical propagation model (Holthuijsen, Booij, & Herbers, 1989; Booij & Holthuijsen, 1995) was used to resolve exposure to wave energy at the local scale. Regional bathymetric information taken from logs of 1:25,000 Admiralty Charts was used to input topographic information into the model, and significant and maximum wave heights and periods were established from 10-year wave records from an offshore buoy. The directional component of the sea-waves was derived from wave roses produced by the Ministry of the Environment (MOPTMA) for the Costa del Sol region. Multivariate simulations were performed to characterize coastal exposure under modal and storm conditions. Mapped output of the spatial distribution of wave energy dissipation along the coastline then enabled its segmentation according to vulnerability.

This component of the sensitivity index thus reflects coastwise sediment transport and wave conditions and ranges from a minimum value, where sheltered conditions producing limited surf-zone longshore transport are encountered (e.g., to the west of Fuengirola), to its highest value, where wave energy supply and dissipation is greatest. A good example of the latter conditions is seen at Torremolinos, which is exposed to the *Levante* storm-waves approaching the shoreline from the east.

Population Growth

Two elements, *population growth* and *urbanization*, have been chosen to represent the direct human contribution to coastal stress. Population growth both reflects regional development and provides a measure of the use of the natural coastal resources in terms of water supplies and land requirements for a variety of socioeconomic activities, as well as beaches and inshore waters more specifically for recreational uses.

Population has grown at variable rates along the coast, largely according to relative suitability for tourism development, but a broad division can be drawn between the western and eastern Costa del Sol, the two sections being separated by the city of Málaga (Figure 1). The fastest growth is clearly recorded to the west of Málaga, that stretch of the coast having increased its population by five times since 1900, leaving the eastern coast in its wake (Table 2). Variations within the western and eastern Costa del Sol are also apparent, with the Torremolinos and Fuengirola municipalities standing out strongly as centers of extremely rapid population expansion.

The population growth component included in the sensitivity index is recorded at this municipality level: it is the smallest scale unit at which population data are available in the Spanish census. Five categories of population growth are recognized, two on either side of Málaga's relatively smooth growth this century, which is considered to be modal (Carvajal-Gutiérrez, 1981).

Urbanization

Growth in the resident population does not fully reflect increasing pressure on the coast, as no account is taken of the tourists themselves who so heavily inflate population numbers throughout the year. Unfortunately, no fine-scale spatial data are produced for visitor numbers on the Costa del Sol, although the infrastructure utilized by the tourists is clearly in evidence along the coastal margins. Thus, a second human element has been included by taking account of *urbanization* of the coast. This has been done through the comparison of aerial photographs for the 1950s and 1990s. Three categories were recog-

Table 2
Distribution of population in Málaga province, 1900–1991

	1900		1950		1991	
	Pop.	% of province total	Pop.	% of province total	Pop.	% of province total
West coast municipalities	41,470	7.5	47,745	6.4	230,558	19.3
East coast municipalities	45,555	8.2	55,060	7.3	94,503	7.9
City of Málaga	137,020	24.8	276,222	36.8	569,992	47.6
Málaga province total	551,989	100	750,115	100	1,197,308	100

Source: Censo de Población 1991.

nized based on the percentage of land that has been used for accommodation, commercial, and infrastructural purposes. These divisions were defined as urban, occupied by scattered settlement, or unpopulated.

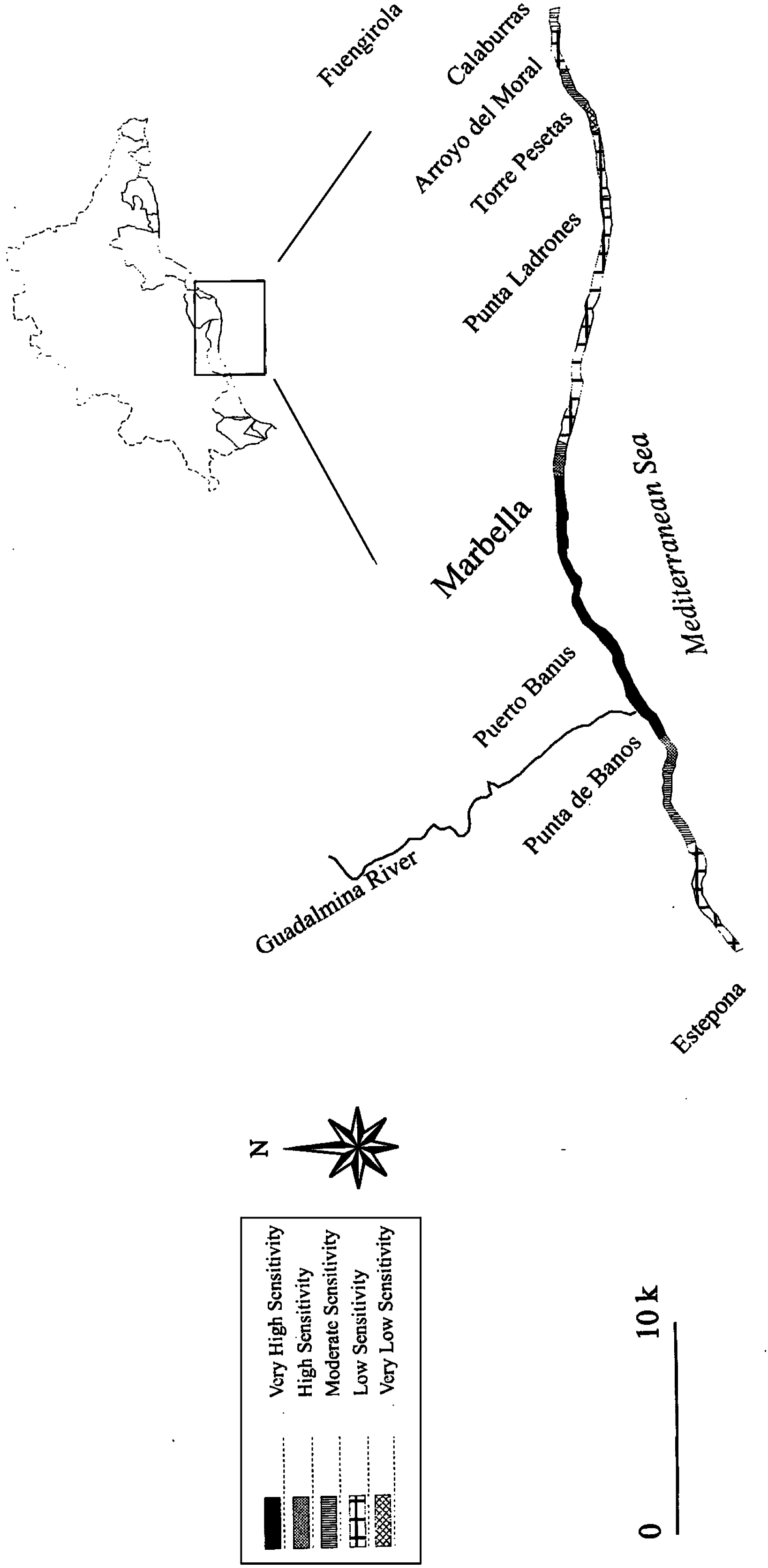
Combined Index

The overall *sensitivity index* is obtained from the addition of the scores of the six variables and the division of the range into five categories based upon the degree of stress suffered by each section of the coast. Although variability was notable along the whole coast, high risk values were predominant (Figure 4 and Table 3). The most stressed section of the coastline is that between Málaga and Fuengirola. Whereas different factors combine to give that final result, *all* sections of this stretch exhibit a similarly high degree of urbanization, reflected in an almost continuous line of settlement from Málaga through Torremolinos, Benalmádena, and Mijas Costa to Fuengirola. The exceptionally high rate of population growth is indeed the factor behind the high index of Torremolinos, but the coast from Benalmádena to Fuengirola is especially exposed to high-energy marine processes, whereas an ephemeral and highly regulated sediment supply is an important causal factor underlying the index of the Málaga city segment. Similarly, although the embayment of Marbella is sheltered from intense marine-related processes, the urbanized environment and the fragility of the narrow beaches characterize it with a high index. In the eastern Costa del Sol, high sensitivity is indicated around the delta of the River Velez, where a combination of sediment starvation and low-lying coastal morphology increase the risk score despite the relatively low degree of urbanization and average population growth rate.

Areas of low overall sensitivity are found where advantageous morphological features dominate. This partly reflects the limited settlement along the high cliff coasts (e.g., near Calaburras and Rincon de la Victoria (Figure 4), which are subject to a sediment regime similar to neighboring regions. A lower vulnerability to marine processes is also evident because these high cliff morphologies represent boundaries between circulatory cells at which no exchange of energy takes place. Elsewhere, intermediate scores occur at scattered locations. These are generally subject to intermediate/high scores from marine processes due to exposure and the predominant circulation, but their overall sensitivity index is reduced by a regular sediment supply, low population growth, and urbanization.

Discussion and Conclusion

Although measurement of coastal sensitivity has formed no part of Spanish planning, the official reaction to the stresses introduced by development along the Costa del Sol provides an informative case study of both the practicality of various engineering responses and the application of an effective legal framework within which to control development. While the verdict of time is still awaited with respect to the latest attempts at beach regeneration, it is palpably clear that the management changes culminating in the *Ley de Costas* have been implemented none too soon. The Act does provide a rigorous regulatory regime which has worried some investors, but many tourist interests have appreciated the long-term benefits, particularly in helping to counteract the image of anarchic development along Spain's Mediterranean coast. $25,000 mn was earned by the Spanish tourist industry in 1997, and 85% of this industry is coastally based. In such an economic climate the importance of safeguarding the resource that supports such an industry can hardly be gainsaid. The only question is the means by which it should be done.


Fuengirola
Calaburras
Arroyo del Moral
Torre Pesetas
Punta Ladrones
Marbella
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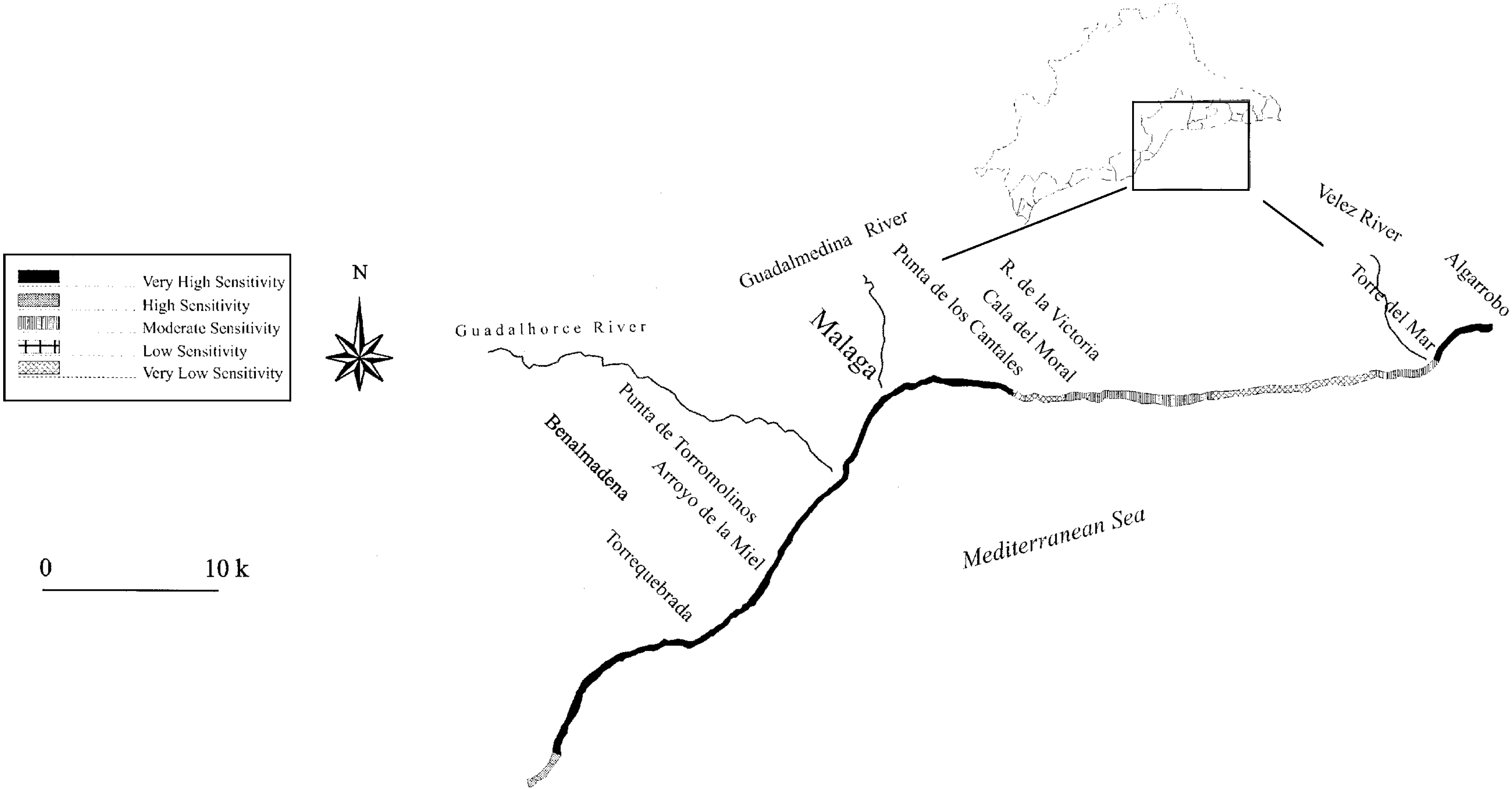

Figure 4. Final combined sensitivity index applied to Costa del Sol.

Table 3
Components of the sensitivity index on the Costa del Sol

Component	Score	Sensitivity description	Component type	Coast length (kms)	% of coast
Lithology	1	Very low	Hard rock	4.91	4.38
	2	Low	Low metamorphism	5.94	5.30
	3	Moderate	Most sedimentary	4.99	4.45
	4	High	Coarse sediments	22.01	19.64
	5	Very high	Sands	74.21	66.22
Landform	2	Low	Medium cliff; indented coast	1.26	1.12
	3	Moderate	Low cliff; platform	5.48	4.89
	4	High	Wide beach–dunes/backbeach	39.98	35.67
	5	Very high	Narrow beach	65.36	58.32
Fluvial sediment supply	1	Very low	Permanent	5.56	4.96
	2	Low	Intermittent	44.77	39.96
	3	Moderate	Frequent yield; partial regulation	37.41	33.39
	5	Very high	Total regulation	24.29	21.68
Exposure to marine processes	2	Low	Not applicable	1.78	1.59
	3	Moderate	Not applicable	49.22	43.90
	4	High	Not applicable	28.61	25.52
	5	Very high	Not applicable	32.50	28.99
Population growth	3	Moderate	Modal (Málaga) rate	16.39	14.62
	4	High	Above average; steady	33.95	30.29
	5	Very high	Very rapid; exponential	61.73	55.08
Urbanization	3	Moderate	2–4.9 houses per sq. km.	53.49	47.74
	4	High	5–10 houses per sq. km.	8.22	7.34
	5	Very high	>10 houses per sq. km.	50.33	44.92

Source: Authors.

It is somewhat ironic that Spain has reversed its previously unenviable position whereby its coastal planning procedures could be considered derisory, to a position where at the end of the 20th century its policies are among the most respected in world terms. While the legacy of the Franco period provides a perfect example of how not to do things where urban esthetics, environmental sustainability, and perhaps even long-term economic development are valued, recent developments provide a model for sensible management of a sensitive coastline. Even so, priority has still been given to economic and planning-related features in the new coastal policy. A more holistic scientific basis for the analysis of environmental conditions and the physical processes that occur along the coastal fringe remains to be put in place. A sensitivity index strongly founded on the analysis of such physical parameters coupled with the integration of socioeconomic variables in the manner described in previous sections is proposed as a valuable tool for those involved in coastal management and related decision making.

The bringing together of physical and human elements in the planning process is perhaps more crucial in a coastal environment than in any other. This study has attempted to provide the essential balance that underpins an accurate understanding of the processes impacting on the coast, and also goes some way toward measuring the combined impact of human and physical forces. Its application to the Costa del Sol provides an archetypal example of demand quickly outstripping the environment's ability to supply the combined needs of agriculture, tourism, and urban communities, thus inducing the severe stress manifested in the disruption of marine processes and consequent erosion damage to the vital resource base of the local economy.

The approach adopted in this study of measuring stress through the amalgamation of physical and human indicators provides a potentially invaluable planning tool. As defined in this study, the sensitivity index did not include engineering work as one of its component elements and was thus not predetermined to identify high stress or engineered coasts. Rather, it has a predictive quality through its combination of physical components reflecting shoreline and marine conditions that exhibit long-term stability, river discharge that is highly vulnerable to human interference, and the human elements of population growth and urbanization that can also be subject to rapid change. The index is thus well suited to use in "what if" scenarios, examining the impact of dam construction on river discharge/sediment supply, or the end result of planning decisions that lead to different degrees of urbanization of the coastline. Whereas examining alternative options might have limited applicability in a Spanish Mediterranean context where settlement has already reached saturation point along substantial tracts of coastline, opportunities abound on the northern and western coasts of the Iberian Peninsula as well as elsewhere in the Mediterranean and beyond.

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