Remote sensing of the coastal zone: an overview and priorities for future research

TIM J. MALTHUS* and PETER J. MUMBY†

*School of Earth, Environment and Geographical Sciences, University of Edinburgh, Drummond St, Edinburgh EH8 9XP, Scotland, UK; e-mail: tjm@geo.ed.ac.uk
†School of Biological Sciences, Hatherly Laboratories, University of Exeter, Prince of Wales Road, Exeter EX4 4PS, UK; email: p.j.mumby@exeter.ac.uk

(Received 31 March 2000; in final form 1 February 2001)

Abstract. This paper uses the Special Issue of the International Journal of Remote Sensing on Remote Sensing of the Coastal Marine Environment to highlight recent advances in knowledge of remote sensing of the coastal zone and to define a series of priorities where future research into the application should be addressed.

Advances were identified in the benefit of high spatial and spectral resolution data and complementary remote sensing techniques (e.g. optical and acoustic, optical and Synthetic Aperture Radar (SAR)). Further benefits are identified in rapid and more frequent data acquisition, faster and more automated processing and a greater sampling intensity over conventional field-based techniques. Issues associated with adoption of remotely sensed data for management are discussed.

Research priorities include the need for improved understanding and description of biotope classes and the functional interpretation of biotope maps and continued developments in understanding the radiative transfer properties of coastal environments. New knowledge is required on spatial and temporal variations of water column optical properties and its constituents. Methods for the best approaches to processing hyperspectral data require further investigation, as does the need for further testing of hyperspectral sensors for bottom type discrimination using data obtained at space-borne altitudes. Areas of value which continue to remain poorly investigated include the improvements to be gained from synergistic use of multi-wavelength remote sensing approaches, change detection techniques and multi-temporal comparisons and knowledge-based approaches to improve classification. The importance of specifically dedicated coastal zone sensors is discussed, as is alternative means of deployment (e.g. International Space Station (ISS) and Un-inhabited Aerial Vehicles (UAVs)). The potential role of airborne digital photography for marine mapping is highlighted. The lack of accurate near-shore bathymetric data is identified as a key limitation in the application of geospatial data to coastal environments.

1. Introduction

Useful reviews of the value of remote sensing of the coastal zone have been published elsewhere (e.g. Cracknell 1999). The aims of this paper are (i) to provide an overview of the contribution of this Special Issue to coastal zone remote sensing;
The coastal zone represents a comparatively small but highly productive and extremely diverse system, with a variety of ecosystems extending from coastal terrestrial habitats to deep water regions approaching 200 m in depth (using LOICZ definition). The diversity of the ecosystems it contains is reflected in the 12 papers comprising this Special Issue. The papers have covered such ecosystems as mangroves (Held et al.), seagrasses (Calvo et al.), coral reefs (Call et al., Karpouzli et al., White et al.), lagoonal microbial mats (Andrefouet et al.), shoreline features (Moore et al.), sublittoral zone benthos (Foster-Smith and Sotheran, White et al.) and overlying water column features (Hu et al.). In so doing, all the studies have consistently indicated the fragile and degraded nature of many of the potentially highly productive ecosystems under study and their general inaccessibility.

All of the papers in this issue have been seeking to apply remote sensing methodologies as an aid to greater understanding of the often unique characteristics of coastal zone ecosystems and habitats. A diversity of remote sensing techniques has been applied and evaluated, ranging from sub-surface acoustic techniques (Foster-Smith and Sotheran, White et al.), digital elevation models derived from aerial-photography (Moore et al.), airborne optical and Synthetic Aperture Radar (SAR) sensors (Andrefouet et al., Calvo et al., Held et al., Thompson et al.) and optical satellite-based sensors (Andrefouet et al., Call et al., Hu et al.), A number have based their analyses on extensive collection of optical data in situ (Andrefouet, et al., Call et al., Hu et al., Karpouzli et al.). In so doing, many of the authors have highlighted the challenges associated with remote sensing in such environments, particularly in tropical environments, ranging from prolonged cloud cover, low accessibility, high and low temperatures, and high humidity.

The range of analyses employed have also been diverse, from empirical models (Karpouzli et al.), multi-spectral classification (Foster-Smith and Sotheran, Call et al., Calvo et al., Held et al., White et al.), expert systems (Moore et al.), to neural networks (Calvo et al., Held et al.).

Significant advances in knowledge and understanding have been highlighted.

- The benefits of high spatial and high spectral resolution data, which are better able to match the rich spectral and spatial diversities observed in coastal systems (e.g. Andrefouet et al., Call et al., Held et al., Thompson et al.). The delineation of coastal zone features is thus largely dictated by the characteristics and capabilities of specific satellite sensors. The limitations of moderate resolution (e.g. 30 m or so, such as those available on Landsat 7 ETM+ and SPOT) satellite data from traditional sources were identified by a number of studies, from poor spatial resolution (Calvo et al., Held et al.), limited spectral capabilities, where wavelength regions containing the most useful signatures can fall outside the visible bands provided by such sensors (Call et al.), and low temporal resolution (Petersen et al.). Moderate resolution data are thus restricted to coarse descriptive level mapping only.
- The benefit of combined optical and SAR-based approaches in improving classifications over some coastal habitats was demonstrated (e.g. Hall et al. for mangrove systems). Classification accuracies were also shown to be increased with the use of greater spatial resolution data and alternative
classification methods such as contextual classifiers (Andrefouet et al.) and neural networks (Calvo et al., Hall et al.).

- The bio-optical properties, even of what may be considered as ‘clear’ oceanic waters, can show significant spatial and temporal variation over a range of scales (Hu et al., Karpouzli et al.). This has implications for both the interpretation of compositive temporal ‘averages’ of such information at the mesoscale (Hu et al.), as well as for assumptions of averaged bio-optical properties when used in water column depth correction procedures in bottom reflectance studies (Karpouzli et al.).

- Acoustic ground discrimination systems (AGDS) offer significant advantages for benthic mapping where light absorption is high and light penetration low (Foster-Smith and Sotheran, White et al.). Such methods pose challenges to interpolation and interpretation of track point data and issues of optimal spacing of tracks that instruments such as the RoxAnn system deliver. Nevertheless, there are commonalities to optical remote sensing methods where classification is based on similar approaches, namely supervised classification. Classification benefits from the use of multi-frequency data and systems and the inherent dimensionality in acoustic data. AGDS offers levels of accuracies of classification similar to optical satellite data where both systems are not capable of discriminating all benthic classes. It is also important to note that biotope maps produced from AGDS are not a representation of reality but a prediction of biotope distribution. Positional and locational errors are greater with this type of data compared to satellite data. There are also issues associated with the variable resolution of the ensonified surface on the sea floor which varies markedly as depth changes.

2. Priority areas for further research

Despite advancing the body of knowledge in coastal remote sensing the collection of papers in this issue also highlights a number of areas where understanding is lacking and significant further research is required.

2.1. Coastal zone monitoring

It is clear that remote sensing has an active role as a monitoring tool for the coastal zone but is a technique still in need of significant further development. For example, the need for accurate habitat maps for the coastal zone is widely recognized, but conservation agencies show a high degree of reluctance to adopt remote sensing technologies routinely in their monitoring programmes (Dekker et al. 2001). Part of the problem arises out of fundamental differences in how accuracy and precision are assessed in field monitoring programmes versus remote sensing. For example, the health of coral communities on the Great Barrier Reef is often monitored using diver-operated video cameras. One of the key variables of interest is the percent cover of living coral and how this varies in space and time (Carleton and Done 1995). The sampling strategy is designed to enable a 10% change in coral cover to be detected with a high (>90%) statistical power using tests of analysis of variance (ANOVA). Clearly, this is a very different presentation of precision to that of confusion matrices which are often used in remote sensing (Congalton 1991). In a recent study which used airborne remote sensing to predict the cover of living coral in a series of 25 m² plots, Mumby et al. (2001a) attempted to bridge this
‘statistical gulf’ by simulating how remotely-sensed data would enable coral cover to be monitored using ANOVA. The analysis suggested field and remote sensing methods would achieve similar statistical power if identical areas were surveyed. Although such comparisons may help convince management and conservation agencies that remote sensing may be an appropriate tool for monitoring, they do injustice to remote sensing methods. Obviously, remote sensing can sample an entire statistical population (e.g. the entire reef) rather than merely a sample of quadrats and therefore the comparison of statistical power with field methods is unrealistic; the sample size and power associated with remote sensing will be larger than that used in the comparison. Second, the real value of remote sensing is that it reveals how pattern changes across a near-continuum of spatial scales. It is vital to acquire such broad perspectives of pattern in order to identify the scale at which disturbance events elicit change in the marine environment. For example, thermal stress generated by the 1998 El Niño-Southern Oscillation caused unprecedented damage to coral populations world-wide (Wilkinson et al. 1999, Wilkinson 2000). At reef scales, however, the effects of thermal stress (coral bleaching) are extremely patchy (Hoegh-Guldberg 1999; Mumby et al. 2001b) and are probably determined by a complex interaction of physical oceanography, local atmospheric conditions and small-scale biological factors. Disentangling these factors requires synoptic data at multiple scales. Only then may we reach a point where we may predict where such events may occur at finer scales.

Continuing research is required into the techniques employed for assessing change in the coastal environment. To date such techniques are limited by existing approaches in that traditional image-based interpretations (on classifications) of remote sensing data are typically sensor specific, site specific and often time specific (Kutser et al. 2002). The development of techniques for assessing change in the coastal zone with true multi-temporal validity requires standardization of methods for application to time-series of datasets. This includes consistent application of such procedures as atmospheric correction. Some vital research is still missing, for example the variation in reflectance with phenology and the influence of epiphytic growth on reflectance. Research also needs to be linked to methods to determine resolvability and hence performance of different sensors of bottom types (spectrally) and the maximum depth limits to which they are resolvable (influence of depth and turbidity).

2.2. Biological integrity and functions of biotope or habitat classes

The Special Issue includes several papers on habitat mapping with sensors as fundamentally different as acoustic and optical. Such diversity in sensors highlights the need for careful description of habitat or biotope classes being mapped. It is unlikely that acoustic and optical methods will resolve habitats in the same way and such differences, if they exist, should be made clear to users of the map. Similar issues occur when habitat maps are combined from different originating data or organizations, each of which often have a unique classification scheme of habitats. Unless the categories are clearly described, for example with quantitative descriptors of characteristic features, it is difficult to know which habitat categories are synonymous and which are not. These sorts of inter-map calibration issues are likely to become more important as government, donor and conservation agencies move to ever-larger transboundary management projects, in recognition of the
There is a requirement for improved understanding in the remote sensing community of the meaning of ‘habitat or biotope classes’. Spectrally-distinctive features in a remotely sensed image often arise from changes in the composition of several species and the subtleties of these changes should be reflected in the description of each feature. How such mixtures of species and substrates translate into optical and acoustic signatures also needs to be better understood. It is evident that greatest classification accuracies are achieved using a hierarchical approach where accuracy increases with the greater aggregation of biotope classes; in other words increasing accuracy with a decrease in descriptive resolution. The appropriateness of field-based biological sampling strategies adopted for the validation of remotely sensed data also warrants further investigation – it must be borne in mind that ‘ground-truth’ data are far from perfect data themselves (e.g. White et al.).

Perhaps one of the most important areas for further research is the functional interpretation of mapped biotopes; what do they tell us about the ecosystem and conservation issues? For example, what do such maps reveal about patterns of productivity or essential fish habitat? To what extent can ecological processes (e.g. predation, herbivory) be given a spatially-explicit dimension through the use of biotope maps? How will such information lead to better design of marine reserve networks? Addressing these issues, through multidisciplinary research, will undoubtedly raise the value of biotope maps as an informative management tool.

2.3. Optical properties and radiative transfer modelling of aquatic systems

There is a need for continued improvements in understanding of the radiative transfer properties of coastal environments, particularly with respect to their spatial variation in the diversity of environments encountered there (e.g. Karpouzli et al.). To use remote sensing to monitor water quality effectively requires an established relationship between water colour and constituent bio-optical water quality parameters (e.g. suspended inorganic matter, dissolved organic matter, bottom-related organic and inorganic matter, chlorophyll containing biota both suspended and bottom living and detritus). Yet the coexistence and covariance of some or all of these parameters, particularly in Case 2 waters means that algorithms developed for Case 1 waters are not applicable here. Further research is required using radiative transfer models (e.g. the Hydrolight model from Sequoia Scientific), to understand inherent optical properties and the factors affecting them to truly model optical processes in Case 2 waters (both physically and spectrally).

In this Special Issue Karpouzli et al. highlight the need for understanding of the scale of variations in optical water quality parameters, both spatially and temporally, and of their influence on inherent and apparent optical properties. Whilst their results suggest that caution may be required in interpretation of depth-corrected remotely sensed imagery where average attenuation has been used, they also indicate that in certain environments the behaviour of important optical properties may be generalizable using potentially easily determined physical parameters (e.g. depth and proximity to potential input sources). These and other results indicate that improvements in existing water column correction approaches may be achieved where the spatial variations in inherent and apparent optical
properties are predicted from distributions of chlorophyll and other optically important water quality parameters predicted either from physical models (e.g. Hu et al. 2003) or inferred from the remotely sensed data themselves (e.g. Lee et al. 1999). The degree to which partitionist approaches, such as the biological province concept used to model oceanic productivity (e.g. Platt et al. 1995), are translatable to the more local scales of coral reefs and other coastal systems also warrants further research.

The spectral reflectance characteristics of bottom features within submersed coastal environments are often optically similar, which leads to confusion in their subsequent identification in remotely sensed data. There is thus a major challenge to distinguish different classes, particularly of vegetation, on the basis of spectral reflectances (the influence of epiphytic infestations on complicating spectral identification requires further investigation). Higher spectral resolution reflectances are needed to perceive the subtle differences (e.g. Holden and LeDrew 1998, Call et al.). Classifications based on high spectral resolution airborne data (e.g. CASI and AVIRIS) tend to provide the best results but may also benefit from the improved spatial resolutions such data have provided. However, there is a need for the verification of high spectral resolution results at satellite altitudes and the Hyperion and future NEMO sensors offer valuable research platforms with which to evaluate these approaches (e.g. Dekker et al. 2002).

The best methods to process hyperspectral data volumes have yet to be established, both generally and with respect to littoral environments. Can we really use spectral libraries to identify features in remotely sensed data of aquatic systems given the high degree of variability in such systems? What is the relationship between spectral distinctiveness and variations in brightness, the latter being one of the strongest attributes for separating substrate type (e.g. Call et al.)? Radiative transfer modelling will be valuable in aiding algorithm development, for example in further exploring techniques such as the use of derivatives (Holden and LeDrew 1998, Louchard et al. 2002) and spectral unmixing (Andrefouet et al.).

The depth limits to which useful above-surface spectral signatures can be derived which still allow for the discrimination of habitat types need to be better understood, as does their relationship to varying water column optical properties. For example, two separate studies on very different regions have shown that the point at which signatures begin to resemble water column optical properties rather than substrate signatures ranged from 7 m for a coral reef system (Call et al.) to 8.5 m for an Outer Hebridean coastal system (Malthus and Karpouzli 2003). Furthermore, the extent to which spectral separability of habitats is affected by sensor signal to noise ratios needs to be further evaluated (e.g. Dekker et al. 2002).

2.4. Taking advantage of imagery with high spatial resolution

The inadequacies of spatial resolution for satellite data have been highlighted in a number of papers in this issue (e.g. Held et al., Call et al.) where sub-pixel-scale mixing prevents accurate identification of community type, even at small scales (Andrefouet et al.). Remotely sensed data offering increased spatial resolution offer richer information in the form of variability in spectral and spatial diversity which may lead to improved classification. For example, Calvo et al. highlight a critical resolution of around 4 m for mapping seagrass in their lagoonal system. These results emphasize the potential value of the higher spatial resolution IKONOS and
QuickBird satellite sensors in improving the mapping of littoral zones, although spectral resolution may still be a latent limitation and cost may be an issue if extensive coverage is required (Mumby and Edwards 2002).

2.5. *Dedicated sensors for the coastal zone*

Although there is an apparent lack of sensor data to choose from, the general features of the coastal zone make the lack of specifically dedicated coastal zone sensors an important issue (Peterson *et al.*), particularly in tropical regions where acquisition of suitable field and satellite data is affected by prolonged cloud cover, low accessibility, high temperatures and high humidity. There is a need for spectral resolution of coastal zone sensors to be driven by spectral signatures from the coastal zone, particularly where discriminating wavelengths are not separable in existing sensors. Furthermore, it is highly unlikely that remote sensing will ever be able to map living corals to species level because intraspecies variability in reflectance spectra is as high as interspecies variability (Call *et al.*). There is also a need for frequent observation over the coastal zone where change can be dynamic.

Performance characteristics of future sensor designs and deployment vehicles (e.g. in terms of efficiency, reliability, flexibility, coverage, frequency and risk) need to be evaluated against scientific and practical objectives, to provide an optimum data acquisition strategy (Peterson *et al.*). Alternative means of deployment (e.g. on the low orbit International Space Station (ISS) or on a Un-inhabited Aerial Vehicles (UAVs)) offers benefits in terms of frequency of coverage, spatial resolution, flexibility in spectral resolution and maintenance and calibration. UAVs have the advantage of being deployed during windows of good weather but the spatial coverage is relatively poor.

The role of digital airborne colour and infrared photography is increasing in importance, although much of its use goes largely unreported in the scientific literature. Such data potentially provide a cost-effective method for marine survey, particularly in the developing world and warrant further evaluation as to their quality and accuracy. The use of digital technologies better facilitates change detection compared with conventional aerial photographic techniques. But this is perhaps the least studied area in shallow marine survey applications. Digital cameras utilize light-sensitive computer chip (CCD) technology to acquire true colour or false colour infrared photographic imagery digitally through an array of pixels rather than conventional film emulsion. This reduces the need for survey film, processing chemicals and printing paper, which in turn significantly reduces costs. Digitally captured multi-spectral images typically offer superior spectral fidelity when compared to images scanned from colour infrared film. A number of companies have produced digital cameras specifically for use on aircraft (e.g. the RMK Top from ZI Imaging and the ADAR 5500 from Positive Systems). Pixel sizes approximate those achieved with conventional aerial photography, generally ranging from 10 cm to 50 cm and above, depending on flying acquisition height and speed. All images can then be accurately rectified and analysed on computer. The challenges to the application of such data over littoral and sublittoral regions are (i) the need to convert radiance to reflectance in order to improve mosaicking of imagery along adjacent flightlines; and (ii) the need for accurate geometric correction of the data given the potential absence of verifiable ground control points over major parts of the imagery.
2.6. Acquisition and use of bathymetry data

With the importance of depth-correction methods recognized for improving shallow water habitat classifications from optical image data (e.g. Mumby et al. 1998), there is a growing need for improved regional and local scale near-shore bathymetric data for large areas of the globe. Whilst now available in digital form at the global level via such datasets as the GEBCO Digital Atlas (e.g. BODC 2002) and others (e.g. Smith and Sandwell 1997), these datasets are of the scale of 1:500 000 at best and have little to no value in the correction of remotely sensed optical data for depth effects or in other applications of geospatial data in coastal environments. As is increasingly the case with global-scale data, local-scale charts should represent the integration of depth estimates from multiple sources if available, including traditional bathymetric chart and depth sound data, acoustic methods, geophysical ship track data, SAR imaging and topographic LIDAR. Issues of resolution and accuracy may need to be resolved. The utility of optical remote sensing data for bathymetric studies of shallow coastal zone has long been recognized (e.g. Lyzenga 1978), which require correction for water column effects and bottom reflectance (e.g. Lyzenga 1981, 1985, Bierwirth et al. 1993). Whilst such approaches may work well in areas of relatively homogeneous bottom type and reflectance (with local ‘calibration’ required), issues of application in heterogeneous target areas still need sorting out although some new theoretical approaches are beginning to emerge (Hedley and Mumby 2002).

2.7. Synergies from using multiple instruments for remote sensing

Despite increasing evidence as to complementary benefits, there is a surprising lack of studies on the synergy of alternative remote sensing approaches, including above-surface optical, SAR and LIDAR techniques, and sub-surface acoustic methods. Sonar offers easy deployability, independence from cloud cover problems, modest cost but limited coverage, especially in more inaccessible shallow water areas (e.g. White et al.). LIDAR offers high data density for bathymetric studies. Optical satellite remote sensing approaches offer spectral information with a degree of penetration into the water column and wide spatial coverage. SAR and sonar data offer information on structural components of the habitat, in onshore and sub-surface regions, respectively. These components are much less evident in optical data. For example, improvements in mangrove classification demonstrated by Held et al. from 67% accuracies to 76% based on classification of integrated optical and SAR data (improved further to 80% using a neural network). Knowledge of the upper limit of notable habitats is important for management as it is near the shoreline, is frequently a dynamic limit, and is closer to human influences. However, establishment of the upper limit can be complicated, where some technologies (e.g. sidescan sonar) cannot be used but others (e.g. optical remote sensing) have potential utility. Similarly, establishing the lower limits of habitats, which may be determined by light penetration, current flow, or changes in bottom type, may require alternative techniques (e.g. sidescan sonar) where light limitation restricts others (e.g. optical remote sensing).

Improvements in the habitat classification accuracies reported in some of the studies in this Special Issue, were only achieved on the basis of complementary use of different remote sensing approaches, or structural and contextual approaches to the classification. Furthermore, it is well known that the determinants of variation
of certain biotopes are important environmental gradients, for example, bathymetry, salinity, tidal and other geomorphological and geological gradients. Editing signatures on the knowledge of environmental limits of certain biotopes was suggested to mitigate some classification problems (Foster-Smith and Sotheran). Contextual decision rules were noted of potential benefit to classify microbial mats (Andrefouet et al.). An expert systems approach was adopted by Moore et al., where it was used to classify eroding coastal landscape features. The incorporation of knowledge-based approaches into image processing packages, such as ERDAS Imagine, suggests that the incorporation of contextual information can only benefit and further improve accuracies of classifications on the basis of remotely sensed data.

3. Conclusions

Significant advances have been made recently in remote sensing of littoral environments, as reflected by articles in this Special Issue. Although we argue the technique has an active role as a monitoring tool for the coastal zone it is still in need of significant development. A number of issues and priorities have been highlighted where further research is required which continue to concentrate on spectral, spatial and temporal questions.

The challenge is to have remote sensing techniques adopted as a routine tool in assessment of change in the coastal zone. Issues of adoption may be partly due to inadequacies on the part of the remote sensing community, the technology itself, its perceived high costs and the science. However, it is also incumbent on coastal managers (as end-users) to recognize the need for synoptic data at multiple scales to address key coastal zone problems. Remote sensing may be the only technique to deliver data at a multi-scale level.

It is difficult to place a monetary value on remotely sensed information despite its great utility for illuminating natural and disturbance dynamics in coastal systems. It is likely, however, that the political acceptability of remote sensing as a necessary component of coastal monitoring will continue to increase as scientists continue to develop new products and draw fresh insight into coastal dynamics.

References


