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THE USE OF GIS IN THE DESIGN OF MANAGED REALIGNMENT SCHEMES

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Abstract

This paper describes a range of GIS techniques, which have been developed over the last 5 years and successfully employed in the design of over 15 realignment schemes in a range of UK estuaries. A proposed scheme in the Humber Estuary is used to illustrate the applicability of the methods. GIS is seen to be fundamental at all stages of the design process. This starts with establishing the historical site evolution, the current site elevations/gradients, the existing habitats and the nature conservation designations. The paper describes how topographic survey data can be combined with remotely sensed information to create a digital terrain model for the managed realignment scheme, which can then be adapted to create a new 'design' surface for the proposed scheme. Further explanation is given various aspects of scheme design, including (i) the prediction of the habitats which are likely to colonise the scheme, (ii) the need to maintain a sediment balance within the scheme, (iii) the calculation of tidal prisms, and; (iv) the mapping of sampling locations. The GIS analysis provides valuable information for the design, consultation and environmental assessment process. The ability to overlay various layers of information and to create 2 or 3D representations of the scheme, are seen to be particularly powerful GIS features.

Introduction

Managed realignment is the process of removing sea defences and returning land to the sea. In the UK, the main drivers for managed realignment have been the requirement to provide compensatory habitat for the loss of natural areas to development or "coastal squeeze", coupled with the requirement to reduce flood defence costs and provide more sustainable defences. Over the last decade, the number of intertidal managed realignment schemes being planned and implemented has increased markedly and such schemes seem likely to become increasingly common in the future. The Royal Society for the Protection of Birds (RSPB) has assessed that the future potential for intertidal habitat creation around the UK coast could exceed 33,000 hectares (Pilcher et al., 2002).

This paper describes the use of GIS in the design of managed realignment schemes. The methodology described has been developed over the last 5 years and successfully employed in the design of over 15 such schemes in a range of estuaries around the UK. An explanation is given of the following GIS techniques:

1. Defining the site mask
2. Creating a baseline digital terrain model
3. Matching scheme design to scheme requirements
4. Calculating predicted habitat areas
5. Calculating the volumes of earth movement required
6. Creating a scheme design digital terrain model
7. Producing iterations of the scheme design
8. Analysing the scheme
9. Presenting the scheme

The following sections explain the GIS processes used, the pitfalls of standard approaches, and the development of a rigorous audit system. The techniques described are illustrated by the reference to a case study at Welwick in the Humber estuary, which was designed and analysed using ESRI's ArcGIS and ArcView software.

Overview of scheme

The managed realignment scheme proposed at Welwick is being undertaken to offset the impacts of port developments in the Humber Estuary. Planning permission is being sought and an Environmental Impact Assessment (EIA) has been prepared. Information for an Appropriate Assessment has also been provided to meet the requirements of the Conservation (Natural Habitats &c.) Regulations 1994.

The proposed realignment site at Welwick is located at Outstray Farm on Sunk Island, on the north bank of the outer Humber Estuary (Figure 1). To the edge of the saltmarsh, which fronts the current sea defence, the site covers a total area of some 54ha and has an approximate elevation of 2.8m ODN, compared to the level of Mean High Water Spring (MHWS) tides at Grimsby of 3.2m ODN. Landward of the current defences, the site area covers approximately 50ha, whilst the current sea defence accounts for 1.2ha and saltmarsh seaward of this covers 3ha. The retreat area is currently used for agricultural land, but was formerly composed of intertidal flats and saltmarshes.

The final design option for the scheme was based on ecological requirements, technical issues and the concerns of English Nature and the Environment Agency. The following broad objectives have been established for the scheme:

- The creation of mudflat habitat;
- Existing saltmarsh to be left in place;
- Additional marsh to be created on the site, if possible, to create a transition from mudflat to marsh;
- No removal of sediment from the site;
- No addition of sediment to the site; and,
- No excessive earth movement within the site.

Based on these objectives, the final scheme at Welwick involves the complete removal of the existing sea defence to create a shallow embayment (Figure 2). The saltmarsh which fronts the current defences will be left in place, except for two breaches created to link the newly created site with the wider estuary. The scheme design also involves the reduction of elevations from their current levels in order to reduce the likelihood of forming marsh vegetation at the front of the site. This was undertaken because the site was artificially 'warped up' as part of the reclamation process and the elevations are currently around 1m higher than before reclamation occurred.

In order to limit the landward extent of tidal inundation, it is proposed to reconstruct new defences along the north and east of the site (Figure 2). The new defences will be constructed in line with Environment Agency guidance with side slopes of at least 1:3, a crest width of at least 3m and a minimum height of 6.1m above ODN. The height of the new sea defences was determined by considering the 1 in 50 year design event obtained from a joint probability analysis of large waves/water levels (ABP Research, 1999) and included an allowance of 300mm for future sea level rise.

Figure 1. The proposed location of the Welwick site

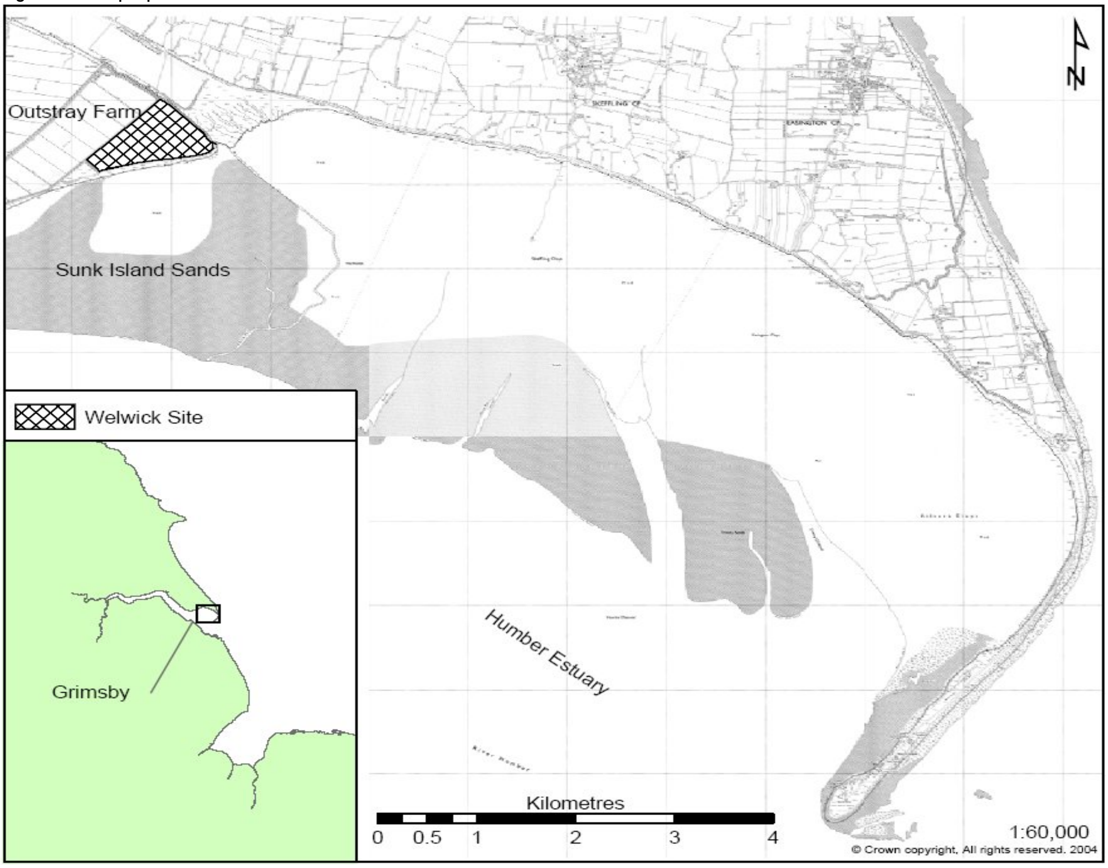
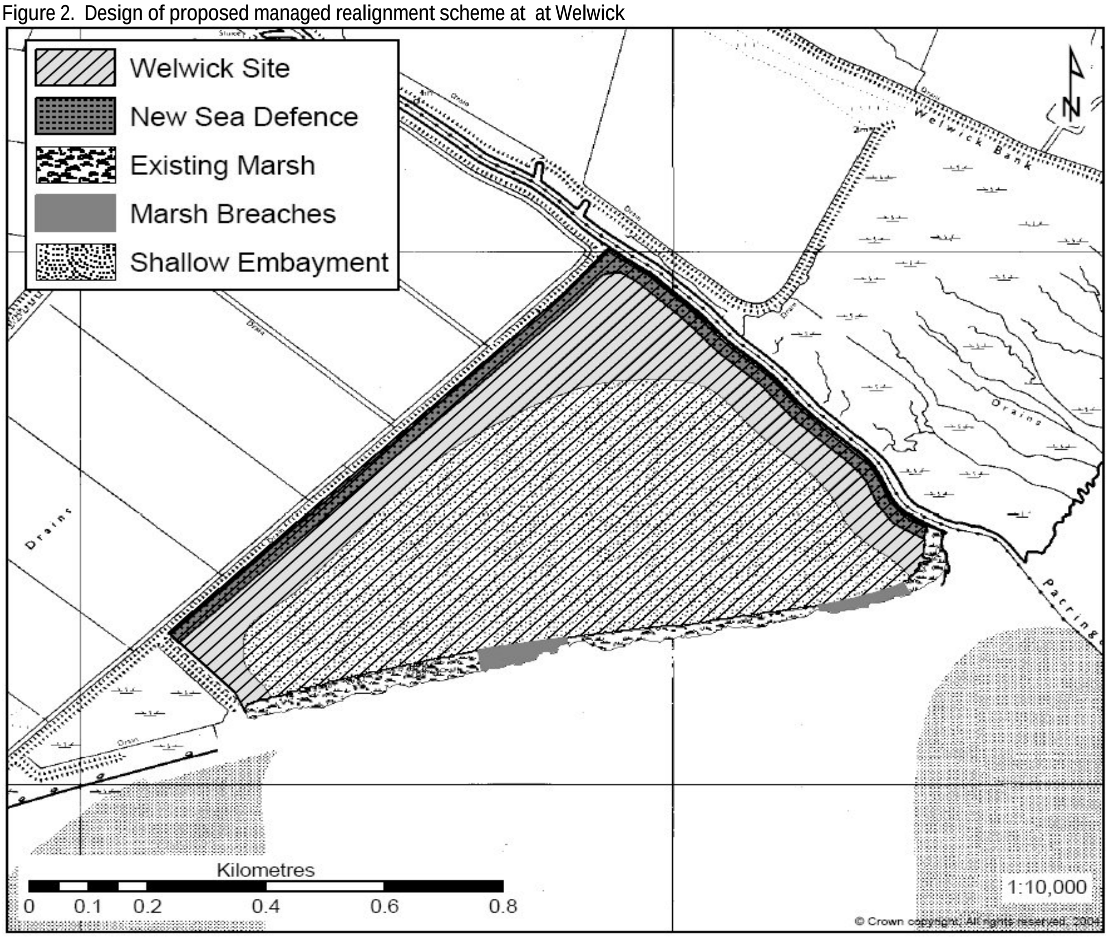


Figure 2. Design of proposed managed realignment scheme at at Welwick



Techniques used

The GIS was used as a tool for both managing and analysing the data, in order to allow informed decisions to be made throughout the design and planning process. One of the first tasks was to use the initial input data to define and create a site mask for the scheme. The definition of a constant site mask is important to the GIS, since it ensures efficient data purchase and enables detailed and accurate area analysis of many datasets to be successfully undertaken later in the project lifecycle.

Current 1:10,000 Ordnance Survey mapping was used to define the general area for the scheme. This was then enhanced through the use of detailed aerial photography to identify and map existing features at the site. The aerial photography was particularly useful in defining the boundary of the saltmarsh that currently fronts the site, as well as providing a detailed mask of the current sea defence. It was also important to create the scheme in an area that lies outside any current conservation designations. The relevant Site of Special Scientific Interest (SSSI), Special Area of Conservation (SAC), Special Protection Area (SPA) and Ramsar boundaries were downloaded from the Multi-Agency Geographic Information for the Countryside (MAGIC) website and loaded into the GIS. This information was used to ensure that the proposed site boundaries did not conflict with these areas.

The scheme design also required an appreciation of the way in which the present site had evolved through time. This allowed predictions to be made about the future evolution of the scheme and ensured that the new scheme resembled the intertidal area that formerly existed at the site. This historical appreciation was achieved through purchasing historical Ordnance Survey maps from LandMark and georeferencing them within ArcMap. This then allowed a short animation sequence to be built up in MS PowerPoint, to illustrate the changes that had occurred at the site.

Light Detection And Ranging (LiDAR) elevation data was purchased from the Environment Agency and used to form a Digital Terrain Model (DTM) of the existing topography at the site. LiDAR is an airborne mapping technique which provides a ground elevation every 2 metres horizontally. This data has a vertical accuracy of +/- 15 cm and a horizontal accuracy of 0.4 m *(Optech, 2004)*, and can be improved by combining it with topographic survey points recorded to a higher level of accuracy. For Welwick, the LiDAR was corrected using a topographic survey of over 6,500 points recorded to a vertical accuracy of +/- 2 cm and a horizontal accuracy of +/- 1.5 cm (Halcrow, 2002).

The GIS enables the elevation of the closest LiDAR point to be attached to each survey point. Additionally, the GIS also calculates the distance between the survey point and the closest LiDAR elevation. Using this information, survey points that did not have a LiDAR point within a 1-metre radius were discarded from the analysis. For the remaining survey points, the residual (difference in elevation between the LiDAR point and the survey point) was calculated. The result for Welwick (Table 1) shows that on average the survey point elevations were 10 cm below the LiDAR elevations. On the basis of this, the GIS was used to lower all of the LiDAR elevations by 10 cm within the Welwick site mask. The corrected LiDAR grid was then used as the baseline DTM from which schemes could be designed and compared against.

Table 1. Statistical comparison of LiDAR elevation and survey elevations at the Welwick site.

Count of Residuals	5165
Mean of Residuals (m)	-0.101
Maximum of Residuals (m)	1.438
Minimum of Residuals (m)	-1.617
Standard Deviation	0.281

Table 1 shows that 5165 survey points had a LiDAR point within a 1-metre radius. Of these, the maximum positive residual was 1.44 metres and the maximum negative residual was 1.62 metres. On average the survey elevation points were 10 cm below the LiDAR elevations and therefore the whole LiDAR baseline DTM was lowered by this amount.

GIS & The Scheme Design Criteria

The scheme at Welwick was designed as a DTM within the GIS and this was then analysed to predict the physical and ecological properties of the scheme. As mentioned above, the scheme was required to achieve certain objectives in order to compensate for the loss of habitats associated with the proposed port developments. The most important requirements were to create the maximum area of mudflat and minimum area of saltmarsh, whilst ensuring that no sediment was moved onto, or off, the site. Following the creation of a potential scheme DTM, ArcView 8.2 with 3D Analyst was used to calculate the indicative habitat areas as well as the cut and fill volumes within the site mask. The volume of cut is the amount of material in areas where the design DTM is lower than the baseline DTM, whilst the volume of fill is the volume of material in areas where the design is higher than the baseline DTM.

The cut and fill calculations required the GIS analysis of both a 'baseline' and 'design' surface within the site mask. The 'baseline' DTM was constructed using corrected LiDAR elevations, whilst the 'design' surface was the DTM of the scheme design. Because the scheme was required to maintain a sediment balance, any sediment gained through lowering the front of the site was offset by the increasing the volume of material contained in the new sea defences and higher ground at the rear of the scheme. The cut and fill volumes were calculated using the 'cut/fill' command within the 3D Analyst menu of ArcMap. In order for this function to be performed it is necessary for the cells of the two grids being analysed to overlap. This was achieved by mirroring the origin and cell size from the baseline DTM when creating the scheme design DTM grid. The 'cut/fill' function interrogates each cell from both grids and produces an output grid which has the change in cell elevation. This was then interrogated to provide the volume and area of both cut and fill.

Because a key objective of the scheme was to provide mudflat habitat, it was necessary to assess the nature of the habitats which would be formed within the scheme. One of the main factors governing the type of intertidal habitat is the elevation of the surface with respect to the tidal frame. Previous work in the Humber has shown that existing marsh habitats occur at given elevations relative to the tidal frame (BBV, 2000; Table 2).

Table 2: Relationship between intertidal habitat type and elevation with respect to the tidal frame in the Humber Estuary (from BBV, 2000)

Habitat boundary		Height Relative to MHWS (m)	Height relative to ODN
Brackish Marsh	Grassland	0.31	3.51
Upper Marsh	Brackish Marsh	0.03	3.23
Mid Marsh	Upper Marsh	-0.06	3.14
Pioneer Marsh	Mid Marsh	-0.10	3.1
Mudflat	Saltmarsh	-0.49	2.71

Based on MHWS at Grimsby of 3.2m ODN

However, these predictions are for existing marshes exposed to normal levels of wave and current action. For areas of reduced tidal and wave action, such as within managed realignment sites, the lower limit of marsh vegetation may be further reduced. BBV (2000) found that within the Humber, the transition between mudflat and marsh habitats occurred at a mean value of 0.49m below MHWS, but that this value had a standard deviation of 0.6m. The importance of fetch in limiting the downshore extent of saltmarsh has been demonstrated by Gray *et al*. (1992, 1995). Regression equations applied to determine the vertical limits of saltmarsh species have shown that a 10km fetch, such as occurs at Welwick, has the potential to raise the lower limit of saltmarsh by 0.8 m (Gray *et al.,* 1992, 1995). Because of this variability, the likely habitats to be created within the scheme at Welwick were assessed in two ways:

1. Using the same approach as adopted at the nearby Paul Holme Strays managed realignment site, based on the elevations quoted in Table 2.

2. A worst case scenario based on the various habitats occurring 0.6m lower than in (1), on the basis of reduced wave energy.

The habitat areas were calculated using the ‘area and volume statistics’ command within the 3D Analyst menu of ArcMap. Two-dimensional areas were calculated below the tidal levels that correspond to indicative habitat boundaries. When these areas were subtracted from each other they showed the predicted plan area for each habitat. It is also possible to predict the 3-dimensional surface areas of habitats created. However, this option was rejected because it would enable the total areas of predicted habitat to be larger than the two-dimensional areas of the site masks, which are referenced in various documents such as the Planning Application, the Environmental Statement, the Appropriate Assessment and a Legal Agreement. The results are shown in Table 3.

Table 3. Predicted habitat types (ha) based on methods 1 and 2

Method	Mudflat	Saltmarsh	Grassland	Total
1	37.9	11.9	3.8	53.6
2	15.2	27.9	10.5	53.6

Scheme Design Methodology and Iterations

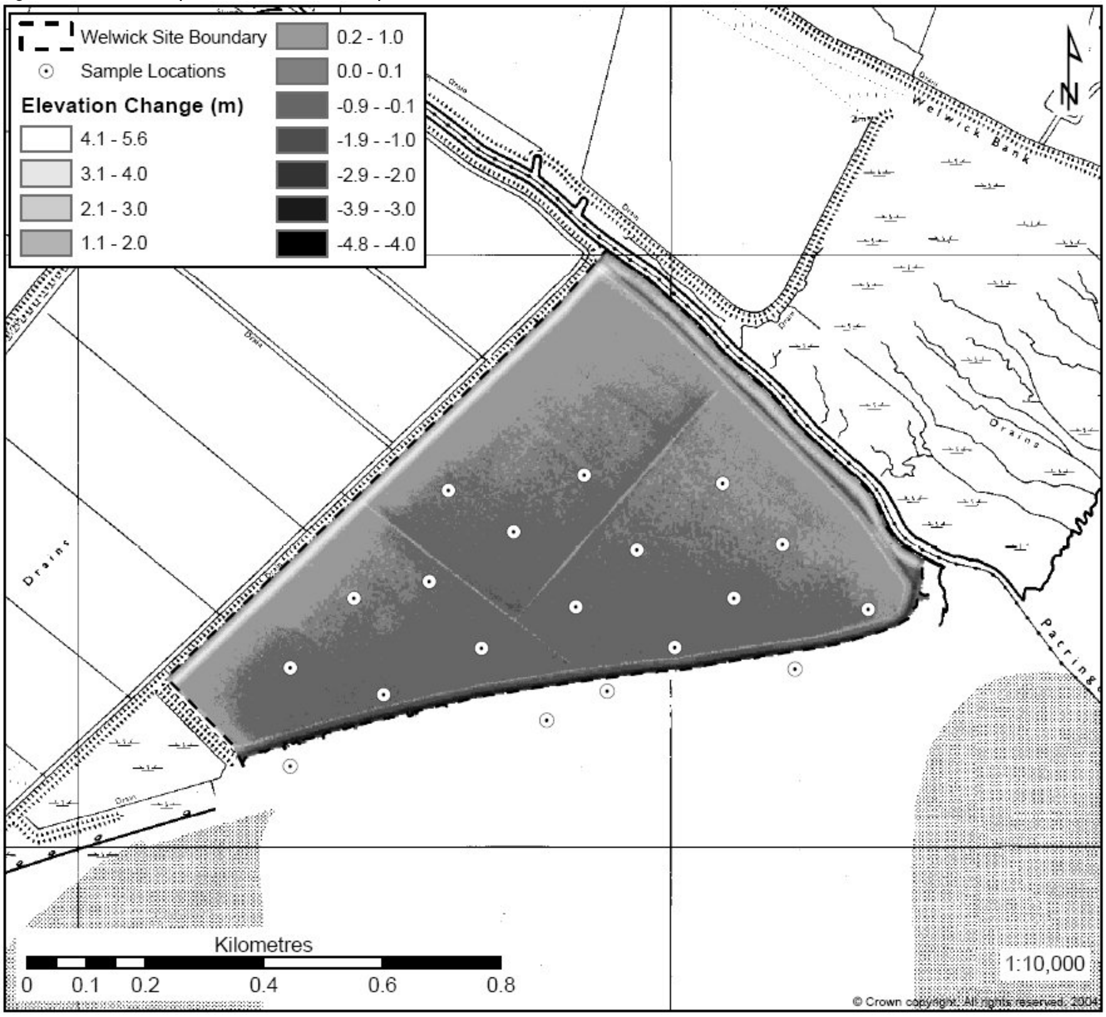
The scheme designs at Welwick went through a number of iterations before a satisfactory combination of habitat areas and sediment balance was achieved. Each design DTM was based upon contours that defined the key features within the scheme and which were designed in two stages. Firstly, the contours that defined natural breaks in habitat were placed to establish the basic layout of habitat areas within the scheme. Secondly, the contours that defined the new sea defences and the breaches within the fronting marsh channels were added. The initial design DTM was simply achieved using a linear interpolation between these key contours and the existing LiDAR elevations around the edge of the site mask. LiDAR elevations were included to ensure that the scheme design fitted exactly into the existing landscape along every edge of its footprint. ArcMap was used to interpolate these data into a Triangular Irregular Network (TIN), and then to produce the scheme design DTM grid.

As the objectives for the scheme design at Welwick developed, it became necessary to produce new design DTMs which created different predicted percentages of saltmarsh and mudflat habitat. This led to the alteration of the surface elevations throughout the scheme, which in turn changed the cut and fill volumes (i.e. the sediment balance), thus creating the need for further design iterations in order to re-establish the sediment balance. Following the habitat and sediment volume analysis, detailed contours were exported from the scheme DTM to form the basis of the next scheme iteration. If required, the key habitat contours were adjusted to modify the habitat areas. Additionally, the contours within each habitat zone were moved, raised or lowered in order to improve the sediment balance. For example, if the scheme analysis had shown acceptable habitat areas, but excessive volumes of cut, the key habitat contours for the next iteration were left unaltered. However, the contours at the front and rear of the scheme were raised to reduce the cut and increase the fill, thereby creating a more acceptable sediment balance. This process continued until satisfactory habitat areas and sediment balances were achieved.

GIS Calculations

Following the creation of a scheme that achieved both the sediment and habitat criteria, the GIS was used to extract more in-depth information about the design, which helped coastal geomorphologists and engineers to plan many detailed aspects of the scheme. For example, using simple grid subtraction a scheme isopach showing the change in elevation was created. The difference grid highlighted areas of cut and fill as well as the level of change within these areas. This information was then used in the Environmental Statement and Appropriate Assessment, which supported the Planning Application for the scheme. Overlaying the locations of sediment samples on this isopach map assisted the collection of sediment samples in the field (Figure 3). These samples were analysed to ensure that the sediments to be relocated on the site, as well as those sediments to be exposed by the re-profiling operation, were not contaminated. The OS national grid co-ordinates were extracted from the GIS and entered into a differential GPS, which was then used to navigate to the sampling points with a quad bike in the field. This process allowed samples to be taken at the correct locations and to sufficient depths. The GIS was also used to plot the location of existing samples to assess if they were suitable for inclusion in the current project.

Figure 3. Scheme isopach and sediment sample locations.



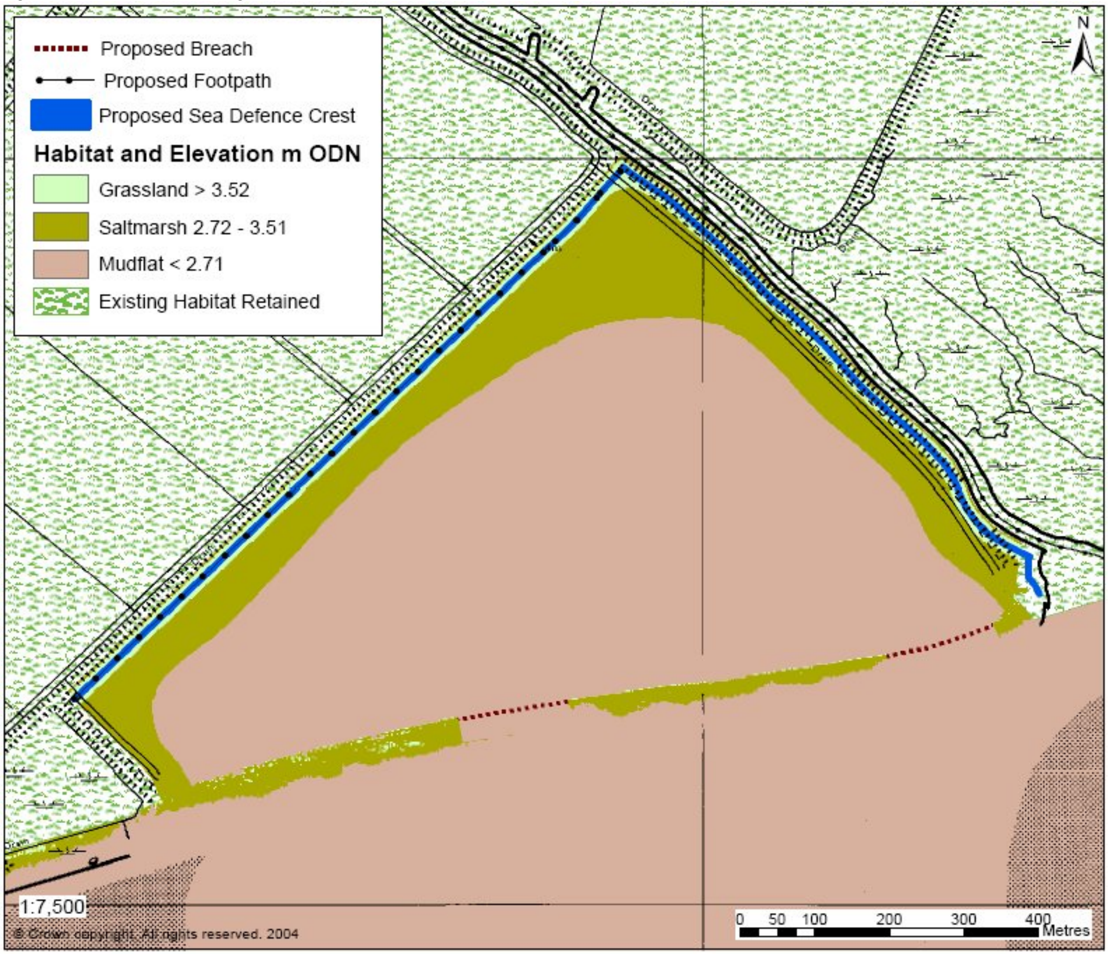
Detailed analysis of the baseline and design DTMs, using masks, was also undertaken to calculate sea defence volumes. This information was used in the Environmental Statement to estimate the volumes of sea defence to be removed and relocated in the various stages of the works. Additionally, the volume of the new sea defences allowed the dimensions of the borrow pits, required to obtain the material to construct the new defences, to be determined. This information was valuable during discussions with various stakeholders concerned with the environmental impacts of the scheme. The estimates of sea defence volume were also required during the design process to ensure that the scheme design retained a sediment balance and did not require earth to removed from, or brought to, the site.

At Welwick, these calculations highlighted the importance of keeping accurate updated masks for these areas. In the early iterations of the scheme design, there were no constant masks for the existing or proposed sea defences. This meant that the areas and volumes of the sea defence appeared to differ between iterations, even though the data underlying the DTMs in these areas remained the same. After some investigation, it was established that the sea defence masks needed to be based upon the DTM elevation. This meant that the same criteria could be used to define the sea defence between different scheme iterations. Once this procedure was in place, the calculation of sea defence volume became much more accurate and the same methodology could be used between any scheme iterations creating directly comparable results.

The GIS also allowed the analysis of the slopes and gradients within the scheme. The gradients, crest widths and elevation of new defences were carefully planned in order to comply with Environment Agency guidance. The gradients of slopes at the rear of a design were designed to encourage the sustainable development of saltmarsh communities, whilst the area of mudflat was given a nominal gradient of 1:1000 to ensure the adequate drainage of tidal waters.

The volume of water over the site at MHWS tidal level is known as the spring tidal prism. At Welwick, the value of tidal prism was obtained from the GIS and, together with information on the rate of rise and fall of the tide, was used in the design of stable breaches in the fronting marsh. The width of these breaches was assessed by calculating the discharge through the breach and considering the critical threshold for erosion of sediment. The final width of the breaches, 150m (Figure 4), was chosen to be large enough for the velocities to be below the critical threshold for erosion. This should mean that once the breaches are constructed they should not increase in size due to the flow of water through them. These breaches were added to the scheme DTM in order to predict the areas of existing marsh habitats lost due to breach construction and reappraise the cut and fill balance for the scheme. Once again, this information was incorporated in the environmental documents that supported the planning application.

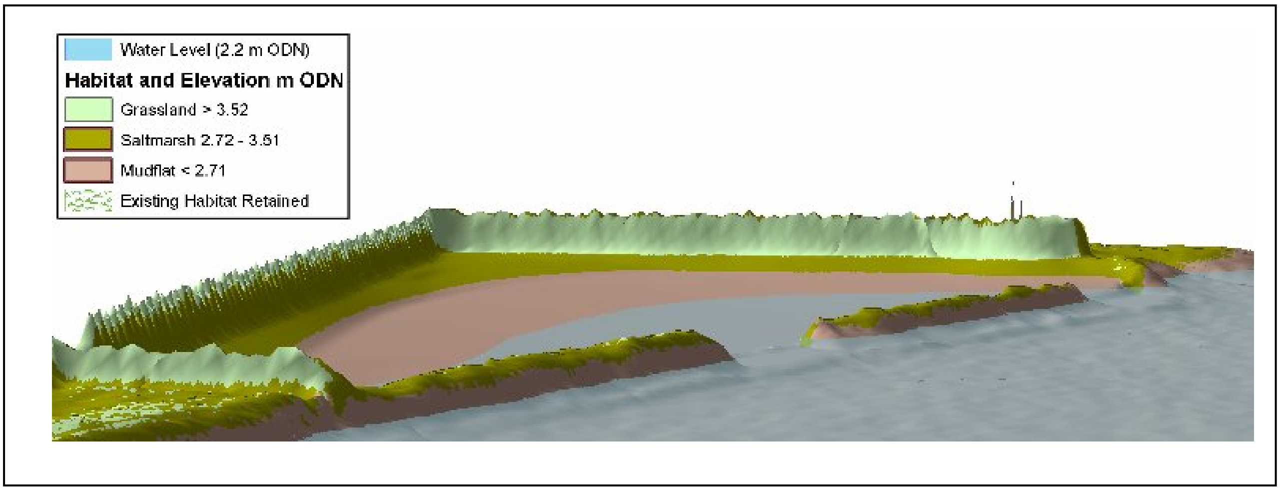
Figure 4. Final Scheme design at Welwick



GIS Outputs

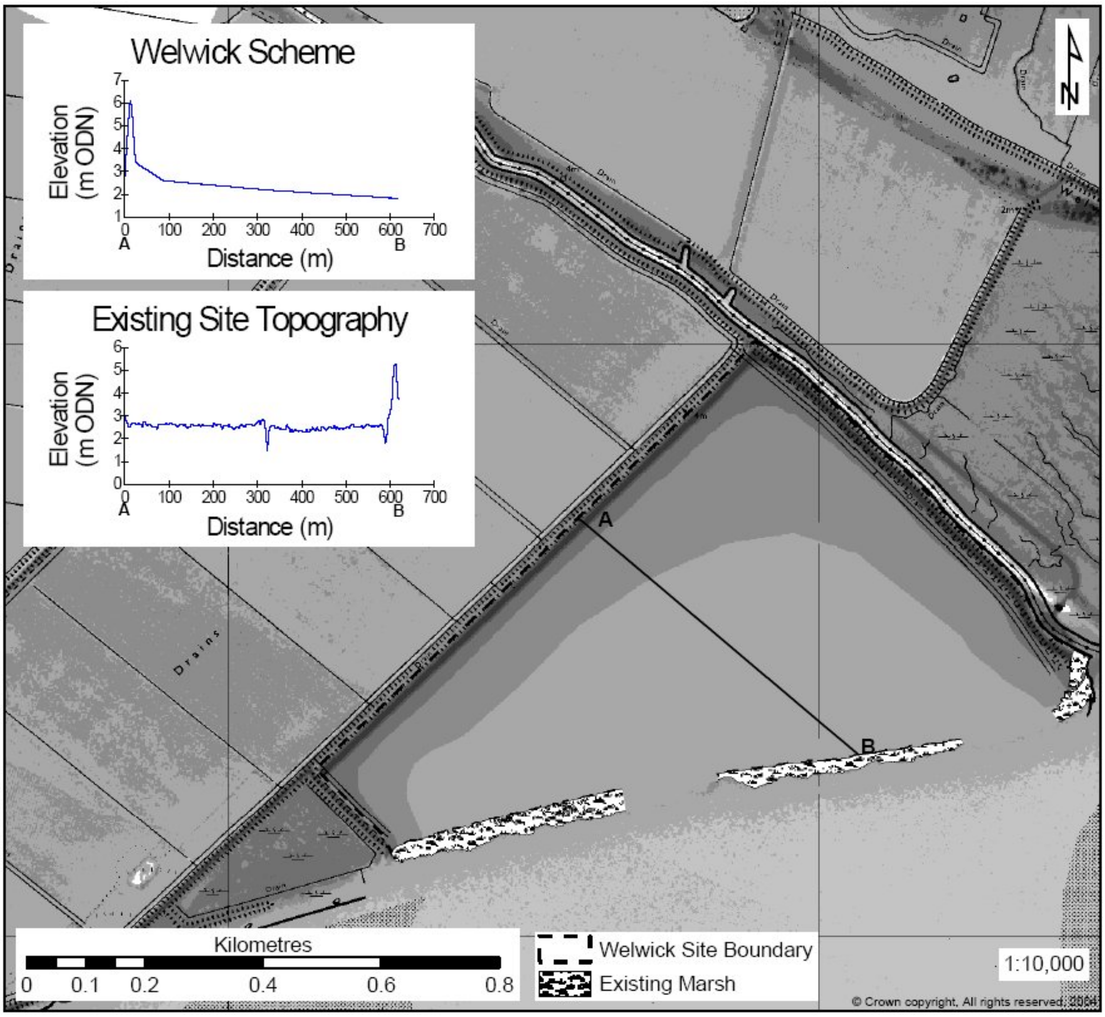
Many of the values that were extracted using the GIS provided useful information for the environmental impact assessment process. Such information included the area and tidal prism of the scheme versus that of the estuary, the volumes of material to be moved on site, and the areas of habitats gained and lost in the scheme. The GIS was also invaluable in producing numerous figures that assisted with scheme design and assessment. The creation of a full DTM for both the existing and proposed topography enabled three-dimensional visualisations to be produced for each, which were combined with other GIS data and used as a tool to help analyse the scheme design. Such figures were also useful for disseminating the scheme to a wider audience and showing how the scheme fits into the surrounding landscape (Figure 5).

Figure 5. 3D visualisation of the proposed scheme design and surrounding landscape with a water level 2.2 m ODN.



The GIS was also be used to extract contours from the DTMs. At Welwick, the 3D Analyst extension in ArcView 8.2 was used to interpolate lines across both the baseline and scheme DTMs. This created profile cross-sections which outlined the surface height against profile chainage (Figure 6). The use of cross sections was useful in allowing various members of the project team to visualise the form of the scheme design. Furthermore, such information also enabled engineers to calculate design wave heights in front of the new sea defences, by allowing the calculation of water depths for given water elevations.

Figure 6. Profile cross-section graphs showing the form of the baseline and scheme DTMs.



Discussion

The experience gained in designing the Welwick scheme suggests that the development of a design that is acceptable to all parties, may require numerous iterations before the final design is achieved. Often small changes, such as the requirement to create a little more saltmarsh within the scheme to compensate for the loss of some existing saltmarsh in front of the scheme, can result in many further iterations of the scheme design. This is both time consuming and requires close management of the scheme analysis and data.

In other scheme designs an alternative approach has been used to create the initial scheme designs. This approach involves the drawing of schematic contours by hand onto a hard copy of a site plan, which is then digitised and interpolated into a TIN in the GIS software. New contours that represent defence features are created using engineering specifications separately from the scheme TIN. These are then combined as DTM grids in the GIS; clipping the defence features to ensure that they smoothly integrate with the existing landscape and scheme design. However, compared with the approach adopted for the Welwick site, this technique offers less control of habitat areas and sediment volumes and it is therefore best applied when there is a clear scheme design at the outset of the project.

For other managed realignment schemes, the GIS has been used to analyse the relationship between volume of sediment removed and the area of habitat created. By systematically lowering the contours used to define channels and creeks within a scheme, it is possible to generate a series of deeper scheme DTMs relatively quickly. Using similar techniques to those described at Welwick, it is possible to establish the relationship between the volume of earth moved and the areas of various habitats created. This can be combined with engineer's estimates for the cost of sediment relocation to calculate the area of habitats created for each pound spent on earth moving. These relationships can be used in the cost benefit type assessments of the viability of various scheme designs, which can be useful in determining preferred scheme designs.

During the Welwick project, enforced changes to the scheme design resulted in many more than the anticipated number of iterations being completed. The study also highlighted the importance of knowing the true source data for any iteration, as well as the source of any habitat or volume calculations produced. This led to the requirement to produce a GIS scheme worksheet, which was used to track changes to the scheme designs. This worksheet contained information showing the file path to key datasets, such as site masks, source data, baseline and scheme DTMs. It also recorded the elevations and methodology that lay behind any indicative habitat predictions, as well as any habitat areas or sediment volumes produced. The scheme worksheet also provided a formal record of the QA assessment of the GIS aspect of the scheme designs. During the design process for the Welwick scheme, additional QA measures were introduced when it became clear that the volume of data being created through the continuous iterations in scheme design was becoming unmanageable. This additional QA took the form of prefixing each data file from each different version of scheme design with the number of that iteration. Whilst this sometimes resulted in the duplication of files (e.g. the site mask may not change between iterations), it provided a clear audit trail for each iteration. Provided this procedure is followed correctly, none of the files can be overwritten, and this facilitates the rapid retrieval and comparison of any earlier design iterations.

Conclusions

The Welwick scheme involved over 2 years of detailed GIS work in its design and represents the first scheme in the UK to advocate wholesale removal of the fronting seawall. The GIS was invaluable at a number of stages in the design and planning process, including feasibility design, consultation and environmental impact. The generation of full pre- and post-DTMs for a managed realignment scheme has many potential advantages, allowing:

- existing and potential scheme habitat areas to be predicted
- the volumes of sediment movement and tidal prisms to be calculated
- two and three-dimensional visualisations of the scheme design to be produced, which then allow additional analysis or facilitate the discussion during the design process.

However, the development of the scheme DTM also raises some challenging issues. Any slight change in scheme criteria can result in the design process being started from scratch. Scheme data for each iteration needs to be managed carefully, so that it is clear how habitat areas and sediment volumes have been derived. The creation of each iteration is a complex and often time consuming process, which can require numerous iterations before the scheme fulfils the criteria that it is aiming for.

The work undertaken at Welwick highlighted the need to develop a method of tracking changes to the scheme DTM. This was achieved by creating a GIS worksheet, which has evolved to a successful QA document for the data management of other scheme designs. The Welwick example also highlighted that good planning and clear scheme goals at the outset of the project can vastly reduce the number of scheme design iterations required. This saves both time and money and makes the management of the GIS data and analysis a far simpler task.

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