Chapter 1

Landscape Response to Climate Change

1.1 The importance of climate change in landscape evolution

Climate is perhaps the most important variable driving landscape evolution (Summerfield, 1991; Schumm, 1999). It not only determines levels of precipitation within a region, but also rates of evapotranspiration and consequently the hydrology and geomorphic processes which operate on the landscape (Charlton, 2008; Tricart and Callieux, 1972). Climate is one provider of energy to geomorphic systems. Regions which experience stable climates may tend towards equilibrium landforms (Schumm, 1999), with landforms and landscapes (a collection of landforms) remaining stable over long (>1000 year) periods. However, in locations where changes in climate are being experienced, energy levels may fluctuate and induce changes in the dominant geomorphic processes and the intensity with which they act. This has the potential to result in relatively rapid landscape evolution (10 - 1000 years, e.g. Frankl *et al.*, 2011). With recent trends in global climatic change now “more likely than not” to be human induced (Solomon *et al.*, 2007; Jenkins *et al.*, 2009, p.34), there is clear potential for changes in climatic regimes to have effects on the landscape at both global, and regional scales.

The latest report from the Intergovernmental Panel on Climate Change (IPCC; Solomon *et al.*, 2007) states that global temperatures are projected to rise by approximately 2.5°C by 2099 (under the A1Fl emissions scenario, see chapter 5 for further details). More locally, the recently published United Kingdom Climate Projection (UKCP) data suggests that across the UK mean daily maximum temperatures will increase by between 2.2°C and 6.8°C by 2095 (under a medium emissions scenario; Jenkins *et al.*, 2009). Winter precipitation levels will also increase dramatically (up by ∼33%) in the western UK, with a decrease in summer precipitation (down ∼40%) in parts of southern England by 2095 (under a medium emissions scenario; Jenkins *et al.*, 2009). It should be noted that these figures, which focus on mean changes, disguise important changes in the timing and intensity of future events, which may be more pertinent to geomorphic response. The UKCP report claims that extreme precipitation events, characterised by shorter, more intense, periods of precipitation, are likely to become more common (Jenkins *et al.*, 2009). It is extreme precipitation events which often generate intense runoff. This intense runoff may exceed erosion thresholds and be key drivers of geomorphic change (Summerfield, 1991).

These projected changes in temperature, precipitation and associated changes in potential evapotranspiration (PET), a variable constrained by the local soil moisture (Kingston *et al.*, 2009), may result in dramatic geomorphological changes in landscape features such as river valleys and incised channels (features which rely on moisture to drive processes resulting in their stability/growth; Lane *et al.*, 2007). Susceptibility to change may be enhanced in coastal regions which, as well as the shifts in precipitation and PET regimes, will experience rises in sea level of between 0.23 m and 0.51 m by 2099 (under the A2 emissions scenario) and increased storm surges (Solomon *et al.*, 2007), both of which play important roles in the geomorphological evolution of the coastal zone (Dodd *et al.*, 2008).

It is recognised that even without the perceived threat of climate change, understanding how landscapes develop under stable climates warrants investigation. However, given the projected changes in climate outlined briefly above, understanding how perturbations in future climate may effect the landscape is necessary if management and adaptation strategies aimed at preserving landscapes with societal and ecological significance are to be successful. For effective impact assessments to be made, approaches which utilise observed physical relationships between erosion and/or deposition and climate are required. Such an approach is best applied within a numerical modelling framework.

1.2 Modelling the effects of changing climate on landscape evolution

Modelling studies which assess the impact of a changing climate upon the landscape, and which subsequently attempt to provide quantitative assessments of these impacts, have begun to increase in number over the past decade (e.g. Tucker and Slingerland, 1997; Coulthard *et al.*, 2000; Coulthard, 2001; Hancock, 2009; Temme *et al.*, 2009; Coulthard *et al.*, 2012, figure 1.1). Computational models, such as Landscape Evolution Models (LEMs), provide powerful tools for assessing the impacts of varying parameters, such as rainfall, discharge and sediment yield, upon a landscape (Coulthard, 2001; Pazzaglia, 2003; Willgoose, 2005; Tucker and Hancock, 2010). Such models typically represent landscapes using a regular or irregular grid upon which governing laws of weathering, sediment transportation, fluvial erosion and tectonic uplift are applied (see section 2.5

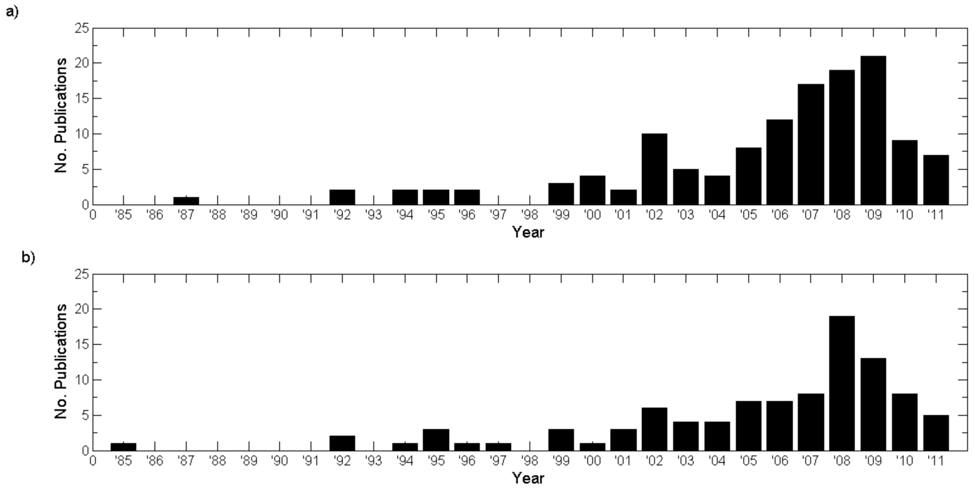

Figure 1.1: Number of journal publications and conference proceedings by year. Numbers obtained the Web of Science search engine (wok.mimas.ac.uk) for the search terms a) Modelling + Climate Change + Geomorphology + Landscape and b) Climate Change + Landscape Response + Geomorphology.

for further details on LEMs). These processes are modulated by the representation of climatic variables such as rainfall. These tools, therefore, allow quantitative assessments of the effects of changing climate parameters upon landscapes to be made. It is, however, noted that not all landscapes fall within the current scope of LEMs. Tucker and Hancock (2010) claim that landscapes in areas dominated by aeolian processes, heavily karstified terrain and glacial landscapes lie outside the scope of the current suite of LEMs. In addition to this, coastal locations are exempt from the scope of current LEMs, due to a lack of representation of coastal processes. As such, although LEMs may provide suitable tools for the assessment of changing climate variables on landscape dynamics, there exists potential to increase the scope of landscapes to which the models can be applied.

By applying governing laws of erosion and deposition over the whole landscape, LEMs facilitate the assessment of the response of landscapes as a whole, and individual landforms, to changes in climate (Temme *et al.*, 2009; Tucker and Hancock, 2010). Indeed, it has been noted that certain landforms may provide more useful indicators of a changing climate than others (Poesen *et al.*, 2003; Valentin *et al.*, 2005; Temme *et al.*, 2009).

1.3 Gullies as sensitive indicators of climate change

A modelling study by Temme *et al.* (2009) identified gullies as landscape features highly sensitive to variations in climate. Gullies are one form of incised channel that represent landscapes which have undergone a disturbance in their equilibrium state (Schumm, 1999). They form via the process of incision caused by a period of disequilibrium or vertical instability (Simon and Darby, 1999). Gullies comprise one of the most important sources of sediment within the drainage basin landscape unit, accounting for between 10% and 94% of overall sediment production in some locations (Poesen *et al.*, 2003; Valentin *et al.*, 2005). Gully erosion can be described as the

> "erosion process whereby run-off water accumulates and often recurs in narrow channels and, over short periods, removes soil from this narrow area to considerable depths" (Poesen *et al.*, 2003, p.92)

It has been noted that an in-depth knowledge of gully erosion, its effects, processes and magnitudes is necessary to fully comprehend and predict future landscape evolution (Dietrich and Dunne, 1993; Kirkby and Bull, 2000). Rill (micro-channels a few centimetres in depth; Summerfield, 1991) and gully initiation has been the focus of much work over the past few decades (e.g. Bull and Kirkby, 1997; Kirkby and Bull, 2000; Poesen *et al.*, 2003; Valentin *et al.*, 2005; Kirkby and Bracken, 2009). Despite this an understanding as to how these systems respond to changes in climate is lacking. Rill and gully development has been seen as a response to individual storms, during which the increased run-off intensity is of a sufficient value to exceed the critical shear stress required for sediment entrainment (Kirkby and Bull, 2000). This idea is further developed by reasoning that, for large storm events, channel development occurs far upstream resulting in an extension of the network. For smaller storms these conditions are met further downstream within the network, thus resulting in the incision or widening of pre-existing channels (Kirkby and Bull, 2000). Therefore, under climate change scenarios where storm events are likely to become more intense (Haylock *et al.*, 2006; Jenkins *et al.*, 2009), it is conceivable that gully systems will extend upstream. Further, the development of rills on slopes surrounding the headwaters of the drainage network will not be affected by small storms, thus implying that rill and gully development of headwater slopes is only initiated under large storm conditions. Again, in this case, gully erosion is likely to be more prominent under scenarios of future climate change which promote more intense storm events.

However, despite a knowledge of the processes of gully initiation and development (see chapter 2 for more details),there are large gaps in our knowledge of gully behaviour. For example, Poesen *et al.* (2003) and Valentin *et al.* (2005) highlight the lack of information regarding the response of gully systems to changes in climate variables. It is recognised that changes in climate will place more environments at high risk of enhanced gully erosion (Valentin *et al.*, 2005). Despite this recognition there have been few quantitative analyses evaluating how changes in climate will affect rates of gully erosion. Poesen *et al.* (2003) propose that gradual changes in climate will result in more pronounced gully erosion. Whilst Valentin *et al.* (2005) recognise that there is little information in the existing literature as to how gully systems may respond to climatic changes, demonstrating that in study areas where a decrease in rainfall has been observed (such as the hillslopes of Vietnam and Laos), high level rainfall events have not subsequently decreased, thus permitting the continual development of gully.

As can be seen, gully erosion is a highly dynamic process which is responsive to changes in climate. However, the exact response of these systems to changes in climate is, as of yet, unknown. Although studies imply that gully erosion is likely to increase in the future (Poesen *et al.*, 2003; Valentin *et al.*, 2005), quantitative studies regarding the response of gully erosion to changes in climate are lacking. The potential for large sediment yields associated with gully systems, their ubiquitous nature occurring in virtually all climatic regimes across the globe, and their sensitivity to changes in climate make them an important indicator of climatic changes. Accordingly, understanding how these features evolve and develop under future climate change is a highly pertinent and under studied area.

1.4 Incised coastal gullies

The majority of work on gully systems and incised channels in general has focused on environments where incision is initiated by base-lowering (Schumm, 1999). In coastal locations, which here are defined as areas adjacent to oceans and lakes, gully systems may be exposed to multiple incision events as the processes of cliff retreat and sea level rise interact to constantly alter base-level (Flint, 1982; Bledsoe *et al.*, 2002; Leyland and Darby, 2008). These processes result in a specific form of gully known as an incised coastal gully. Incised coastal gullies are often characterised by permanent streams, however occasionally these streams may be ephemeral, flowing only after extreme rainfall events. Streams which do not have the required excess energy to erode the cliff are often characterised by coastal waterfalls. In cases where the stream can erode the cliff, incised channels form on many scales; from large river valleys and estuaries (extreme forms of incised coastal gully which develop over large time scales) to smaller scale features of low stream order (1^{st} or 2^{nd} order under the Strahler (1952) system) with drainage areas of 12 km^2 or less.

Incised coastal gullies are exposed to climatic changes in the form of increased storminess and sea level rise, as well as changes to precipitation described above. These types of gullies are found in many climatic and geological regions worldwide, including the alluvial coastal plain of South Island, New Zealand (Schumm and Phillips, 1986), the Pleistocene sandstones of the North Island, New Zealand (Pillans, 1985), the glacial clays of Lake Huron, Canada (Burkard and Kostaschuk, 1995) and the basaltic, volcanic deposits of Hawaii (Kochel and Piper, 1986). In essence, any coastal location in which the direction of drainage enables water to flow over a soft cliff may be predisposed to incised coastal gully erosion.

Numerous examples of coastal gullies occur along the south west coast of the Isle of Wight, UK and are locally known as “Chines" (figure 1.2). The Chines of the Isle of Wight have been shown to develop via a combination of knickpoint recession and cliff erosion (Leyland and Darby, 2008). However, other incised coastal gully systems have

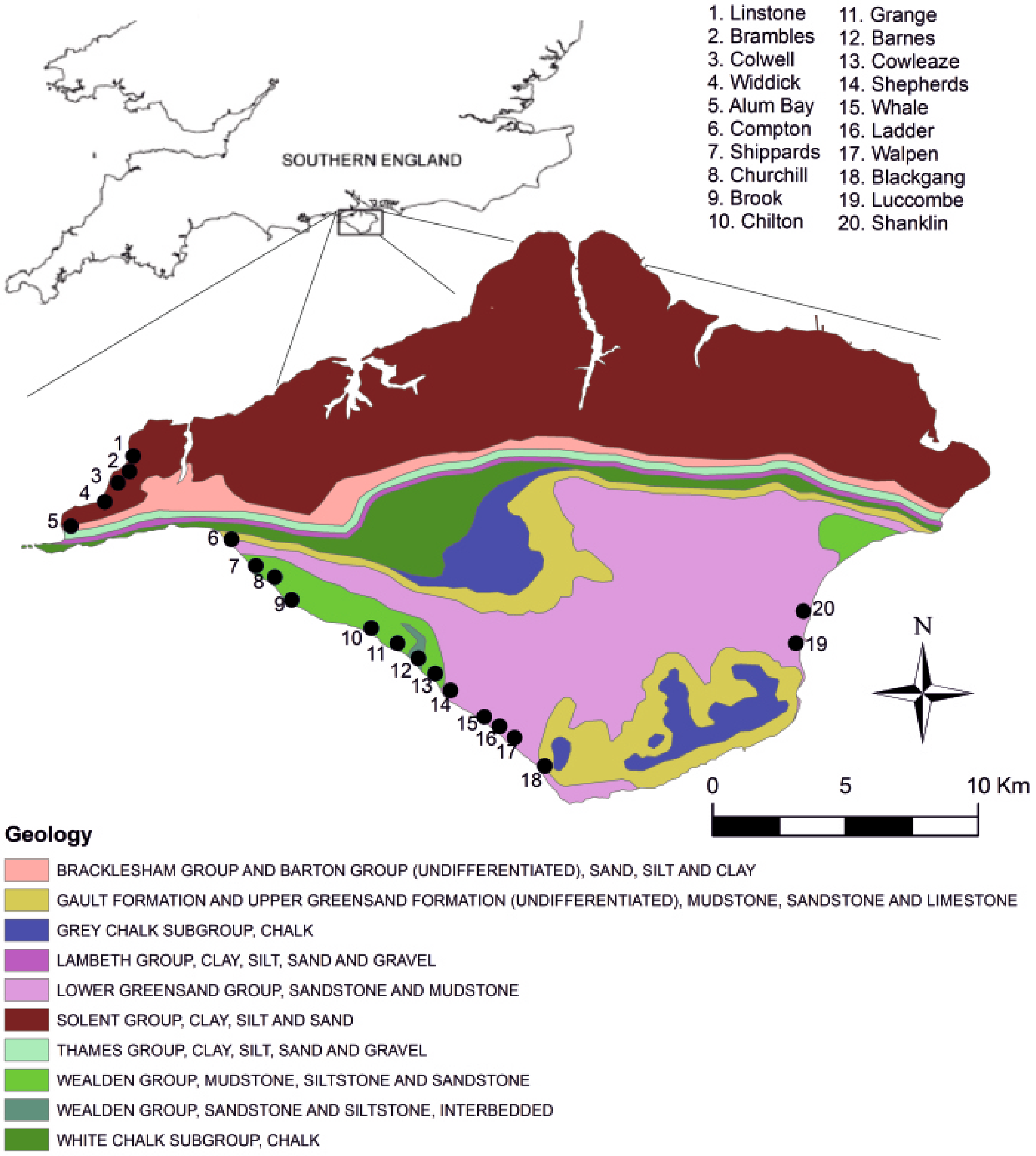

FIGURE 1.2: Location of the Chines along the South West coast of the Isle of Wight overlaid on a British Geological Survey 1:625000 bedrock geology map of the Isle of Wight (adapted from Leyland and Darby (2008).)

been shown to form through seepage erosion (Schumm and Phillips, 1986) and through run-off processes (Kochel and Piper, 1986). Therefore the processes driving the formation of these features appears site specific, if not specific to the geologies in which they form.

1.4.1 The Chines of the Isle of Wight

Although incised coastal gullies have been documented in many locations worldwide (Kochel and Piper, 1986; Schumm and Phillips, 1986; Burkard and Kostaschuk, 1995; Leyland and Darby, 2008), those found on the Isle of Wight are especially important because of their ecological and geological setting. The Chines are formed in an area of soft cliff, defined as cliff composed of unconsolidated materials such as sands and shales (Damgaard and Dong, 2004). Specifically, the south west Isle of Wight is comprised of Wealden Shales and Marls, Upper and Lower Greensands and Gault Clays (figure 1.2).

The soft cliff environment is an important ecological resource. Howe (2002) found that soft cliffs provide habitats for 29 species of invertebrate, of which 23 are Red Data Book species. In particular, the soft cliffs of the Isle of Wight provide the only breeding habitat in the UK for the Glanville Fritillary Butterfly (*Melitae cinxia*) and the digger wasp (*Psen atratinus*), both Red Data Book species. It is the combination of bare substrate (an important requirement for many invertebrates), the constant working of this substrate due to the processes operating within, and at the mouth of, the gully, and the provision of sheltered locations upstream which make this habitat vital ecologically. The importance of this environment is recognised in the designation of the south west coast of the Isle of Wight as a special area of conservation (SAC) and a site of special scientific interest (SSSI).

The incised gullies found along this coastline provide an extension of the soft cliff environment, which itself is a limited resource in the UK. The 41.5 km of soft cliff found along Isle of Wight coastline represents a significant (16%) amount of the total UK soft cliff resource (Dargie, 1996). Furthermore, the processes which occur within the gullies (i.e. incision and rejuvenation of the gully system) help maintain and create variations in aspect and shelter, vital to supporting diversity in invertebrate communities.

As mentioned above, gully systems are highly dynamic and sensitive features which may respond drastically to perturbations in climate (Valentin *et al.*, 2005). As described in section 1.1 (and outlined in further detail in chapter 5), the southern regions of the United Kingdom are likely to undergo major changes in precipitation over the next 100 years (Haylock *et al.*, 2006; Jenkins *et al.*, 2009). It has been shown that gully systems are highly sensitive to changes in rainfall (see section 1.3), however the incised coastal gullies of the Isle of Wight will also be influenced by future changes in the marine climate, specifically changes in sea level and wave climates. It can therefore be seen that these special types of gully systems may experience a complex and uncertain response to changes in climate. On the one hand, the increased likelihood of intense, extreme, precipitation events (Haylock *et al.*, 2006; Jenkins *et al.*, 2009) may result in increased gully erosion (Poesen *et al.*, 2003; Valentin *et al.*, 2005). Conversely, rises in sea level and subsequent increases in rates of coastal erosion (Nicholls *et al.*, 1995; Dickson *et al.*, 2007; Walkden and Dickson, 2008; Nicholls and Cazenave, 2010; Trenhaile, 2010) may truncate the gully system, reducing their extent.

Whatever the response of incised coastal gullies to changes in climate, the effects will be manifest upon the ecological habitats they support. As these environments are of such importance internationally, understanding the geomorphic response of coastal gully systems to perturbations in climate, and subsequently its effects upon the ecology of these systems, is highly important if managing such an environment, and its associated biodiversity, is to be successful.

1.5 Aims of this research

The above sections have highlighted the importance of incised coastal gully systems, specifically those found along the south west coast of the Isle of Wight, UK (figure 1.2). Furthermore, a gap in the literature regarding the response of these systems, and gully systems in general, to changes in climate has been highlighted. The aim of this research is to bridge the gap between studies of large scale climatic change and local scale impacts by applying scenarios of future climate change at a sufficiently high resolution (temporally and spatially) within a landscape modelling framework to provide a quantitative insight into the future evolution of incised coastal gullies, with specific reference to the Chines of the Isle of Wight, UK. The key aims of this study are, therefore:

- To develop a process-based model of cliff retreat which can be coupled to an existing Landscape Evolution Model to represent changes in the driving factors of cliff retreat, namely sea level rise and wave climate, as projected by climate change scenarios.

- To couple this process-based model of cliff retreat with an existing landscape evolution model to provide the first coupled marine-terrestrial landscape evolution model.

- To develop and employ downscaled Global Climate Model simulations at a suitable temporal and spatial resolution for small catchments. Thus forming the inputs to the coupled marine-terrestrial landscape evolution model.

- To evaluate the significant uncertainty surrounding the set-up and parameterisation of the model, the inherent uncertainty with projecting future precipitation scenarios, and the inherent uncertainty with future projections of sea level rise, in order to more clearly elucidate the future evolution of the Chines.

- To provide quantitative outputs describing the response of incised coastal gully systems to perturbations in climate and outline the implications of these responses for management and policy decisions.

The stages required to achieve these aims are highlighted in figure 1.3.

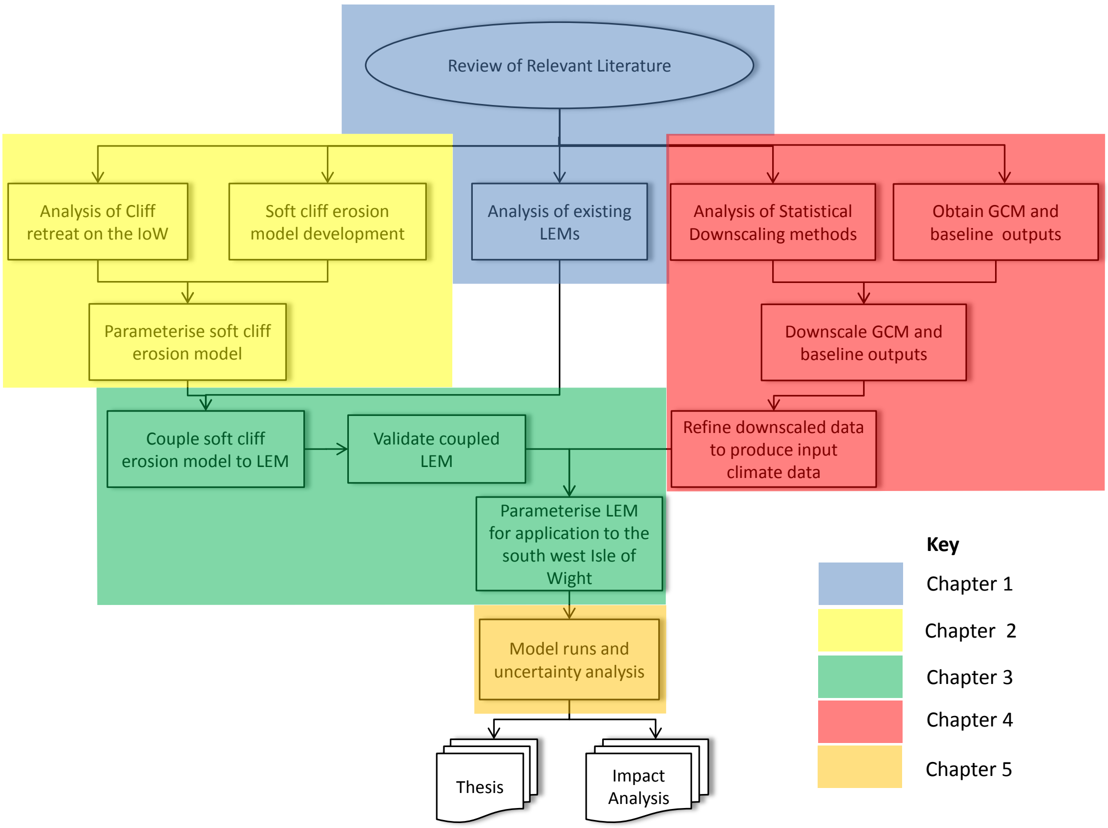

FIGURE 1.3: Conceptual diagram showing the stages involved within the project and necessary tasks for the aims to be achieved. Areas are coloured by the order in which the work was undertaken.

1.6 Thesis layout

Following this introduction to the study, chapter 2 reviews the current state of science regarding incised coastal channels, the processes involved in their evolution and development, with reference to their application within a modelling framework, and the suite of models which can be used to help address the aims listed above. Chapter 3 describes the development of a simple process-based model of soft cliff retreat, capable of being integrated into an existing landscape evolution model. Chapter 4 outlines the modifications necessary to integrate the model developed in chapter 3 into a landscape evolution model. It then goes on to describe the calibration and validation of the integrated model by applying it to a historical simulation. Chapter 5 outlines the techniques used in downscaling future scenarios of climate change from Global Climate Model outputs, and details the scenarios developed therein. Chapter 6 outlines the set-up of the coupled marine-terrestrial landscape evolution model and describes results from the model runs. In order to account for the uncertainties inherent with the climate downscaling undertaken in chapter 5 probabilistic metrics of change in gully morphometrics are reported, before the climate drivers responsible for these changes are quantified. Finally, chapter 7 places the findings of the research into a global context, offering a synthesis of the findings and providing conclusion.