# The Scott Simpson Lecture

## Investigating the role of landscape evolution in determining ground conditions for engineering: examples from South-West England

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The vast majority of civil engineering works take place within 100 m of the ground or sea level surface, so most construction activities will interact with the landforms that make up terrestrial and near-shore landscapes. Therefore, understanding the evolution of these landscapes is central to producing safe and economic engineering designs of civil works. This premise is the rationale behind the setting up of Commission 22 in 2006 by the International Association for Engineering Geology and the Environment. This paper explores aspects of the effects that landscape formation can have on engineering design decisions in relation to a suggested outline of the long term evolution of the southwest England landscape. It is concluded that the link between design decisions and knowledge of the formation of the landscape is neither straightforward nor easy to quantify but can be significant. It is also apparent that research is still needed into many aspects of the evolution of the southwest England landscape.

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## Introduction

Engineering geology is a discipline committed to the investigation, study and solution of the engineering and environmental problems which may arise as the result of the interaction between geology and the works and activities of man as well as to the prediction and the development of measures for prevention or remediation of geological hazards (Statutes of the International Association for Engineering Geology and the Environment, 1994). In their collection of case studies in engineering geology Anderson and Trigg (1976) stated, *"The basic task of the engineering geologist is to collect data relating to the stability of the geological environment, taking into account the fact that this environment is itself changed by the engineering works."* However, many geological processes take place on a timescale of millions of years (e.g. sediment lithification, isostatic change, volcanic intrusion, tectonics). Therefore, these processes might have little direct relevance to engineering except as a resource for construction materials or as the soils and rocks identified as forming the foundations to engineered structures. The use of the term geohazard (International Centre for Geohazard Research, 2010) is recognition that some geological processes do occur on much shorter timescale, (such as fault movements, extrusive volcanic activity, landslide, earthquake, and ground subsidence) and, therefore, represent the subset of geological processes that affect humans in the shorter term. Geohazards all relate to changes in the geological environment that can occur within the design life of an engineering structure and may have a significant and immediate effect on the nature and properties of the surface of the Earth (either on land or underwater). Thus geohazards are likely to bring about immediate and persistent changes to the shape of the terrestrial or submarine landscape. However, the development of the contemporary landscape needs to be seen within the framework of the overall evolution of landscapes within which geohazards occur. In this broader context it is recognised that geological processes are not the only ones involved in the creation and evolution of landforms, there may also be climatic, hydrological, and biological processes to be taken into account. The long term interaction of all these processes created the contemporary landscape, and the investigation of the way this has and continues to evolve is part of the discipline of geomorphology. Brunsden (2002) described geomorphology as the study of the forms of the earth's surface, their origin, the processes involved in their development, the properties of the materials from which they are made, and predictions about their future form. From this definition it is apparent that geomorphology can provide information of direct relevance to civil engineering design.

At present the majority of civil engineering projects take place in the terrestrial, coastal and nearshore zone, within 100 m of the ground or sea level surface (the main exceptions are deep tunnels, deep sea drilling and production rigs, and cross-ocean cables). Thus the overwhelming majority of construction works and engineering structures will interact with the landforms that make up terrestrial and near-shore landscapes. Recognition of this close link between the features of the landscape and civil engineering has led to the development of engineering geomorphology, a subject where practitioners are able to provide practical support for engineering decision-making with respect to project planning, design and construction (Fookes *et al.*, 2007). A core component of that support comes from the recognition that the Earth surface is not a static environment and landscapes change over time through weathering and surface processes of erosion, sediment transport and deposition, faulting, neotectonics, volcanicity etc.

The particular significance of landscape evolution to engineering projects was demonstrated by Fookes (1997) who, in relation to the use for regional geomorphological mapping of a mine in Papua New Guineas, specified the need to:

1) Characterize landforms by origin;
2) Characterize landforms by currently acting geomorphological processes in order to provide rates of landform development and the frequency of geomorphological processes;
3) Identify areas of geomorphological hazard;
4) Provide a basis for the interpretation of geomorphological hazards.

The fundamental importance of understanding the geomorphological development of a site, and in particular its Quaternary history, was clearly identified by Hutchison (2001) and was a core theme in the Total Geological History concept proposed by Fookes *et al*. (2000). Examples where the geomorphological history has been taken into account are provided by Baynes *et al*. (2005) for a railway in Western Australia, and Hearn (2002) for roads in Nepal. Despite these well established guidelines and examples, it is still too often assumed in civil engineering works that the extant conditions remain static during the design life of a structure. Therefore, in late 2006 the International Association for Engineering Geology and the Environment (IAEG) set up Commission 22 to provide a practical evaluation of the way landscape evolution can be included in civil engineering project studies and investigations undertaken by engineering geologists supported by the still relatively few engineering geomorphologists (Griffiths *et al*., 2010). The full scope of Commission 22 is presented in Table 1. This paper draws on the preliminary results of the commission which show that landscape evolution does have an effect on civil engineering design decisions. The discussion on these effects is framed in the context of our understanding of the formation of the landscape of southwest England.

There are a number of basic questions that Commission 22 raises which have a direct bearing on engineering design decisions:

1. Is there anything in the historical development of the landform/landscape which might have bearing on the engineering design for the proposed works ?
2. How will the landforms/landscape change over the planned life of the works ?
3. How will the planned works affect the landform/landscape ?
4. How can any potential future changes in the landform/landscape be incorporated in the design ?
5. How do we investigate and monitor the landform/landscape in order to make confident predications about its behaviour over time ?

Answering these questions accurately and effectively can have a significant benefit to the costs, whole life costing and safety of a construction project. However, to assess how landscape development might have a bearing on southwest England it is first necessary to provide a broad framework of the evolution of the landscape in the region.

| | |
|---|---|
| 1 | Design life of structures – how long do the designers expect the structure to survive? |
| 2 | Risk registers – are all the potential risks to the works identified before construction starts? |
| 3 | Reference conditions – is it possible to define the ground conditions before the works commence to enable comparative tenders and the basis for negotiation for unforeseen circumstances? |
| 4 | Geohazards – has there been a full appraisal of the natural hazards? |
| 5 | Relict processes/landforms – are there components in the natural landscape developed under previous climatic conditions that might affect the design? |
| 6 | Climate change – over a typical 50 to 100 year lifetime of a structure the evidence is that significant changes to the climate will occur; what are these changes and how might they affect the design? |
| 7 | Thresholds – some landforms are presently stable but often minor changes to the extant conditions can have a dramatic affect on processes; how can landforms in this situation be identified and allowed for? |
| 8 | Magnitude/frequency – geomorphological and geological processes have been shown to have a generalised frequency distribution for given magnitude events, this may be measured in years, decades, centuries of even millennia. How can relatively short-lived engineering structures take these events into account. |

***Table 1.*** *IAEG Commission 22 – assessing the engineering geological implications of landscape evolution to civil engineering; issues to be addressed.*

## South-West England landscape evolution

Forty years ago Brunsden and Gerrard (1970) published a review of the physical environment of Dartmoor in the classic book "Dartmoor – a new study" (Gill, 1970). This summarized the understanding of the geological history of the development of the Dartmoor landscape and the surrounding terrain at that time. The view was that there were a series of high level fluvial erosion surfaces created during the Tertiary starting from an early Tertiary (sub-Eocene?) summit plain at 580-520 m (1900-1700 ft) in the north of the moor. At 210 m (690 feet), was located the first of the many erosional marine terraces that formed during the Plio-Pleistocene (Balchin, 1952) as the sea level fell. The highest surface was equated with the Plio-Pleistocene Calabrian marine transgression that had been identified in southeast England (Wooldridge and Linton, 1939; 1955). The Calabrian marine platform was believed to be widespread, and subsequent river incision left extensive remnants of this surface that viewed at a distance appeared as an extensive plateau surface throughout the West Country

(Wooldridge, 1954; Brunsden, 1963). Subsequently the landscape was subject to a series of intense periglacial periods which accounted for the tors, head deposits and stone stripes found on Dartmoor. Studies of the Dartmoor tors and associated weathering products by Linton (1955), Waters (1964, 1965) and Palmer and Neilsen (1962) developed models of formation that suggested joint control, deep weathering, possibly during the Tertiary, and erosion during periglacial conditions in the Pleistocene. This left the tors and stone stripes as relict features and explained the extensive sweeps of unconsolidated head deposits around the region.

The landscape evolutionary history of southeast England during the Tertiary and early Pleistocene Periods, which formed the model for the southwest, has now been completely reinterpreted (Jones, 1999a, 1999b). It is believed that a landscape changing Calabrian marine transgression did not occur (Jones, 1981), although for the southwest the *'Geology and Landscape Factsheet'* (Dartmoor National Park Authority, 2005) still makes reference to an *"ancient shoreline at about 212 m at the edge of moor"*. If this is still the perception then the evolutionary history of the southwest landscape should be reappraised to take into account more recent work, whilst still acknowledging the value and importance of the studies undertaken by Linton, Waters, Palmer and Neilson. However reference should be made to our extensive knowledge of the Quaternary deposits of the region which have been comprehensively described and the data collated (Campbell *et al.*, 1998); assessments of long term landscape evolution (Coque-Delhuille, 1991; Clayton and Shamoon, 1998, 1999; Smith *et al.*, 1999; Migoń and Goudie, 2001); the history of major rivers in southern England during the Tertiary (Gibbard and Lewin, 2003); and the findings of Walsh *et al.* (1987; 1999) with respect to Miocene elements in the landscape of western Britain.

It is suggested that the landscape evolution of southwest England is both polycyclic (repeated phases of erosion and deposition over time) and polygenetic (the result of a multitude of processes acting both together and independently). Geomorphologists use the term palimpsest to describe a landscape comprising landforms of contrasting origins and ages (Chorley *et al.*, 1984) and this term is ideal for southwest England. In very broad terms, and not without considerable controversy and debate, it is suggested in this paper that the evolution of the landscape of southwest England might be summarized as follows:

1) There is emergence from beneath the sea that began during the late Cretaceous and was completed by the early Palaeocene. This was the land surface upon which the main UK drainage system developed (Gibbard and Lewin, 2009).
2) During the early Eocene there appears to have been linkage with the eastward flowing Solent River and its tributaries that is likely to have had its headwaters in Dartmoor (Gibbard and Lewin, 2003). This river network deposited the gravels of different ages found, for example, on the Haldon Hills and in the Aller Gravels near Newton Abbott. These deposits contain material derived from Dartmoor and its aureole (Daley and Balson, 1999). The clay mineralogy is indicative of a savannah (i.e. tropical wet/dry) type climate with intermittent dry periods. The weathering processes and presence of lateritic profiles in Devon would appear to confirm this interpretation of the general Palaeogene climate (Isaac, 1983).
3) Within this period there was weathering and erosion of the Early Tertiary granite intrusion of Lundy. Arthur (1989) suggested that about 4 km of its cover rock has been removed by erosion since the Eocene. It must be concluded that similar quantities of material must also have been eroded from the rest of the region over this same period of time.
4) From the mid to late Eocene tectonic activity along the NW-SE trending Sticklepath-Lustleigh wrench fault led to the formation of a series of enclosed sedimentary basins and severing of the upper headwaters of the Solent River. Sedimentation into the basins continued in the Oligocene with the rate of sedimentation keeping pace with subsidence (Edwards, 1976). The climate indicated by these sediments was sub-tropical. This was probably the period in which much of the folding of the Mesozoic sediments in East Devon and Dorset took place leading to the development of the familiar cuesta landscape, although evidence from southeast England suggests the phasing of tectonic activity throughout the Tertiary is still not fully understood (Jones, 1999a, 1999b).
5) For the post-Eocene period data is provided by the work of Walsh *et al.* (1987, 1999) who examined the Oligocene and Miocene outliers at St Agnes and identified these as terrestrial deposits formed under a sub-tropical or Mediterranean type climate. Based on their assessment, etchplanation (i.e. stripping of a saprolite cover) presumably of the sub-Cretaceous surface, had by the time of the pre-Upper Miocene created an undulating plateau surface. Where it is found in west Cornwall Walsh *et al.* (1987, 1999) called this the Reskajeage surface. Whilst not specifically established, this etchplanation surface probably forms the main plateau level developed on the Palaeozoic rocks below the heights of the granite and Devonian sandstone moorlands found throughout Devon and Cornwall as well as the high level surfaces in the Mesozoic sediments in east Devon and Dorset. This evolutionary history is in contrast to southeast England where there was an extensive marine transgression during the Miocene (Gibbard and Lewin, 2003; Zagwijn and Hager, 1987).
6) As indicated by the St Erth beds there appears to have been a minor marine transgression during the early Pleistocene in west Cornwall (Walsh, 1999) but this does not appear to have had a significant effect on the landscape.
7) During the early to mid-Pleistocene the south-west was subject to a number of cold periods, some associated with the formation of glacial ice elsewhere in the UK and Europe. The culmination of this was the extensive Anglian Glaciation which reached Barnstable Bay and the Isles of Scilly (Campbell *et al.*, 1998; Scourse and Furze, 2001). The actual affects on the landscape of the glaciations in southwest England appear to have been relatively minor, although the ice front has been used as a component of one hypothesis explaining the Valley of the Rocks above Lynmouth in North Devon (Motteshead, 1967; Dalzell and Durrance, 1980). Also there was the deposition of a deposit, the Fremington Till, which is possibly of glacial origin (Croot *et al.*, 1999; see the debate in Scourse and Furze, 2001). It should also be noted that Harrison *et al.* (1998; 2001) postulated that there was a small ice cap and glacial tills located on Exmoor (Figure 1) although the evidence is questioned by Straw (2001).
8) Notwithstanding the lack of actual glacial ice in the south-west, during the cold phases the region was subject to intense periglacial activity although the extent and depth of permafrost is still subject to debate (Ballantyne and Harris, 1994; James, 2004). However, a range of classic periglacial features have been identified (e.g. cryoturbation, Scourse, 1987; tors, Eden and Green, 1971 – Figure 2; cryoplanation surfaces, Gerrard, 1988; boulder fields, Harrison *et al.*, 1996; patterned ground – Figure 3; pingos, Miller, 1990) and elsewhere in the region there can be found an almost ubiquitous head (i.e. solifluction) cover (Harris, 1987; Motteshead, 1971; Scourse, 1987, Figure 4) plus extensive deposits of

**Figure 1.** *Punchbowl 'cirque' on Exmoor – postulated as possible evidence of a North Devon glacier (photograph by M. Stokes).*

**Figure 2.** *Great Staple Tor, Dartmoor.*

**Figure 3.** *Patterned ground below Great Staple Tor, with hummocks in the foreground on Cox Tor, Dartmoor.*

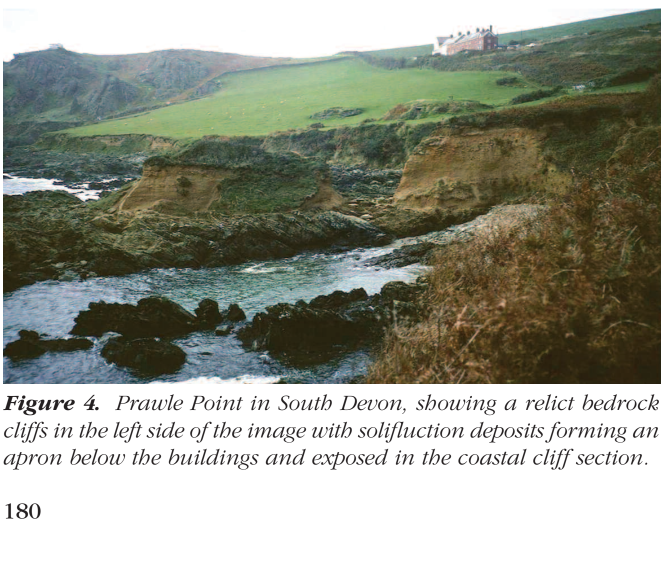

**Figure 4.** *Prawle Point in South Devon, showing a relict bedrock cliffs in the left side of the image with solifluction deposits forming an apron below the buildings and exposed in the coastal cliff section.*

loess (Catt and Staines, 1982; Griffiths and Lee, 1989). With respect to the formation of the tors, the model developed by Palmer and Neilsen (1962) of deep tropical weathering during the Tertiary Period followed by exhumation during the Pleistocene Period by periglacial activity remains in favour. This is despite Eden and Green (1971) attempting to demonstrate that the clay mineralogy of the weathered granite (the growan) does not suggest weathering under tropical conditions.

9) Sea level fluctuations during the Pleistocene (and Holocene) created a number of coastal and near-coastal features that are evident in the terrestrial landscape such as raised beaches (Scourse, 1987; Orme, 1960), river terraces (e.g. the River Axe Valley, Shakesby and Stephens, 1984) and relict cliff lines (e.g. Prawle Point; Griffiths and Croot, 2000 - Figure 4). The distinctive rias (flooded estuaries) of the southwest, as well as parts of the Somerset levels, are also the result of these sea level fluctuations with the rivers grading to lower sea levels during glacial advances and then subsequently being infilled with sediment as sea levels recovered. Offshore there is also evidence of former cliff lines and coastal features that are now submerged (e.g. Start Bay; Hails, 1975).
10) The Holocene is marked by the initial flooding of the coastline as sea level rose from a position some 70-100 m below present level during the late Devensian glaciation (Synge, 1977). Massey *et al.* (2008) identified a 21 m ± 4 m rise over the past 9,000 years. However, what is happening at the present day is subject to some debate (Gehrels, 2010). Shennen and Horton (2002) suggested that the coastline of southwest England is undergoing a relative subsidence rate greater than other UK coasts (*c.* 0.9-1.4 mm/yr) but the work by Massey *et al.* (2008) finds no evidence of anomalous subsidence in the region.
11) The present day is one in which climate change is now generally recognised as a reality and the Intergovernmental Panel on Climate Change (IPCC) predicts that by 2100 the sea level will be 0.5-1.4 m higher than the 1990 level. Associated with climate change will be an increase in the annual number of storms and higher rainfalls, which are both likely to lead to increased rates of coastal erosion, more frequent coastal and fluvial flooding, and increased slope instability.

Although the above is only a very brief summary, it gives an indication of some of the developing ideas and on-going debates about the history of the southwest England landscape. In an attempt to summarize the landscape created by this evolutionary history Foster (2007) prepared a classification of the terrain in Devon and Cornwall (Figure 5). This highlights the nature of the plateau surface developed in Cornwall and on the Culm Measures rocks in Devon, the east Devon cuesta in the Mesozoic rocks, the uplands formed by the older sandstones and igneous rocks, the dissection by rivers and the coastal flooding that created the rias. In conjunction with the detailed descriptions of the terrain units contained in Foster (2007), this terrain classification provides a useful framework to underpin the reconnaissance stages of geotechnical site investigations and/or geohazards assessments in Devon and Cornwall as it highlights the terrain types with an indication of their geomorphological development.

The second part of this paper is concerned with how facets of this evolutionary history might have a bearing on determining ground conditions for engineering development in the region. Specifically two issues from Commission 22 are assessed in relation to southwest England: 1) relict processes and landforms; 2) magnitude and frequency of geomorphological processes. The importance of examining the first issue stems from the unique aspects of the landscape in the

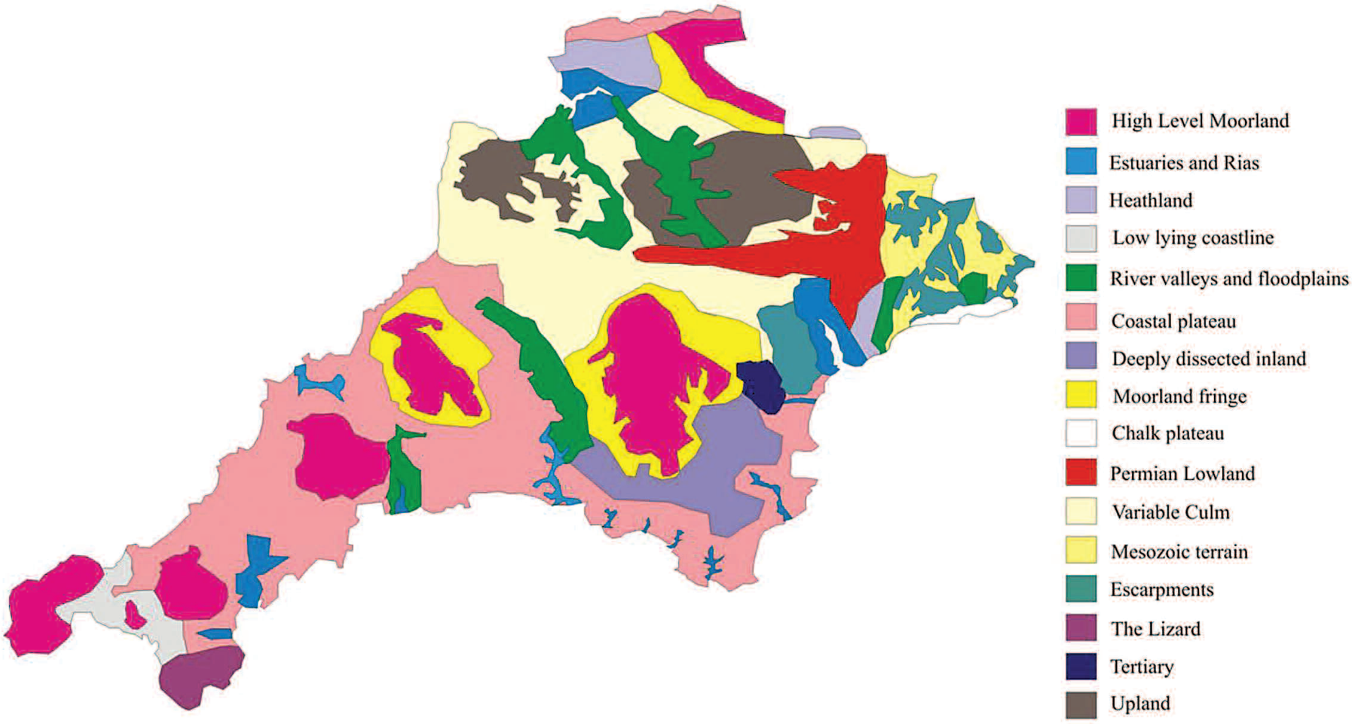


***Figure 5.*** *Subdivision of Devon and Cornwall into major terrain units (published with permission from Foster, 2007).*

region. As Migoń and Goudie (2001) state: *"the distribution of inherited landscape across the British Isles is generally patchy … most inherited landscape facets have been recognised in the western part of Britain, and particularly in the south-west."* The second issue is a more widespread concern but in this paper the flood magnitude and frequency concept is examined as it is widely used in design of flood protection schemes in the region (Environmental Agency, 2009).

## RELICT PROCESSES AND LANDFORMS

The polycyclic nature of the landscape in southwest England means that it contains many legacies of landforms formed under different climatic conditions; hence use of the term palimpsest to describe the contemporary landscape. Figure 6 represents a schematic of the cuesta landscape in east Devon in the vicinity of Axminster, which exemplifies this concept. The potential issues that are relevant to engineering design decisions which emerge from an evaluation of the geomorphological history of this palimpsest landscape are discussed below.

The ground model in Figure 6 was produced as part of the investigations for the Axminster by-pass (Griffiths and Marsh, 1985). At the top of the slope (right-hand side of the figure) is a bench that is likely to have developed on the *in situ* Upper Greensand and would be the result of early to middle Neogene (*c.* 24-5.3 Ma BP) subaerial denudation that eroded any Paleogene/Eocene and possibly any Oligocene deposits (*c.* 65-24 Ma BP) leaving this high level erosion surface (a strath or etchplain). Subsequently the overall hillside and river valley landscape morphology will have formed during the Neogene but notably in the Plio-Pleistocene (*c.*5.3 Ma BP, through to the present day), as a result of the River Axe eroding the landscape in response to the isostatic and eustatic changes in sea level and possibly ongoing tectonic uplift.

The river terrace shown would have been formed during the last Interglacial period (the late Pleistocene Ipswichian Interglacial, *c.* 120-80 ka BP) when sea levels were higher than the present day. There were most likely older terraces from previous interglacials that have now been eroded completely leaving no trace in the contemporary landscape. River terrace deposits are usually a good source of construction aggregates.

During lowered Pleistocene sea levels the River Axe would have eroded down to a lower base level and cut a valley that is now buried by the alluvial infill. This could have a bearing on the depth of any piled foundations for bridges across the floodplain. The large ancient landslides, now covered by solifluction deposits, will have developed during high groundwater periods during the Devensian (*c.* 80-10 ka BP). Whilst they are now inactive they could be reactivated by constructions works, river erosion or significant changes in climate. The solifluction lobes mostly likely formed in one of the last cold phases of the Devensian (e.g. the Older Dryas, 18-15 ka BP). Again these are currently stable but, as found on the Sevenoaks by-pass (Skempton and Weeks, 1976), these features can be reactivated by road works. A more contemporary process that might directly affect construction works would be recent landslides, which, based on UK landslide studies (Jones and Lee, 1994; Hall and Griffiths, 1998/99), probably first developed during the 'little ice-age' of the Middle-Ages (*c.* 1550-1850 AD – Matthews *et al.*, 1997). Actual contemporary processes that would have to be taken into account would be flooding on the River Axe floodplain.

The Axminster example illustrates how an understanding of the geomorphological history of the area can help identify potential civil engineering raw materials/resources (the terrace deposits), hidden hazards (potential shear surfaces in buried landslides; Devensian solifluction deposits; buried valley beneath the floodplain), and surface hazards (Holocene landslides; the contemporary floodplain). These components of the geomorphological history were incorporated in the interpretative report from the site investigation for the Axminster by-pass on which the subsequent detailed design was based (Griffiths and Marsh, 1986).

A contrasting historical example is provided by construction works associated with the Burrator reservoir on the western edge of Dartmoor near Tavistock (Keene, 2001). Completed in 1898, the reservoir required two dams, the first across the River

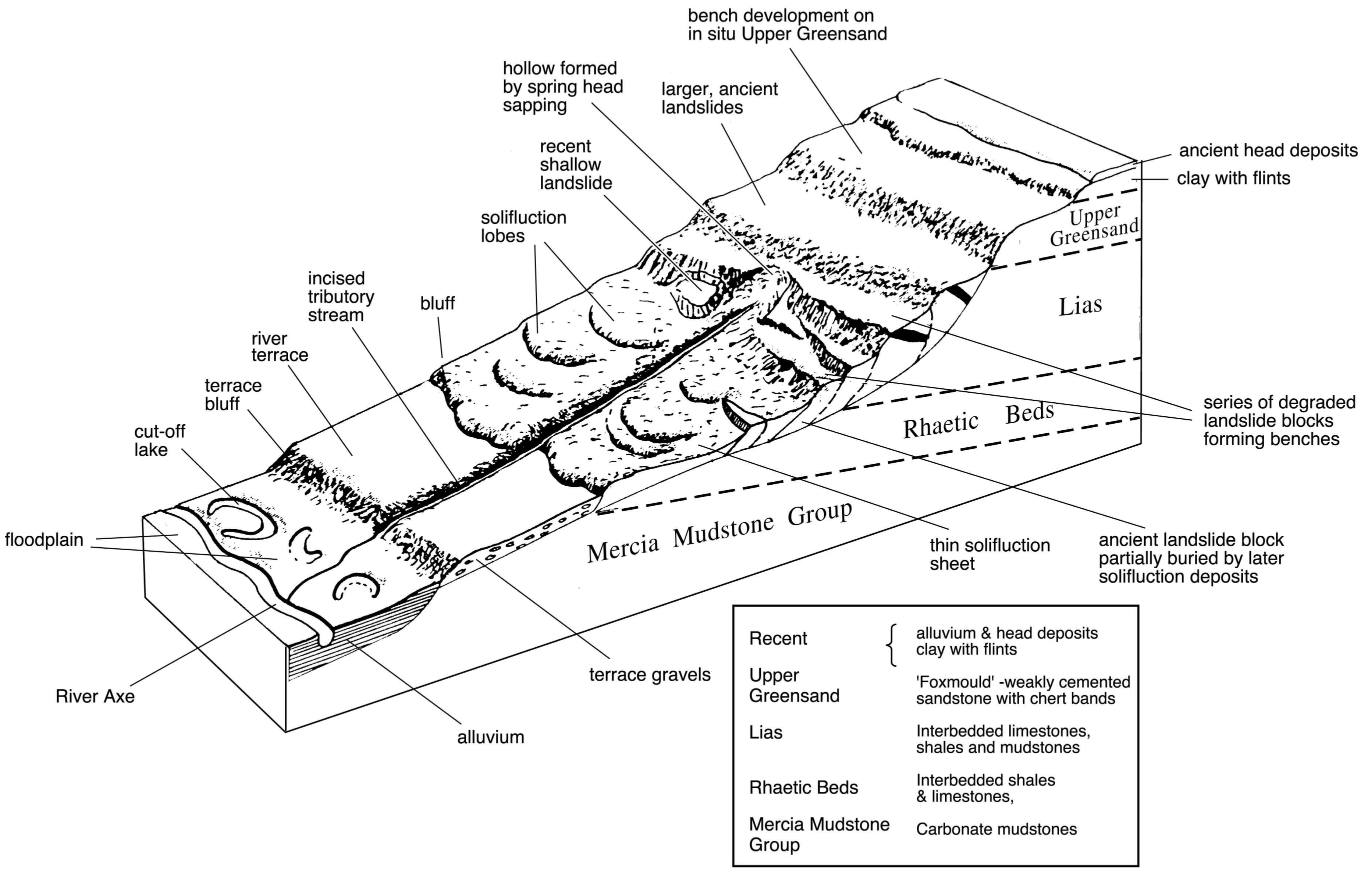


***Figure 6.*** *Schematic cross-section through the landscape in the Axminster area, East Devon (reproduced from Croot and Griffiths, 2001, with the kind permission of the Geological Society of London).*

Meavy and the second over a low watershed above the village of Sheepstor. The Sheepstor dam proved problematic because when the foundations were excavated the granite was found to be deeply weathered. Granite described as unweathered was finally located over 30 m below the ground surface. To produce an effective watertight dam required digging a 32 m deep foundation trench that had to be filled with concrete. This was despite two trial pits being dug before excavation commenced that found solid granite near the surface. Because of the more extensive knowledge of the long term landscape development of region, there is now a better understanding of the nature and variability of the relict weathering profiles in and around Dartmoor. In addition, modern ground investigation techniques are much more efficient and these days boreholes and geophysical survey of the site would be carried out before the works started. Hopefully such problems would no longer arise.

Large components of the southwest landscape contain elements associated with relict processes. Whilst site investigation techniques have developed significantly since the problems encountered at Burrator reservoir, it is still critical that any ground model developed for a structure in the region takes these processes into account. For instance, the failure of the Carsington Dam in Derbyshire in 1984, when a solifluction deposit containing relict shear surfaces was wrongly identified as *in situ* weathered shale (Skempton and Vaughan, 1993), remains as a salutary lesson of the importance of getting the ground model correct by ensuring the nature of the relict processes and their associated ground conditions are understood. The importance of bringing all this material together to create a *'total geology model'* (Fookes, 1997; Fookes *et al.*, 2000; Griffiths and Stokes, 2008) cannot be over-emphasised.

## Magnitude and frequency of geomorphological processes

On the 14th August 2004 the village of Boscastle suffered a flood event with a peak discharge of around 140 cumecs ($m^3/s$). This extreme event was generated within a 20 $km^2$ river catchment. The Environment Agency report (Forrabury and Minster Parish Council, 2005) describes this as a 1 in 400 year event with a rainstorm that had a recurrence interval, or return period, of 1 in 1300 years. The UK is fortuitous in that it has rainfall records that go back the middle of the 19th Century, but even so the rainfall estimate provided can only be based on a statistical analysis of the data with extrapolation for return periods beyond the length of record. The same is the case for the runoff data, although the records are usually much shorter. Any reliable estimate of both rainfall and flood flows, will therefore, contain a margin of error, or more specifically, have statistically calculated confidence limits. However, the return period concept is widely used in both the popular press and the scientific literature, and suggests, in the context of floods and other geohazards, that magnitude and frequency relationships exist.

The return period concept has a long history in the geomorphological literature and there have been debates, for example, over whether it is high magnitude/low frequency or the low magnitude/high frequency events that are the most effective in shaping both contemporary and relict landscapes (e.g. Wolman and Miller, 1960; Wolman and Gerson, 1978). In examining landscape development it was suggested by Chorley and Kennedy (1971) that geomorphological processes and landforms could be regarded as process-response systems that were in various states of equilibrium (Table 2). The definitions in Table 2 demonstrate that it is only if the process-response

| Type of equilibrium | Effects on landform (e.g. size) or rate of activity (e.g. erosion rate) |
|---|---|
| **Static Equilibrium** | no change over time |
| **Stable Equilibrium** | form or rate returns to its original value following a disturbance |
| **Steady State Equilibrium** | form or rate has short-term fluctuations with a longer-term constant mean value |
| **Dynamic Equilibrium** | form or rate has short-term fluctuations with a changing longer-term mean value(i.e. an increasing or decreasing trend) |
| **Metastable Equilibrium** | form or rate settles on a new value after having crossed some threshold value |

***Table 2.*** *Types of natural equilibrium for geomorphological systems (Chorley and Kennedy, 1971).*

system is in static, steady state or stable equilibrium that the return period concept has validity. If there is an underlying long term trend, such as global sea level rise in connection with coastal flooding frequency, then the return period concept has significant flaws. If the landscape is shown to be in metastable equilibrium where a threshold event occurs that changes the whole process-response system then the return period concept has no validity. The conclusion must be that in order to use the return period concept there must first be an evaluation of the nature of equilibrium of the geomorphological system under investigation.

In terms of incorporating landscape development information into engineering design decisions, the debate over magnitude/frequency relationships of geomorphological processes does have important engineering implications. The concept has been widely adopted by engineers and planners to provide a basis for design, notably in flood studies (see the Exe Catchment Flood Management Plan; Environment Agency, 2009) but also in relation to other geohazards such as earthquakes (Lane, 1983) and landslides (Moore *et al*., 1991). Hence it is a concept that links together landscape forming processes and engineering design but there must be questions as to how appropriate it is to use return period for an evaluation of a natural process.

For river flood management studies the recurrence interval concept is illustrated schematically in Figure 7 (after Bennett and Doyle, 1997) in the production of a hypothetical building control plan on an area of river floodplain. The area of the active channel and the immediately surrounding floodway is deemed to have a 1 in 5 year probability of flooding, and here there is restriction on all non-essential development. Beyond that is Hazard Zone 1, which is liable to flood 1 in 25 years and has certain planning restrictions. Hazard Zone 2 has only specific restrictions along with some design recommendations and is associated with a 1 in 50 year flood event. The highest level above the contemporary river is Hazard Zone 3 with few restrictions and is only expected to be affected by a 1 in 100 year event. If it is assumed that there is an accurate and reliable data set for this hypothetical site then it will be possible to plot a clear return period versus peak discharge graph as shown in Figure 8. However, even with over 100 years of data the graph indicates a widening zone for the upper and lower confidence limits as the return period lengthens. Therefore, as exemplified in Figure 8, the hypothetical 1 in 100 year event is calculated as 150 cumecs, but the inclusion of confidence limits demonstrates that statistically it could be between 120 and 250 cumecs. Similarly for the other flood zones in the hypothetical site: the 50 year flood might be between 100 and 180 cumecs; the 25 year flood between 60 and 110 cumecs; and even the 5 year flood, which would be the most accurate with a 100 year record, would be between 25 and 55 cumecs. To put these flood values in perspective, the mean annual flood on the River Thames is approximately 320 cumecs and it drains an area of just under 13,000 km$^2$ (for comparison the River Exe has a catchment area of around 1500 km$^2$).

The Boscastle village now has a comprehensive flood risk management scheme in place which is designed to deal with a 1 in 75 year flood (Halcrow, 2010). Similarly, the Environment Agency flood management plan for the River Exe makes reference to dealing with the 1% probability event (i.e. the 1 in 100 year flood) (Environment Agency 2009). Therfore, the design of flood management schemes in the south-west is making use of the return period concept.

Returning to the hypothetical site model discussed above, Figure 8 indicates that a conservative estimate for the 1 in 100 year flood taking the upper confidence limit value is 250 cumecs. Taking this value for the design of a flood alleviation structure, an analysis can be made of the relative costs where annual cost is plotted against the design discharge, as shown in Figure 9. Figure 9 indicates that the higher the design discharge the greater the capital cost (blue line) of the structure. However, the higher the design discharge, the less likely the

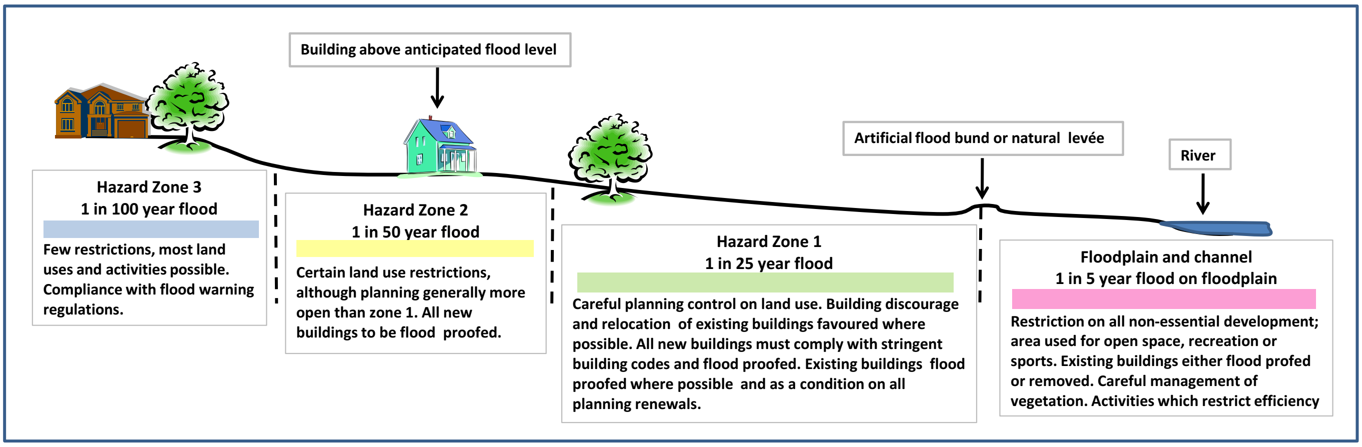


***Figure 7.*** *Schematic diagram of a typical river floodplain zoning system for land use planning.*

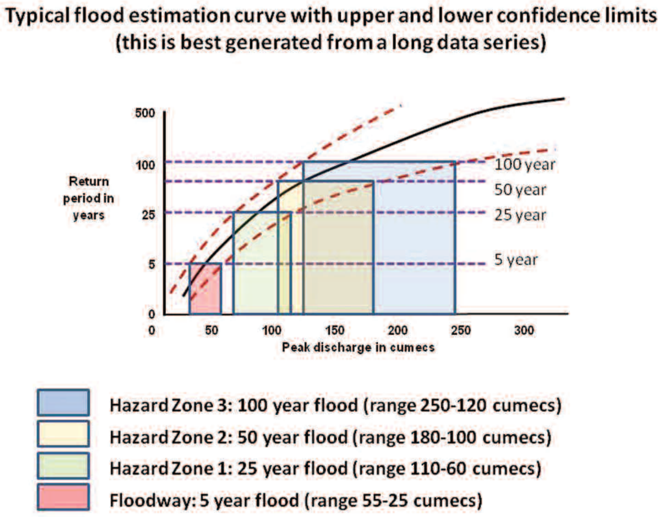


***Figure 8.*** *Flood estimation curves in relation to the flood planning scheme in Figure 7.*

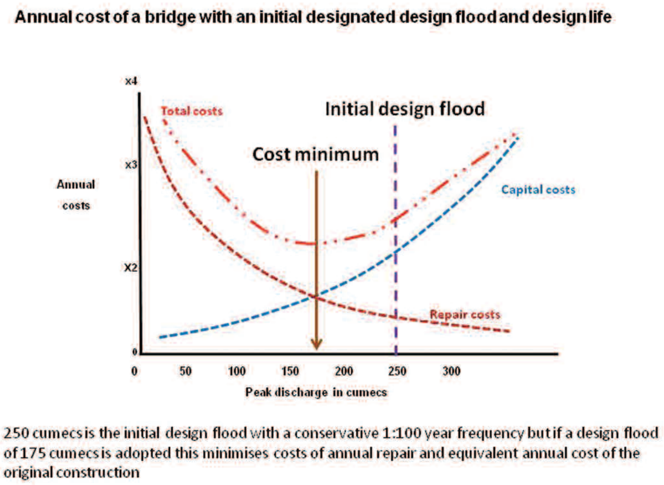


***Figure 9.*** *Cost decision plot for a flood alleviation scheme based on the data in Figure 8.*

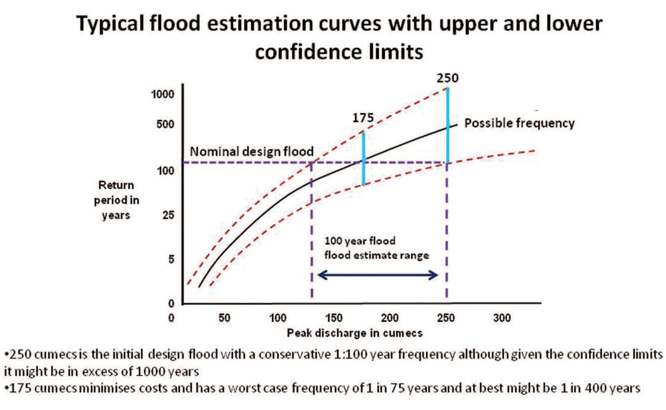


***Figure 10.*** *Difficulties in actually defining the magnitude of a flood flow.*

structure is to suffer functional failure and damage, hence the annual repair cost drops with discharge (brown line). Adding the capital and repair cost curves together provides the total cost curve which has minimum value (red line). In this example the minimum costs correspond to a design discharge of 175 cumecs, significantly lower than the initial design discharge. Returning to the flood discharge data for the hypothetical site, Figure 10 shows the full flood range for a 100 year flood and indicates that the original design flood estimate of 250 cumecs could have a return period of between 100 and 1000 years, whereas the lower costing design flood of 175 cumecs might be anywhere between 1 in 75 and 1 in 400 years. The question that arises is what is the appropriate design flood and what is its actual recurrence interval?

As an alternative to ascribing a particular recurrence interval to a flood, perhaps it might be better to assess the cost of the consequences of various flood magnitude events. This approach is illustrated in Figure 11 (from Whitworth – personal communication 2009). With this approach the frequency of the flood is the secondary consideration, it is the magnitude that is important, as well as establishing what form of equilibrium exists for the geomorphological system. The potential flooded area and consequences of the floods can be calculated for different magnitude events and a decision made on what level of damage to infrastructure, people and environment is deemed acceptable. The frequency for this magnitude of flood could then be estimated using the available data to see if this fitted into the broad categories that make allowance for the confidence limits, such as frequent, regular, rare or extreme. This would avoid the problem of attempting to assign design recurrence intervals to natural processes, which geomorphologists recognise as just a means of expressing complex phenomena that have a degree of cyclic behaviour but in reality are subject to wide variations in frequency and magnitude even where the geomorphological system is in a suitable form of natural equilibrium. Effectively as the concept is a statistical construct (e.g. two 1 in 100 year floods could occur in concurrent years) perhaps its value for engineering design and planning guidance should be questioned. However, the popular press does find it an easy means of expressing the rarity of extreme events so the use of the concept will probably remain.

## Conclusions

The two very different examples discussed above give an indication as to how the research for engineering applications from understanding landscape evolution is progressing. It is clear from the work that landscape evolution does have a bearing on engineering design decisions but the relationship is neither straightforward nor easy to quantify. The value of understanding the geomorphological history is most clearly demonstrated by the Axminster by-pass case study, whilst the ambiguities are illustrated by the hypothetical flood studies presented above. What is recognised is that, as yet, building in an understanding of landscape evolution, particularly the historical development, is rarely incorporated in standard approaches to investigating the ground for any proposed development. IAEG Commission 22 aims to provide a framework to allow the facets of landform development relevant to engineering geology to be included in site investigations. The full range of issues, as presented in Table 1, will be explored in detail in the final report, but a preliminary review is provided by Griffiths *et al.* (2010). However, it is interesting to note that whilst engineering geologists have become aware of the importance of understanding the history of the development of the landscape over the past 30 years, at the same time geomorphologists have moved away from this field of study to concentrate more on smaller scale process-response studies (Smith *et al.*, 2002). Hopefully IAEG Commission 22 might also re-stimulate the interests of geomorphologists in this critical field of applied geomorphology.

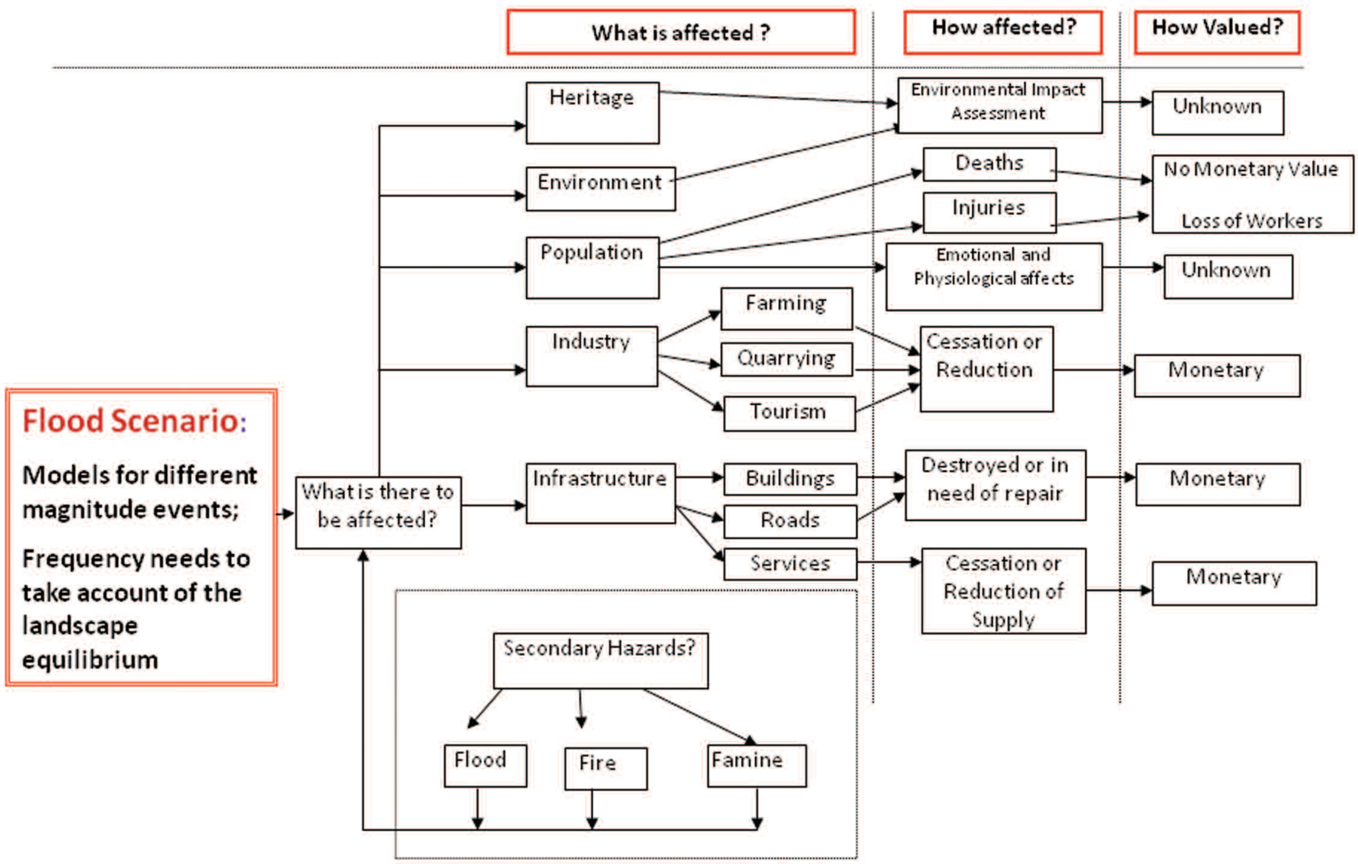


***Figure 11.*** *Consequence comparison approach to evaluating the design flood (Whitworth – personal communication 2009).*


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