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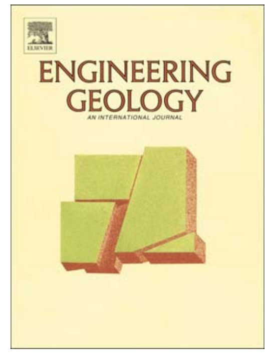

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'The application of geomorphic indices in terrain analysis for ground engineering practice'

Abstract

Keywords: Geomorphology, Geohazards, Geomorphic Indices, Engineering Geology, Sorbas Basin

Terrain analysis studies for long linear engineering projects provide critical engineering geological and geomorphological data that inform project design options, route selection and construction methodologies. This paper introduces the use of geomorphic indices alongside methods of aerial photograph interpretation and remote sensing in the desk study phase of engineering terrain evaluations in the identification of landscape changes and geohazards in active tectonic regions. Three geomorphic indices (hypsometry, river long profile analysis and stream-length gradient index) are applied to freely available DEM data in order to develop the qualitative and quantitative (relative to study area) understanding of how the hillslope and river systems respond to the effects of tectonic activity and climate change. A hypothetical pre-feasibility study corridor (10 km width) located in the Sorbas Basin (SE Spain) is used to develop the methods of application, which could represent a proposed rail, road or pipeline routing. The results of the scaled indices approach, from catchment to reach (i.e. section of uninterrupted river channel) investigations, indicate a variable response of landscape processes. 'Active' erosional conditions are found in the central and northern limits of the basin relating to a known zone of tectonic deformation, the Infierno-Marchalico Lineament, and also to the effects of a river capture-related base-level lowering. 'Active' conditions are typically linked to an increased occurrence of landslides and badland formation. 'Stable' conditions are more common in the west and east of the basin where drainage channels are effectively coupled to base level. The combined results of geomorphic indices and aerial photograph interpretation are used in the identification of engineering constraints and geohazards as related to gully development, badland formation and the formation of landslides. A simple geohazard constraints map is produced which demonstrates ground related hazard to the wider project team and can be used to target field investigations and further inform construction methodologies and limitations.

1. Introduction

The early stages of large civil engineering projects for long linear infrastructure (e.g., highways, railways, oil and gas pipelines, etc.) often require rapid regional assessments to be made of the potential geological and geomorphological ground conditions that might be encountered, usually with limited information available. Results from these assessments can then be used to inform design options, route selection and construction methodologies, with lasting implications for the project. It is important that geology, geomorphology, geohazards information and other terrain-related geo-engineering issues can be determined along the proposed route corridor or alignment as accurately and as quickly as possible. In particular, the identification of landslides (both existing and potential first time failures), active erosional rivers and patterns of regional and local erosion are important (e.g., Lee, et al., 2016).

An approach often used for oil and gas pipeline projects is Engineering Terrain Evaluation (e.g., Griffiths, 2001; Fookes, et al., 2001; Fookes et al., 2005; Shilston et al., 2005; Hearn, 2011; Hearn et al., 2012;). This approach combines the knowledge and expertise of a project 'Geoteam' with regional remote sensing interpretation (e.g. satellite imagery, aerial photographs, etc.) and analysis of available mapping or digital datasets (e.g., digital elevation models, published maps of geology, topography, etc.) to derive engineering outputs (e.g., maps, drawings, tables, reports, etc.) that can be used to assist route selection, avoidance of geohazards and design of subsequent site investigations. The use of digital datasets, such as Digital Elevation Models (DEM), allows for the application of geomorphic indices. Geomorphic indices are quantitative analyses of topography that use DEM datasets in conjunction with Geographical Information System software. They are a long standing and rapidly expanding area of quantitative geomorphological analysis within academic research (e.g. Keller, 1986; Lee and Tsai, 2010; Antón et al., 2014) yet to be widely realized by the engineering industry.

The success of any terrain evaluation is governed by a number of factors (Figure 1). The ability of the Geoteam (i.e. collective of experienced project personnel from a range of related disciplines such as geologists, geotechnical engineers and mechanical engineers) to accurately qualify and quantify landscape attributes is strongly influenced by their combined experience in the geological/geomorphic environment and their ability to analyze landscape data over a range of temporal and spatial scales (Lee and Charman, 2005, Hart et al., 2009). The landscape data used in long linear infrastructure projects aim to support interpretations of landscape stability (i.e state of a landscape and its propensity to change) which are important when defining route suitability (Mollard et al., 2008). Aerial photograph interpretation (API) is a routine mapping approach for assessing morphology and rates of landscape change over set time intervals. API is widely applied in engineering projects and is supported by the increased usage of freeware such as Google Earth (e.g. Mather et al., 2015). The definition of key landscape attributes from publically available terrestrial DEMs (e.g. SRTM), such as slope angle and length, has also become increasingly useful in pipeline, road or rail routing studies (Mollard et al.,2008). However, these techniques provide little insight into relative landscape activity, with key elements of slope incision, stream channel migration or formation of larger landscape instabilities unaccounted for.

Geomorphic indices extract a combination of height, distance, area and slope data for input into simple equations. Index approaches are low-cost and rapid, allowing engineers to qualify and quantify landscape activity attributes such as rates of gully erosion, headwall retreat or river erosion, which depending on location/setting, are key geohazards for linear infrastructure investigations (Table 1) (Charman et al., 2005). The quantitative assessment of geohazards is important in many stages of engineering design, including river crossings (Veldman, 2008) or routings through steep / mountainous terrain (Hearn, 2011), where observations from API can be limited by data coverage, shadows, distortions or image quality. In such settings, index approaches can be employed to produce map derivatives that allow for clear comparisons with other geological and geomorphological datasets, such as landslide density derived from API. These data form vital baseline inputs for routing studies and can be input into engineering constraints maps in order to develop geohazard related project risks (Hearn et al., 2003; Shilston et al., 2004; Hearn and Hart, 2011; Hearn et al., 2012). Furthermore, indices can be remotely applied allowing the Geoteam to gain key information from challenging environments (e.g. tectonically active, semi-arid/arid/temperate and tropical) where access can be difficult due to the hazardous terrain and / or political unrest (Walsh et al., 1998; Silva et al., 2003; Pedrera et al., 2009; Dehbozorgi et al., 2010).

This paper introduces three geomorphic indices (hypsometric curve, river longitudinal profiles and stream length gradient index) illustrating their contribution to constraint map development and targeting field investigations for linear infrastructure projects. The indices are used to demonstrate the relative geomorphological activity of a landscape in forward planning exercises (i.e. desk-based studies) within tectonically active domains hindered by a lack of contemporary landscape data. Because indices are quantitative, they can also be used retrospectively, allowing post-event investigation of landscape instabilities or natural hazards, such as identifying areas of landscape instability previously unaccounted for in engineering studies. Geomorphic index approaches should not replace standard landscape interpretation methods (e.g. API) but instead provide added value when used alongside, complementing factual observational data, such as landslide occurrence, with contemporary landscape data, such as relative hillslope and river activity.

To illustrate the application of geomorphic indices for terrain evaluation in engineering practice, indices are simplistically presented using a hypothetical pre-feasibility study corridor (10 km width), which could represent a proposed rail, road or pipeline routing option (Figure 2). The study corridor crosses the Sorbas Basin (SE Spain), a dryland desert mountain and basin setting that is geologically complex and tectonically active. This location has posed notable challenges in the recent design and construction of local infrastructure (e.g. road upgrading), regional transport routes (e.g. AVE Almería-Murcía high speed rail link) and transnational pipelines (e.g. the Medgaz pipeline). Geomorphological research within the Sorbas Basin has demonstrated the importance of: (i) non-uniform rates of tectonic uplift, (ii) climatic variations in fluvial and hillslope activity on a Quaternary timescale, (iii) internal variations in lithological strength and (iv) internal landscapes processes (e.g. river capture) upon the engineering setting of the region (Hart, 1999; Hart et al., 2000; Griffiths et al., 2002; Mather et al., 2002; Stokes et al., 2002; Hart, 2004; Griffiths, et al., 2005). The area benefits from the availability of free digital data (e.g. 25 m ortho-corrected imagery and 90 m SRTM data) required for the index approach.

The paper outlines the geomorphic indices to be used, providing insight into their approach and application. The indices are then applied to the Sorbas Basin route corridor adopting the approach of a Geoteam looking to develop a comprehensive Terrain Map, which couples the combined findings of API, DEM interrogation and an appraisal of geomorphic indices. Finally, the index results are discussed in relation to their engineering constraints value and identification of geohazards.

2. Geomorphic Indices

The rates at which stream incision, escarpment retreat, hillslope failure and other geomorphic processes occur are important for geohazard studies (Fookes et al., 2005). Landscape change can be estimated in terms of relative system activity, defining either 'Active' or 'Stable' gross landscape settings by the calculation of different geomorphic indices over a range of scales. The indices applied here, notably: hypsometric curves, river longitudinal profiles, and stream length gradient index allow for the assessment of key drivers of landscape change from the catchment to reach scale on engineering time scales (1 to 100 years based on upper limit design life of 120 years for earthworks) associated with the effects of climatic forcing (i.e. global changes which occur beyond patterns of weather) (Dijkstra et al., 2014), lithological strength/structure and/or tectonic uplift and deformation (i.e. active faulting) (Griffiths and Stokes, 2008).

The indices used (Table 1) are selected based on their ease of application and value for engineering geology/geomorphology studies. For example, the analysis of hypsometric curves from ephemeral bedrock rivers or shallow alluvium rivers (alluvium thickness <10 m) allows for the identification of geohazard processes within catchments such as the progressive development of gullies in hillslopes or landslides. In contrast, river longitudinal profile analysis and the stream length gradient index allows for the investigation of relative activity in individual streams, rivers or drainage reaches produced by changes in rock strength or relative incision rates at a local scale. There are other index approaches in the literature (e.g. mountain front sinuosity: Keller and Pinter, 1996) but they are not considered due to their limited engineering value.

2.1 Hypsometric analysis

Landscape stability (and resultant risk to engineering infrastructure) in tectonically active domains is largely governed by rates of vertical fluvial incision and lateral erosion (Whipple and Tucker, 1999). Where a river network (including gullies and low order streams) is at, or near grade (i.e. a river near equilibrium with a gentle gradient in the downstream direction), the available energy is low (stream power law of Bull, 1979) and risk to infrastructure from hillslope geohazards is limited. Conversely, if a river network is subjected to variations in sediment availability or discharge the rate of erosion is high and the risk to infrastructure can be significant.

Erosional activity within a river catchment can be described by the distribution of topography above a given point of known area measured by its hypsometric curve (Strahler, 1952). The hypsometric curve represents the area and elevation of a drainage catchment typically normalized to one. A convex hypsometric curve with a large proportion of the catchment lying at high elevations (Fig. 3) indicates an ‘Active’ river in engineering terms. Active catchments are typically driven by hillslope processes (e.g. landsliding, rain-splash, inter-rill erosion and soil creep) with high potential power that pose a notable risk in terms of gullying, soil erosion and landslide development (Table 1) (Willgoose & Hancock, 1998). A concave hypsometric curve indicates a 'Stable' catchment where the bulk of the catchment area resides at a relatively low elevation (Figure. 3). In 'Stable' catchments, well developed channelised fluvial processes dominate (Willgoose & Hancock, 1998) and risk from lateral and/or vertical erosion is low. An 'S' shape hypsometric curve indicates an intermediate stage catchment, whereby a complex interplay of landscape processes are occurring (Giaconia et al., 2012). For example, the lower end of a catchment might be located in a weaker lithology with higher erodibility or be subject to non-uniform rates of tectonic deformation. In such catchments non-uniform rates of drainage development are typical and geohazard formation might be focused in areas of increased incision.

Hypsometric curves can be generated from DEM's using GIS software. In the early study stage, a number of catchments should be analyzed to develop regional baseline conditions and further identify local differences. Standard approaches collate elevation data in a number of set bins, which are represented as histograms and fit against a measure of cumulative area (http://gis4geomorphology.com/). Various automated extensions exist that operate in ESRI ArcGIS software to generate hypsometric outputs (e.g. Hypsometry toolbox; CalHypso (Pérez-Peña et al., 2009). However, the scale of catchment delineation (i.e. low order hillslope systems to regional rivers) is typically assessed against the requirements of the study.

2.2 River longitudinal profiles

River responses to changes in sediment and stream discharge (stream power) can be described using its longitudinal profile (Antón et al., 2014). This is a plot of channel elevation against channel distance from the drainage divide to the river mouth or confluence. The profile shape can be used to classify a river as either 'Active' or 'Stable' in engineering terms. Figure 4 shows a convex long profile, representing an 'Active' river with a high channel gradient. Similar to hypsometric curves (catchment scale), 'Active' rivers pose greater risk to infrastructure due to increased rates of vertical / lateral incision and associated hillslope instabilities. A longitudinal profile with a smooth downstream concavity represents a 'Stable' river with lower rates of incision and thus a lower engineering risk rating (Figure 4). Profiles which display both 'Active' and 'Stable' conditions represent a decoupled system which requires specific investigation. A switch from a stable river to an active river could occur as: (i) a result of tectonic reactivation and active faulting, (ii) the crossing of a lithological boundary and/or (iii) enhanced base-level change occurring externally to the fluvial system (e.g. river capture event, lake collapse or drainage reversal) (Antón et al., 2014). These processes can either occur independently, or be coupled in nature and require detailed investigation based on field data.

In addition to relative channel activity, localized profile disturbances such as knickpoints / knickzones (over-steepened channel reaches) can be identified. They can be formed by: (i) changes in rock strength, (ii) stream discharge increases at tributary junctions (Bishop et al., 2005), (iii) localized tectonic disturbances such as faults with a surface expression (Clark et al., 2005) or (iv) landslide damming (Korup, 2006). Such anomalies represent 'hotspots' for landscape disequilibrium and are of high importance in terms of engineering risk.

River longitudinal profiles can be easily produced at a range of spatial scales in order to investigate the effects of forcing mechanisms upon the river system. In the early stages of investigation, many individual channels are analyzed in order to enable identification of baseline and variable conditions. Profile data are generated from DEM's or digitized topographic maps. However, it is important to define the scale of investigation prior to implementation. For example, regional river systems might initially be assessed for large geographic areas (10's-100's km^2); yet a more detailed appraisal based on stream order principals (i.e. Strahler stream order) might be applied in small scale studies (<10's km). In either case, it is important that landscape interpretations are made at a range of predefined data scales which meet the requirements of the study at hand. There are a large number of landscape evolution studies that use river profiles (Table 1), but careful attention should be paid to the relative nature of measurements and the requirements for calibration against other index values and resultant field investigations.

2.3 Stream length gradient index

The stream length gradient (SL) index was defined by Hack (1973) in the study of rock resistance in upland and mountainous streams in the southeastern United States. The index utilizes the adjustment of rivers as they attempt to reach a dynamic equilibrium. Similar to longitudinal profiles, the SL index can be used to identify local hotspots of gradient change along a river which might be important in engineering terms. A benefit of the SL Index is that a quantitative measure of gradient change is calculated by normalizing the river channel against the longest regional drainage, forming relative quantitative measures of local river system perturbation.

The SL index is defined as:

$$SL = (\Delta H - \Delta Lr)\ \Delta Lsc \qquad \text{(Equation 1)}$$

where ΔH is change in altitude across the channel reach, ΔLr is length of the channel reach at the midpoint, and ΔLsc is the horizontal length from the watershed divide to midpoint of the channel reach (Fig. 5a) (Hack, 1973).

Low SL-index values (relative within a study area) suggest less tectonically active areas and/or areas where rivers cross less resistant bedrock, representing ‘Stable’ conditions. High SL-index values indicate more tectonically active areas, highly erosion-resistant bedrock, or migrating knickpoints typically driven by localized base-level lowering events (Keller and Pinter, 1996), which represent ‘Active’ conditions. The SL index has been used extensively to evaluate: (i) the roles of tectonics in active landscapes, with variations in SL values when river systems develop in areas of differential uplift (e.g. Keller and Pinter, 1996); (ii) lithological controls, where variations in relative strength lead to perturbations in channel erodibility (e.g. Hack, 1973), and (iii) base-level changes, which can drive variations in channel erosion as a result of local (e.g. river capture or lake breaching) or regional forcing mechanisms (Antón et al, 2014).

The data requirements for SL calculation are presented in Figure 5B, and include the generation of a drainage catchment(s), drainage line(s) and a reference DEM or digitized topography. Two approaches can be adopted for calculation purposes (ΔLr, Eq. 1) where either: (1) the reach is defined by a notable change in slope gradient (ΔLr is variable), or (2) the reach is kept constant for the duration of analysis (e.g. 50m reaches) and ΔLr is fixed. When adopting approach (2), attention should be taken to define a reach distance that allows for the appraisal of stream fluctuations that might occur at localized knickpoints or knickzones. In best practice a range of reach distances are applied in order to define optimal values.

Similar to river longitudinal profiles, the generated SL data is treated as relative to the study area and interpretations should be based on comparisons between multiple drainage catchments. SL data are commonly presented in map form where the stream midpoints are colored to represent variations in the SL values. In engineering studies, a color ramp can be applied that is associated with a risk rating (low = green, high = red). Interpolated maps can also be used to represent data (e.g. Giaconia et al., 2012); however, interpolation techniques are restricted in accuracy and precision over large geographical study areas (Geach et al., 2014).

3. Study Area: Sorbas Basin

The study corridor is located within the Sorbas Basin of SE Spain (Fig. 2). It is elongated west-east following the basin axis and entering the southern margin of the adjacent Vera Basin terminating at the Mediterranean Sea coast. This arrangement includes the ephemeral trunk river of the east flowing Río Aguas and tributaries sourced from mountains to the north (Sierra de los Filabres and Sierra de Bédar) and south (Sierra Alhamilla and Sierra Cabrera) (Fig. 2).

Geologically, the study area comprises a Palaeozoic- Mesozoic metamorphic basement and a Neogene sedimentary basin infill (Fig. 6) of variable rock strength linked to lithology and structures. The basement geology comprises schist and metacarbonate lithologies (Figs. 7B and C) (IGME 1973a,b; 1975; 1980) that are regionally configured into low amplitude and long wavelength anticlines formed by the ongoing plate collision between Africa and Europe (Weijermars, 1991). The basin fill sequence comprises Miocene-Pliocene limestone, gypsum, sandstone and mudstone and Quaternary conglomerate lithologies (IGME 1973a,b; 1975; 1980). These are folded into a broad synclinal structure with an E-W fold axis in the basin center. The southern basin margin shows a high degree of localized fault and fold-related deformation (e.g. Fig. 7E) along the entire length of the Sierra Alhamilla-Cabrera mountain front (Sanz de Galdeano, 1987). There is also a NE-SW orientated deformation zone, the ‘Infierno-Marchalico Lineament’ that crosses the entire basin to the east of Sorbas town passing up into metamorphic basement of the Sierra de Bédar (Mather and Westhead, 1993). This zone appears to be a long lived structure that has been continuously active since the Miocene (Mather et al., 1991; Mather and Westhead, 1993). It forms part of a series of major strike-slip fault systems that form the central part of the Trans-Alboran Shear Zone (TASZ) that some consider to be the boundary between Africa and Europe (Weijermars, 1988; De Larouziere et al., 1987). Many of the TASZ strike-slip faults generate shallow-intermediate depth earthquakes of Mw 2-4, and rarer >Mw 5 (Martínez Solares and Mezcua, 2002; Martínez-Díaz et al., 2012), some of which trigger landslides (García-Mayordomo et a., 2009).

The geomorphology of the proposed route corridor shows a close relationship to the bedrock geology and structure. The mountain ranges to the north and south and the southern basin margin region (Fig. 7A.) are characterized by the highest relief, reflecting the largest and highest uplift rates (Mather, 1993; Braga et al., 2003). Superimposed onto this tectonically controlled relief is a rock strength control on landscape morphology. The lithologically strong metacarbonate, limestone, gypsum, and well cemented conglomerate units all form wide, box-shaped valley / canyon forms (Fig. 7C and D), contrasting with weaker sandstone and mudstone units that commonly form v-shaped valley and badland terrains (Fig. 7E; Harvey, 1987; Mather et al., 2002). Of morphological note is the gypsum bedrock which forms an extensive low relief plateau region in central-western basin areas (Fig. 7F), an area affected by sub-surface drainage and karst development (Calaforra et al., 2003).

The main processes shaping the landscape are fluvial incision and landsliding driven by interplay of tectonics, climate and rock strength. The effects of global eustatic sea-level change have been minimal in the Sorbas Basin since to Late Pliocene due to its inland location. Fluvial incision post-dates the basin fill sequence and is recorded within a series of inset Quaternary river terrace landforms (Harvey, 1987; 2007). The largest amounts of valley incision coincide with areas of high uplift (e.g. southern basin margin: Fig. 7E) but are also associated with a site of a basin scale river capture that took place between 100-70ka (Late Pleistocene) (Fig. 7F: Harvey and Wells, 1987; Candy et al., 2005). This capture is important for controlling landscape morphology and processes since it represents a significant perturbation to which the landscape is still responding to today (Griffiths and Stokes, 2008). The capture involved two drainage channels 1) a headward eroding Lower Aguas system that drained the southern margin of the Vera Basin eastwards to the coast (Figs. 7F) and, 2) the Aguas-Feos system (Figs. 7D and F) that drained the Sorbas and routed southwards to the coast in the Almería-Carboneras Basin. The headwards erosion of the Lower Aguas is driven by the differential uplift between the Sorbas and Vera Basins and the development of a regional topographic gradient (Stokes, 2008). At the capture site (Fig. 7F), the capturing Lower Aguas was some 90m below the upstream Aguas-Féos system (Harvey and Wells, 1987). Post capture, this 90m base level difference has propagated upstream into the captured system as a wave of fluvial incision and landsliding (Hart, 1999; Hart et al., 2000; Mather et al., 2002; Stokes et al., 2002; Griffiths et al., 2005). The capture-related incision wave, with a progressive reduction in valley incision amount, has transmitted some 20km upstream of the capture site with numerous knick point / zone occurrences reflecting incision adjustments, especially at major lithological boundaries (e.g. Sorbas town region). Beyond the influence of the capture in the western Sorbas Basin region the landscape is flat and relatively un-dissected (Fig. 7A). In contrast to the captured Upper Aguas system, the beheaded southwards flowing Féos has lost its catchment area, resulting in valley abandonment and infilling from hillslope tributary fan sediment inputs and negligible / limited fluvial incision (Fig.7F; Maher et al., 2007). Downstream of the Aguas-Feos capture site, the Río Jauto has also undergone drainage capture (Ilott, 2014; Harvey, 2007) with high incision and river gorge development in metacarbonate basement at its confluence with the Río Aguas (Fig. 7C) and anomalous drainage patterns with spatially variable incision in upstream regions (Fig. 7B).

The contemporary semi-arid setting of the corridor is important for influencing geomorphic changes on valley floors and sides. The climate is characterized by a marked seasonality of long hot summers and short mild winters, with mean annual temperatures of 18 °C and rainfall as low as 170 mm (350 mm average) (Martin-Rosales et al., 2007; Machado et al., 2011). Low frequency–high magnitude precipitation events frequently activate the ephemeral river systems resulting in erosion, deposition and landsliding (Capel-Molina, 1981; Thornes, 1974). An exceptional precipitation event occurred in October 1973 where up to 600 mm of net rainfall was recorded in close proximity to the study area triggering flash flood discharges of ~500 m^3/sec in the Río Aguas at Sorbas (Capel-Molina, 1974; Thornes, 1974, 1976; Mather and Stokes, 2016).

4. Methods: Geomorphic Indices

61 drainage catchments were defined for hypsometric analysis using the publically available Hypsometry toolbox (http://arcscripts.esri.com/). Concave hypsometric curves were termed ‘Stable’, S-shaped curves ‘Complex’ and convex curves ‘Active’. Drainage lines and

catchments were created using the ArcGIS Hydrotools utility (http://resources.arcgis.com/) with stream definition verified against the drainage blue line 1:25,000 topographic map data.

River longitudinal profiles were generated from public sources using 25 m orthocorrected imagery with vertical accuracies of <5 m (Centro Nacional de Información Geográfica, 2013). Profiles were normalized to enable basin scale correlation of drainage channels (Antón et al., 2014). Concave up profiles were termed 'Stable', convex up profiles as 'Active' and profiles with both concave and convex elements as 'Complex'. Although more common on Active and Complex rivers, knickzones can occur on all forms of profile and they are noted spatially on base maps by individual points.

Upon appraisal of numerous spacing distances (e.g. 50m, 100m, 150m), a midpoint spacing of 50m was used in the generation of elevation data for the SL index analysis (i.e. a drainage line was separated in to a point feature based on a 50m spacing). Elevation data were extracted using the 'Extract values to point' tool in the ArcGIS Spatial Analyst toolbox from the 25 m DEM. 3703 data points were exported from the GIS as .txt files for use in analysis, taking less than 2 hours processing time. SL data were generated along the same rivers used for longitudinal profile analysis. Data analysis was conducted in a Microsoft Excel worksheet and then appended to the point features in ArcGIS using a 'joins/relate' function. Data were normalized and represented for point features only and not interpolated into a continuous surface based on the scale of data coverage in this study. Normalized SL values at 1 represent 'Active' landscape conditions, SL values were then grouped at increments of 0.25 towards a 'Stable' landscape condition at 0.

The combined appraisal of all index data was undertaken using a simple overlay map. The scales of analysis for the catchments, rivers and knickpoints were assessed in order to demonstrate interpretations met real world scenarios. For example, drainage lines and catchments were compared with aerial imagery to ensure computed outputs were real.

5. Results and Discussion

To demonstrate the applicability of geomorphic indices in identifying patterns of landscape change attributed to geological and geomorphological processes the results for each index are presented separately for the Sorbas Basin. The combined significance of index data in the identification of geohazards are then presented in relation to engineering constraints.

5.1 Hypsometric Analysis

Hypsometric analysis results are presented in Figure 8. A regional pattern of variable landscape activity is notable across the Sorbas Basin. 'Stable' catchments occur in the east and west of the basin, with 'Active' and 'Complex' catchments dominating the basin centre. Comparison of catchment with geological data (Figure 6) suggests a pattern of Active catchments forming in the central-northern area which occur in faulted metamorphic bedrock. This region lies along the northeastern extent of the Infierno-Marchalico Lineament where tectonic deformation has produced anomalous drainage patterns and spatially variable incision (Harvey, 2007; Ilott, 2014). The 'Active' catchments in the central/western basin occur in proximity to a number of key features including: (i) the SW portion of the Infierno-Marchalico Lineament, (ii) a major lithological boundary with drainage channels crossing from weaker conglomerate to stronger limestone, and (iii) the zone of river-capture related fluvial incision upstream of the river capture point (Fig. 8 dashed box). The hillslopes within the catchments contain multiple erosion features such as rills, gullies and active badlands (Figure 7E).

Catchments in the east of the basin appear to be near equilibrium with current base level (i.e. sea-level) and the catchments in the far west of the basin preserve a relic stage of landscape equilibrium which existed before the Aguas-Feos river capture event (Fig. 7A: Mather et al., 2002; Stokes et al., 2002). Catchments in the basin center are still responding to the river capture, with the effects propagating into the west of the basin as recorded by the change from 'Active', 'Complex' to 'Stable' hypsometric forms. Therefore, the physical conditions recorded in the 'Active' drainage channels should not be taken as stationary with a likely trend of upstream propagation of gully and hillslope instabilities. Typical landscape morphology is subdued with limited incision and stable extensive pediment surfaces (Figures 7A and 7B).

5.2 River longitudinal profiles

River longitudinal profile analysis results are presented in Figures 9 and 10. All basin drainage channels (Figure 9) are visually comparable to the hypsometric analysis, with a dominance of 'Active' drainage lines in the central and north eastern regions of the basin and stable conditions recorded in the west of the basin. This would suggest that the catchments are well coupled with their drainage lines and misfit conditions do not exist whereby the active channel is incising in a relatively stable catchment (Howard, 1967).

Detailed analysis of 10 of the longest drainage lines is presented in Figure 10. Profiles show a variable response across the basin. With focus on the axial fluvial system (Río Aguas, Fig 10B), the drainage shows a 'Complex' profile with variations in channel gradient in the upstream (-0.09) and downstream (-0.07) system reaches. Two notable knickzones are also identified by the dashed boxes on Figure 10B. Knickzone 1 relates to lithological changes where the axial channel passes from relatively strong conglomerates and limestone into relatively weak mudstone that dominates the basin center (Figure 6). The knickzone is further enhanced by relative increases in discharge at the confluence with the Rambla Marques (located on the catchment map). Knickzone 2 does not form on any major lithological boundaries yet it is found within the Infierno-Marchalico Lineament deformation zone. Knickzone 2 also relates well to the location of the river capture event (star on Fig. 10). The knickzone suggests that the effects of the capture-related ~90m base-level lowering are still being transmitted throughout the current fluvial system (Stokes et al., 2002).

In the east of the basin, the river longitudinal profiles are characterized by multiple knickzones, with variations in channel gradients and channel configurations far from equilibrium. Most notable are gradient changes in the Rambla Rocio (Fig. 10C) (-0.22 upstream vs. - 0.01 downstream) where the downstream system appears to be near equilibrium and the upstream system appears over steepened. These gradient variations relate to a combination of uplift and rock strength. The axial drainage parallels the basin margin fault zone where relative uplift has occurred (Braga et al., 2003). The fault zone also has marked variations in rock strength, especially where tributaries pass from metamorphic basement onto sedimentary basin infill (Figure 11). The effects of active faulting is also recorded in the Rambla Azagador which crosses a region of lithological heterogeneity (knickzone 3, Fig. 10C).

In the west of the basin, most of the drainage lines (Ramblas Marques, Góchar, Mora and Mójonera) are near equilibrium with smooth concave morphologies throughout. The maturity of upstream catchments compared to their downstream counterparts (i.e. west of basin vs east of basin) probably supports a major decoupling of the Sorbas Basin, as shown in hypsometric analysis, whereby the effects of the Aguas-Feos river capture event are yet to be evidenced in the far west of the basin. Notable knickzones are highlighted in the Ramblas Góchar and Peral (Fig. 10A), which relate to either: (i) the propagation of base-level change from the capture point, or (ii) deformation along the Infierno-Marchalico Lineament as there is little change in lithology across the catchment. The Rambla Peral profile is highly variable and is characterized by numerous knickzones which extend over distances of 400m. The variation here is related to the close proximity of the capture site.

The river longitudinal profiles show that drainage channels in the center of the basin are over steepened and will likely be subject to higher rates of hillslope incision, badland formation and further landslide activity. Knickzones and major changes in gradient are identified in the central and eastern basin areas in association with (i) changes in rock strength, such as the transition from relatively strong indurated Góchar conglomerates into the weaker marls, (ii) deformation along the Infierno-Marchalico Lineament and (iii) differences in base levels as related to the capture event in the basin center (Figure 12). Knickzones pose a challenge to any engineering study as the position and rates of headward retreat, and therefore the level of risk they pose, are hard to assess. Knickzones with variable gradients are also often the focus of enhanced river incision during flow events and resultant hillslope instabilities.

The effects of tectonic deformation are noted along the Infierno-Marchalico Lineament and the Sierra Cabrera mountain front. Without field evidence or supporting data, the relative activity or rates of deformation in these areas are hard to define. However, the focus of perturbation in both the catchment analysis and longitudinal profile data suggests that active or recent tectonic activity is of importance in the central and southern flank of the basin.

5.3 Stream length gradient index

The results from SL index analysis are presented in Figure 13. At a basin scale, with all drainage values normalized, two significant perturbation zones are noted. They occur along the Río Aguas axial drainage (Figure 13A) and are illustrated by high frequency changes in SL value when presented as raw data (Fig. 13B). Zone 1 occurs in proximity to the Infierno-Marchalico Lineament, major lithological boundaries and includes capture-related incision (also highlighted in the profile data). Zone 2 occurs at the river capture site itself. Analysis of the raw data (Fig. 13B) highlights that upstream of Zone 1 the perturbation is of greater magnitude than downstream of its Zone 2 counterpart; however, the downstream perturbation is apparent over a longer channel reach (5.0 km upstream vs. 6.3 km downstream). This suggests that the current drainage system is still responding to the capture-related base-level changes.

In addition to the major perturbations in the axial fluvial system, variations in channel gradient are also noted in the headwaters of the Rambla Marques and Río Jauto. These likely represent lithological changes, passing from metamorphic basement of the bounding Sierras into weaker basin sediments. However, active faulting could be a factor in the Río Jauto with deformation along the Infierno-Marchalico Lineament.

The SL analysis results provide a more detailed appraisal of local changes in stream gradient than offered from river longitudinal profiles. At a basin scale it is possible to identify regions where the relative change is greatest. As shown here, the position of the knickzones identified between the methods are the same (Figure 12), however, changes along the main axial drainage are greater than those in the basin tributaries. Therefore, the two knickzones identified on the axial channel would likely pose the most notable engineering risk in terms of indicating areas of hillslope instability. This information becomes very important when targeting field investigations.

5.4 Assessment of Geomorphic Indices and relation to Engineering Constraints

A combination of all index values applied in this study is presented with an overlay of areas of landscape instability (badlands and actively eroding gullies) mapped from API by Hart (2004) (Figure 14). This study has not undertaken additional API. 'Active' catchments and drainage lines in the central and northern basin occur in close proximity to (relatively) small and moderate sized landslides (estimated volume ~< 250,000 m^3) and badlands which identifies important coupling between these major hillslope geohazards.

A limited number of the largest landslides occur in 'Stable' catchments with 'Complex' or 'Stable' drainage lines. In these settings, the landslides are relic features which relate to the geological and topographic configuration of the basin. The large landslides have formed in Miocene limestone (Figure 11) that dips steeply into the basin center. This indicates that the current drainage system is not recording the effects of strong lithological control on landslide formation in this location. These very large landslides likely occurred before the development of the current drainage configuration. This indicates the importance of a coupled investigation with the use of both API and field investigations.

Adopting the approach of Shilston et al., (2005), the index values can be spatially integrated with further methods of desk based assessment in constraints maps in order to better understand the geological and geomorphological setting of a region. The relative significance of constraints identified from the index approach can be assigned a weighted multiplier when compared with hazards identified from other means of qualitative investigation such as API (see Shilston et al., 2005 for comprehensive discussion). This approach helps target subsequent fieldwork in order to further refine the engineering terrain evaluation. Detailed statistical or nearest neighbor analysis can also be undertaken when producing constraints maps, however this is beyond the focus of this study.

A constraints map which combines geological, geomorphological and geomorphic index data for the proposed study corridor is presented in Figure 15. The broad zones shown range from Minor, Moderate to Difficult, to Very Difficult geohazard constraints (terminology from Shilston, et al., 2005) as qualitatively described in Table 3. Landslides are identified as individual features which would require specific focus in further study.

Zones of geohazard constraints can be related to construction considerations which would include, as example:

- Detailed alignment control in areas of focused incision and landsliding. Measures should be taken to avoid knick points and ongoing badland formation.
- Careful earthwork, design, spoil handling measures and reinstatement in zones of notable landsliding.
- Detailed design of pipe bridges or maintain sufficient depth of burial in 'Active' drainage channels.
- River control, although potentially avoidable by routing through 'Stable' reaches of drainage lines.
- Careful design of earthworks, cross drainage and erosion protection measures in 'Active' and 'Complex' catchments where focused incision is noted.
- Detailed route planning to avoid the disturbance of active, relict or areas of potential landslide formation.

6. Conclusion

This paper has demonstrated the use of geomorphic indices in terrain analysis studies for application in the desk study phase of investigations. An outline of how the different geomorphic indices work in the identification of landscape processes has been presented for a hypothetical study corridor using a scaled approach from catchment to reach. The case study presented shows how the use of index values combined with techniques of API offer valuable contemporary landscape data for use in the identification of areas of landscape perturbation and potential geohazards. The relative correlation of geohazards has allowed for the spatial zoning into a constraints map which forms a potential basis for ongoing construction considerations.

From the outset of this study, it is noted that accuracy of geomorphic index data is based on: (i) an appreciation of the scale of the study area and (ii) an understanding of the complexity of the geological and geomorphic environment which is often defined by the combined knowledge of the Geoteam. It is also stated that the use of indices in terrain evaluations should supplement, and not replace, standard techniques of API, remote sensing, field mapping/investigation and monitoring.

Key conclusions are:

- Geomorphic index values can be applied in tectonically active regions to develop a qualitative and quantitative (relative to study area) understanding of how the hillslope and river systems respond to the effects of tectonics, climatic and bedrock geology. This adds value and context to the other desk study sources of information frequently used for regional assessments of potential geological and geomorphological ground conditions for large infrastructure projects.
- With focus on the Sorbas Basin, this study shows that index values can be used to identify zones of geomorphic perturbation as driven by the effects of tectonic deformation, variations in rock strength and important internal landscape events such as river captures.

- A variable response of landscape processes is shown in the catchments and drainage channels of the Sorbas Basin. ‘Active’ conditions are focused in the central and northern limits of the basin and relate well to deformation along the Infierno-Marchalico Lineament and the effects of a tectonically driven capture event. ‘Active’ conditions are typically linked to an increased occurrence of landslides and badland formation. ‘Stable’ conditions are more common in the west and east of the basin where drainage channels are well coupled with base level.
- The combined analysis of geomorphic indices and other desk based studies such as API has allowed for the identification of engineering constraints and geohazards as related to gully and badland formation and the formation of landslides. A simple geohazard constraints map is provided (Fig. 15) which aims to demonstrate ground related risk to the wider project team, such as the Client or their design engineers.
- The index values applied were based on freely available DEM data and the analysis was undertaken using GIS freeware. Methods of data interpretation were relatively straight forward and easily reported as both qualitative and semi- quantitative data for the Sorbas Basin (e.g. SL values).

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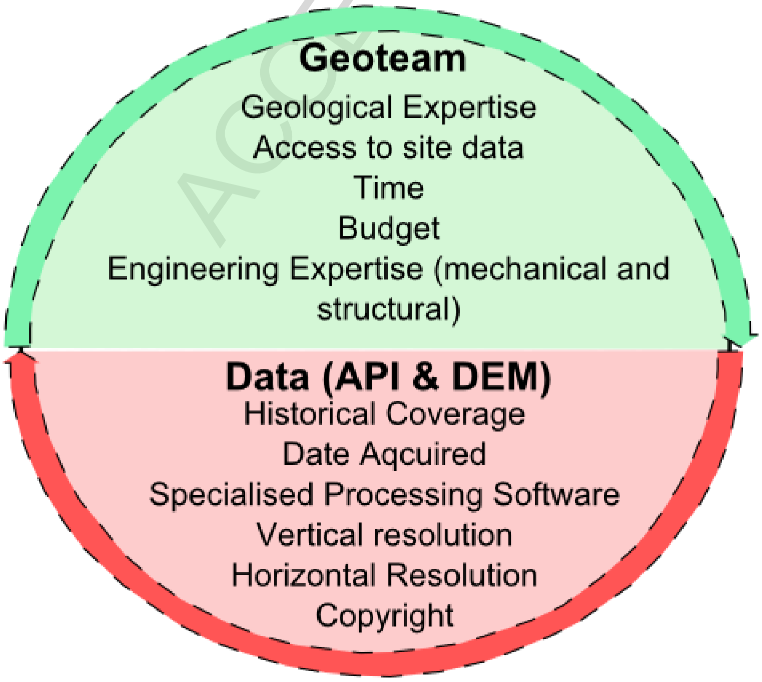

Geoteam
Geological Expertise
Access to site data
Time
Budget
Engineering Expertise (mechanical and structural)
Data (API & DEM)
Historical Coverage
Date Aqcuired
Specialised Processing Software
Vertical resolution
Horizontal Resolution
Copyright

Fig. 1

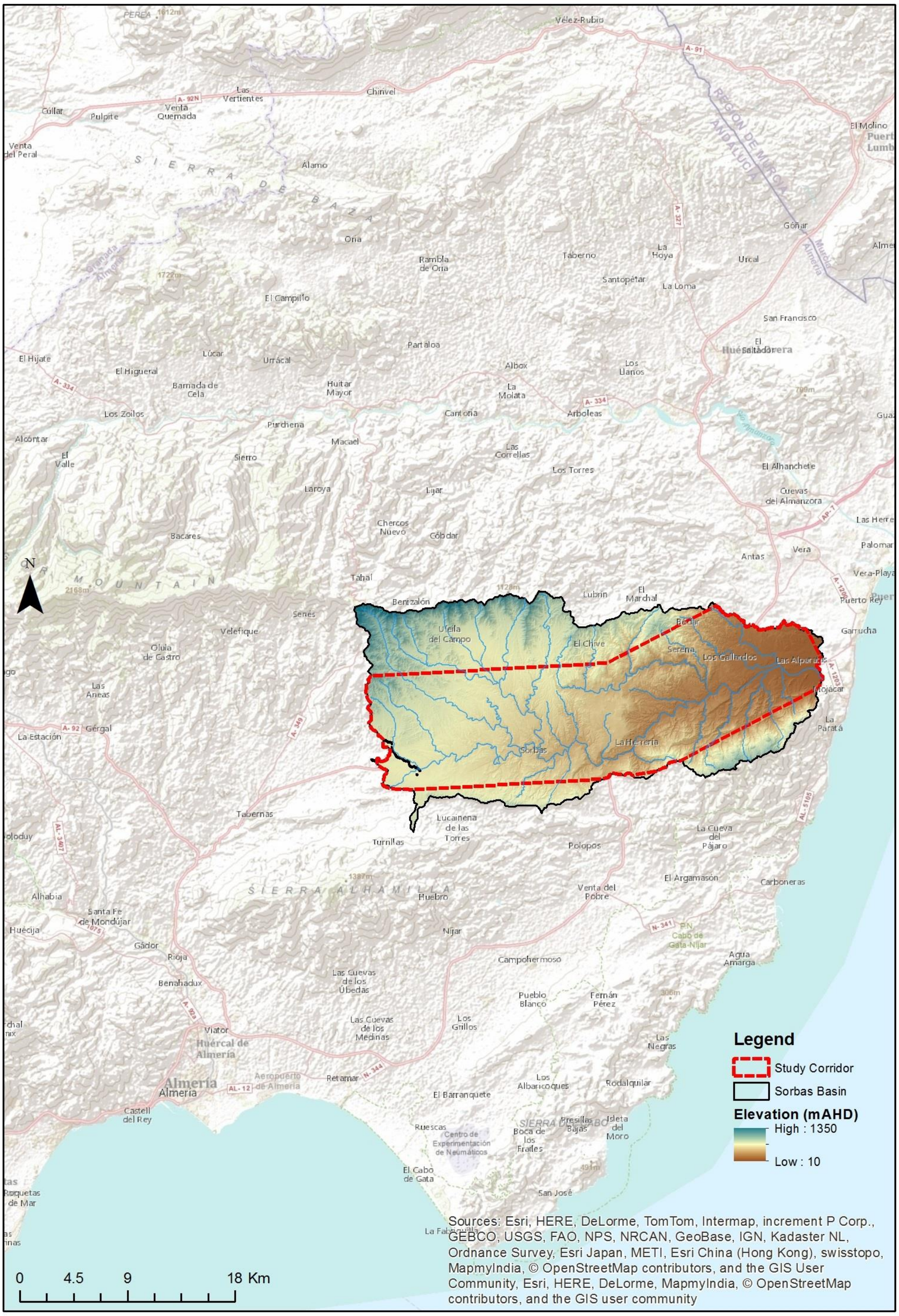

Legend
Study Corridor
Sorbas Basin
Elevation (mAHD)
High : 1350
Low : 10
0 4.5 9 18 Km
Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Fig. 2

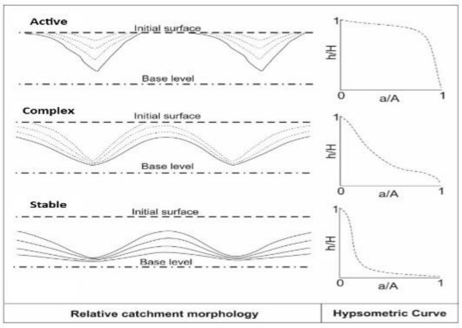
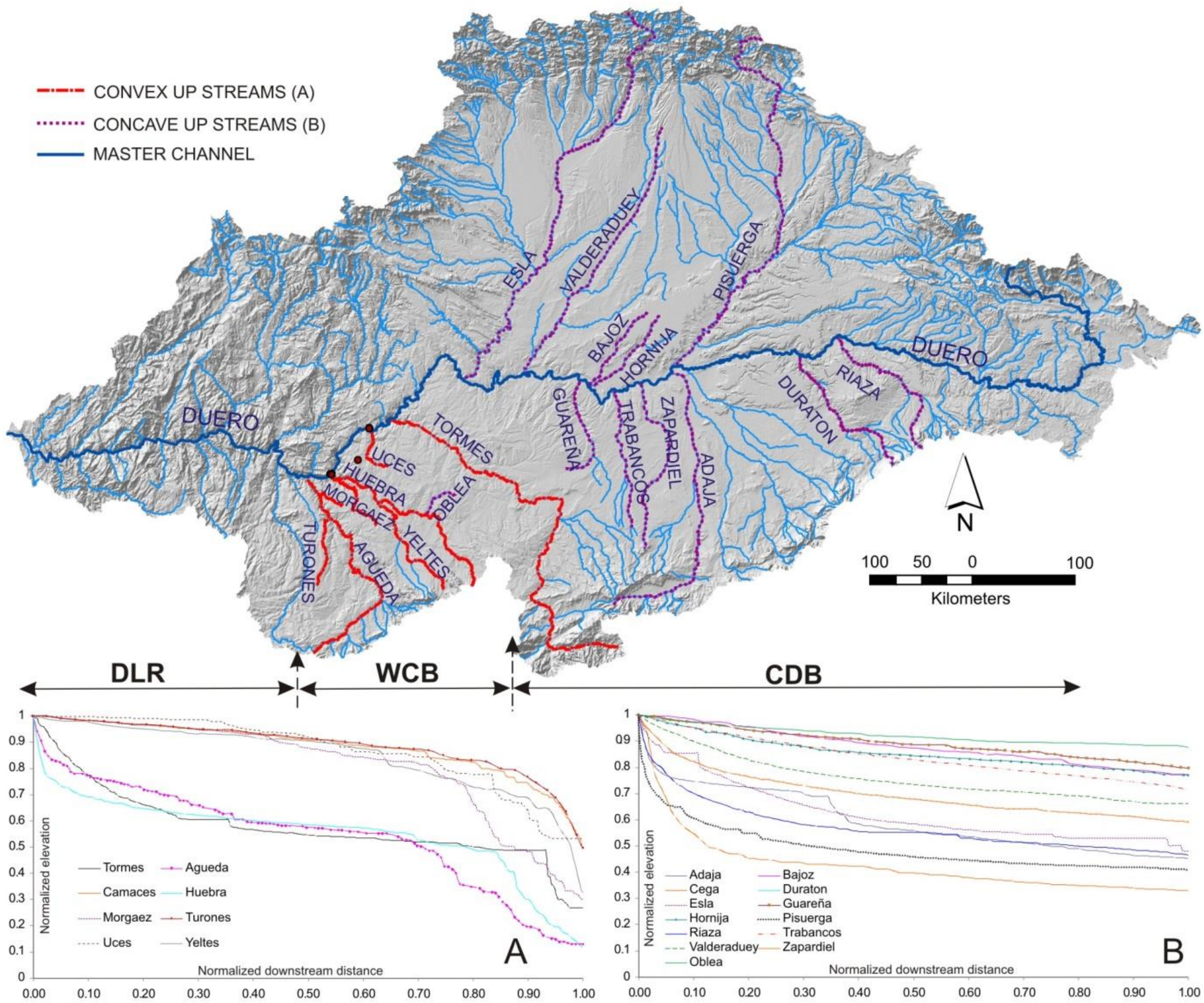

Active
Initial surface
Base level
Complex
Initial surface
Base level
Stable
Initial surface
Base level
h/H
a/A
0
1
1
Relative catchment morphology
Hypsometric Curve

Fig. 3



CONVEX UP STREAMS (A)
CONCAVE UP STREAMS (B)
MASTER CHANNEL
DUERO
ESLA
VALDERADUEY
PISUERGA
BAJOZ
HORNIJA
GUAREÑA
TRABANCOS
ZAPARDIEL
ADAJA
DURATON
RIAZA
TORMES
UCES
HUEBRA
MORGAEZ
YELTES
OBLEA
TURONES
AGUEDA
N
100 50 0 100
Kilometers
DLR
WCB
CDB
Normalized elevation
Normalized downstream distance
Tormes
Camaces
Morgaez
Uces
Agueda
Huebra
Turones
Yeltes
A
Adaja
Cega
Esla
Hornija
Riaza
Valderaduey
Oblea
Bajoz
Duraton
Guareña
Pisuerga
Trabancos
Zapardiel
B

Fig. 4

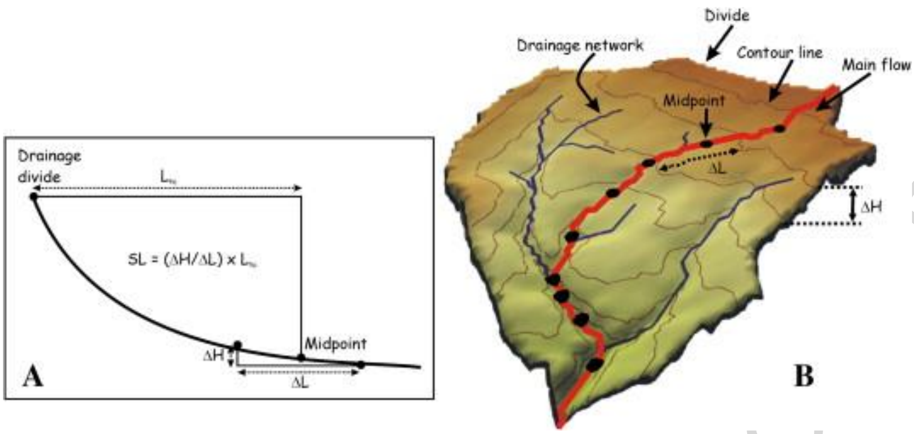

Drainage divide
SL = (ΔH/ΔL) × L
ΔH
Midpoint
ΔL
A
Divide
Drainage network
Contour line
Main flow
Midpoint
ΔL
ΔH
B

Fig. 5

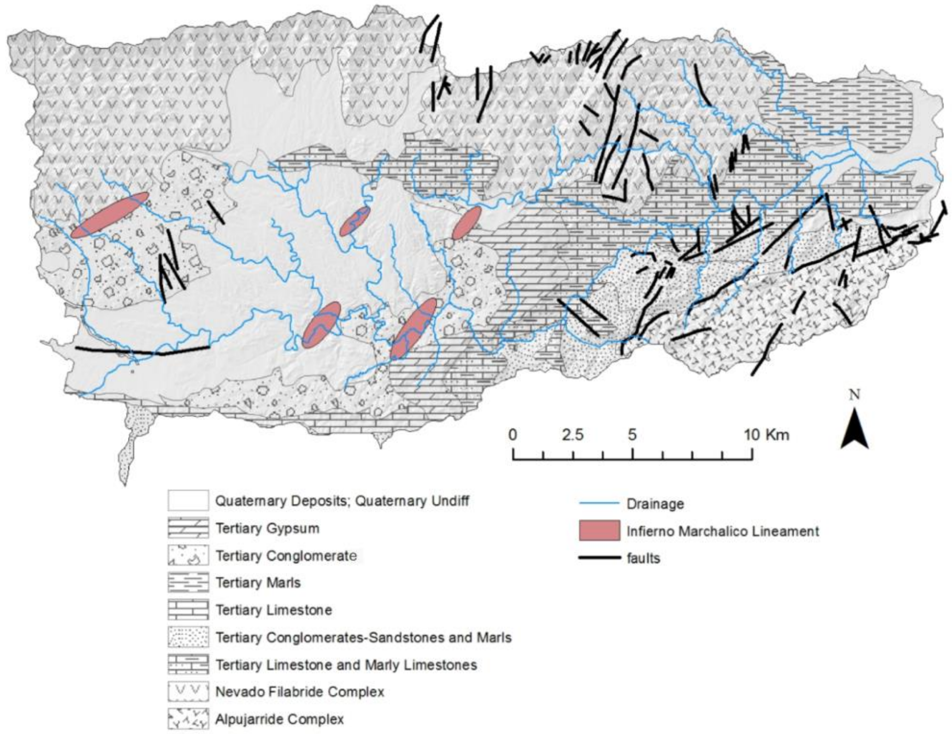

0
2.5
5
10 Km
N
Quaternary Deposits; Quaternary Undiff
Tertiary Gypsum
Tertiary Conglomerate
Tertiary Marls
Tertiary Limestone
Tertiary Conglomerates-Sandstones and Marls
Tertiary Limestone and Marly Limestones
Nevado Filabride Complex
Alpujarride Complex
Drainage
Infierno Marchalico Lineament
faults

Fig. 6

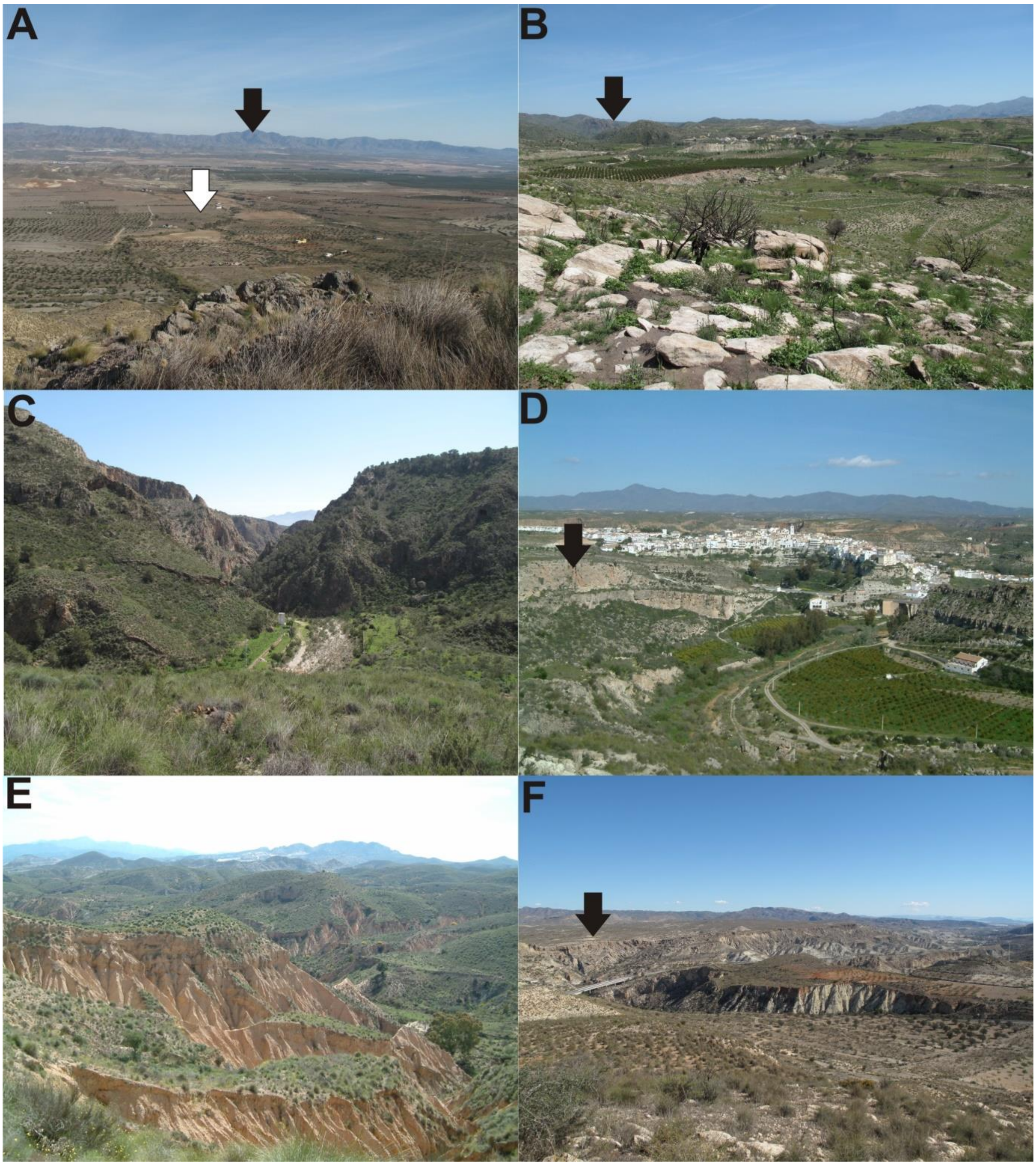
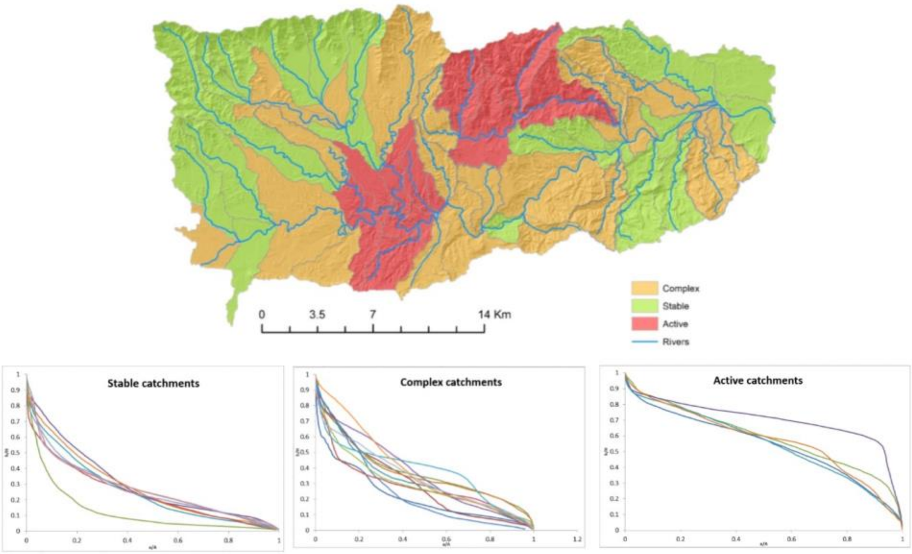


Fig. 7



0
3.5
7
14 Km
Complex
Stable
Active
Rivers
Stable catchments
Complex catchments
Active catchments

Fig. 8

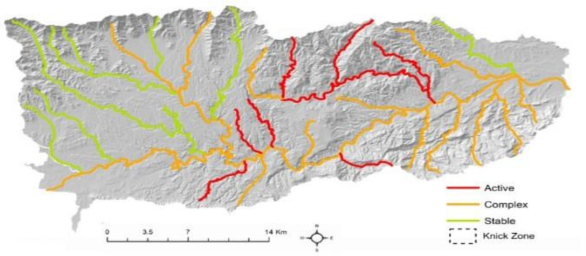
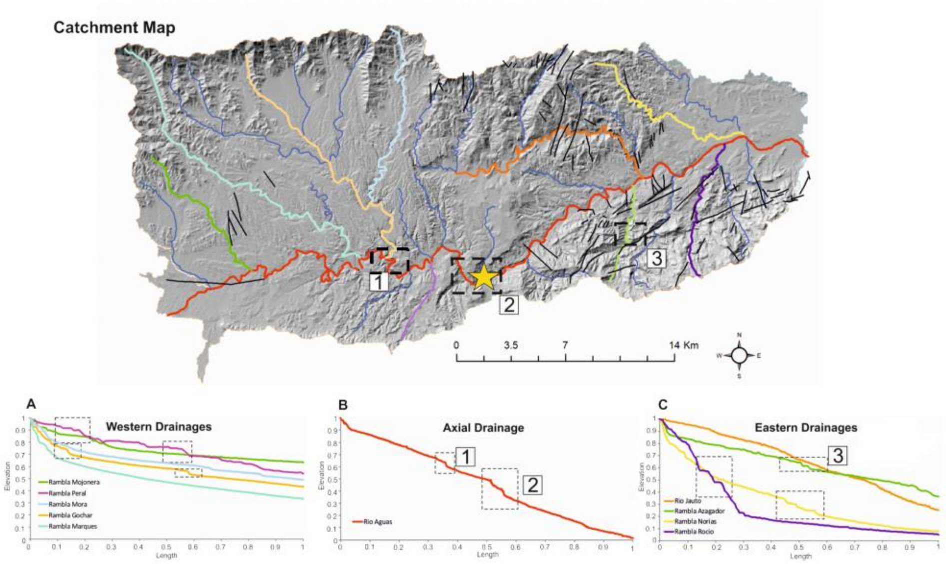


Fig. 9



Catchment Map
1
2
3
0
3.5
7
14 Km
A
Western Drainages
Rambla Mojonera
Rambla Peral
Rambla Mora
Rambla Gochar
Rambla Marques
Elevation
Length
B
Axial Drainage
Rio Aguas
C
Eastern Drainages
Rio Jauto
Rambla Azagador
Rambla Norias
Rambla Rocio

Fig. 10

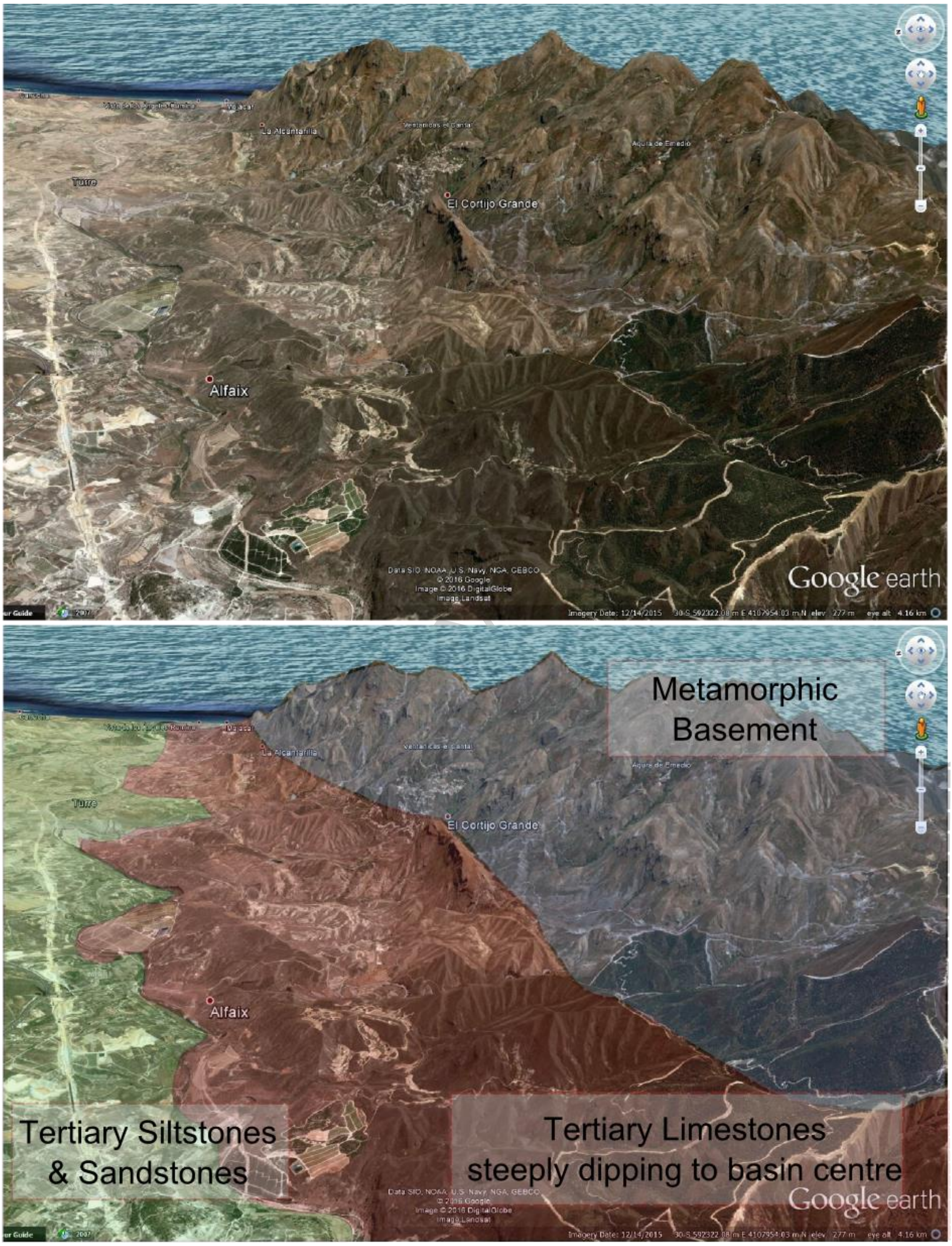

El Cortijo Grande
Alfaix
Metamorphic Basement
Tertiary Siltstones & Sandstones
Tertiary Limestones steeply dipping to basin centre
Google earth

Fig. 11

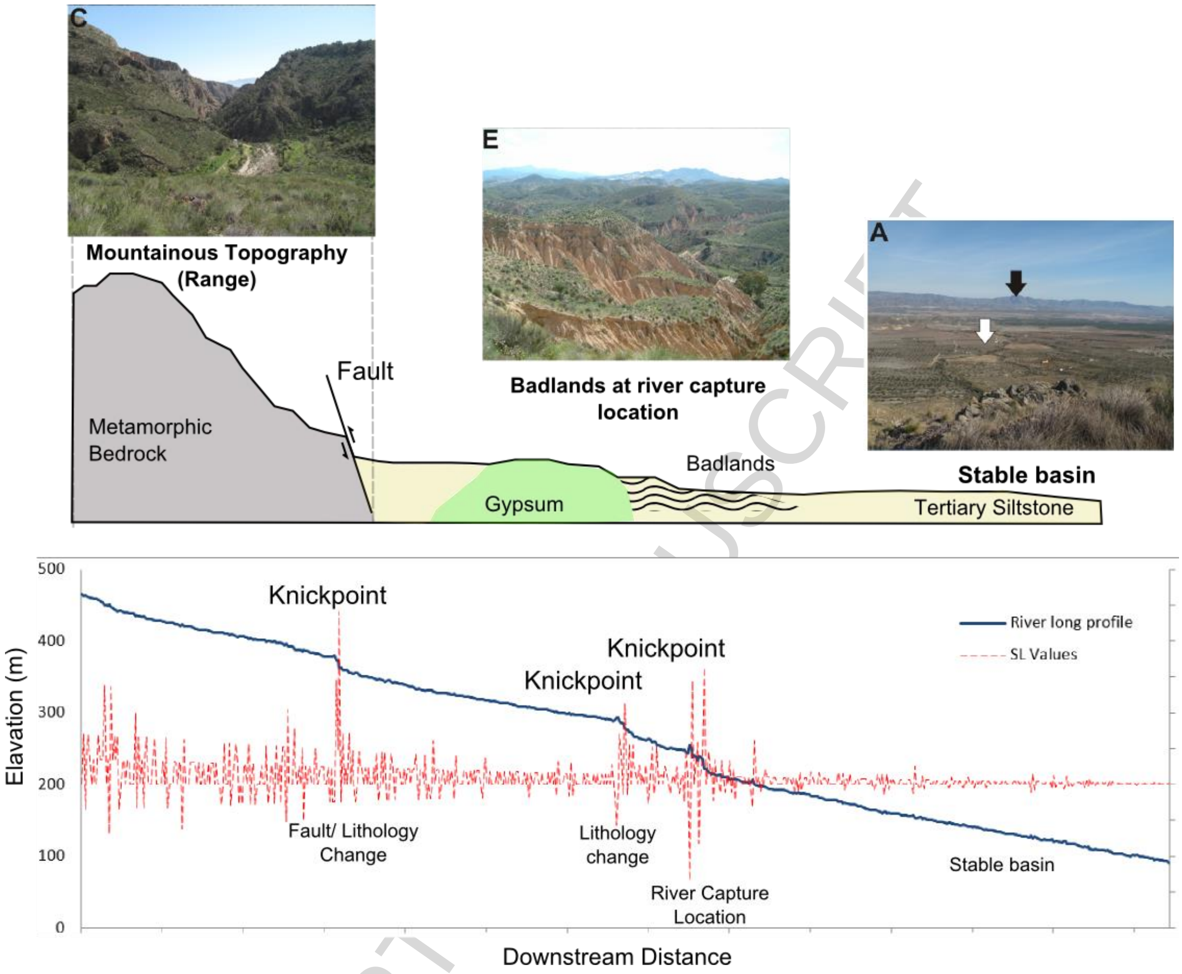

C
Mountainous Topography (Range)
E
Badlands at river capture location
A
Stable basin
Fault
Metamorphic Bedrock
Gypsum
Badlands
Tertiary Siltstone
Knickpoint
Knickpoint
Knickpoint
River long profile
SL Values
Elavation (m)
500
400
300
200
100
0
Fault/ Lithology Change
Lithology change
River Capture Location
Stable basin
Downstream Distance

Fig. 12

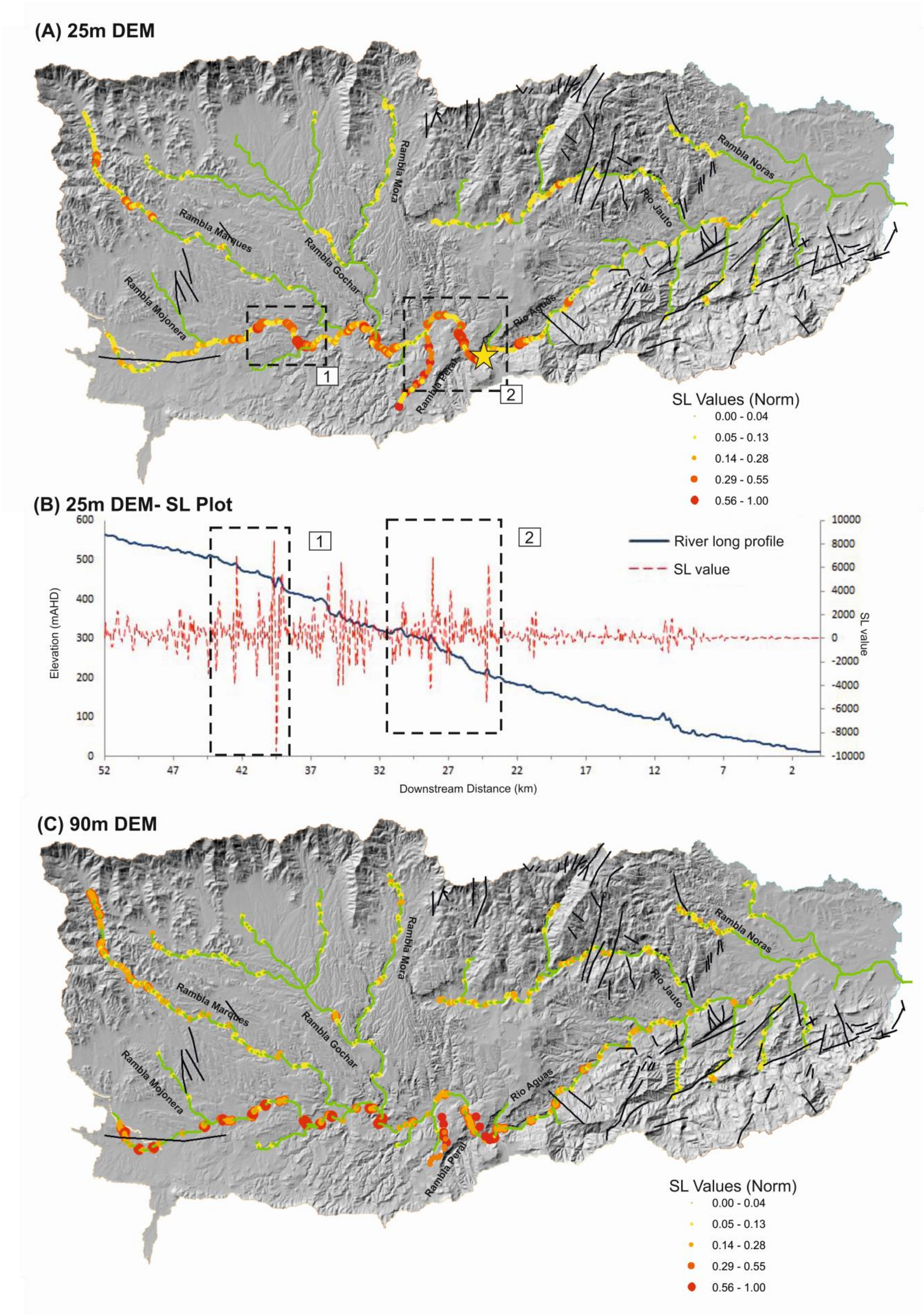
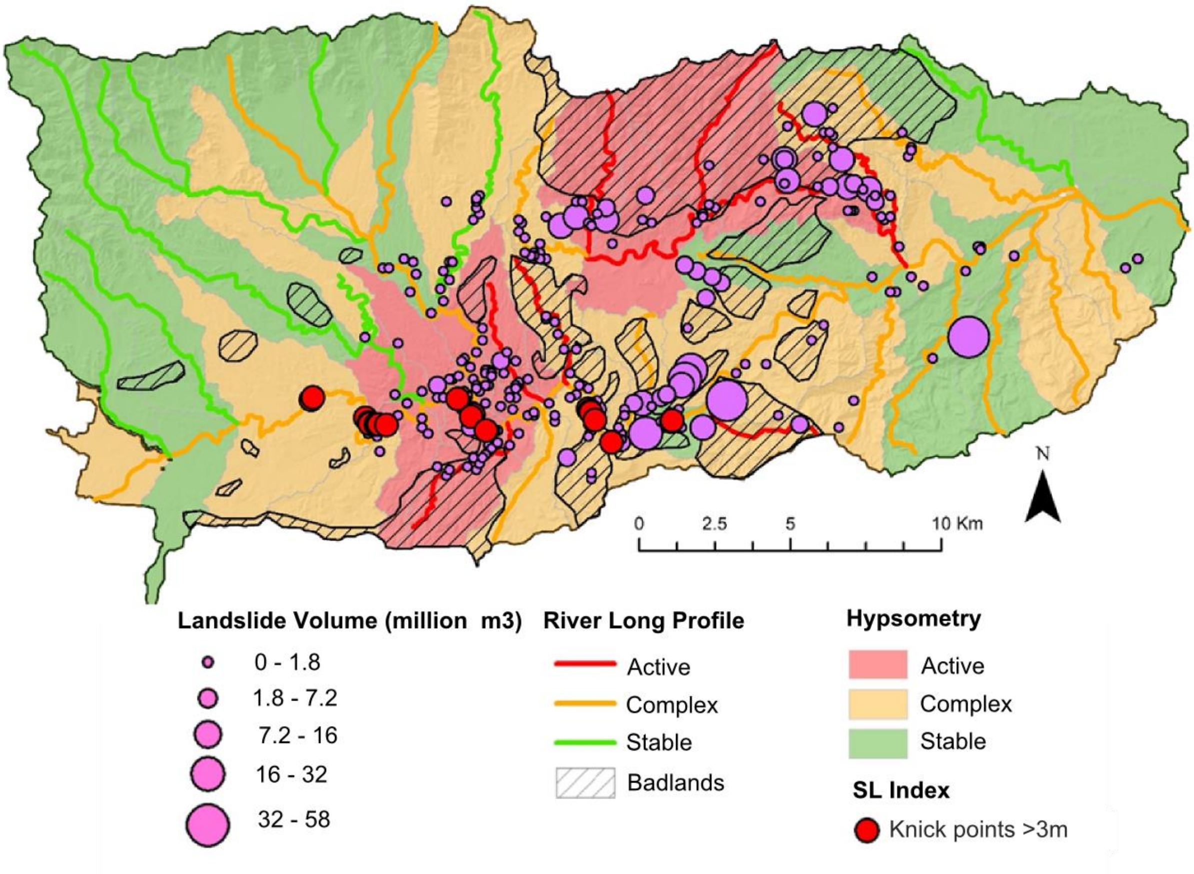

(A) 25m DEM
Rambla Mora
Rambla Noras
Rio Jauto
Rambla Marques
Rambla Gochar
Rambla Mojonera
Rio Aguas
Rambla Peral
1
2
SL Values (Norm)
0.00 - 0.04
0.05 - 0.13
0.14 - 0.28
0.29 - 0.55
0.56 - 1.00
(B) 25m DEM- SL Plot
River long profile
SL value
Elevation (mAHD)
SL value
Downstream Distance (km)
(C) 90m DEM

Fig. 13



N
0
2.5
5
10 Km
Landslide Volume (million m3)
0 - 1.8
1.8 - 7.2
7.2 - 16
16 - 32
32 - 58
River Long Profile
Active
Complex
Stable
Badlands
Hypsometry
Active
Complex
Stable
SL Index
Knick points >3m

Fig. 14

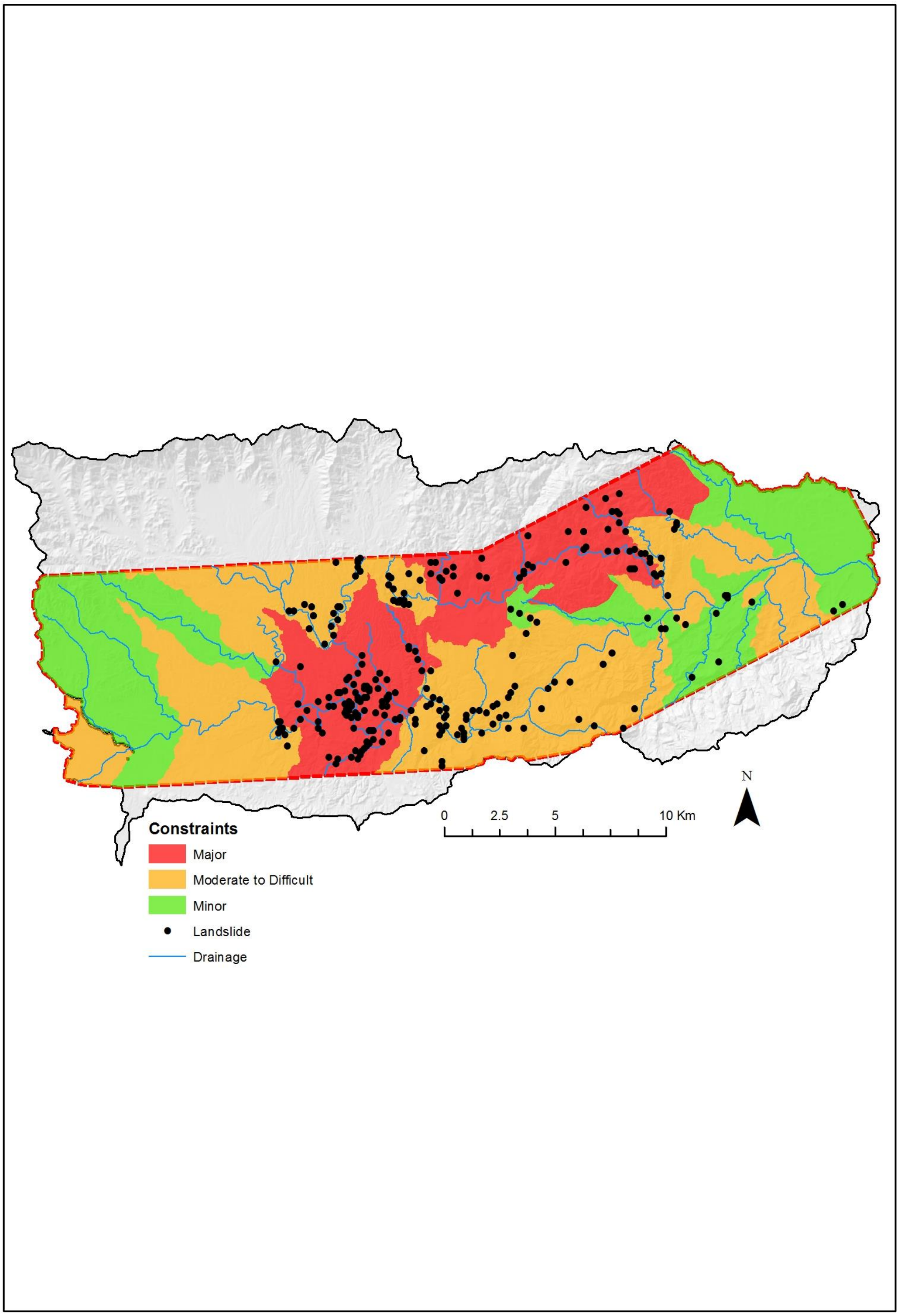

Constraints
Major
Moderate to Difficult
Minor
Landslide
Drainage
0
2.5
5
10 Km
N

Fig. 15

Figure 1. Controlling factors in engineering studies for long linear infrastructure.

Figure 2. DEM for the Sorbas Basin overlain over regional topography. Location of hypothetical routing corridor is marked by red polygon.

Figure. 3 Conceptual development of drainage basins demonstrating the evolution of catchments from young to mature stages and their representative hypsometric curves, developed from Willgoose & Hancock, (1998). In a young catchment the area of degraded materials relative to the initial surface is low forming steeply incising channels. As the catchment matures the total area of degraded materials increases relative to the initial surface and the morphology of catchments becomes more open.

Figure 4. Example application of river long profiles from the Duero Basin, Iberia applied in the identification of variable landscape response to forcing mechanisms, from Antón et al., (2014). The Use of long river profiles identifies multiple 'relic' stages of fluvial development, evidenced by benches in longitudinal profiles which relate to the opening of the Cenozoic inland basin as a result of major river piracy. These relic profiles are used to quantify variations in incision rates across the basin. The drainages given can be grouped into low risk and high risk regions based on profile shapes. Convex up streams represent active systems and concave up represent stable systems.

Figure 5 (A) Stream length gradient measurements after Hack, 1973. (B) Watersheds objects needed for *SL* processing, from Font et al., (2010), note how midpoints for measurements (ΔL) are set at near equal distances. Changes in altitude (ΔH) can be taken from the DEM or from mapped contours.

Figure 6 Geology map for the Sorbas Map based on 1:50,000 sourced from http://info.igme.es/. Digital data sourced from: Centro Nacional de Información Geográfica (CNIG, 2013).

Figure 7. Field imagery of the proposed corridor route. A: View NE across western margin of the Sorbas Basin depicting the undissected basin fill surface (white arrow) and metamorphic basement basin margin mountains of the Sierra de los Filabres (black arrow). B: NE Sorbas Basin margin mountain front (black arrow: Río Jauto); C: Río Jauto gorge cut into metacarbonate basement. D: Sorbas town region, central basin setting showing canyon valley morphology and capture-related valley side landsliding (black arrow). E: Southern basin margin zone of highest uplift showing deformed basin fill sediments, deeply dissected v-shaped valley forms and badland development. F: River capture site (mid ground), showing the capturing Lower Aguas system (background) and beheaded undissected Feos system to the mid-right (south). Note gypsum plateau (black arrow).

Figure 8. Results of Hypsometric Analysis for the Sorbas Basin. The range of hypsometric curves is shown graphically. Digital data sourced from: Centro Nacional de Información Geográfica (CNIG, 2013).

Figure 9. River long profiles calculated from 25m DEM for all of the basin drainages. Digital data sourced from: Centro Nacional de Información Geográfica (CNIG, 2013).

Figure. 10 River long profiles calculated from 25m DEM for 10 major drainages in the Sorbas Basin as separated into geographical regions. Note all drainages are normalized to allow for representation at a basin scale. Colors relate to drainages on the mapped DEM. Dashed boxes indicate knickpoints or knickzones, with representative numbering shown on the catchment map. Blue lines indicate minor drainages. Black lines indicate faults as taken from 1:50 000 base maps. Digital data sourced from: Centro Nacional de Información Geográfica (CNIG, 2013).

Figure 11. Google earth extract showing the variable geological terrains which form the catchment of the Rambla Rocio. The geological structure controls rates of river incision with very steep drainage gradients recorded in basement and steeply dipping Limestone bedrock. Imagery: Google Earth.

Figure 12 Conceptual model relating the results of River Longitudinal Profile and SL Analysis across the Sorbas Basin. Drivers of knickpoint formation are shown as a result of structural (faults), lithological changes (Gypsum to Tertiary Siltstones) and base-level change (river capture). The photographs reproduced from Figure 7 demonstrate typical landform in these locations.

Figure 13. (A) Normalized stream length (SL) gradient index data for the Sorbas Basin. (B) Demonstrates the perturbations in raw SL data as sourced for the axial drainage system. Black lines depict known faults. Star depicts capture point. Digital data sourced from: Centro Nacional de Información Geográfica (CNIG, 2013).

Figure 14 Combined GIS output overlaying the results of geomorphic indices over landslide data and areas of badland formation interpreted from aerial imagery. The index values correlate well with a combined frequency of landslides <250,000m^2 and zones of badland formation. The isolated very large landslides in the east of the basin relate to configuration of very steeply dipping geology in the Sierra Cabrera shown in Figure 10.

Figure 15. Constraints map for the proposed study corridor which combines results from geomorphic indices with areas of badland formation. Landslides are shown as local features which require investigation in the field. Badlands and geological controls are adopted in the analysis along with the results of geomorphic indices. The approach used here is qualitative however statistical or weighted overlay analysis could also be used.

Geohazard	Description	Operation & Maintenance Risks	Geotechnical Mitigation Options		
			Investigation	Routing	Design & Construction
Earthquakes – fault ruptures	Movement likely along pre-existing fault lines during earthquake activity.	Displacement, deformation, rupture, uncontrolled spillage. Can be trigger for landslides and ground collapse.	Locate fault zones. Assess earthquake history.	Detailed alignment control in fault zones.	Special trench design.
Earthquakes - liquefaction	Ground shaking causes liquefaction or loose fine, granular and metastable soils.	Loss of support, displacement, Deformation, rupture, uncontrolled spillage.	Locate and classify material types and soil structure.	Avoid susceptible soils by lateral realignment or deepening.	Soil Improvement.
Volcanos	Dome eruption, lava flows, ejected material, lahars	Displacement, deformation, rupture, loading, uncontrolled spillage	Locate existing domes and flow channels	Avoid and local alignment control to negotiate existing flow channel	
Landslides	Slow or rapid ground displacement caused by change in geometry, ground water level or Seismicity, includes rock fall, shallow soil slides, deep rotational slides, debris and mud flows to significant distance from source.	Loss of support, displacement, deformation, rupture, loading, uncontrolled spillage	Locate existing landslide- landslide prone terrain and extent of sidelong ground	Detailed alignment control to avoid existing landsides. Minimize potential unstable sideling ground	Careful earthwork, design, spoil handling measures and reinstatement.
Karst-Limestone	Limestone that has been or continues to dissolve in groundwater resulting in a network of sinkholes, caves, etc. Prone to sudden collapse.	Loss of support, displacement, deformation, rupture, uncontrolled spillage into groundwater system.	Assess and classify extent of karstification.	Avoid, minimize, detailed alignment control	Ground improvement measures
Karst-Gypsum	Gypsum or other sulphate enriched soils and rocks that have been or continue to dissolve in groundwater resulting in a network of sink holes. Caves, etc. Prone to sudden collapse.	Loss of support, displacement, deformation, rupture, uncontrolled spillage into groundwater system.	Assess and classify extent of karstification	Avoid, minimize, detailed alignment control	Ground improvement measures
River Channel Migration	River channels migrate across wide valley floors and sudden changes in location can occur under flood conditions	Loss of support, displacement, deformation, rupture, uncontrolled spillage into river system.	Map valley floor Assess catchment and hydrological history.	Minimize crossing length.	Pipe bridges or maintain sufficient depth of burial, river control.
Gullying and Soil Erosion	Removal of soil by water action across and adjacent to the pipeline. Existing gullies prone to enlargement by erosion and scour of banks and headwall	Loss of support, displacement, deformation, rupture, loading, uncontrolled spillage	Assess extent of sidelong ground, locate gullies and assess catchment	Minimize sidelong ground and avoid areas of active erosion.	Careful design of earthworks, cross drainage and erosion protection measures.

Table 1. Terrain constraints and geohazards affecting pipeline routings from Charman et al. (2005). Hazards highlighted in bold are investigated herein by means of Geomorphic Indices.

Geomorphic Index	Approach	Limitations	Literature
Hypsometric analysis	Qualitative assessment of relative catchment maturity based on the distribution of topography against drainage area. The shape of a hypsometric plot is related to maturity with convex forms being youthful and concave forms mature. Coupled with the hypsometric integral the techniques can be used to perform a high level analysis of regional catchments. Hypsometric analysis is often performed as a first step appraisal of relative landscape activity.	• Only one value is taken as representative of a catchment; however, focused analysis can be defined for regions of interest. • Study areas need to be defined accurately based on project focus. • Can be time consuming if not conducted in a capable GIS software (e.g. ArcGIS, GRASS, MatLAB).	• Pike and Wilson, (1971); • Willgoose & Hancock, (1998); • Pérez-Peña et al., 2009 • Cheng et al., 2012
River long profile	Plot of channel elevation over channel distance from the drainage divide to the river mouth. Data generated from DEM at fixed intervals as based on study scale. The channel shape relates to relative activity of channel in relation to external forcing mechanisms (tectonic uplift) or internal landscape characteristics (lithology or base-level changes). Approach is of use in the identification of major knick points or knick zones or differences in channel gradients across a study area.	• Qualitative data only • Study areas need to be defined accurately based on project focus. If too coarse a scale is defined then important landscape data will be missed. • DEM accuracy	• Hack, (1973); • Angelier and Chen, (2002); • Antón et al.,(2012; 2013); • Korup, (2006)
Stream length gradient (SL) index	Index value which quantifies the elevation change along a channel for use in identifying areas of enhanced incision within channels. Perturbations in the channel gradient are forced by lithological changes, tectonic deformation, faulting or base-level change. The SL index is a quantitative measure that can be assessed at a range of scales.	• Stream definition needs to be undertaken accurately in order to identify perturbations. • Study areas need to be defined accurately based on project focus. • Only gives an assessment of surface displacement and regional tectonic trends cannot be defined from this index alone.	• Hack, (1973) • Keller and Pinter (1999;2002) • Giaconia et al., (2012)

Table 2. Summary of geomorphic indices with a description of the approach used, limitations of methods and suitable literature.

Constraint	Spatial Occurrence	Geohazards and landscape features
Very Difficult	Centre and northern flank of the basin. Active' catchments and 'Active' drainage lines are well coupled. Indices demonstrate the effects of ongoing tectonic deformation along the Infierno-Marchalico Lineament, and base-level change as a result of river capture event.	Hillslopes are highly incised with typical formation of badland slopes in the catchments. Ongoing development of badland gully formation linked to mechanisms of landsliding posing a notable threat to engineering structures. Landslide occurrence is likely ongoing within weak mudstone lithologies which are located in the basin centre. Multiple Knickzones in drainages which relate to the ongoing effects of base-level change and are not stationary in their current position. Knickzones can also be indicators of major lithological changes. The location of Knickzones should not be taken to be stable along the drainages upstream of the river capture point.
Moderate to Difficult	Bounds zones of Very Difficult Constraints across the basin. Catchments and drainage lines show a complex response to ongoing tectonic deformation and base-level change.	Gully formation is isolated to headward migrating reaches of 'Active' drainage lines associated with 'Active' catchments. Landslide occurrence is less frequent and focused along 'Active' drainage lines or in weak Mudstone lithology. Many Knickzones are recorded in drainages which relate to the ongoing effects of base-level change and are not stationary in their current position. In many instances the Knickzones are located on transition to Active drainages and Very Difficult Constraints.
Minor	Limited to catchments and drainages in the west and far east of the basin.	Stable hillslope conditions with limited number of Knickzones. Drainage lines are responding to a relic base-level much higher than that of the basin centre in the west, and are well coupled with sea-level in the east. Low rates of hillslope degradation related to rill and gully formation. Overall incision in the drainages limited by the relatively high base level. Limited relic landsliding in catchments formed as a result of geological configuration, additional investigation would be suggested. Ongoing tectonic deformation is limited.

Table 3 Summary of engineering geological constraints groupings

Highlights

- Geomorphic indices are applied to freely available DEM data
- Develops understanding of hillslope and rivers response to tectonics, climatic and land use change
- Identify engineering constraints/geohazards related to gully, badland formation and landsliding