INVESTIGATION OF THE RELATIVE SENSITIVITY OF DRAINAGE BASINS TO CLIMATE CHANGE IN SEMI-ARID AND HUMID-TEMPERATE ENVIRONMENTS

INTRODUCTION

Large magnitude climate change has been observed in geomorphic and stratigraphic records for many years, and there is now much concern about future climate change of various magnitudes (IPCC, 2007). As drainage basins are the fundamental unit of landscapes (Chorley, 1971), understanding their response to perturbations such as climate change is vital to understand past and present changes in landscapes. Drainage basins vary in sensitivity to these perturbations, and this sensitivity depends on the prevailing climate. This project will investigate this further.

BACKGROUND

SENSITIVITY

Usher (2001) provides the following formula for a 'sensitivity index', which also functions as a definition of sensitivity:

$$Sensitivity = \frac{\Delta(Change\ in\ system)}{\Delta\ (Change\ in\ landscape\ descriptor)}$$

Werritty and Leys (2001) suggest two types of landforms: 'robust' or 'responsive', with 'robust' landforms reacting to change very modestly, crossing only intrinsic thresholds (Schumm, 1979) whereas 'responsive' landforms react violently to change crossing extrinsic thresholds and resulting in a new assemblage of fundamentally different landforms. Of course, all landscapes consist of a mixture of 'robust' and 'responsive' landforms, but the overall behaviour of a landscape tends to be either 'robust' or 'responsive'.

When analysing the sensitivity of drainage basins it is important to remember that landscape sensitivity and response is very complex (Brunsden & Thornes, 1979) and varies over time and space (Thomas, 2001).

Climatically-induced Changes

Huntington (1914) suggested that increased aridity would lead to a loss of vegetation cover, resulting in increased sediment flux and the aggradation of channels. This is backed up by Zhu et al. (2008).

Coulthard et al. (2000) found that both climate and vegetation cover significantly influence drainage basin sediment yield, but that climate has the larger effect. However, when climate and vegetation cover change at the same time, the impact is multiplied.

Tucker & Slingerland (1997) also suggest that vegetation cover is one of the most significant controls on catchment development. They notice that drainage basins generally have a high sensitivity to changes in the erosion threshold value, and find that there is a delicate balance between flow-driven erosion and diffusive transport. They suggest that altering the climate can push the whole catchment below the erosion threshold. As well as affecting channel incision, increases in vegetation cover can also affect lateral channel migration, causing changes in channel pattern (Murray & Paola, 2003). Collins et al. (2004) suggest that the most important effect of plants is to reduce erosion, and vegetated basins tend to have a steeper topography and a lower drainage density.

All of the above studies used humid-temperate environments, but no literature was found on the sensitivity of semi-arid environments[1]. Similarly, no literature was found on the sensitivity analysis of models with no vegetation-climate coupling.

Metrics

"The drainage density is the heart of the balance between climate, geomorphology and hydrology" (Moglen et al., 1998, p855). According to them the effect that climate change has on drainage density depends on the climatic regime: this should become apparent in the results of this study. In semi-desert conditions the drainage density was found to increase with precipitation because erosivity dominates, and increases with precipitation, but in humid conditions the drainage density was found to decrease with precipitation because erodibility dominates and decreases with precipitation. This reliance on the prevailing climatic regime is

[1] Searches performed using Google Scholar, Scirus and ISI Web of Knowledge using the keywords *semi-arid*, *sensitivity*, *climate change* and *drainage basin* in various combinations.

due to the coupling between climate and vegetation, showing the importance of running coupled models.

Another of Moglen et al.'s (1998) observations is that drainage density is more sensitive to change in arid areas than in humid areas. This provides a sound basis for examining the sensitivity exhibited in the results of this study.

An observation from Madduma Bandara (1974) is that for low precipitation values there is a negative relationship between effective precipitation and drainage density, but a positive relationship for higher precipitation values. This is because at high effective precipitation values erodibility reaches a plateau where the vegetation cover cannot be increased by further increases of precipitation.

The hypsometric curve and integral (Strahler, 1952) is another important metric. It has been used to infer the stage of drainage basin development, and has relationships with runoff and erosional process (Huang & Niemann, 2008; Willgoose & Hancock, 1998). It can be used as a measure of the amount of erosion a catchment has experienced, meaning an increase in precipitation is likely to reduce the hypsometric integral. Care should be taken as it is not independent of basin area (this is thought to represent the varying importance of fluvial and hillslope processes with basin area: see Hurtrez et al., 1999; Walcott & Summerfield, 2008).

Aims and Objectives

Based on the background discussed above, gaps in the literature have been found:

- There have been no quantitative comparisons of the sensitivity of drainage basins in very different climatic regimes.
- There have been no comparisons of sensitivities obtained with both coupled and uncoupled models.

This study aims to address this literature gap with the following hypotheses (shown in Table 1).

Number	Hypothesis	Rationale
1	Semi-arid drainage basins are significantly more sensitive to climate change than humid-temperate basins.	Moglen et al. (1998) have shown that drainage densities are more sensitive to climatic perturbations in semi-arid climates compared to humid-temperate climates. Semi-arid climates tend to have higher drainage densities. This increases the coupling between the hillslopes and the fluvial system, thus allowing the response to climatic change to be transmitted easily throughout the basin, and to be magnified by the channel network.
2	The coupled model will produce more 'realistic' outputs than the uncoupled model.	In the real world there is coupling between vegetation and climate, which affects the erodibility of the landscape. A model which takes this into account is providing a more accurate representation of the real world, and is therefore likely to produce more realistic results.
3	The sensitivity to climate perturbations will be greater in the uncoupled model than in the coupled model.	In the coupled model, each change in precipitation will be accompanied by a change in erodibility. This is likely to mitigate the precipitation changes, reducing the sensitivity of the coupled model.
4	An increase in precipitation will cause an increase in drainage density in semi-arid environments, but a decrease in humid-temperate environments	This was found by Moglen et al. (1998) in their study, but the coupling in this model may not be complex enough to replicate this result.

Table 1 - Hypotheses, and the rationale behind them

METHOD

CHOICE OF DRAINAGE BASINS

The Walnut Gulch Experimental Watershed, Arizona (WG) was chosen as the semi-arid watershed for this study. This drainage basin is used for experiments by the US Department of Agriculture, therefore much data is available (see Southwest Watershed Research Centre, 2009).

The River Tyne, UK, (RT)was chosen as the humid-temperate drainage basin. The climate classifications were obtained from Milne (2005) and Peel et al. (2007), see Figure 1.

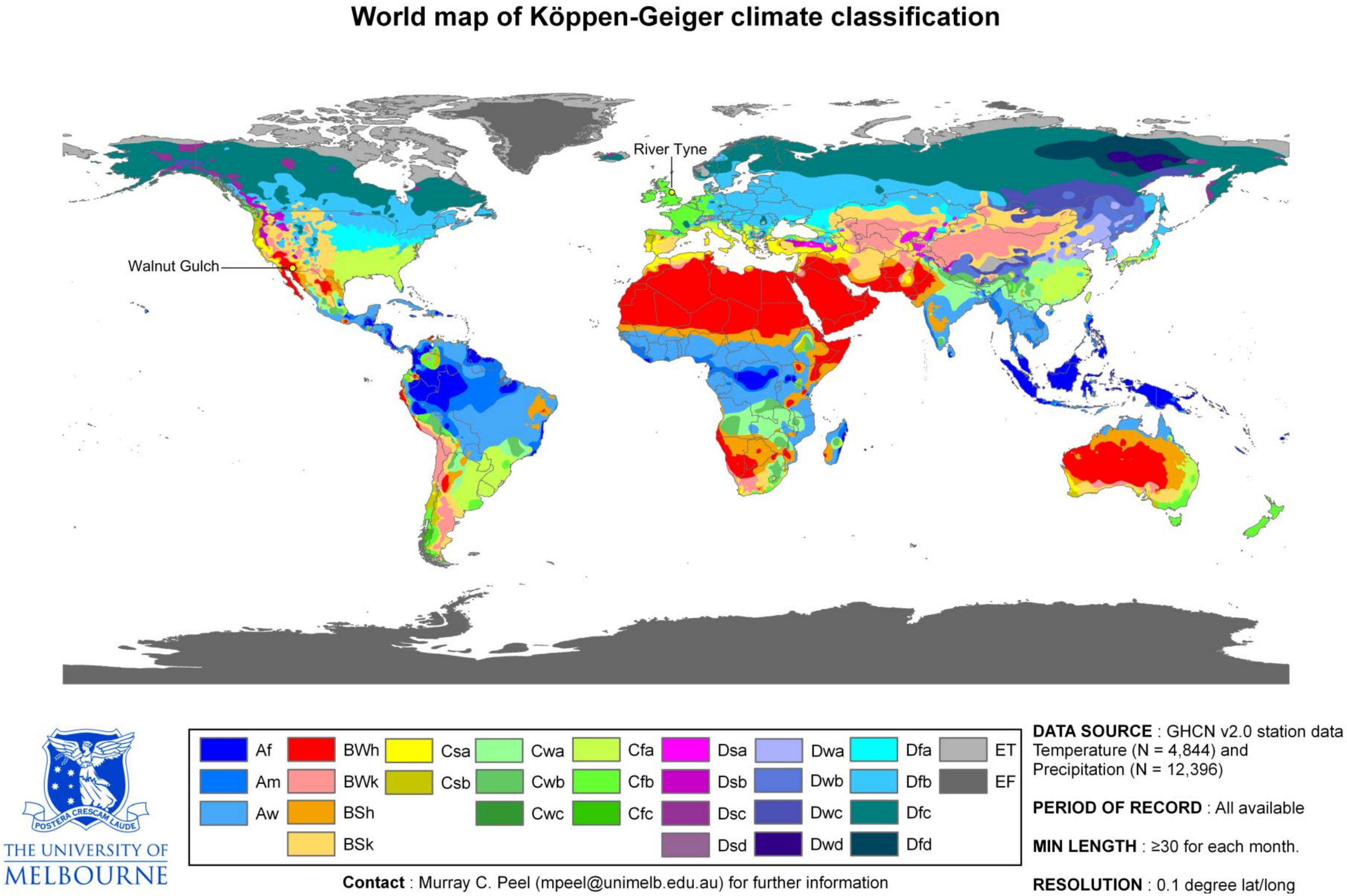


Figure 1 - Location of Walnut Gulch and River Tyne shown on a climatic classification map (source: Peel et al., 2007)

CHOICE OF MODEL

There is a wide range of Landscape Evolution Models available today (Coulthard, 2001). This project will use the Web-based Interactive Landform Simulator (WILSIM), which is a rule-based cellular automata landscape evolution model. The implementation is based on Chase (1992) and, although it uses "very simple approximations intended to capture the synoptic effects of fluvial processes", it has the ability to "provide insight into how climatic and tectonic variables affect the evolution of landscapes" (Chase, 1992, p55). This follows the *Apparent Realism* approach of Dietrich et al. (2003). Details of the implementation are provided in Luo et al. (2004). The 'Advanced User' version of WILSIM (Luo, 2008; Luo et al., 2006) will be used for this research as it has improvements over the standard version: it uses nonlinear rules to simulate sediment erosion, transport and deposition, the simulated precipitation events are interdependent and it provides fractal dimension values as output.

It is important to note that all models are simplifications of reality, and that a fundamental assumption underlying all geomorphological modelling work is that these models can accurately represent reality. WILSIM will be critically examined in Table 2.

Discretisation	WILSIM uses a regular square grid with a maximum size of 200 by 100 cells. There is no parameter specifying cell size: this is left entirely to the user to apply when looking at WILSIM's outputs. This suits this project as two drainage basins of different sizes will be modelled.
Process representation	WILSIM does not represent threshold gravity-mediated processes such as landsliding and debris flows. This would make WILSIM unsuitable for modelling areas with steep slopes and high relief, or in humid areas. However, the chosen study areas do not have any of these characteristics. Vegetation and climate are not coupled in the standard WILSIM model, but manual adjustments of erodibility have allowed simple coupled modelling to be carried out. The limitations of this simple approach to coupling will be analysed later.

Parameterisation	WILSIM variables (consisting of uplift, erodibility and precipitation) are specified in non-dimensional form, with discrete values at 0.01 intervals from 0.01 to 0.05. This means that time series of parameters are not required, simplifying the parameterisation process. Of course this simplification comes at a price, as it is only possible to control these parameters quite coarsely. However, Chase (1992) showed that even simple parameterisation can lead to meaningful results.

Table 2 - Critical analysis of WILSIM

PARAMETERISATION

Parameterisation was carried out for four groups of scenarios: uncoupled and coupled models of Walnut Gulch and River Tyne, through a range of climatic conditions including present and last glacial conditions.

All model scenarios were set to run for 100,000 iterations, each iteration representing one year.

INITIAL CONDITIONS

The initial conditions for the drainage basins were set using data from Milne (2005). In both cases one of the parameters was set to the maximum WILSIM allows, and the other scaled to keep the aspect ratio correct. This is important as the shape of the drainage basin will influence its behaviour (Boyce & Clark, 1964; McArthur & Ehrlich, 1977). The slope was calculated using the relief data, and adjusted to the closest value WILSIM allows. In both cases, the modelled relief is within 10% of the actual relief.

	WG Real	**WG Modelled**	**RT Real**	**RT Modelled**
Length	26.4km	200 cells	70.8km	150 cells
Width	10.1km	75 cells	47.2km	100 cells
Slope	0.0126	0.01	0.009	0.01
Relief	335m	317m	644m	706m
Cell size	N/A	100m x 100m	N/A	220m x 220m

Table 3 - Initial conditions for Walnut Gulch and River Tyne, showing differences between the actual drainage basins and their modelled equivalents

BOUNDARY CONDITIONS

The boundary conditions in WILSIM are listed in Table 4.

Location	Condition
Top	Zero sediment flux
Sides	Periodic (flows leaving one side of the grid enter on the other)
Bottom	Forced equilibrium (efflux from lower boundary equal to influx from upslope cell

Table 4 - Boundary conditions in WILSIM

PARAMETERS

The *m* and *n* exponents used in the shear-stress power law have a large influence on the modelling process and are related to the erosion process, hydraulic geometry and basin hydrology (Whipple & Tucker, 1999). Stock and Dietrich (2003) provide an table of *m/n* values for a large number of drainage basins. Two drainage basins have been selected with a similar climate and geology to the study basins (*Tulahuencito, Chile* for Walnut Gulch; *Toplodolska, Serbia* for River Tyne) to provide *m/n* values for the study basins.

Whipple et al. (2000) found that values of *n* varied according to the dominant erosion process: plucking, abrasion or cavitation. *n* = 1 was chosen for both Walnut Gulch and River Tyne as this was consistent with plucking being the dominant process due to the extensive sub-metre jointing in the geology of both basins. From the *m/n* value and the *n* value, the value of *m* could be calculated, shown in Table 5[2]

	m/n	n	WILSIM m	WILSIM n
Walnut Gulch	0.41	1	1	1.40
River Tyne	0.72	1	1	1.70

Table 5 - m and n values for Walnut Gulch and River Tyne from the literature, and the final WILSIM values

VARIABLES

Erodibility

The coupled model parameterisation changed erodibility as climate changed, to take into account the fact that as precipitation varies, vegetation also varies considerably (Foley et al., 1998; Levis et al., 1999) and this affects drainage basin processes (Tucker & Bras, 1999).

The calculation of erodibility values for the coupled model was performed using two of the Revised Universal Soil Loss Equation (Insititute of Water Research, 2002) co-efficients: the soil

[2] NB: WILSIM uses *m* and *n* the opposite way round to the rest of the literature (see equation 1 in Luo et al., 2006). Also, WILSIM's version of the power law uses a contributing area exponent of *n-1* rather than the standard *n*, requiring 1 to be added to values of *n* in the literature before use.

erodibility co-efficient (K) and the cover-management factor (C). The K value for Walnut Gulch was obtained from soil erodibility records kept in the USA (Natural Resources Conservation Service, 2009) and for River Tyne it was obtained from European Soil Bureau maps (Knijff et al., 2000).

The C values were obtained by using generalised C values for non-agricultural regions designed for use by the US Army (Purdue Research Foundation, 2004) along with vegetation maps and aerial photography (Google, 2009; Skirvin et al., 2008). Qualitative vegetation descriptions for the last glacial period were obtained from Pécsi et al. (1992), and these were then converted to C values as above. Values for other scenarios were chosen in accordance with the corresponding precipitation values.

For calculating the erodibility for the uncoupled model, intermediate values of the cover-management factor were used. The values for both models were then scaled to the WILSIM erodibility co-efficient range.

Uplift

Uplift values were obtained from GPS time series (NASA JPL, 2009). The closest measurement stations to the two drainage basins were used, and were then scaled to the WILSIM uplift co-efficient range. The uplift for both basins was found to be the same, and it has been suggested that in these circumstances it would be acceptable to set the uplift to zero (Darby, Personal Communication, 2009). An advantage of this is that channels in the modelled landscape stand out better when there is no uplift (due to the colours WILSIM uses to display the modelled landscape).

Precipitation

The WILSIM precipitation co-efficient represents precipitation intensity, but, as the time-step used in WILSIM is assumed to represent one year, annual precipitation values can be used for parameterisation. Precipitation values for the present were obtained from a global terrestrial water balance model (Arnell, 2003) parameterised with a global climatology at a 0.5 by 0.5 degree resolution (New et al., 1999). Past precipitation values for around 18-14ka BP were obtained from Pécsi et al. (1992). These were then scaled to WILSIM precipitation co-efficient values using a maximum precipitation range of 2400mm/yr obtained from Arnell (2003). The actual precipitation range is around 2700mm/yr but this was adjusted to 2400mm/yr to ensure that different scenarios received different WILSIM values. Scenarios were then created with precipitation values ± 0.02 from the present value.

Simple Model – Walnut Gulch					
	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
		14ka BP	Present		
Erodibility	0.03	0.03	0.03	0.03	0.03
Precipitation	0.05	0.06	0.07	0.08	0.09
Uplift	0	0	0	0	0

Simple Model – River Tyne					
	Scenario 6	**Scenario 7**	**Scenario 8**	**Scenario 9**	**Scenario 10**
	14ka BP		Present		
Erodibility	0.04	0.04	0.04	0.04	0.04
Precipitation	0.06	0.07	0.08	0.09	0.10
Uplift	0	0	0	0	0

Coupled Climate-Vegetation Model – Walnut Gulch					
	Scenario 11	**Scenario 12**	**Scenario 13**	**Scenario 14**	**Scenario 15**
		14ka BP	Present		
Erodibility	0.01	0.02	0.03	0.05	0.05
Precipitation	0.05	0.06	0.07	0.08	0.09
Uplift	0	0	0	0	0

Coupled Climate-Vegetation Model – River Tyne					
	Scenario 16	**Scenario 17**	**Scenario 18**	**Scenario 19**	**Scenario 20**
	14ka BP		Present		
Erodibility	0.03	0.03	0.05	0.05	0.05
Precipitation	0.06	0.07	0.08	0.09	0.10
Uplift	0	0	0	0	0

Table 6 – List of scenarios and parameters for the uncoupled and coupled models.

OUTPUT

The outputs used in this study are listed in Table 7.

Output	Source
Final landscape (3D view)	Direct output from model
Final landscape (plan view)	Direct output from model
Landscape at 25% of total iterations	Direct output from model
Landscape at 50% of total iterations	Direct output from model
Landscape at 75% of total iterations	Direct output from model
Hypsometric curve	Direct output from model
Hypsometric integral	Calculated from hypsometric curve
Fractal Dimension	Direct output from model
Drainage density	Calculated from plan view image
Local relief	Measured from row profile graph (at the 25th percentile row)
Basin relief	Measured from column profile graph (at the 50th percentile column)

Table 7 - Outputs from WILSIM, and how they are obtained

Drainage density is an important landscape morphometric, but WILSIM does not provide a drainage density output. A relatively crude method was used which involves tracing the channels seen in the final plan view image into black lines on a new image. The black pixels in this image are then counted using a Python program (see Appendix A), multiplied by the cell size to get the channel length, and used to calculate drainage density. Hypsometric integrals were calculated similarly by filling the area under the hypsometric curve and counting the pixels.

RESULTS

Uncoupled Model – Walnut Gulch					
	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
		14ka BP	Present		
Precipitation (WILSIM units)	0.05	0.06	0.07	0.08	0.09
Drainage Density (km^{-1})	0.69	1.73	1.87	2.05	2.20
Hypsometric Integral (%)	87.91	84.34	83.77	83.80	84.34
Basin Relief (WILSIM height units)	2.1	1.4	1.3	1.7	1.8
Local Relief (WILSIM height units)	0.9	1	1.2	1.2	1.2
Fractal Dimension	2.044	2.044	2.044	2.044	2.044

Table 8 - Results for the uncoupled model of Walnut Gulch

Uncoupled Model – River Tyne					
	Scenario 6	**Scenario 7**	**Scenario 8**	**Scenario 9**	**Scenario 10**
	14ka BP		Present		
Precipitation (WILSIM units)	0.06	0.07	0.08	0.09	0.10
Drainage Density (km^{-1})	0.34	0.38	0.50	0.61	0.68
Hypsometric Integral (%)	84.81	85.14	81.26	80.93	79.96
Basin Relief (WILSIM height units)	1.1	1.8	1.4	2.2	1.4
Local Relief (WILSIM height units)	0.8	0.9	1	1.1	1.1
Fractal Dimension	2.036	2.036	2.036	2.036	2.036

Table 9 - Results for the uncoupled model of River Tyne

Coupled Climate-Vegetation Model – Walnut Gulch					
	Scenario 11	**Scenario 12**	**Scenario 13**	**Scenario 14**	**Scenario 15**
		14ka BP	Present		
Precipitation (WILSIM units)	0.05	0.06	0.07	0.08	0.09
Drainage Density (km^{-1})	1.66	1.67	1.75	0.51	0.61
Hypsometric Integral (%)	85.28	83.77	84.00	87.31	87.24
Basin Relief (WILSIM height units)	1.2	1.9	2.1	1.8	1.8
Local Relief (WILSIM height units)	1.5	1.3	1.2	0.7	0.8
Fractal Dimension	2.044	2.044	2.044	2.044	2.044

Table 10 - Results for the coupled model of Walnut Gulch

Coupled Climate-Vegetation Model – River Tyne					
	Scenario 16	**Scenario 17**	**Scenario 18**	**Scenario 19**	**Scenario 20**
	14ka BP		Present		
Precipitation (WILSIM units)	0.06	0.07	0.08	0.09	0.10
Drainage Density (km^{-1})	0.56	0.37	0.39	0.41	0.58
Hypsometric Integral (%)	81.16	84.34	83.70	82.78	81.21
Basin Relief (WILSIM height units)	1.2	2	2.1	2	2
Local Relief (WILSIM height units)	1	1.1	0.7	0.8	1
Fractal Dimension	2.036	2.036	2.036	2.036	2.036

Table 11 - Results for the coupled model of River Tyne

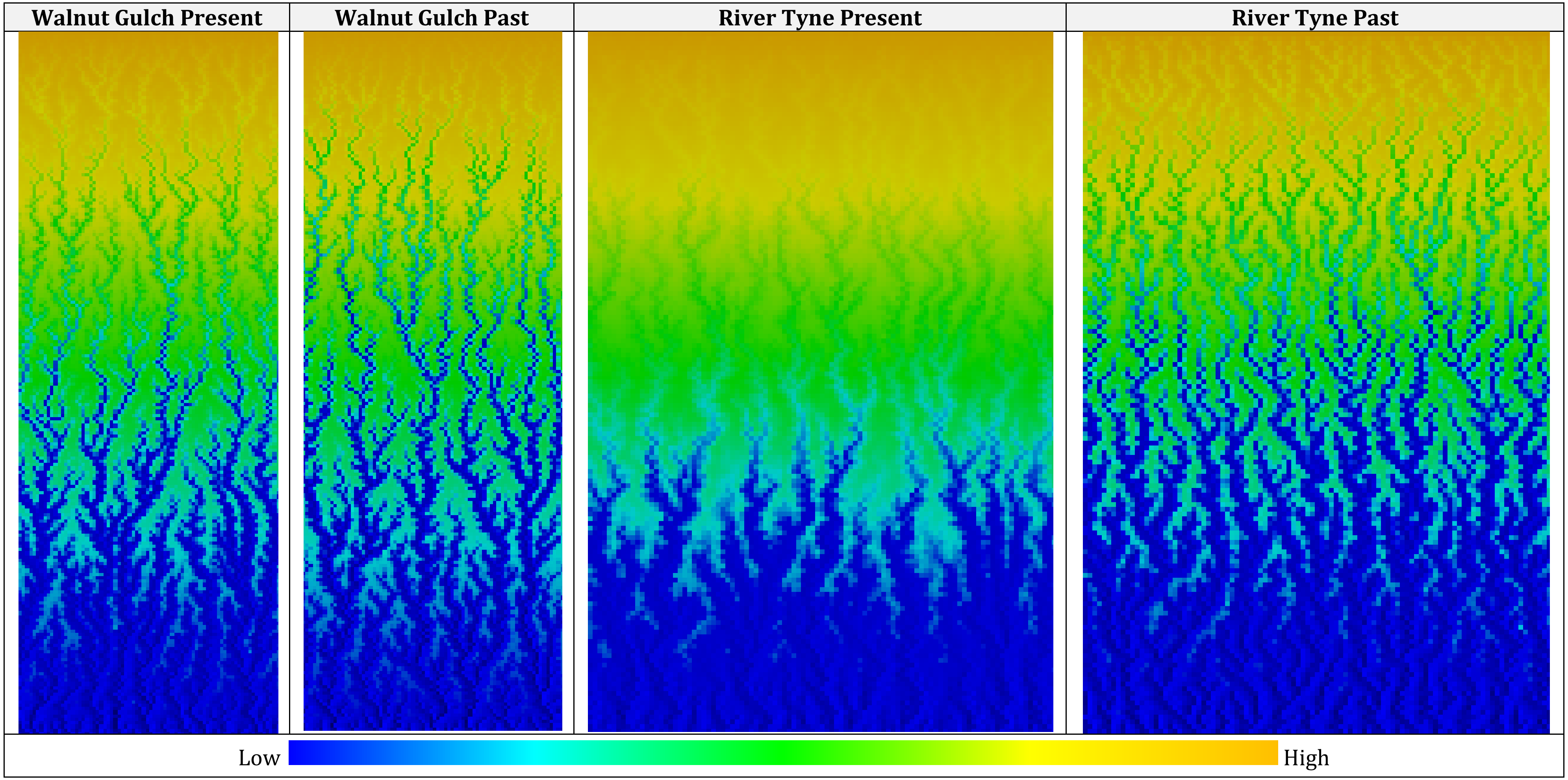
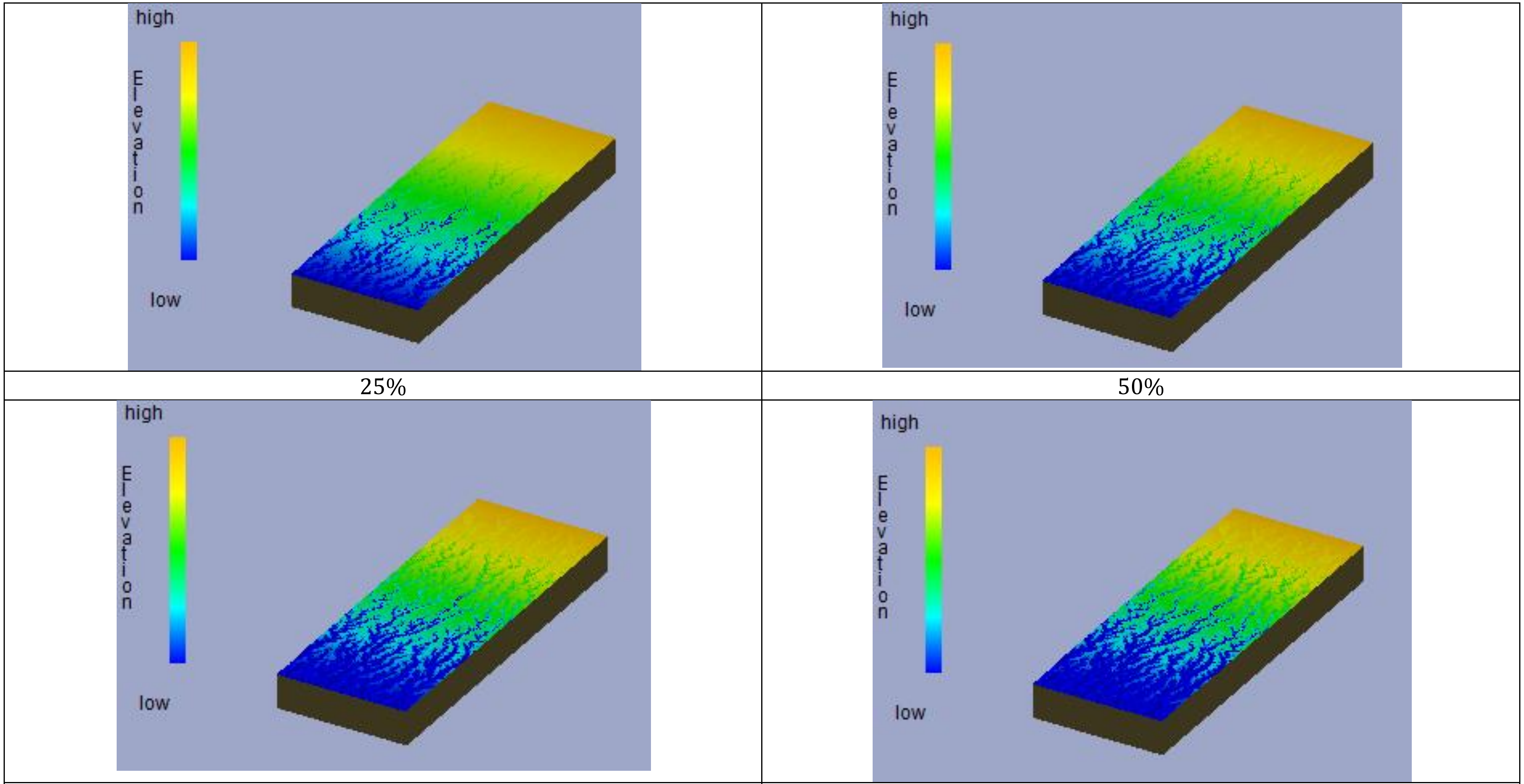


Figure 2 – Plan view output for four key model scenarios: past and present for each basin. Note the increase in drainage density between the past and present for River Tyne. A similar increase is found for Walnut Gulch, although it is slightly less noticeable.

The graphs below show sensitivity as the gradient of the trend lines (following the graphical sensitivity analysis method of Frey & Patil, 2002). The steeper the trend line, the more rapidly the value changes, and therefore the more sensitive the metric.



25% | 50% | 75% | 100%

Figure 3 – Views of model output for Scenario 13 (Walnut Gulch, present) at various proportions of the total iterations. This is typical of the output for the rest of the basins, showing gradual incision and deepening of channels, particularly at higher elevations (channels in the top part of the catchment can barely be seen in the first image, but are quite clear in the final image).

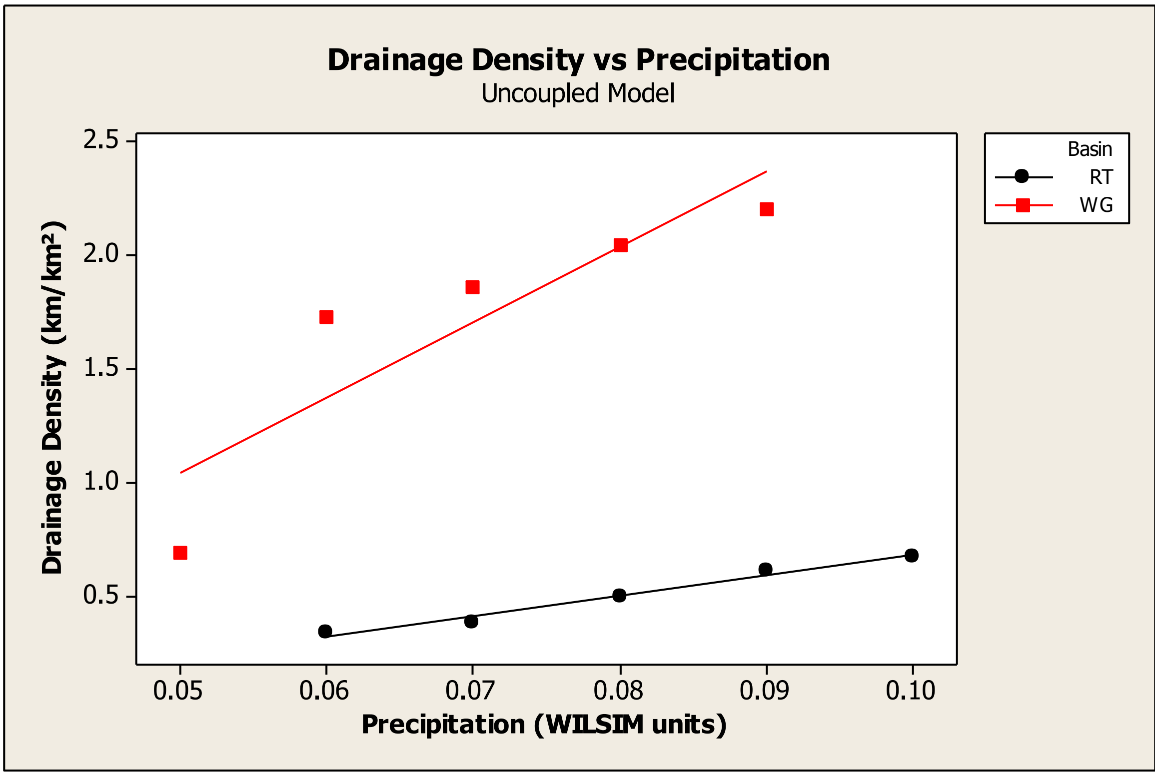


Figure 4 – Drainage density of River Tyne and Walnut Gulch from the uncoupled model, for the whole range of precipitation values modelled. Note the linear positive trends for both basins (particularly if the first outlying data point for Walnut Gulch is ignored).

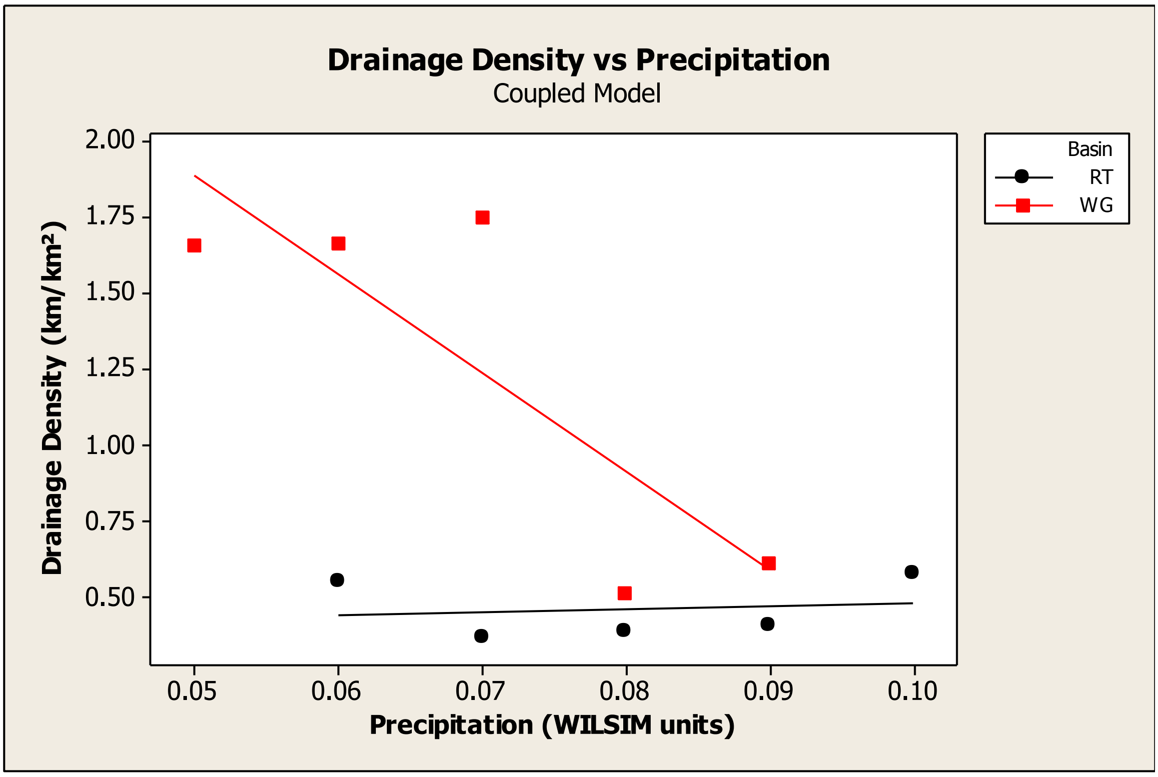


Figure 5 - Drainage density of River Tyne and Walnut Gulch from the coupled model, for the whole range of precipitation values modelled. Note the differing trends: negative overall for Walnut Gulch, and a slight positive trend for River Tyne.

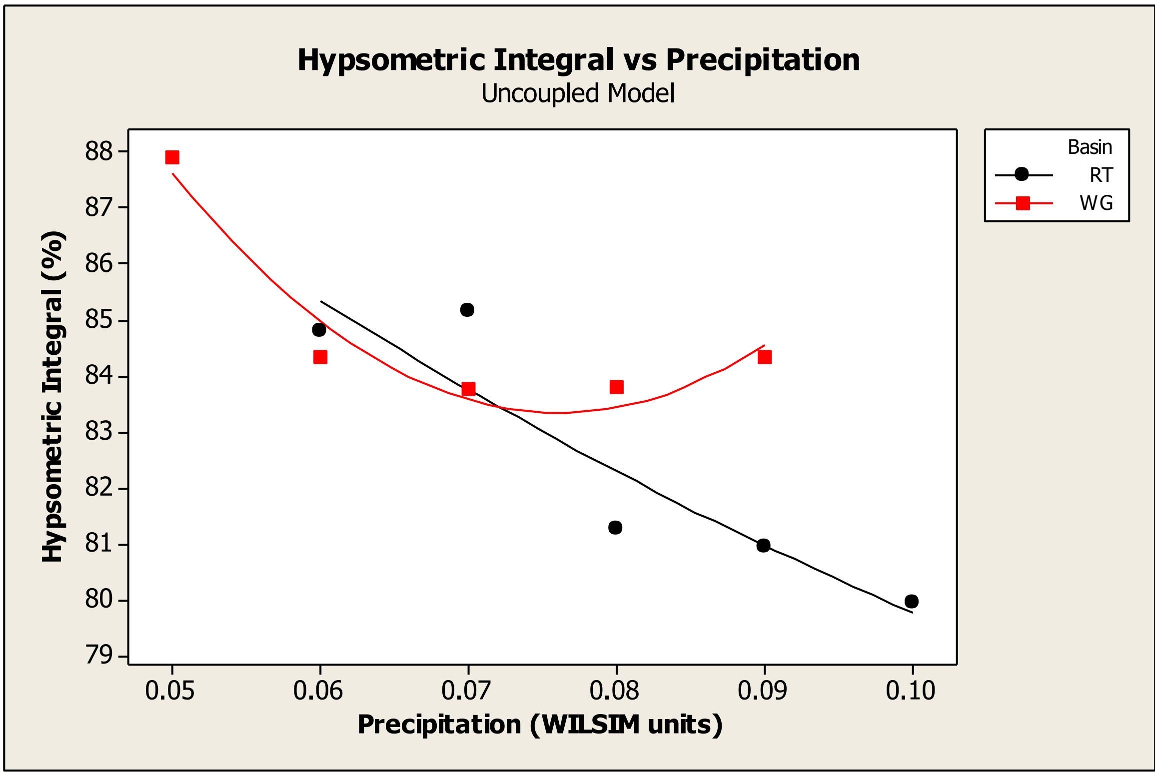


Figure 6 – Hypsometric Integral of River Tyne and Walnut Gulch from the uncoupled model, for the whole range of precipitation values modelled. Note the curved trend for Walnut Gulch, and the linear negative trend for River Tyne.

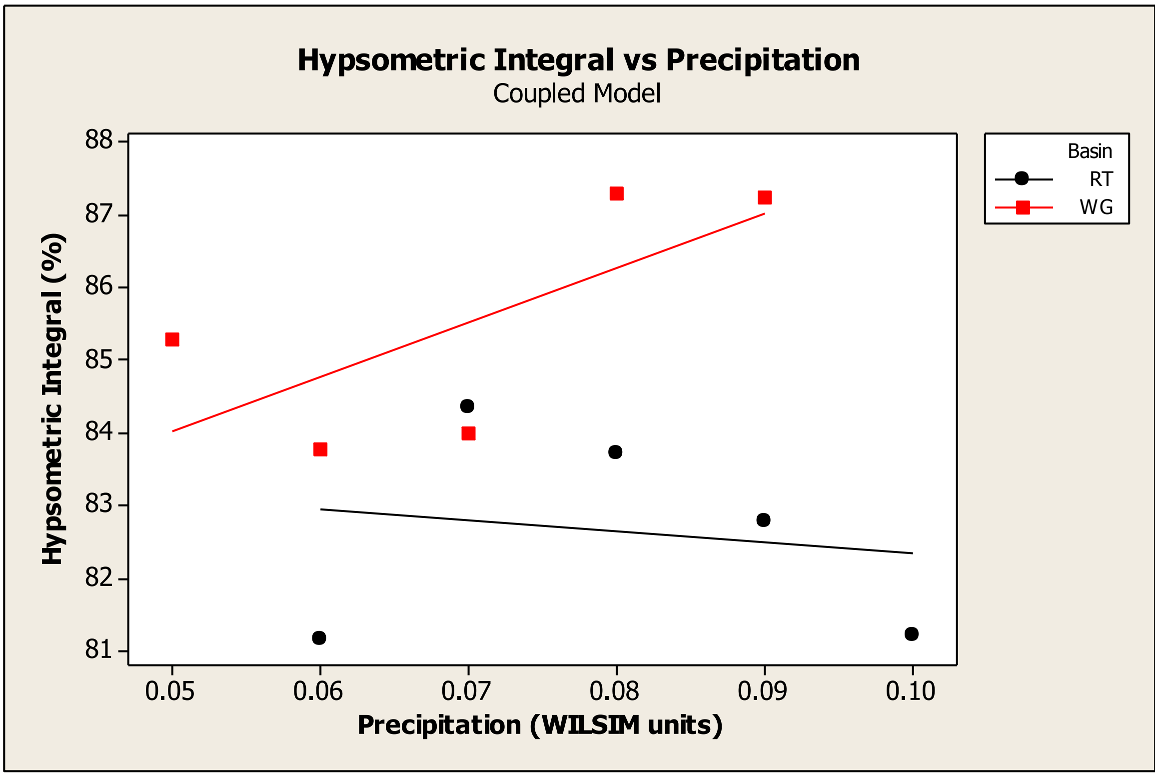


Figure 7 - Hypsometric Integral of River Tyne and Walnut Gulch from the coupled model, for the whole range of precipitation values modelled. Note the differing trends: positive for Walnut Gulch and negative for River Tyne.

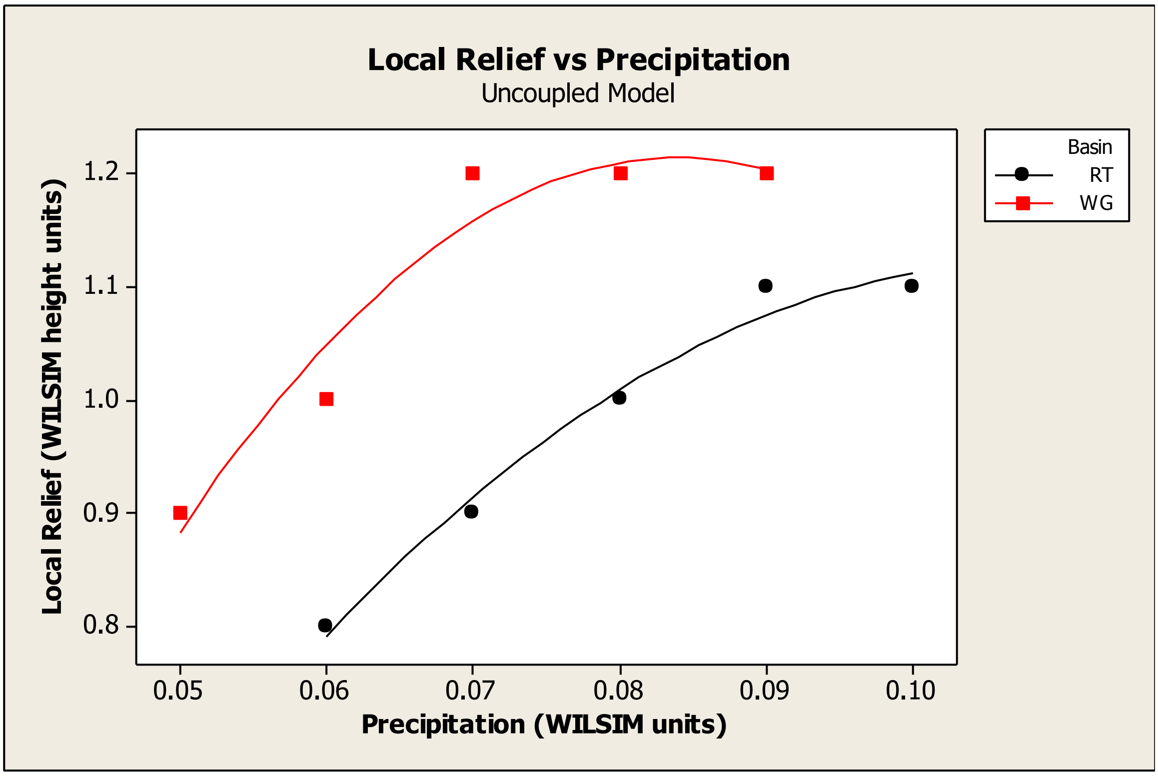


Figure 8 – Local relief of River Tyne and Walnut Gulch from the uncoupled model, for the whole range of precipitation values modelled. Note the curved trend lines, particularly Walnut Gulch which reaches a plateau from around a precipitation of 0.07 onwards.

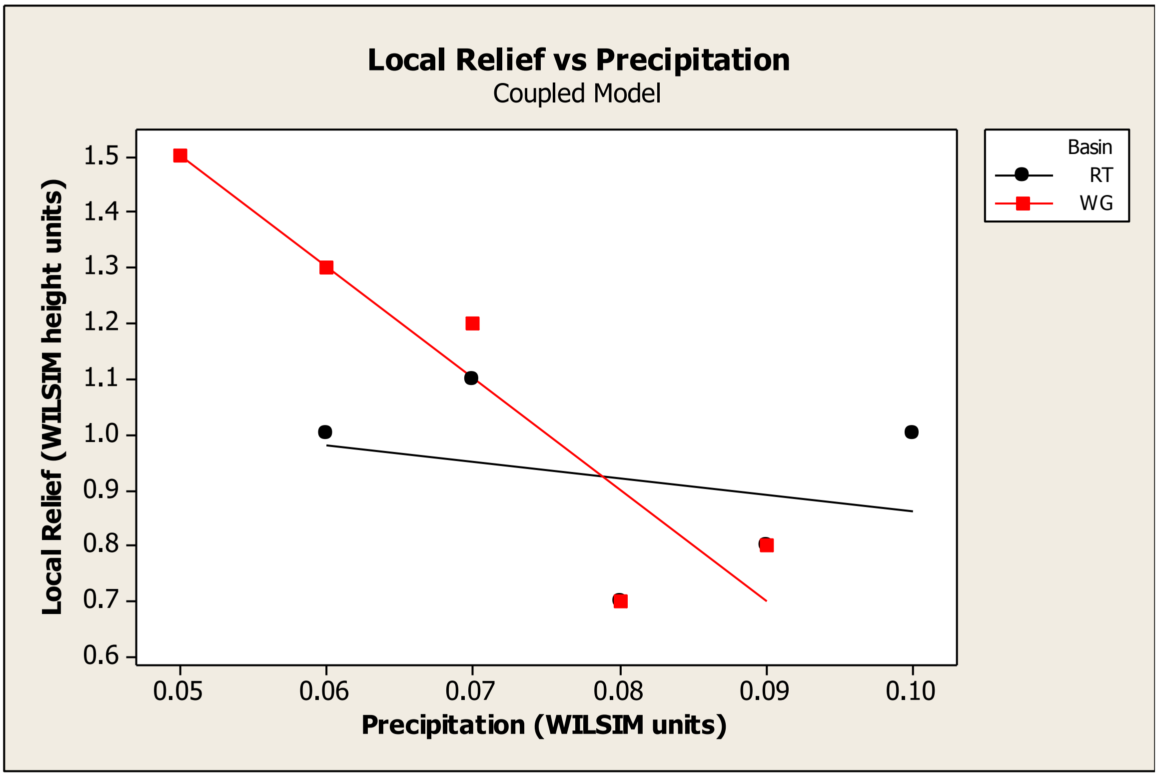


Figure 9 - Local relief of River Tyne and Walnut Gulch from the coupled model, for the whole range of precipitation values modelled. Note the trends: Walnut Gulch has a strong negative trend, and River Tyne has a weaker negative trend.

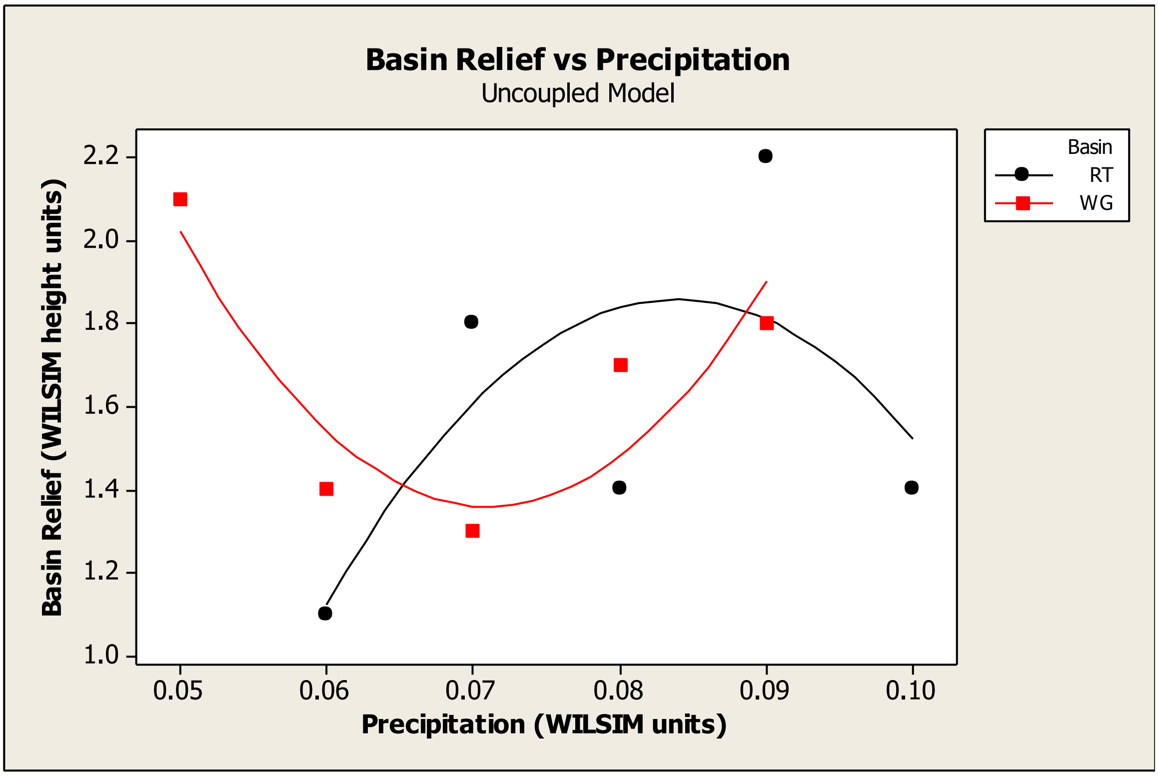


Figure 10 - Basin relief of River Tyne and Walnut Gulch from the uncoupled model, for the whole range of precipitation values modelled. Note the parabolic trends: positive for Walnut Gulch, and negative for River Tyne.

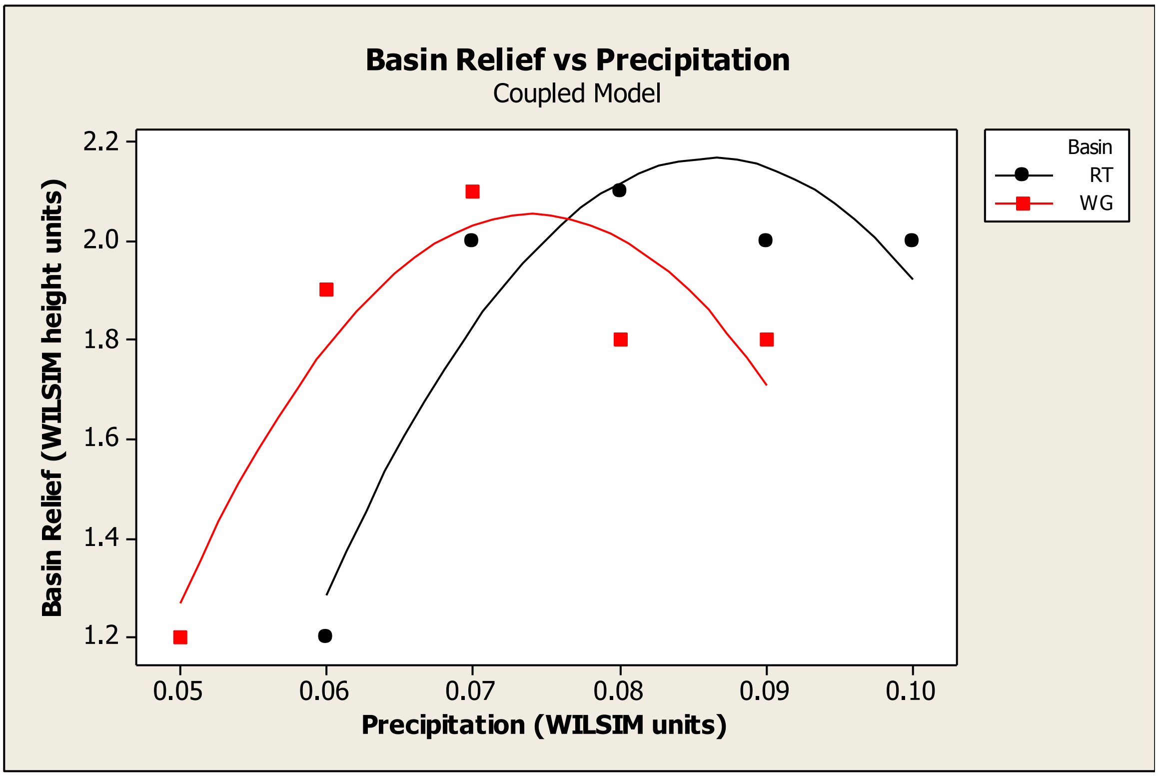


Figure 11 - Basin relief of River Tyne and Walnut Gulch from the coupled model, for the whole range of precipitation values modelled. Note the curved trends, both with low starting values, reaching a peak midway through, and then tailing off.

ANALYSIS AND DISCUSSION

This analysis will be based on the quantitative outputs from the model, excluding fractal dimension values as they remained constant for each drainage basin.

VALIDATION

The models were validated by comparing output from the model scenarios designed to reflect current conditions with metrics from the field. However, obtaining similar values does not prove that the model is accurate: there could be errors that have, by chance, combined to produce a 'correct' result.

It can be seen from Table 12 that the coupled model gives drainage densities closer to those measured in the field than the uncoupled model does. This suggests that the coupled model is more realistic than the uncoupled model, supporting hypothesis 2. This comparison cannot be carried out with the other metrics as there are no measured values available for the hypsometric integral or local relief, and the basin relief values are unable to be compared[3].

	Drainage Density (km^{-1})				
	Coupled Model	**Uncoupled Model**	**Field**	**Percentage Difference: Field vs. Coupled**	**Percentage Difference: Field vs. Uncoupled**
Walnut Gulch	1.75	1.87	1.77	1%	5%
River Tyne	0.39	0.50	0.43	8%	14%

Table 12 – Differences between measured and modelled drainage density using the present scenario for the coupled and uncoupled models. Measured drainage density taken from Milne (2005)

The modelled hypsometric integrals are not within the range of 25-75% given by Summerfield (1991), but this is likely to be because of the initial conditions of the model. Real drainage basins do not start from a planar surface, and this is likely to affect the distribution of elevations in the model output.

As the coupled model has been shown to be more realistic than the uncoupled model, it will be used for all other analyses, except when a comparison between the coupled and uncoupled model is required.

[3] This is because there is no conversion factor in the literature to convert from WILSIM height units to metres.

Relative Sensitivity

A simple method of measuring the relative sensitivity of Walnut Gulch and River Tyne is to calculate the range of the metrics calculated for each basin (see Figure 12). For three out of the four metrics (drainage density, hypsometric integral and local relief), Walnut Gulch is shown to be more sensitive than River Tyne when the coupled model is used. This can also be seen in the graphs above: Walnut Gulch always has a steeper trend.

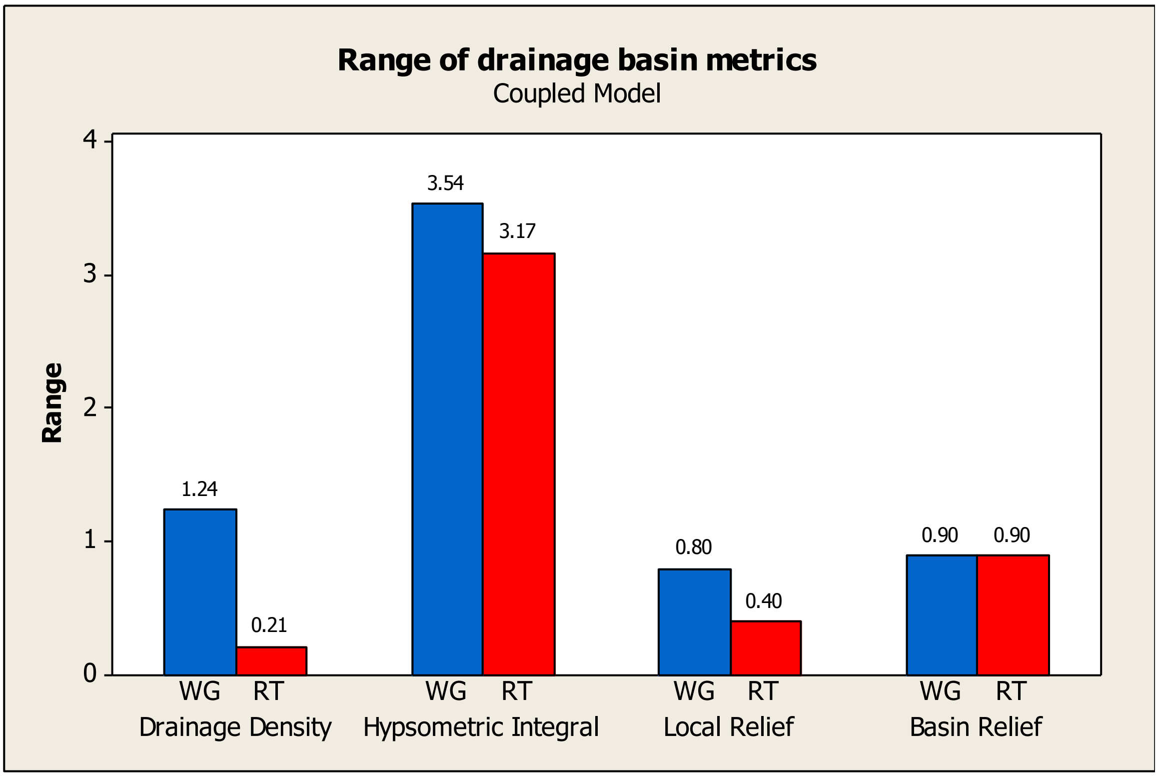


Figure 12 –The range of four drainage basin metrics calculated for Walnut Gulch and River Tyne with the coupled model. A large range means that parameter has a high sensitivity to climatic perturbations of that drainage basin. Note the large difference in ranges between Walnut Gulch and River Tyne for drainage density, and the equality of the ranges for basin relief.

More complex measures of sensitivity such as Usher's equation (Usher, 2001) can be used. This produces a sensitivity index (listed in Table 13 and Table 14 displayed graphically in Figure 13), with small values indicating high sensitivity. This shows that, according to all metrics, Walnut Gulch is more sensitive to climatic perturbations than River Tyne. This is supported by the results of Moglen et al. (1998). The mean sensitivity indices for the drainage density of Walnut Gulch and River Tyne are significantly different at the $p=0.10$ level, but no other differences are statistically significant. However, this may not reflect correctly on their significance, as there is a smaller sample size than is recommended when performing t-tests.

Walnut Gulch appears to be more sensitive to increases in precipitation than to decreases: values for the sensitivity indices for all metrics show this, although the differences are not statistically significant. This is likely to be because in a semi-arid area like Walnut Gulch, an increase in precipitation shifts the area from a semi-arid climate to a humid-temperate climate, causing a large change in the erodibility due to vegetation growth, resulting in a large change in the drainage basin metrics. This supports hypothesis 1.

Precipitation Change	Sensitivity Index of Drainage Density	Sensitivity Index of Hypsometric Integral	Sensitivity Index of Local Relief	Sensitivity Index of Basin Relief
-0.01	0.12	0.043	0.100	0.050
-0.02	0.23	0.016	0.067	0.022
+0.01	0.01	0.003	0.020	0.033
+0.02	0.02	0.006	0.050	0.010
Average	0.09	0.016	0.059	0.029

Table 13 - Sensitivity Index for all metrics for Walnut Gulch for perturbations of precipitation away from the present value of 0.07.

Precipitation Change	Sensitivity Index of Drainage Density	Sensitivity Index of Hypsometric Integral	Sensitivity Index of Local Relief	Sensitivity Index of Basin Relief
-0.01	0.47	0.016	0.025	0.100
-0.02	0.12	0.008	0.067	0.022
+0.01	0.50	0.011	0.100	0.100
+0.02	0.10	0.008	0.067	0.200
Average	0.30	0.100	0.065	0.106

Table 14 - Sensitivity Indices for all metrics for River Tyne for perturbations of precipitation away from the present value of 0.08.

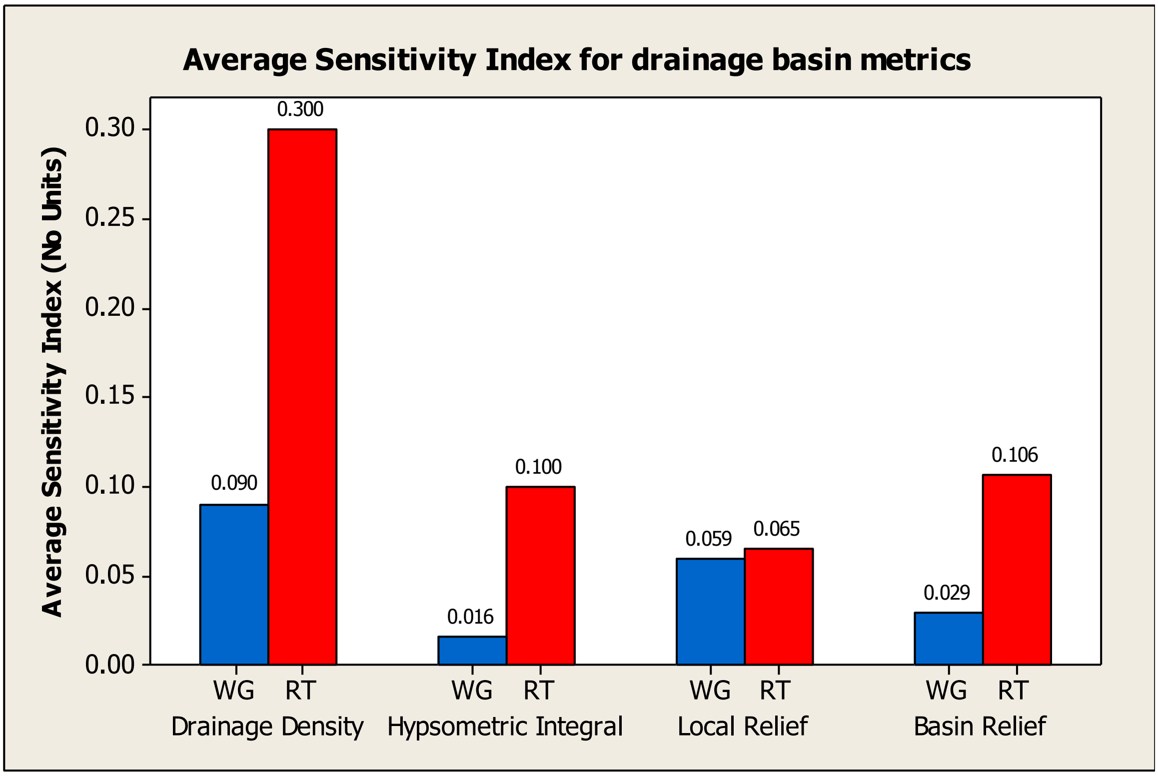


Figure 13 –Average sensitivity indices calculated for Walnut Gulch and River Tyne using the coupled model. Lower values mean higher sensitivity. Note that Walnut Gulch is shown to be more sensitive by all four metrics.

THE EFFECT OF COUPLING ON SENSITIVITY

Hypothesis 3 states that the sensitivity to climate perturbations will be greater in the uncoupled model than in the coupled model. Figure 14 shows that, in Walnut Gulch drainage density and hypsometric integral are more sensitive in the uncoupled model, but both local and basin relief are more sensitive in the coupled model. In River Tyne (Figure 15), all metrics except local relief are more sensitive in the uncoupled model, and the values of local relief for the two models are so close as to be insignificant.

These results suggest that the uncoupled model is generally more sensitive to change because in the coupled model there are erodibility changes which mitigate the effects of the precipitation changes. However, the sensitivity depends on the prevailing climate: for example Figure 8 shows that the local relief values for Walnut Gulch reach a plateau at a precipitation value of 0.07, meaning that for any values higher than this the sensitivity is very low.

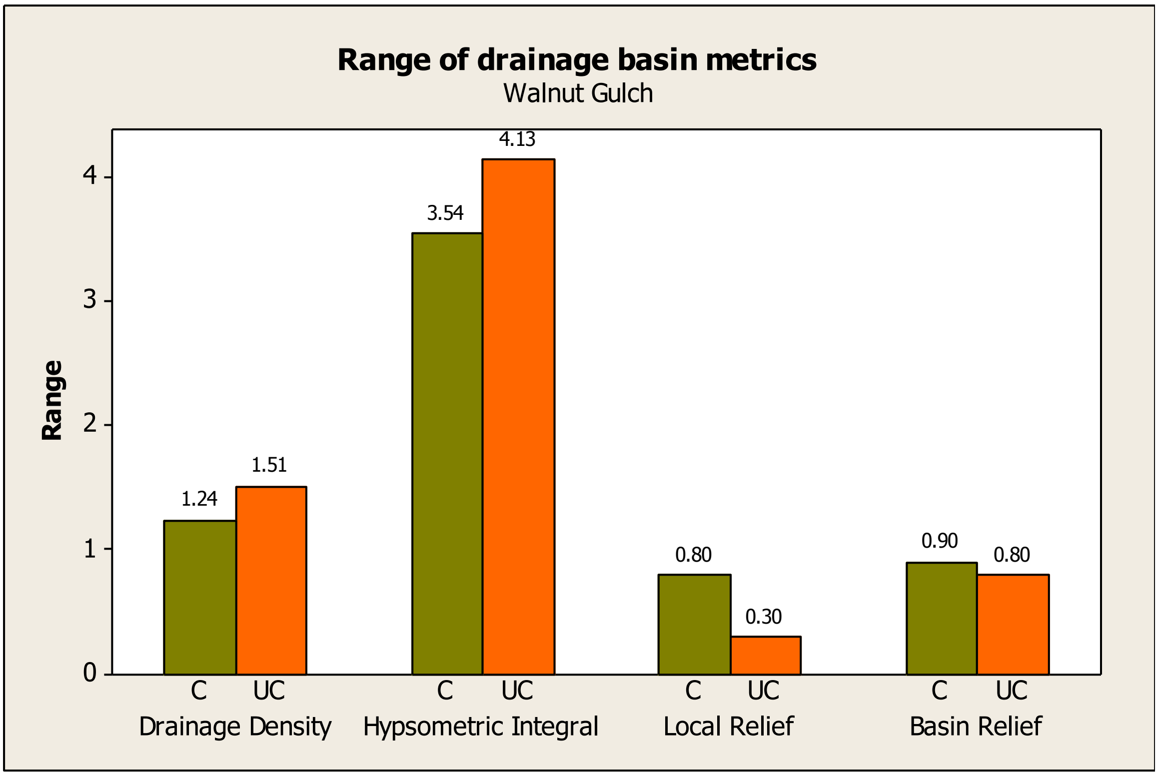


Figure 14 – Range of all four drainage basin metrics for Walnut Gulch in the coupled (C) and uncoupled (UC) models. High values indicate high sensitivity. Note the particularly significant difference between the coupled and uncoupled model for local relief: the uncoupled value is less than 40% of the coupled value.

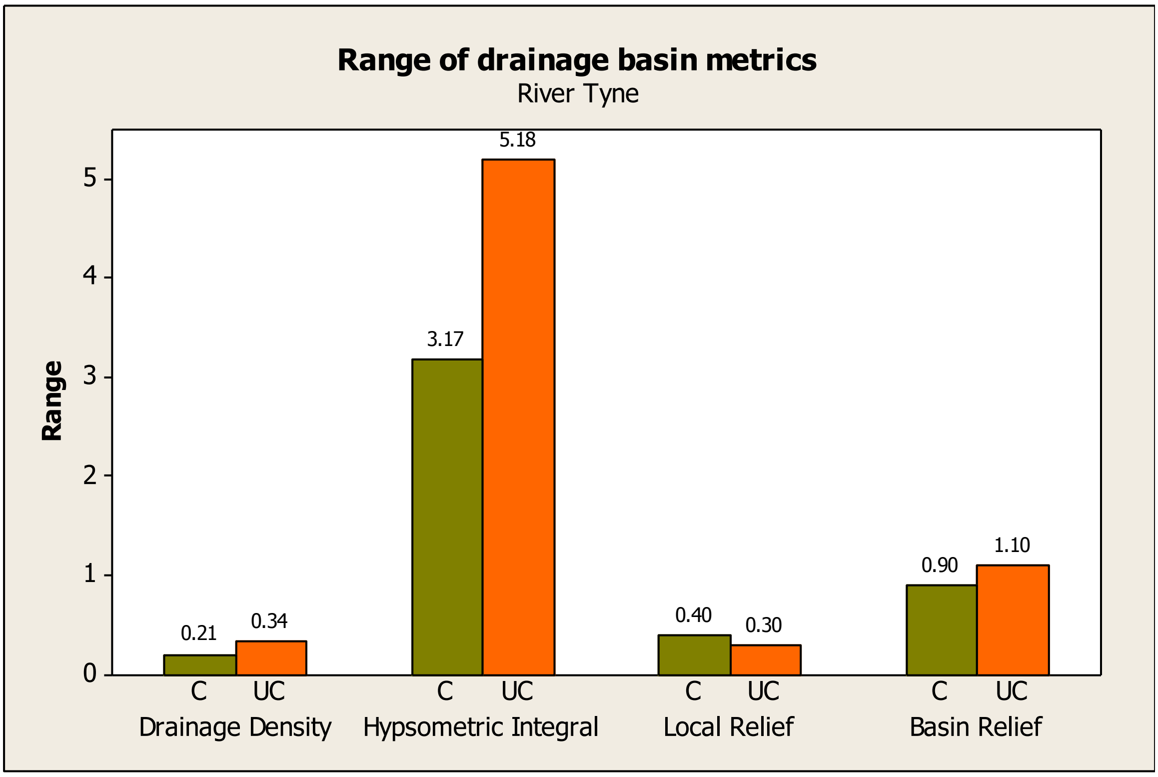


Figure 15 - Range of all four drainage basin metrics for River Tyne in the coupled (C) and uncoupled (UC) models. High values indicate high sensitivity.

DIRECTIONALITY OF DRAINAGE DENSITY CHANGE

Hypothesis 4 suggest that the directionality of the drainage density response depends on the prevailing climatic regime. This would only be visible in the coupled model, as it depends on the relationship between vegetation, precipitation and erodibility. At first glance, Figure 5 suggests the opposite of hypothesis 4: the trend lines show drainage density falling with precipitation for Walnut Gulch, and rising with precipitation for River Tyne.

The drainage density data for Walnut Gulch can be divided into two parts (Figure 16): the first three data points (connected in green), and the last two data points (connected in blue). The first part covers the range of precipitation under which the drainage basin is semi-arid. The big drop between the first and second parts represents a very 'responsive' change due to the drainage basin transitioning from a semi-arid to a humid-temperate climate – with the resultant increase in vegetation and decrease in erodibility. Only the first part truly represents a semi-arid climate and the trend there is positive, supporting hypothesis 4 and Moglen et al. (1998).

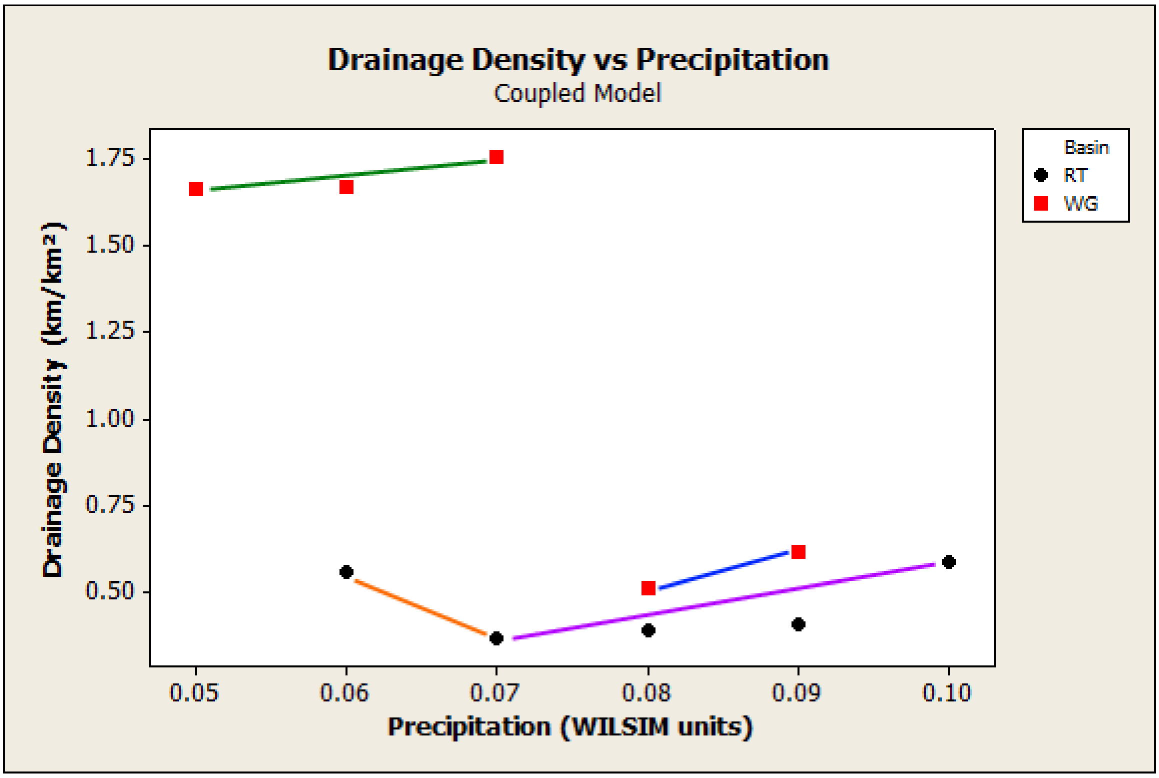


Figure 16 – Drainage density for all modelled values of precipitation, using the coupled model. This is the same graph as Figure 5, but has separate trend lines drawn on it, which are referenced in the text.

Although the data for the River Tyne can also be broken into parts (where the first part, connected by the orange line, is the transition to a humid-temperate climate, and the second part, connected by the purple line, covers the effects of varying precipitation within that humid temperate climate), the result is unchanged: there is an overall positive trend, the opposite to that found by Moglen et al. (1998).

This difference is likely to be because of the very simple coupling employed in this study. Moglen et al. (1998) used a fully coupled model, and they recognised that the interaction between vegetation and rainfall was key to causing directionality of the variation of drainage density. It appears that the coupling in this model (which was performed by manually varying input parameters) is not good enough to simulate detailed effects like this.

UNCERTAINTY

The uncertainty associated with this study is examined with in Table 15.

Uncertainty	Category	Details	Severity	Effects and mitigation
Uncertainty in the modelling process				
Use of a model to represent real world processes	Inherent randomness of nature Reducible ignorance Irreducible ignorance Indeterminacy	The fundamental uncertainty with this study is that a model will never perfectly represent real world processes. This is partly due to the indeterminacy of real world processes, partly due to the inherent randomness of nature, and partly due to the problems with the model. The model does not replicate processes perfectly, and there are many processes and relationships between processes that we don't understand.	High	This adds huge uncertainty to the study, uncertainty which would not exist if the study was based on measurements from the real world. However, modelling is unavoidable in geomorphology, as the phenomena to be examined operate over such large timescales. There have been many studies which have shown that landscape evolution models produce output which is relatively similar to real-world processes, providing much confidence in these models (Anderson, 1994; Hancock & Willgoose, 2002; Hancock et al., 2002). An alternative approach is that of (Oreskes et al. (1994) who suggest that an exact correspondence between models and reality should not be sought, but that models should be used for primarily heuristic purposes, and in many ways this study has followed these principles.
Use of only two real world drainage basins	Lack of observations / measurements	Only one drainage basin was used for each of the climatic regimes studied but Coulthard et al. (2005) showed that there can be very different responses to environment change even in very similar drainage basins.	High	This uncertainty would be drastically reduced if further studies were made of other drainage basins in these climatic environments. All that this study investigates is how Walnut Gulch and River Tyne react, to apply this to other drainage basins will inevitably add uncertainty.

Uncertainty	Category	Details	Severity	Effects and mitigation
Uncertainty in the model				
Use of the shear-stress power law	Reducible ignorance	The shear-stress power law is only an approximation, which has been shown to roughly represent real-life sediment transport. This is based upon various assumptions, and in fact the formula is most often used without a key term representing the threshold of transport.	Medium	If this formula is completely wrong then the whole model becomes invalid. However, there is much evidence that it is a good approximation, for many differing environments (Anthony & Granger, 2007; Tucker & Whipple, 2002; Whipple et al., 2000; Whipple & Tucker, 1999)
No modelling of threshold-based hillslope processes	Reducible ignorance	WILSIM does not model threshold-based hillslope processes such as landslides, rock falls or avalanches	Low	The drainage basins modelled in this study are not particularly susceptible to these processes.
Simple climate-vegetation-erodibility coupling	Reducible ignorance	As WILSIM does not have climate-vegetation coupling by default, simple manual coupling was used. However, reality is far more complex. For example, this model does not take into account the increase in spatial heterogeneity of erodibility caused by a decrease in precipitation suggested by Abrahams et al. (1995), the feedbacks suggested by Ludwig et al. (2005) or the burying of vegetation under conditions of high sediment flux (Brookes et al., 2000; Coulthard, 2005). Simple effects of vegetation such as an increase in infiltration because of roots (Collins et al., 2004) were also not taken into account.	High	The most important effect of vegetation is the reduction in erodibility (Collins et al., 2004). This was taken into account in the model, and as such it can be said to represent the most important element of vegetation in a landscape. This fulfils the ideas of Chase (1992) who suggested that even coarse representations of only the important processes could still lead to realistic results. Complex coupling could not be used in this study as the coupling had to be carried out by manually altering the erodibility values. In a further study, extensions could be made to a model (WILSIM or another model) to enable more complex vegetation effects to be modelled.

Uncertainty	Category	Details	Severity	Effects and mitigation
Uncertainty in input parameters				
Uncertain values for *m* and *n*	Lack of observations / measurements	*m* and *n* values from other drainage basins were used, as there were no measurements for Walnut Gulch and River Tyne. The *m/n* ratio for River Tyne was outside the standard range given by Whipple & Tucker (1999).	High	*m* and *n* values have a large effect on the processes operating within the modelled drainage basin. Small variations in these parameters can lead to large changes in model output (Whipple & Tucker, 1999). A sensitivity analysis for these parameters will be carried out (see Appendix B and Appendix C). This showed that a change of 0.1 in the value of *m* or *n* could lead to up to 30% change in drainage density – equivalent to the change from the present to past scenario in Walnut Gulch.
Uncertain values for precipitation	Lack of observations / measurements	Although present precipitation values were taken from Milne's (2005) values for Walnut Gulch and River Tyne, the values for the past were taken from coarse-scale maps in Pécsi et al. (1992). These maps are not very detailed, and provide precipitation ranges for each area, rather than individual values. Also, the global precipitation range was altered to allow each scenario to have a separate precipitation value. The WILSIM input parameters have a small range, which leads to coarse parameterisation.	Low	A range of precipitation values were used in the model scenarios. This means that any error in the value for the present or the past would be covered by the large range. Each value in the WILSIM precipitation index represents a range of around 400mm in real life. This is larger than the error bands for the individual values, but means that the parameterisation is unavoidably coarse.

Uncertainty	Category	Details	Severity	Effects and mitigation
Uncertain values for soil erodibility	Lack of observations / measurements	The USLE was originally designed for use in agricultural lands in the USA, and applications elsewhere found problems with it. However, RUSLE has had many improvements which make it suitable for a wide range of areas (Renard et al., 1994; Yoder et al., 2001). Values for the cover management factor were chosen by hand from a table of values provided by the Purdue Research Foundation (2004); there was no actual field measurement or examination. The WILSIM input parameters have a small range, which leads to coarse parameterisation.	Low	There would be a problem if USLE had been used, but the improvements in RUSLE make it suitable for use here. Cover management factor values were chosen to correspond with the precipitation values, and with the help of vegetation maps and aerial photographs. The highest uncertainty is in the hindcast scenarios, where there was little data from which to estimate the cover management factor.
Use of zero uplift	Reducible ignorance	The uplift was set to zero for all simulations.	Medium	This was on the advice of Dr. Stephen Darby. Most of this study uses relative comparisons, so this would not be a problem. Obtaining drainage density values very close to measured values suggests that the lack of uplift has little effect on the drainage basin metrics.

Uncertainty	Category	Details	Severity	Effects and mitigation
Uncertainty in outputs				
Calculation of drainage density	Lack of observations / measurements	Output of the drainage density was not provided by WILSIM. Instead, drainage density was calculated from the modelled plan view image using image editing software and a Python program. This method relies on humans tracing the channel network (which is particularly difficult to see on some model images) and also assumes that the channels inside a pixel stretch for the length of one side of the pixel; an assumption which may not be true when pixel sizes are of the order of hundreds of metres.	Low	Although the method was crude, the drainage density values produced were within 10% of measured values for both drainage basins. This lends confidence to the technique.
Drainage density is not independent of basin parameters	Conflicting evidence	There is evidence that drainage density is not independent of parameters such as relief or basin shape (Gregory & Walling, 1968), and may not even be independent of basin area (Gardiner et al., 1977; Pethick, 1975). Rodriguez-Iturbe & Escobar (1982) suggest that drainage density depends on the energy expenditure characteristics of the basin, as well as on climate and erodibility.	Medium	There is much debate about this (Gardiner et al., 1977; Gardiner & Park, 1978). The basins used in this study are very different in terms of basin area and relief, which may mean this is a problem. However, drainage density has been used in many studies as an independent metric, and this study will employ it so as to be comparable to other studies.
Calculation of the hypsometric integral	Lack of observations / measurements	Output of the hypsometric integral was not provided by WILSIM. The hypsometric integral was calculated using a similar method to drainage density: filling the area under the hypsometric curve and counting the pixels. The fill operation was entirely automatic, eliminating human error.	Low	Although this method was crude, it did not rely on human tracing, and follows the well known 'counting squares' method for integrating a curve. This lends it confidence, as does the accuracy of a similar technique used for drainage density.

Uncertainty	Category	Details	Severity	Effects and mitigation
Measurement of the relief values	Inexactness	Outputs of basin relief and total relief were provided on graphs from WILSIM. These values then had to be read from the graphs, with the inevitable inexactness this produces.	Low	Measurements were made using an onscreen ruler to draw a line from the data point to the axis, thus increasing accuracy.

Table 15 - Sources of uncertainty in this study, with classification from Van Asselt and Rotmans (2002)

Conclusion

Based on the models of the drainage basins studied, there is an increased sensitivity to climate change in semi-arid basins compared to humid-temperate basins. Coupled models appear to produce outputs which are more similar to the real world (with a drainage density within 1% of the measured value for Walnut Gulch), and appear to be less sensitive to climate change than uncoupled models. The work of Moglen et al. (1998) was not verified by this study, but this is likely to be because of the simplistic coupling employed.

Further work is needed to confirm these results, as only two drainage basins were studied and a relatively simple model was used.

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APPENDIX A – PYTHON CODE

```
#Import Tk graphics libraries
from Tkinter import *
import tkFileDialog
import tkMessageBox

#Import image manipulation library
import Image

class App:
    #Set up application
    def __init__(self, master):
        frame = Frame(master)
        frame.pack()
        #Create exit button
        self.button = Button(frame, text="Exit", command=master.destroy)
        self.button.pack(side=LEFT)
        #Create select file button
        self.select_file = Button(frame, text="Select File", command=self.process_file)
        self.select_file.pack()

    def process_file(self):
        #Open a select file dialog box to allow the user to select the image file
        filname = tkFileDialog.askopenfilename()

        #Open the image and load the data into the imgdata array
        pic = Image.open(filname)
        imgdata = pic.load()

        #Get the size of the image
        xsize, ysize = pic.size

        #Set the search colour to black (R=0, G=0, B=0) and no transparency (A=255)
        searchcolor = (0, 0, 0, 255)
        counter = 0
        #Check each pixel, if it's black increment the counter
        for x in xrange(xsize):
```

```
            for y in xrange(ysize):
                if imgdata[x,y] == searchcolor:
                    counter+=1
        #Show a message box with the result
        tkMessageBox.showinfo("Result", counter)

#Run the application
root = Tk()
app = App(root)
root.mainloop()
```

APPENDIX B – SENSITIVITY ANALYSIS OF M

Scenarios were run using the present scenario with the coupled model and perturbing the value of *m* (WILSIM *n*) by ±0.1. The results are shown in Table 16 and Table 17.

Perturbation	Drainage Density (km^{-1})	Hypsometric Integral (%)	Local Relief (WILSIM height units)	Basin Relief (WILSIM height units)
-0.1	1.63	85.24	1.2	2.2
Present	1.75	84.00	1.2	2.1
+0.1	2.16	83.87	1.1	2.1
% change for decrease	-7%	+1%	0%	+5%
% change for increase	+23%	0%	8%	0%

Table 16 – Results for sensitivity analysis of the *m* exponent for Walnut Gulch. All percentages reported to one significant figure.

Perturbation	Drainage Density (km^{-1})	Hypsometric Integral (%)	Local Relief (WILSIM height units)	Basin Relief (WILSIM height units)
-0.1	0.27	84.64	0.70	1.90
Present	0.39	83.70	0.70	2.10
+0.1	0.39	84.08	0.90	2.10
% change for decrease	-30%	+1%	0%	-10%
% change for increase	0%	0%	+29%	0%

Table 17 - Results for sensitivity analysis of the *m* exponent for River Tyne. All percentages reported to one significant figure.

There seems to be little pattern to these results. The hypsometric integral does not appear to be very sensitive to changes in *m*, but the drainage density seems far more sensitive. For both basins, Local relief doesn't seem to change for a decrease in *m*, but changes a lot for an increase in *m* and basin relief is the opposite way around.

This shows that the choice of the *m* value is significant, and that even small changes in *m* can lead to changes of up to 30% in metrics such as drainage density and local relief. This change 30% for Walnut Gulch is larger than the change between the past and present scenarios, making it particularly significant in the context of the changes found in this study.

APPENDIX C – SENSITIVITY ANALYSIS OF N

Scenarios were run using the present scenario with the coupled model and perturbing the value of *n* (WILSIM *m*) by ±0.1. The results are shown in Table 18 and Table 19.

Perturbation	Drainage Density (km^{-1})	Hypsometric Integral (%)	Local Relief (WILSIM height units)	Basin Relief (WILSIM height units)
-0.1	2.29	83.30	1.20	2.00
Present	1.75	84.00	1.20	2.10
+0.1	1.72	85.11	1.10	1.70
% change for decrease	+31%	-1%	0%	-5%
% change for increase	-2%	+1%	+8%	-19%

Table 18 - Results for sensitivity analysis of the *n* exponent for Walnut Gulch. All percentages reported to one significant figure.

Perturbation	Drainage Density (km^{-1})	Hypsometric Integral (%)	Local Relief (WILSIM height units)	Basin Relief (WILSIM height units)
-0.1	0.45	83.30	0.70	1.90
Present	0.39	83.70	0.70	2.10
+0.1	0.28	84.57	0.70	1.80
% change for decrease	+15%	0%	0%	-10%
% change for increase	-29%	+1%	0%	-14%

Table 19 - Results for sensitivity analysis of the *n* exponent for River Tyne. All percentages reported to one significant figure.

Again there is little pattern. The local relief values for River Tyne stayed constant, and again the hypsometric integral values changed very little. The drainage density was affected far more in both basins.

This shows that the choice of the *n* value is significant. Perturbations of the value by only 0.1 can cause changes of up to 29% in the drainage density value, as well as significant changes in relief.