Modelling the effects of recent agricultural land use change on catchment flow

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INTRODUCTION

Rural environments in the UK have experienced significant changes over the last century, mainly influenced by human agricultural activities. From the period 1961 – 2005 there have been changes in the crop area, such as large increases in areas planted with wheat. However in the last decade this tendency had been stabilized (DEFRA, 2013a). By 2013 the area cover by agriculture was about 71% of the total UK land (DEFRA, 2013b).

Recent flooding in the UK has focused attention on the role of agricultural land use and management on catchment flow generation. Furthermore, the requirements of WFD necessitate a better understanding of runoff generation, soil erosion and sediment transport in agricultural environments to enable effective targeting of resources to reduce diffuse pollution from agriculture. Physically-based hydrological models have been applied to assess the impacts of changes in land use. However, in the UK, the impacts on water resources at a local scale related to changing land use and management practices over contemporary timescales has received relatively little attention (Rounsevell M. et. al., 2003; Boardman et. al., 2009).

This contribution aims to simulate the effect of changes in recent past land cover on runoff generation and streamflow in an agricultural catchment in southwest England. The model, SHETRAN, was calibrated using the available flow record and concurrent land cover map (2010) with subsequent simulations for all mapped land covers performed using climate records from 2010-2014.

CATCHMENT DESCRIPTION

The Blackwater catchment is located in the southwest of England in Dorset. The catchment covers an area of 18.5 km^2. Elevation rises from 49 m from the outlet to 255 m to the crest in the southeast with low slopes (0 - 6°) in the majority of the catchment and steeper slopes (7 - 18°) in the remaining area. The main texture of the soil is clay loam covering 58%, with silty clay loam and medium sandy loam covering 40 and 2%, respectively (figure 1). Land cover is predominantly agricultural comprising rotational farming (wheat, barley, maize) and livestock grazing.

The land use from 1990 to 2010 (figure 2) has undergone changes related to the extent and spatial distribution of arable crops and pasture (figure 3). These changes may largely reflect field rotations combined with external factors influencing farmer decision making over field plantings. By contrast, urban and natural habitat (woodland) areas have undergone little change in area or spatial arrangement.

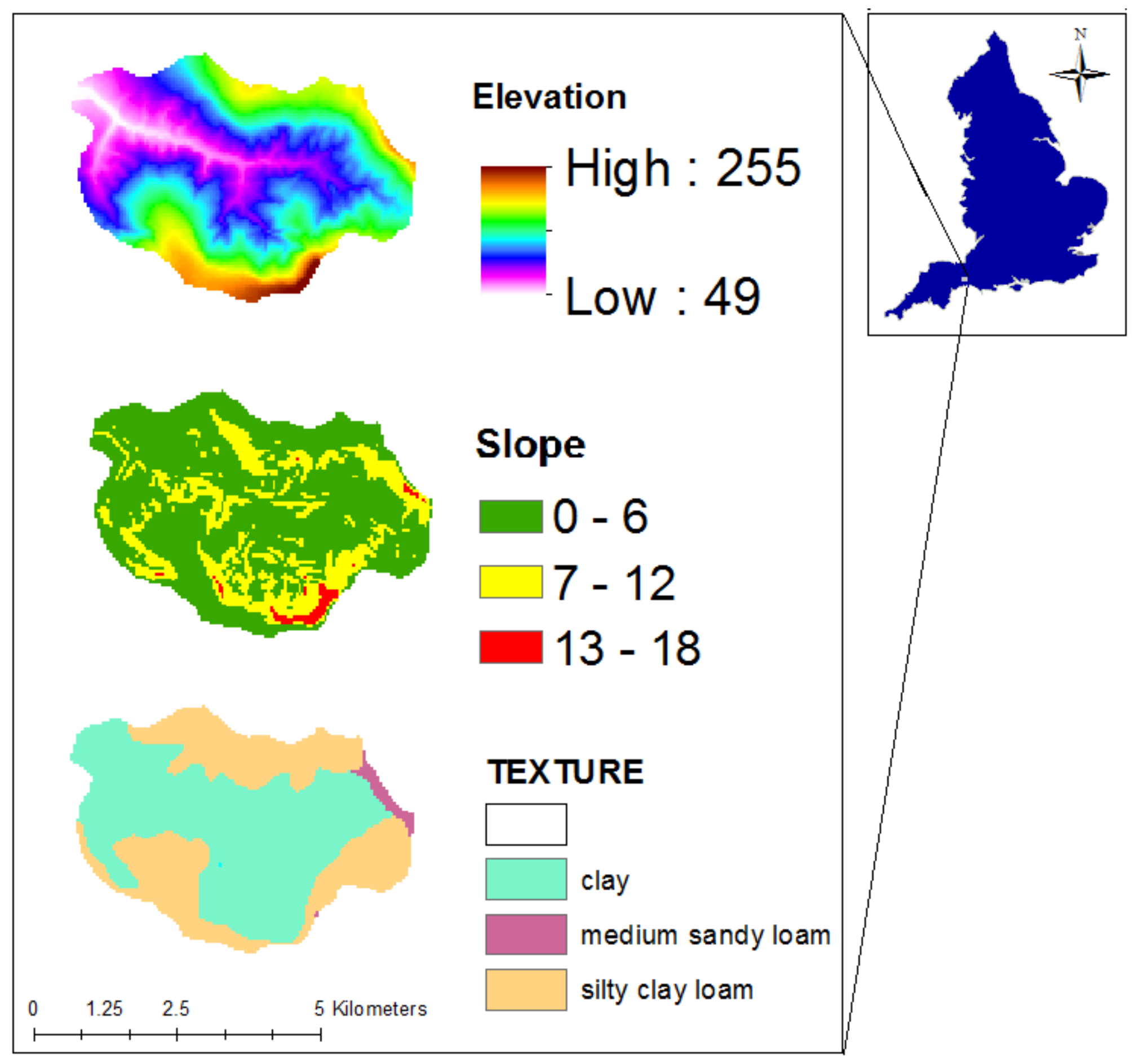

Figure 1.– Description of Blackwater catchment.

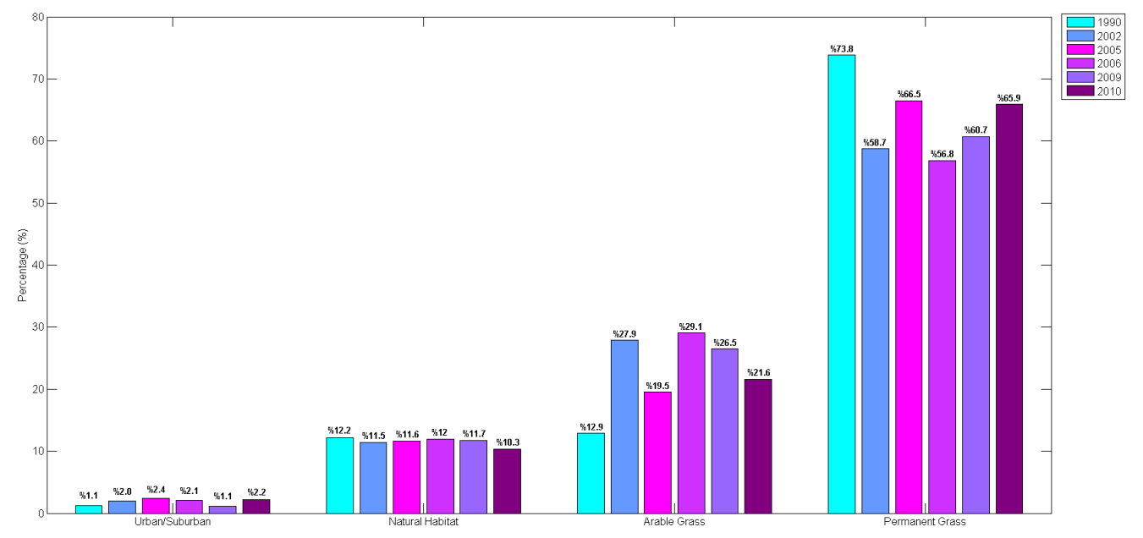

Figure 2.– Historical percentage of land cover in Blackwater catchment.

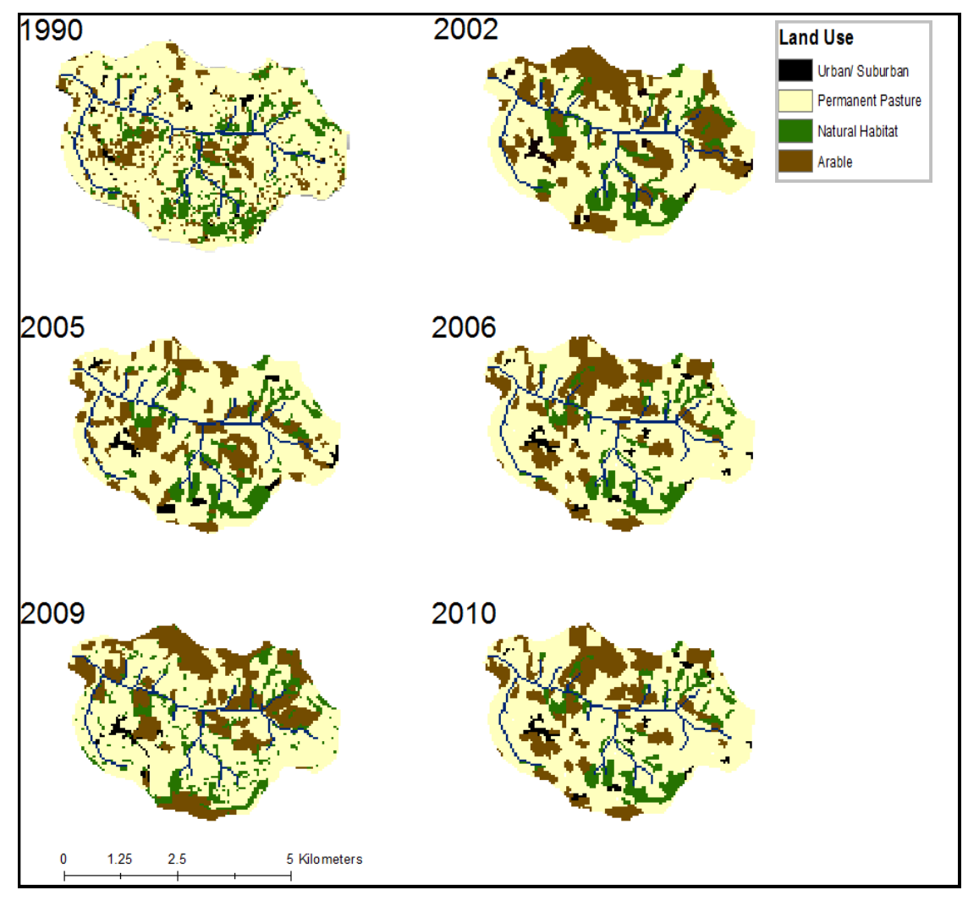

Figure 3.– Historical land cover maps in Blackwater catchment.

SHETRAN

SHETRAN is a physically-based and spatially distributed hydrological model capable of simulated rainfall events on a catchment scale (Ewen et al, 2000). It consists of three hierarchical processes: Water flow, Sediment Transport and Contaminant Transport (last two not used here). The Water flow process comprises three modules (figure 4): Evapotranspiration/Interception (ET), Variable Saturated Subsurface (VSS) and Overland/Channel flow (OC).

Interception is calculated with the Rutter storage model and depends on the proportion of the soil covered by vegetation. Evapotranspiration may be measured or calculated by potential rate (Penman's transfer equation) and actual rate (Penman-Monteith equation). Subsurface flow is simulated for saturated and unsaturated media with a three dimensional equation. Overland/channel flow is modelled based on the diffusive wave approximation of the full Saint Venant equation.

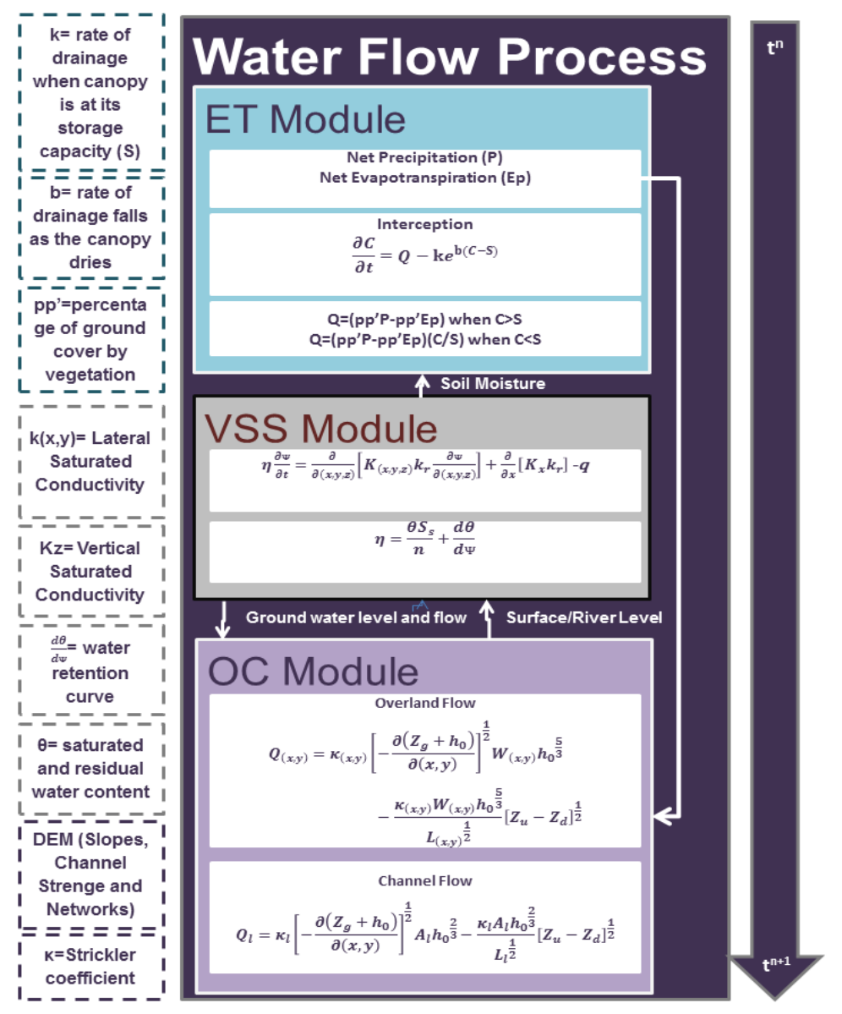

Figure 4.- SHETRAN water flow process structure and equations.

DATA SOURCES

- Digital elevation model (DEM) with 50 m resolution for catchment simulation. Land cover of digitalized Google Earth imagery of 2010, corresponding to available flow data. Vegetation parameters from Slapton catchment (Birkinshaw, 2008) located in southwest England.
- Rainfall data with a 15 minutes temporal resolution from Raymond's Hill gauge station operated by Met Office (50°46'0.84"N, 2°57'46.08"W). Monthly evapotranspiration data using a temperature-based PE model (Kay & Davies, 2008). Temperature data from Slapton station ID 1362 (50°16'59"N, 3°39' W). Both stations located in the south west of England.
- Soil parameters from the Cranfield University NSRI soil database. Fives-layer modelling (0 m – 3.0 m) of five different soil types, parameter values varied according to the land use.
- Pressure (for stage) and turbidity with a 15 minutes temporal resolution from a Troll 9000 Pro XP probe installed in the outlet of the catchment (50°48'55.74"N, 2°57'6.08"W). Conversion of stage data to flow discharge (m^3/s) based on the stage-discharge rating curve (y=2.5598x2-0.36624x+0.22366; R2=0.88). Dataset range from October 2010 to December 2014.

MODEL PERFORMANCE

The Model is particularly sensitive to three key parameters: soil depth, saturated hydraulic conductivity (K_{sat}) and Strickler overland flow coefficient (inverse of Manning coefficient). Calibration was done with a combination of Strickler coefficient values from the period Oct 2010 to Sep 2011; a value of 0.63 of Nash-Sutcliffe coefficient (E_{NS}) was obtained with the model parameters in table 1. The model was run from Oct 2009 to Sep 2010 to obtain an initial phreatic surface depth.

Table 1.- Model parameters

Land Use	Canopy Storage (mm)	Leaf Area Index	Strickler Coefficient	Soil Depth (m)	Lateral and Vertical K_{sat} (m/day)*	Saturated and Residual Water Content*
Urban/Suburban	0.3	1.0	0.7	0 - 3	0.712, 1.033	0.584, 0.124
Natural Habitat	1.5	4.0	0.4	0 - 3	0.688, 0.995	0.496, 0.107
Arable	0.5	1.0	0.5	0 - 3	0.546, 0.764	0.419, 0.099
Permanent Grass	0.1	1.6	0.6	0 - 3	0.724, 1.053	0.574, 0.122

**Wickham predominate type soil, layer of 0.25m*

Rainfall in 3 month intervals is shown in figure 5a. The period Oct-Dec 2012 was the wettest following by Apr-Sep 2012, which was unseasonably wet. Also rainfall was below average for the period from Oct 2010 - Mar 2012.

Measured and simulated discharge over 3 monthly intervals are compared in figure 5b; in most cases the model under-predicts flow.

Simulated discharge for the complete period (Oct 2010 to Sep 2014) was evaluated with the E_{NS} for each hydrological year (figure 6a) and for each Oct-Dec, Jan-Mar, Apr-Jun and Jul-Sep period (figure 6b). The model performs better in wet periods than in dry periods; the principal reason might be that simulated discharge (figure 7) estimates a lower base flow that the measured. The under-predicted flow might be a consequence of the low simulated base flow.

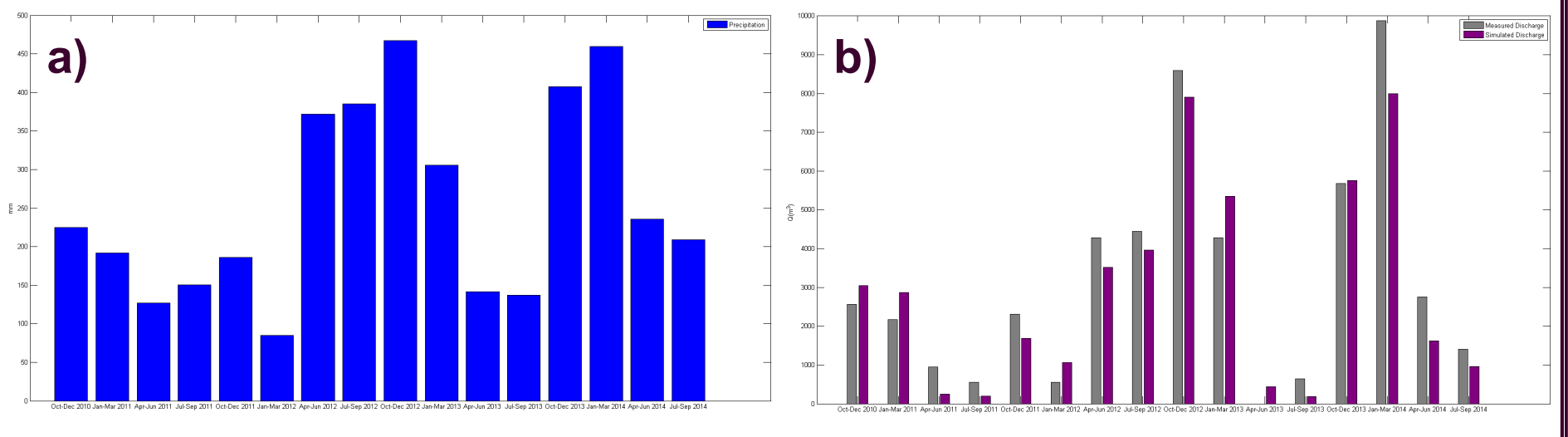

Figure 5.- a) Amount of rainfall, 3 month intervals from Oct 2010 to Sep 2014. b) Flow volume, 3 month intervals for Oct 2010 to Sep 2014.

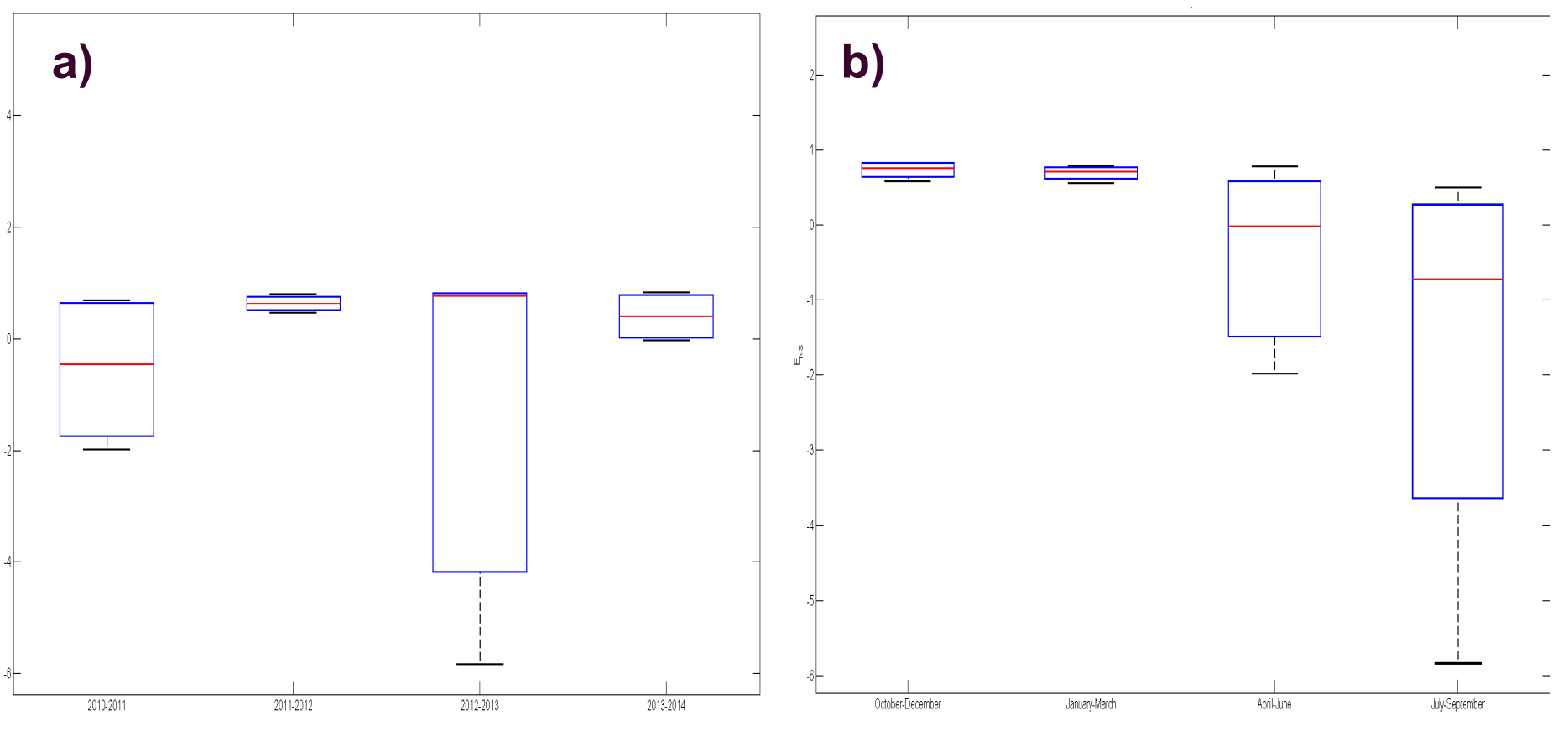

Figure 6.– a) E_{NS} values of each hydrological year. b) E_{NS} values for each Oct-Dec, Jan-Mar, Apr-Jun and Jul-Sep.

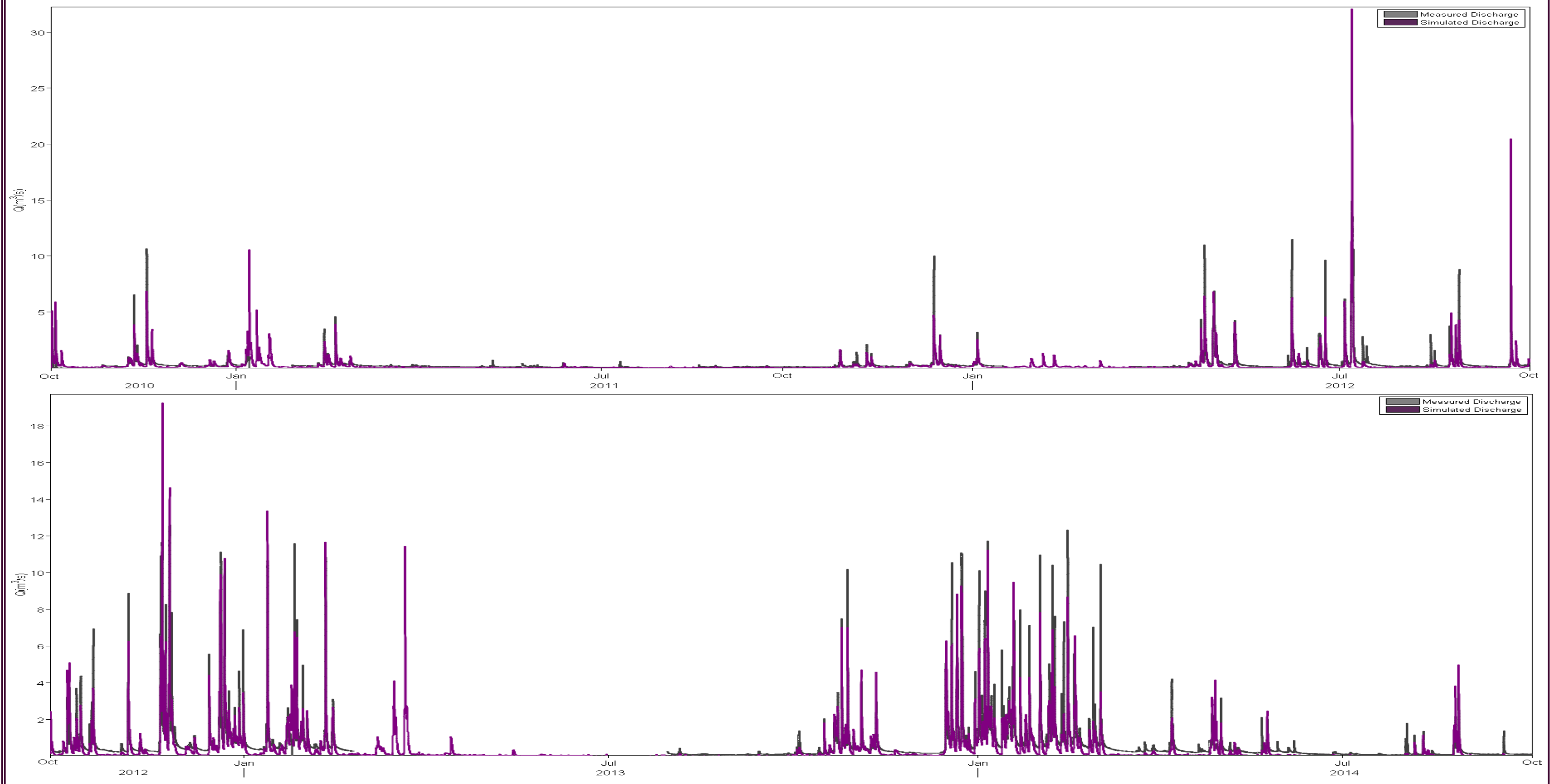

Figure 7.- Measured discharge vs Simulated discharge (2010 map) from Oct 2010 to Sep 2014.

ANALYSIS AND RESULTS

Land cover was simulated on the basis of satellite-derived maps 1990 (Digimap), 2002 and 2005 (Google Earth) and the catchment -scale field survey of 2009 as well as three end-member scenarios [%100 natural habitat (NH), %100 arable (AR) and %100 pasture (PG)]. Flow volume analysis for the complete period in three monthly intervals was done for the simulated discharge of each land cover map (figure 8a).

Compared with the 2010 map, the historical land cover simulations exhibit only small differences in flow (figure 8a). The flow volume for the three end member land cover scenarios shows an important difference (figure 8b), with %100 arable showing the highest 3-monthly flow totals followed by 100% pasture.

Peak flows were selected based on a threshold flow of 0.1 m^3/s which produced 243 events over the complete period. Peak flows were compared between two historic land cover maps, namely 2002 (27.9% arable) and 2005 (19.5% arable).

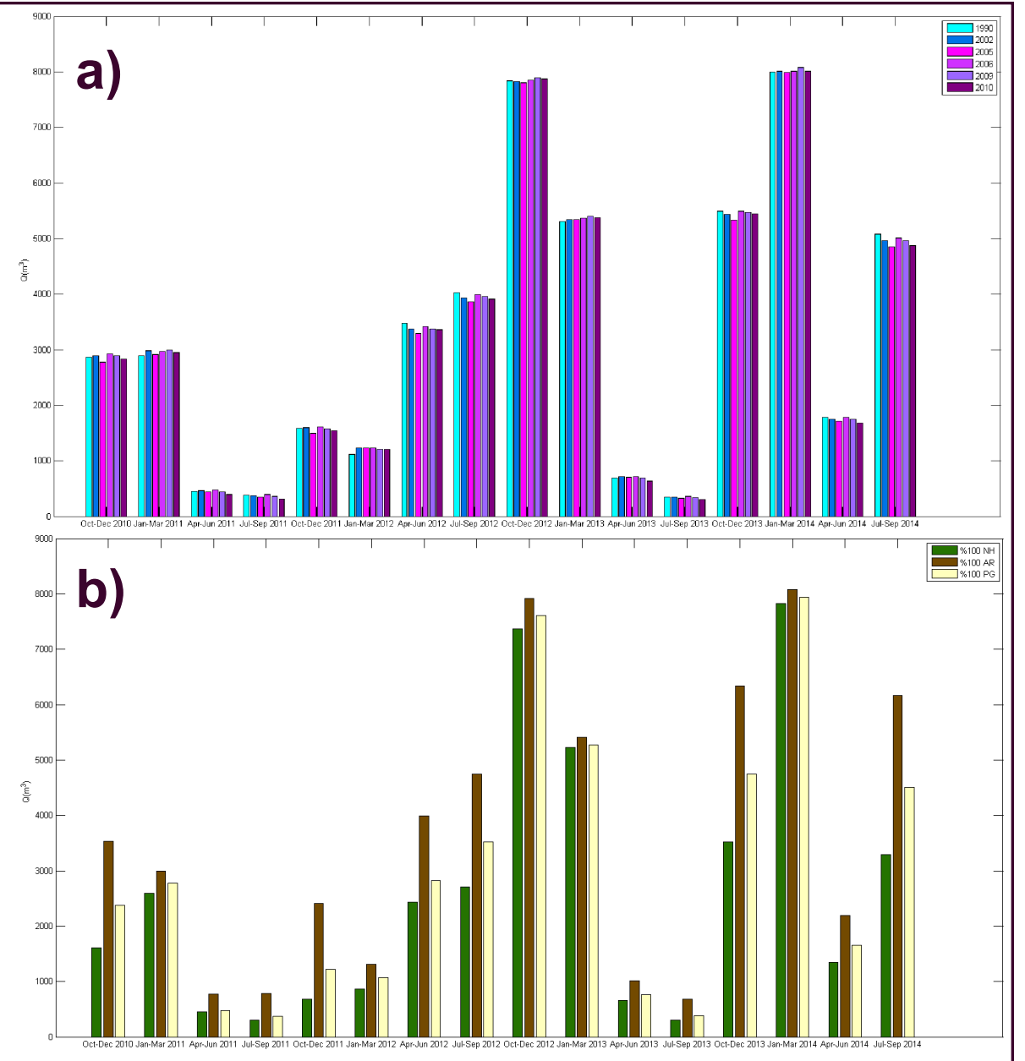

Figure 8.– a) Flow volume for the historic land cover simulations, 3 monthly intervals, b) Flow volume of end member land cover scenarios, 3 monthly interval.

Differences between paired event peak flows from the two land cover simulations were computed and divided by the maximum peak flow to give a percentage normalised difference in peak flow (figure 9b). The positive percentage for most events shows that the simulation with more arable land (2002) produced slightly higher peak flows, but the exceedance is insignificant.

Comparison of simulation results for the 100% arable and 100% pasture land cover scenarios showed that there was minimal difference in peak flows (figure 10a) during the wettest periods (Oct-Dec 2012, Jan-Mar 2013 and Jan-Mar 2014), whereas for periods during and immediately following by low flow periods, the difference in peak flows increased. Catchment flow appears more sensitive to land cover effects during drier periods and re-wetting phases where the difference in saturated hydraulic conductivity and porosity between pasture and arable (lower due to soil compaction) was detectable in streamflow. Events with negative values in figure 10b might be because arable land generates runoff before pasture and event peaks are slightly out of phase. This is most notable during the wettest periods when soil saturation and hence hydrological connectivity will be at their greatest extent.

Historic Land Cover Simulations

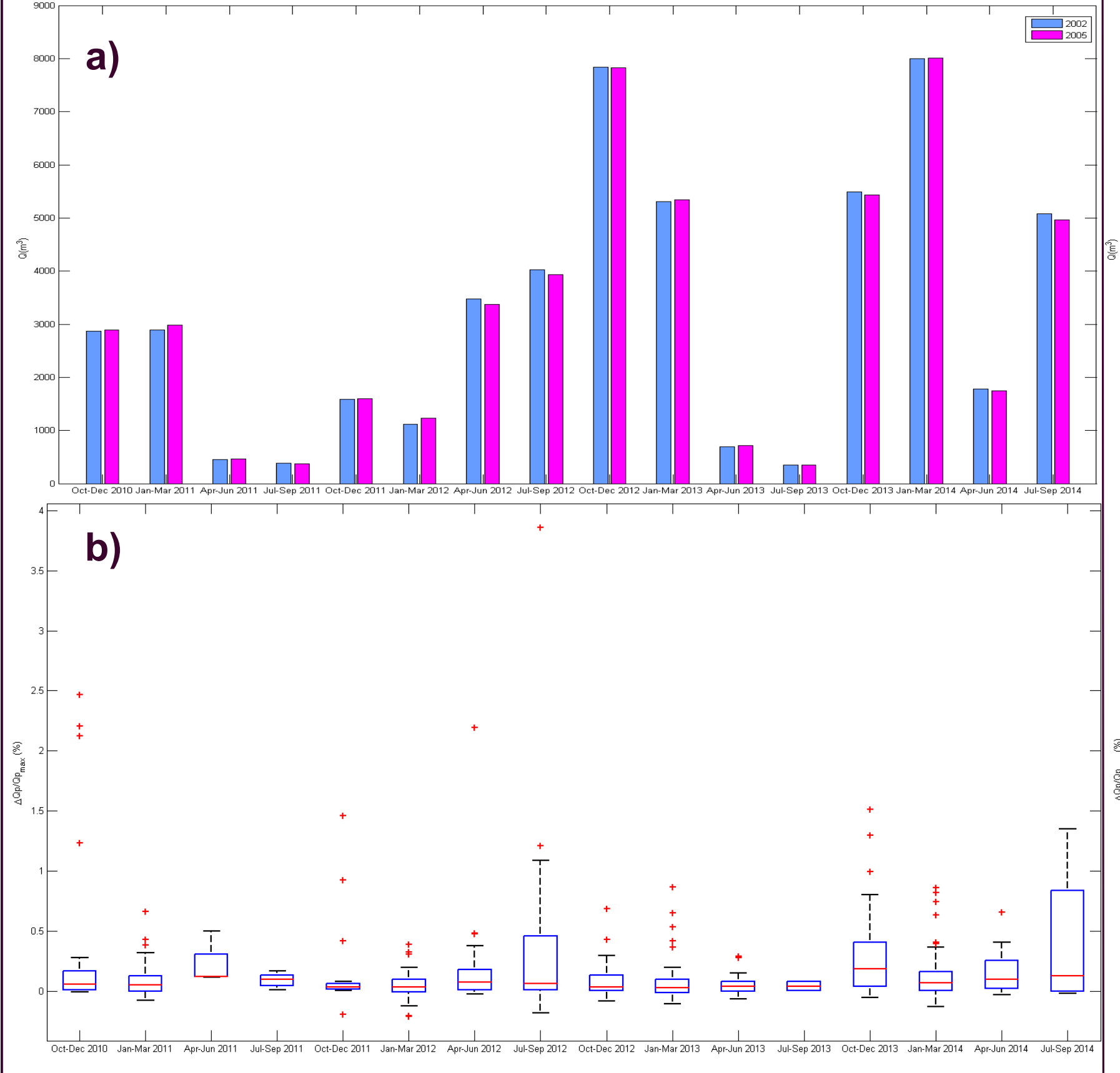

Figure 9.– a) 2002 vs 2005 maps, flow volume in 3 monthly intervals. b) Percentage of normalized difference of 2002 and 2005 map for event peak flows >0.1m^3/s.

Scenario Simulations

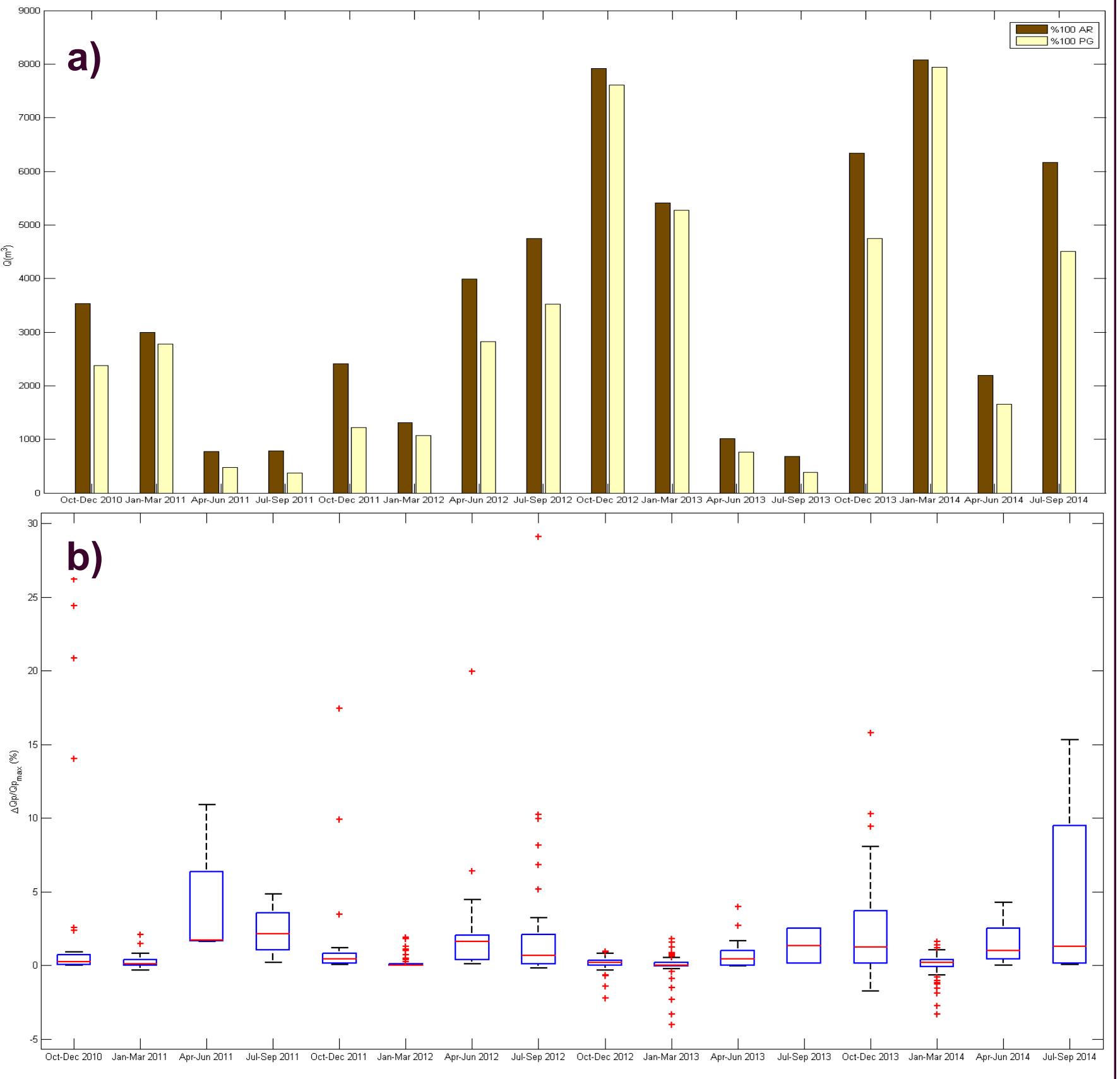

Figure 10.-a) %100 Arable vs %100 Permanent Grass flow volume in 3 monthly intervals. b) Percentage of normalized difference of %100 Arable vs %100 Permanent Grass for the event peak flows >0.1m^3/s.

SUMMARY

In the model calibration, simulated discharge compares well with measured in terms of event timing. However simulated flow is under predicted and low flows are not well estimated. The discharge simulation was more accurate for wet periods than dry periods.

Historical land cover simulations produced only small differences in flow volumes and peak flows. It appears the extent of recent past changes in agricultural land cover were insufficient to significantly impact on flow generation.

The end-member land cover scenarios showed that arable land generates more flow than woodland or pasture land. During wet periods the difference in 3-monthly flow volumes and event peak flows was reduced compared to during drier periods or re-wetting phases.

FUTURE WORK

Future work will focus on simulations of differing spatial arrangements of land covers to determine the extent to which arrangement may influence flow generation. For further comparison, simulations will be extended to another nearby instrumented catchment. The next stage of work will also address soil erosion and sediment transport. Whilst recent past changes in land cover may have only minor effects on flow, in contrast, the effect on sediment generation in response to increasing arable may be more significant. Data on sediment export is available for the research catchments to assess model performance.

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