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Modelling the effectiveness of grass buffer strips in managing muddy floods under a changing climate

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ABSTRACT

Muddy floods occur when rainfall generates runoff on agricultural land, detaching and transporting sediment into the surrounding natural and built environment. In the Belgian Loess Belt, muddy floods occur regularly and lead to considerable economic costs associated with damage to property and infrastructure. Mitigation measures designed to manage the problem have been tested in a pilot area within Flanders and were found to be cost-effective within three years. This study assesses whether these mitigation measures will remain effective under a changing climate. To test this, the Water Erosion Prediction Project (WEPP) model was used to examine muddy flooding diagnostics (precipitation, runoff, soil loss and sediment yield) for a case study hillslope in Flanders where grass buffer strips are currently used as a mitigation measure. The model was run for present day conditions and then under 33 future site-specific climate scenarios. These future scenarios were generated from three earth system models driven by four representative concentration pathways and downscaled using quantile mapping and the weather generator CLIGEN. Results reveal that under the majority of future scenarios, muddy flooding diagnostics are projected to increase, mostly as a consequence of large scale precipitation events rather than mean changes. The magnitude of muddy flood events for a given return period is also generally projected to increase. These findings indicate that present day mitigation measures may have a reduced capacity to manage muddy flooding given the changes imposed by a warming climate with an enhanced hydrological cycle. Revisions to the design of existing mitigation measures within existing policy frameworks are considered the most effective way to account for the impacts of climate change in future mitigation planning.

1. Introduction

The 'off-site' impacts of soil erosion have become a major source of concern in recent decades due largely to the environmental damage and economic costs associated with 'muddy flooding' (Boardman, 2010). Muddy floods occur when high volumes of runoff are generated on agricultural land, initiating the detachment and transport of considerable quantities of soil as suspended sediment or bedload (Boardman et al., 2006). It is therefore a fluvial process rather than a form of mass movement, but is distinguished from riverine flooding because it originates in valleys without permanent watercourses in the form of runoff generated on hillslopes and in the thalweg following rainfall (Evrard et al., 2007a). Muddy floods are reported across the loess belt of western and central Europe (Boardman et al., 1994, 2006; Boardman, 2010; Evrard et al., 2010). A principal cause of muddy flooding in the region is the switch from grassland to arable crops creating intermittently exposed bare land surfaces (Boardman, 2010). In Belgium and France, for example, muddy flooding is generally limited to late spring and early summer when crops such as maize, sugar beet, chicory and potatoes offer low resistance to runoff (Auzet et al., 2006; Verstraeten et al., 2006). In southern England and the Paris basin, muddy floods are associated with autumn and winter cereals (Boardman, 2010). The role of rainfall in triggering muddy floods is a second crucial factor, with spring-sown cereals susceptible to intense thunderstorm activity generating mainly Hortonian runoff, and winter cereals susceptible to both intense and prolonged rainfall generating Hortonian and saturation-excess runoff (Boardman, 2010). A third physical factor in causing muddy floods is the erodible nature of the loess soils in the region. The soils are highly susceptible to crusting (Evrard et al., 2008a). This reduces their infiltration capacity and surface roughness, promoting enhanced runoff. A final factor is the proximity to high density urban areas since, by definition, muddy flooding damages property and public infrastructure (Boardman, 2010). The costs associated with muddy flooding

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demonstrate why it has become a considerable socio-economic issue in recent decades across the European loess belt. There are few extensive calculations of mean annual costs, but several examples of costs related to specific muddy flooding events. For example, muddy floods led to a mean damage cost of €118 ha^{-1} y^{-1} in the village of Soucy, France (Evrard et al., 2010), while damages at four sites in the suburbs of Brighton, England were estimated at €957,000 (Robinson and Blackman, 1990). The most extensive calculation of costs comes from Belgium, where the mean annual cost to private householders is estimated at €1.6–16.5 million, while the damage to public infrastructure is estimated at €12.5–122 million (Evrard et al., 2007b).

Given the high costs associated with muddy flooding, mitigation measures have been adopted across parts of the European loess belt to control the extent of the damage. One type of mitigation is to implement alternative farming practices to address the issue at the source, with the sowing of cover crops and adoption of conservation tillage examples of these measures (Gyssels et al., 2002; Leys et al., 2007). The implementation of these practices depends on the willingness of the farmer, and for this reason they have not been widely adopted across Europe (Holland, 2004). Much more common are measures aimed at buffering, rerouting or storing runoff in order to protect the areas impacted by muddy floods. Grass buffer strips and grassed waterways act to slow runoff, increase infiltration and decrease net soil loss (Le Bissonnais et al., 2004), while retention ponds are constructed to store runoff and reduce peak discharges in downstream areas (Evrard et al., 2007b). The main obstacle to the widespread uptake of these mitigation measures is typically the lack of national-level policy (Boardman and Vandaele, 2010). An exception to this is the ‘Erosion decree,’ established by the Flemish government in 2001, providing subsidies to farmers for mitigation measures (Verstraeten et al., 2003). Within this framework, an erosion mitigation scheme was drawn up at the catchment scale and piloted for the 200 km^2 Melsterbeek catchment. Between 2002 and 2005, 120 grass buffer strips and grassed waterways were installed, and 35 earthen dams constructed (Evrard et al., 2008a). Within the catchment, a pilot thalweg draining to Velm village was extensively monitored between 2005 and 2007 following the installation of a 12 ha grassed waterway and three earthen dams in the preceding three years (Evrard et al., 2007b, 2008b). Peak discharge was reduced by 69%, runoff coefficients decreased by 50% and sediment yield decreased by 93% between the head and outlet of the catchment (Evrard et al., 2008b). Furthermore, the mitigation measures were found to be cost-effective within three years, with a cost of €126 ha^{-1} for control measures for a 20 year period compared to the mean damage cost associated with muddy floods in the area (€54 ha^{-1} y^{-1}) (Evrard et al., 2008b).

The success of these measures may diminish over the coming decades, however, as climate change poses new threats ranging from direct changes in rainfall characteristics to the indirect effects of changing land use and farming practices (Pruski and Nearing, 2002a). Several studies have modelled the impacts of climate change on soil erosion, for example in Austria (Klik and Eitzinger, 2010); Brazil (Favis-Mortlock and Guerra, 1999, 2000); China (Zhang and Liu, 2005; Zhang, 2007; Zhang et al., 2009); England (Boardman et al., 1990; Boardman and Favis-Mortlock, 1993; Favis-Mortlock and Boardman, 1995; Favis-Mortlock and Savabi, 1996); Northern Ireland (Favis-Mortlock and Mullan, 2011; Mullan et al., 2012a; Mullan, 2013a, 2013b); and USA (Phillips et al., 1993; Lee et al., 1996; Nearing, 2001; Pruski and Nearing, 2002a, 2002b; Nearing et al., 2004, 2005; Zhang et al., 2004; O'Neal et al., 2005; Zhang, 2005; Zhang and Nearing, 2005). These studies typically employ a soil erosion model – most commonly the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995) – in conjunction with climate scenarios derived from general circulation models and applied as change factors or in more recent studies downscaled for site-specific impact assessment (e.g., Zhang et al., 2004, 2009; Zhang, 2005, 2007; Zhang and Liu, 2005; Favis-Mortlock and Mullan, 2011; Mullan et al., 2012a Mullan, 2013a, 2013b). A smaller selection of studies have also factored in changes in land use and management (e.g., O'Neal et al., 2005; Favis-Mortlock and Mullan, 2011; Mullan et al., 2012a; Mullan, 2013a, 2013b). While some of these studies have modelled future soil erosion rates in the context of the off-site impacts, no study to date has examined explicitly changes in muddy flooding or the effects of climate change on mitigation measures designed to reduce muddy flooding. The aim of this study is to model the impacts of climate change (temperature and precipitation) on muddy flooding for a case study hillslope where mitigation measures have been implemented within the 200 km^2 Melsterbeek catchment in Flanders, Belgium. Given the success of present-day mitigation measures, the key research question seeks to address if these mitigation measures will continue to be successful in a changing climate. In terms of scientific significance, these results will build on the existing studies that have examined climate change impacts on soil erosion. These studies are important in assisting with conservation planning. Employing the widely used WEPP model alongside the use of downscaling techniques based on the latest state-of-the-art Earth System Models (ESMs) represents an advance on many previous climate change-soil erosion studies. The study is also vital in a more local context since local water authorities, land use managers, farmers and local residents will all be impacted by any changes in muddy flooding that threaten to compromise existing mitigation measures. In particular, results will be disseminated to the local water authority responsible for managing muddy flooding in the Limburg province so they can help influence decision-making on future mitigation planning.

2. Materials and methods

2.1. Study area

The Belgian loess belt is a ca. 9000 km^2 plateau with a mean altitude of 115 m gently sloping to the north (Fig. 1). Belgium has a temperate maritime climate influenced by the North Sea and Atlantic Ocean with cool summers and mild winters. The mean annual temperature is 9–10 °C with a mean annual precipitation range of 700–900 mm (Hufty, 2001). The rainfall distribution is relatively even throughout the year, with a slight peak in rainfall erosivity between May and September (Verstraeten et al., 2006). Soils are mostly loess-derived haplic luvisols (World Reference Base, 1998). Arable land dominates the Belgian loess belt, covering around 65% of the land surface in the area (Statistics Belgium, 2006). The dominant crops are cereal, industrial and fodder crops such as sugar beet, oilseed rape, maize, chicory and potatoes. These summer crops have largely replaced winter cereals in the past few decades (Evrard et al., 2007a). Farmers are encouraged to sow cover crops such as mustard and phacelia during the dormant late spring and early summer period while summer crops establish sufficient cover to protect the soil (Bielders et al., 2003).

The case study site, herein referred to as Kluiskapel hillslope, is a 340 m long hillslope within a 7.3 ha field located in the 200 km^2 Melsterbeek catchment near the town of St-Truiden in the Flanders region of Belgium. The area has been affected by numerous muddy floods in the past couple of decades, with a local water agency tasked specifically with installing and maintaining mitigation measures (Evrard et al., 2007b).The elevation within the slope ranges between 80 and 95 m.a.s.l. As determined from a 10 m resolution digital elevation model (described further in Section 2.3), the slope is broadly convex in the upper half and concave in the lower half, with an average steepness of 4.2% (Fig. 2).

As determined by laboratory testing of soil samples as described in Section 2.3, the soil type is very typical of the European loess belt. It is a silty loam with 81% silt content and 4.5% organic matter. The long-term mean annual temperature, taken from the nearby station in Maastricht in the Netherlands (described further in Section 2.3), is 10 °C, and the mean annual precipitation is 769 mm, with the season occurring in the summer wettest. Fig. 3 shows how long-term temperatures and