Advances in Water Resources 96 (2016) 74–87

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Evaluating the efficacy of distributed detention structures to reduce downstream flooding under variable rainfall, antecedent soil, and structural storage conditions

Nicholas W. Thomas[a,*], Antonio Arenas Amado[a], Keith E. Schilling[b], Larry J. Weber[a]

[a] IIHR-Hydroscience & Engineering, The University of Iowa, 100C. Maxwell Stanely Hydraulics Laboratory, Iowa City, IA 52242-1585, United States
[b] Iowa Geological Survey, The University of Iowa, 300 Trowbridge Hall, Iowa City, IA 52242, United States

ARTICLE INFO

Article history:
Received 14 March 2016
Revised 6 July 2016
Accepted 7 July 2016
Available online 8 July 2016

Keywords:
Numerical modeling
Peak flow reduction
Peak flow scale invariance
Flood mitigation
Antecedent soil moisture analysis

ABSTRACT

This research systematically analyzed the influence of antecedent soil wetness, rainfall depth, and the subsequent impact on peak flows in a 45 km^2 watershed. Peak flows increased with increasing antecedent wetness and rainfall depth, with the highest peak flows occurring under intense precipitation on wet soils. Flood mitigation structures were included and investigated under full and empty initial storage conditions. Peak flows were reduced at the outlet of the watershed by 3–17%. The highest peak flow reductions occurred in scenarios with dry soil, empty project storage, and low rainfall depths. These analyses showed that with increased rainfall depth, antecedent moisture conditions became increasingly less impactful. Scaling invariance of peak discharges were shown to hold true within this basin and were fit through ordinary least squares regression for each design scenario. Scale-invariance relationships were extrapolated beyond the outlet of the analyzed basin to the point of intersection of with and without structure scenarios. In each scenario extrapolated peak discharge benefits depreciated at a drainage area of approximately 100 km^2. The associated drainage area translated to roughly 2 km downstream of the Beaver Creek watershed outlet. This work provides an example of internal watershed benefits of structural flood mitigation efforts, and the impact the may exert outside of the basin. Additionally, the influence of $1.8 million in flood reduction tools was not sufficient to routinely address downstream flood concerns, shedding light on the additional investment required to alter peak flows in large basins.

1. Introduction

In history, the problem of flood mitigation has been described simply as: How large does a reservoir need to be to meet a given inflow demand? (Simonovic, 1992). Alternatively, it could be restated as how many distributed projects are needed to meet a given demand? Distributed flood mitigation through structural or nonstructural measures is not a new concept (Andoh and Declerck, 1997; Kurz et al., 2007; Montaldo et al., 2004), typically applied to urban drainages (Emerson and Traver, 2008; Emerson et al., 2005; Hamel et al., 2013; Ravazzani et al., 2014). The objective behind a distributed flood mitigation approach is to store excess flood water in upland basins, and soils, reducing the accumulation of downstream discharge.

It is common hydrologic knowledge that reservoirs reduce and attenuate inflow hydrograph peaks. Runoff water is stored up to a set maximum capacity and the available storage dictates the magnitude which high flows can be mitigated. Reservoirs built for the purpose of flood mitigation modify the downstream flood frequency (Ayalew et al., 2013).

Distributed storage analyses have often been applied to storm water management of urbanization areas, termed source control (Hamel et al., 2013; Petrucci et al., 2013). Impervious surfaces associated with urban development prevent infiltration of rainfall, as a result runoff volumes and peak flow rates increase. To mitigate these negative effects, networks of storm water detention basins retain and reduce total runoff volume and peak. These structures are often multifunction adapting to sediment and nutrient loss from urban landscapes.

These same concepts can be applied to agriculturally developed areas, also producing more runoff than natural conditions (Babbar-Sebens et al., 2013). Kurz et al. (2007) discussed the use of current roadway and culvert infrastructure modified for flood storage. Each upstream structure mitigates the impacts of intense rainfall at the location where they occur. Distributed structures offer the ability to attenuate peak flows across a basin, significantly reducing costs as compared to a single reservoir (Andoh and Declerck, 1997), and

* Corresponding author.
E-mail address: nicholas-thomas@uiowa.edu (N.W. Thomas).

http://dx.doi.org/10.1016/j.advwatres.2016.07.002
0309-1708/

decentralize the risk of failure. Systems of distributed reservoirs have been shown to systematically reduce flood peaks throughout various catchments with distributed models (Del Giudice et al., 2014; Montaldo et al., 2004; Perez-Pedini et al., 2005; Ravazzani et al., 2014). Peak flow reductions in these studies ranged widely from 0.3% to 36% (Emerson et al., 2005; Perez-Pedini et al., 2005; Ravazzani et al., 2014; Wang and Yu, 2012).

Studies investigating detention basins indicated a dependence of peak flow reduction on pre-event storage conditions (Ayalew et al., 2013; Hancock et al., 2010; Montaldo et al., 2004), precipitation intensity (Hancock et al., 2010), event duration (Levy and McCuen, 1999; Petrucci et al., 2013), and catchment characteristics (Del Giudice et al., 2014; Emerson et al., 2005; Wang and Yu, 2012). Many studies have shown an influence of a soils antecedent moisture condition (AMC) on the fraction of rainfall transformed into runoff (De Michele and Salvadori, 2002; Descroix et al., 2002; James and Roulet, 2007; Meyles et al., 2003; Nishat et al., 2010; Penna et al., 2011; Radatz et al., 2013; Sahu et al., 2007). The predictability of hydrologic response is predicated on the knowledge of soil moisture prior to an event (James and Roulet, 2007; Meyles et al., 2003). Upstream areas in a dry initial state infiltrate the majority of precipitation. Water which exfiltrates back to the surface is reabsorbed by downslope drier soils (Meyles et al., 2003). This produces a disconnection between hillslope and stream response (Dunne and Black, 1970; Penna et al., 2011). In a wet state the subsurface responds in unison with surface runoff producing a progressively increasing response as water moves downstream, unable to reabsorb into subsurface materials (Grayson et al., 1997; Meyles et al., 2003). A soil moisture threshold differentiating wet and dry basin response conditions has been estimated at a soil saturation of 49% (James and Roulet, 2007), 70% (Grayson et al., 1997), 75% (Meyles et al., 2003), 80% (Radatz et al., 2013), and 90% (Penna et al., 2011).

Precipitation intensity and duration directly impact runoff volume and timing of peak flow production (Hewlett et al., 1984; Levy and McCuen, 1999; Petrucci et al., 2013; Radatz et al., 2013). Levy and McCuen (1999) indicated significant effects of design storm duration and depth, on peak flows and storm volumes. Typically, design storms are such that the precipitation is in excess of soil infiltration capacity. Under normal conditions, precipitation in excess of a soils infiltration capacity is a requirement for wide spread runoff production (Bronstert and Bardossy, 1999). Without heavy precipitation, only topographically convergent regions of the watershed contributed to surface flow (Dunne and Black, 1970; Grayson et al., 1997; James and Roulet, 2007; Meyles et al., 2003; Penna et al., 2011).

Peak flows have been analyzed under the guise of spatial scale invariance observed natural systems (Ayalew et al., 2015; Furey and Gupta, 2005; Furey and Gupta, 2007; Gupta et al., 2010; Mandapaka et al., 2009; Ogden and Dawdy, 2003), and simulated systems (Ayalew et al., 2014a,b, 2015; Gupta et al., 1996; Mantilla et al., 2006; Menabde and Sivapalan, 2001). These studies show the fundamental role of the drainage network, catchment physical properties, and event to event variability of precipitation and antecedent conditions in the scaling relationships. Similar relationships are applied for regional flood frequency analysis for prediction of flows over large spatial extents in ungauged or poorly gauged regions (Eash et al., 2013). Ayalew et al. (2015) showed that scaling invariance of peak discharges held true for event scale time periods in the Iowa–Cedar River basin (34,000 km^2). This work indicates that rainfall-runoff information from an abstracted basin offers an identical scale relationship, due to the self-similarity in river networks. This power law relationship offers the expected value of peak discharge, the uncertainty can be quantified using the Horton Law for peak discharges reported by (Gupta et al., 2015).

Our study assessed the effects of distributed flood detention basins within a small catchment and the attenuated impact downstream. We divided the study into 3 main questions: (1) How do variable rainfall and antecedent soil moisture conditions affect peak flow production? (2) How do distributed flood mitigation practices alter peak flows throughout the watershed under variable rainfall, antecedent moisture, and pre-event reservoir storage conditions? (3) How does the influence of flood mitigation strategies affect areas downstream of the altered watershed? The impact of structures was extrapolated beyond the watershed outlet through a peak flow scale invariance assumption for each combination of design features. A coupled hydrologic model forced with synthetic design storm precipitation was applied to investigate the combined stated effects. The manner in which precipitation depth, antecedent soil moisture, and pre-event structural storage conditions compound, determined the total effectiveness of the flood mitigation efforts.

2. Study methodology

2.1. Study area

The focus of our study was the Beaver Creek Watershed (BCW), a 45 km^2 catchment, located in northeastern Iowa, USA. BCW is dominated by row crop agriculture (corn and beans) representing 72% of the catchment. The remaining catchment area is a mix of grassland and deciduous forest, with urban type land uses representing less than 1% of the area. Clay loam and loam type soil textures typify surficial soils in the alluvial deposits, and uplands, respectively (NRCS 2014). The average basin slope is 4.3%, with the majority of relief occurring near the outlet. The surficial geology of the region consists of oxidized and weathered glacial till overlying hard and dense unoxidized till. Unoxidized glacial till is present at depths ranging from 1 m to 18 m below the land surface in the region, the unit exhibits a significant reduction in vertical hydraulic conductivity (Bakhsh et al., 2004; Eidem et al., 1999; Schilling and Tassier-Surine, 2006; Seo, 1996). Hence, we assumed the unoxidized till to represent an impermeable bottom to the basin.

Three multi-purpose wetlands were constructed in the BCW prior to this study. Two of the projects were funded by the Conservation Reserve Enhancement Program (CREP) for nutrient reduction purposes (Fig. 1, site 1 and site 2), and one through private funding sources (Fig. 1, site 4). The CREP structures were built with a standing pool elevation, saturating the soils, enhancing denitrification, and discharging water over the principal spillway (normal pool elevation, Table 1). These structures have an additional emergency spillway at approximately 1 m above the permanent pool elevation, designed for a 0.04 annual exceedance probability rainfall event. The CREP structures were located in the upper one third of the catchment area, draining the least sloped most heavily cultivated areas. In 2015, six new projects were built as dual purpose denitrification and flood mitigation structures, funded by the Iowa Watersheds Project (IWP). The structure designs were completed by private consulting firms and were built to National Resource Conservation Service (NRCS) Conservation Practice Codes No. 410 (NRCS 1985), No. 378 (NRCS 2011), and Iowa Department of Natural Resources (IDNR) Technical Bulletin No. 16 (IDNR 1990).

2.2. Numerical model

Peak flow events were simulated with HydroGeosphere (HGS), a fully integrated, coupled, surface-subsurface hydrologic model. HGS simulates depth averaged two dimensional unsteady flow across the entire surface domain through the diffusion wave approximation of the St. Venant equations. A three dimensional variably saturated form of the Richards equation is solved to describe subsurface flow through a porous media. Coupling of the surface and subsurface is completed through a dual node approach, where a