Effect of Spatially Distributed Small Dams on Flood Frequency: Insights from the Soap Creek Watershed

Tibebu B. Ayalew[1]; Witold F. Krajewski[2]; Ricardo Mantilla[3]; Daniel B. Wright[4]; and Scott J. Small[5]

Abstract: Dams are ubiquitous in the United States, with more than 87,000 influencing streamflow across the nation. The significant majority of these dams are small and are often ignored in real-time flood forecasting operations and at-site and regional flood frequency estimations. Even though the impacts of individual small dams on floods is often limited, the combined flood attenuation effects of a system of such dams can be significant. In this study, the authors investigate how a system of spatially distributed small dams affect flood frequency across a range of drainage basin scales using the 660-km^2 Soap Creek watershed in southeastern Iowa, which contains more than 144 small dams. Results from continuous simulation of the system of small dams indicate that peak discharges reduced between 20 and 70% with the effect decreasing as the drainage area increases. This means that neglecting the effects of the system of small dams may lead to an overestimation of flood risk, which has implications in both flood frequency estimation and real-time flood forecasting. Considering that more small dams are being built across watersheds in Iowa and elsewhere in the country, the results also highlight how the peak discharge attenuation effects of these dams is an additional factor that invalidates the stationarity assumption that is used in at-site and regional flood frequency analysis. **DOI: 10.1061/(ASCE)HE.1943-5584.0001513.** © *2017 American Society of Civil Engineers.*

Author keywords: Small dams; Regulated flood frequency; Stationarity of peak discharges; River network.

Downloaded from ascelibrary.org by Univ of Iowa Libraries on 03/02/17. Copyright ASCE. For personal use only; all rights reserved.

Introduction

According to the National Inventory of Dams (NID) that is maintained by the U.S. Army Corps of Engineers (USACE), there are more than 87,000 dams built in the continental United States (USACE 2013). The majority of these dams are categorized as small with a height between 2 and 12 m and a storage capacity between 0.06 and 1.2 Mm^3. Nationally, the construction of these dams peaked in the 1960s and has since decreased due to recognition of the negative effects of dams on the riverine ecosystem (Collier et al. 1996; Friedman et al. 1998; Graf 2006; Inbar 1990; Ligon et al. 1995). However, considerable numbers of small dams are still being built across the country. For example, in the state of Iowa, where this study is based, the construction of small dams is on the rise with 448, 624, and 664 dams built in the last three decades, respectively. The sheer number of these dams means that their effect on catchment hydrology and geomorphology deserves greater attention.

[1]Senior Hydrologist, Berkshire Hathaway Specialty Insurance, 2633 Camino Ramon, San Ramon, CA 94583 (corresponding author). ORCID: http://orcid.org/0000-0002-7280-8100. E-mail: tibebu.ayalew@bhspecialty.com

[2]Professor, IIHR-Hydroscience and Engineering, Univ. of Iowa, C. Maxwell Stanley Hydraulics Laboratory, Iowa City, IA 52242. E-mail: witold-krajewski@uiowa.edu

[3]Assistant Professor, IIHR-Hydroscience and Engineering, Univ. of Iowa, C. Maxwell Stanley Hydraulics Laboratory, Iowa City, IA 52242. E-mail: ricardo-mantilla@uiowa.edu

[4]Assistant Professor, Dept. of Civil and Environmental Engineering, Univ. of Wisconsin-Madison, Madison, WI 53706. E-mail: danielb.wright@wisc.edu

[5]Assistant Research Scientist, IIHR-Hydroscience and Engineering, Univ. of Iowa, C. Maxwell Stanley Hydraulics Laboratory, Iowa City, IA 52242. E-mail: scott-small@uiowa.edu

Note. This manuscript was submitted on July 6, 2016; approved on December 7, 2016; published online on February 25, 2017. Discussion period open until July 25, 2017; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Hydrologic Engineering***, © ASCE, ISSN 1084-0699.

The impact of large dams on downstream peak discharges at the rainfall-runoff event scale as well as on flood frequency is well documented (e.g., Graf 2006; Laurenson 1973; Magilligan et al. 2003; Williams and Wolman 1984). The complex nature of these impacts has led to regional flood frequency methods that ignore peak discharge information obtained from regulated sites (IACWD 1982). However, these methodologies implicitly assume that streamflow observed at the remaining stream gauging sites is unregulated, thus ignoring the potential impacts of spatially distributed small dams on peak discharges. In addition, the continued construction of small dams can lead to the violation of the assumption of stationarity of the peak discharge distribution, which is a central feature of conventional flood frequency estimation.

Real-time flood forecasting operations also typically ignore the flood attenuation effects of spatially distributed small dams. The limited size of individual small dams can be one of the reasons their role in flood attenuation is ignored both in at-site and regional flood frequency analysis as well as in real-time flood forecasting operations. Collectively, however, they have the potential to abstract a considerable amount of runoff in a given watershed and hence affect the observed peak discharge across a range of spatial scales. As an example, the Des Moines River basin ($A = 36{,}358$ km^2) in the state of Iowa contains 858 dams with a total storage capacity of 3,290 Mm^3 (2,662,906 acre-ft). This roughly translates to 90 mm (3.5 in.) of runoff storage in the basin if all the dams are assumed to store water at their 100% storage capacity.

While some progress has been made in investigating the effect of a single dam on flood frequency, there is limited research on the issue of flood frequency modification by a network of small dams. This issue appears to be gaining interest recently with the main focus on detention basins in an urban setting (e.g., Emerson et al. 2005; Ravazzani et al. 2014; Smith et al. 2015). Emerson et al. (2005) investigated how a system of more than 100 detention basins in the 62-km^2 Valley Creek watershed in Pennsylvania affects the peak discharge at the watershed scale. Based on simulation of six storm events observed in the basin between September 2001 and August 2002, they concluded that the detention basins have

Downloaded from ascelibrary.org by Univ of Iowa Libraries on 03/02/17. Copyright ASCE. For personal use only; all rights reserved.

negligible effect on the peak discharge at the outlet of the basin. In particular, they showed that, in comparison to an unregulated peak discharge, the regulated peak discharge decreased by 4% for one of the events, whereas it increased by 3.5% for another event. They attributed the increase in the peak discharge for one of the events to the higher rate of delayed runoff that came from the portion of the watershed that is regulated by the detention basins, which eventually coincided with the peak discharge that is generated in the unregulated portion of the watershed. Ravazzani et al. (2014) evaluated a system of seven detention basins in the 94.5-km^2 Olona river basin that is located to the north of Milan, Italy. Based on the simulation of the probable maximum design flood of a 100-year return period, they showed that the peak discharge reduced between 31 and 36% depending on how the detention basins are configured in space. A study by Smith et al. (2015) investigated the peak discharge modification effects of a system of detention basins in the 14-km^2 Dead Run watershed that is located in Maryland. The results from their simulation of 21 warm season flood events that occurred in the watershed between 2008 and 2012 showed that, on average, the peak discharge decreased between 0.03 and 27.5% at different scales in the basin. They also suggested that the detention basin efficiency, which they defined as the ratio of percent peak discharge decrease to percent detention-controlled area, decreases with increasing drainage area.

In addition to the preceding studies that looked into the effect of a network of detention basins on the peak discharge in an urban setting, a few other studies also looked into these effects in a rural setting. A study by Thomas et al. (2016) investigated the effects of a network of nine multipurpose detention basins on peak discharges in the 45-km^2 Beaver Creek watershed that is located in northeastern Iowa. The results from their numerical simulation of the watershed using a 24-h design storm of exceedance probabilities of 0.2, 0.1, 0.04, 0.02, and 0.01 showed that the peak discharges at the outlet of the watershed decreased between 3 and 17%. Mamede et al. (2012) investigated the frequency of reservoir overflow in the 25,000-km^2 upper Jaguaribe basin in northeast Brazil, which hosts approximately 4,000 reservoirs whose size varies between 2,500 m^3 and 2,000 Mm^3. Using a 20-year-long numerical simulation of the reservoir network, they showed that the avalanche size, which they defined as the number of interconnected reservoirs that overflow in a single day, follows a power law distribution. Additional results from the investigation of the same river basin and network of reservoirs by Peter et al. (2014) showed that the thousands of small-sized and medium-sized dams in the basin play a critical role in reducing the avalanche size at large basin scales.

The preceding literature review shows that there is a growing consensus on peak discharge reduction due to a network of small dams. The next natural step is to investigate how a network of dams affects the flood frequency across a range of exceedance probabilities, a problem that is not yet fully addressed in the literature. When it comes to single large dams, exploring how to estimate the regulated flood frequency has been an area of research that was proposed in *Bulletin 17B* (IACWD 1982). A notable approach for estimating regulated flood frequencies for locations in the immediate downstream of major dams is the volume-duration-frequency (VDF) based approach used by the USACE (Goldman 2001; USACE 2010). According to this methodology, the regulated flood frequency curve can be computed as follows: First, estimate volume-duration-frequency curves using the unregulated period of record. Second, estimate the inflow duration that leads to the condition that both the inflow volume and the corresponding peak discharge of a particular flood event will have the same exceedance probability. This is an iterative process in which an inflow duration is first assumed and the inflow volume is then calculated for all the available annual maximum peak discharge events. This is followed by the calculation of the volume frequency. The iteration will continue until it identifies the inflow duration that results in flow volume and peak discharge of each flood event in the available sample attaining the same exceedance probability, which is called the critical inflow duration. It may not be always possible to identify a critical inflow duration that works for all the flood events on record, in which case the duration that works for the majority of the events is chosen. Once the critical inflow duration is identified, a relationship between inflow volume and outflow peak discharge can easily be established for the critical duration. A similar volume-to-peak discharge relationship is also used by Bradley and Potter (1992), who proposed an alternative flood frequency estimation framework for simulated flows. Finally, the regulated flood frequency curve can be estimated by combining the volume-duration-frequency curve corresponding to the critical duration and the inflow volume to outflow peak discharge established in the previous step. The VDF approach is subject to significant uncertainty due to complexities associated with the estimation of the critical duration, the initial water level in the reservoir, and uncertainties associated with the operation of the dam (Goldman 2001). Ayalew et al. (2013) showed that the traditional VDF-based regulated flood frequency estimation methodology can lead to the underestimation of flood risk for downstream locations due to the fact that the VDF approach assumes that the initial water level in the reservoir is always at the bottom of the flood control pool.

Uncertainties associated with the initial water level in the dam can be addressed using a continuous simulation approach that allows for the computation of the available storage in the dam as a function of inflow to the dam and different operation rules or outlet structure geometries. Nehrke and Roesner (2004) used a continuous simulation approach with 50 years of hourly rainfall records to study how the design of the release structure (orifice) of detention ponds affects the flow frequency curve. Ayalew et al. (2013) also used a continuous simulation approach that is driven by a stochastically generated rainfall time series to show how the storage capacity, release capacity, and outlet geometry affects the frequency curve of peak discharges regulated by a small dam. These studies demonstrated that a continuous simulation approach can be used to gain insights into how the different design and operation aspects of a single dam affect the flood frequency for downstream locations.

Montaldo et al. (2004) investigated the flood attenuation benefits of a network of 14 hydroelectric dams in the 1,534-km^2 Toce River basin in Italy using a distributed rainfall-runoff model. They simulated single rainfall-runoff events by assuming different initial water levels stored behind the dams. As expected, they showed that the flood peak attenuation is significant on those branches of the river network that are regulated by dams. Liu et al. (2014) explored how a system of small dams affects the streamflow and water quality. Using the soil and water assessment tool (*SWAT*) (Neitsch et al. 2011), they simulated the 75-km^2 South Tobacco Creek watershed in Canada, which is regulated by 26 small dams. Their analysis showed that the daily maximum peak discharge can be reduced by up to 14% depending on the initial water levels behind the dams. These studies highlight the significant role that initial water level behind the dams plays in determining the magnitude of the peak discharge at the catchment outlet. As discussed previously, this problem can be circumvented by adopting a continuous simulation approach in which the initial water level behind the dams is a random function of the inflow and outflow time series.

Ayalew et al. (2015b) used a continuous simulation approach in an idealized setup and investigated how the spatial configuration of dams (in series or in parallel), the storage capacity, and the release

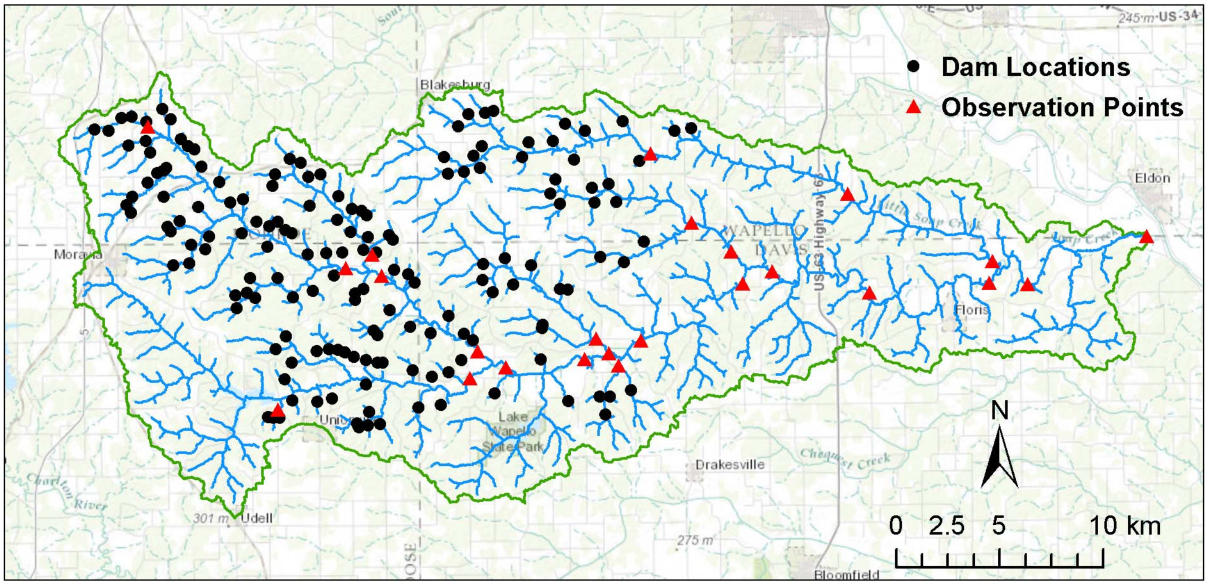

Fig. 1. Soap Creek watershed and the geographic location of the 133 dams (circles) and the simulated streamflow observation points (triangles); only streams of order 3 and beyond are shown for the sake of clarity

Downloaded from ascelibrary.org by Univ of Iowa Libraries on 03/02/17. Copyright ASCE. For personal use only; all rights reserved.

capacity of two small dams relative to their location in the drainage network affect the flood frequency at different locations in the catchment. In particular, they showed that two dams that are configured in parallel offer better flood reduction than the same two dams configured in series. Moreover, they showed that, when two dams are configured in series, emptying the upstream dam first offers a better flood peak reduction than if the downstream dam is emptied first. They also show that if two dams that have different storage capacities are to be configured in series, putting the bigger dam in the upstream section of the catchment provides better flood peak reduction capability. Most importantly, they explained that these results are due to the location of the dams in the drainage network. Specifically, they showed that dams that are placed in the parts of the drainage network that contribute to the width function (Rodriguez-Iturbe and Rinaldo 1997) maximums offer greater flood reduction capability than dams placed elsewhere in the catchment.

The present study is a continuation of a systematic study on the subject of flood frequency modification by small dams (Ayalew et al. 2013, 2015b; Mantilla et al. 2012). Ayalew et al. (2013, 2015b) used a hypothetical but realistic catchment-dam system to address the issue. The present study expands the analysis to an actual system in the 660-km^2 Soap Creek watershed located in southeastern Iowa, with the main objective of quantifying the effect of 133 spatially distributed small dams on flood frequency across a range of spatial scales in the watershed. The results provide new insights on how spatially distributed small dams affect the flood frequency across a range of spatial scales.

Study Watershed

The 660-km^2 Soap Creek watershed is located in southeastern Iowa and is a tributary to the Des Moines River, which is one of the major tributaries of the Mississippi River. Examination of data obtained from USACE (2013) shows that the watershed is regulated by a network of 144 spatially distributed small dams. In the United States, the definition of what is called a small dam can vary from state to state depending on the state's dam safety program. A review of these reports indicates that those dams that have a storage capacity of less than 1.2 Mm^3 (1,000 acre-ft) and a height of less than 12.2 m (40 ft) are generally categorized as small dams. The 144 dams scattered across the Soap Creek watershed have an average storage capacity of 343,000 m^3 (278 acre-ft) and an average height of 9 m (30 ft) and hence generally satisfy the definition of a small dam. Although there are 144 small dams reported in the NID database, only 133 of the 144 small dams have complete engineering design information. Hence, only the 133 dams, whose locations are shown in Fig. 1, are used in this study.

The 144 dams that are reported in the NID database have been built over several decades and many more dams are either under construction or planned to be constructed in the near future. Fig. 2 summarizes the number of dams built in the watershed per decade. In can be seen that the majority of the small dams were built in the 1990s and 2000s. Moreover, according to the NID database, there were 15 dams built between 2010 and 2012, which suggests that there is an increasing trend in the construction of small dams in the watershed. Fig. 2 also shows that the total storage capacity of the dams, which is the summation of the individual storage capacity of the small dams, has significantly increased with time and currently stands at 41×10^6 m^3. This corresponds to 60 mm (2.4 in.) of

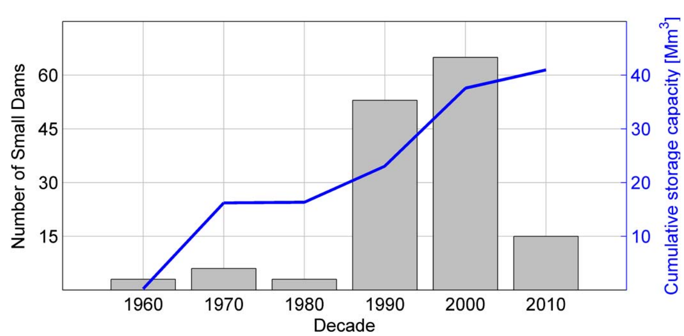

Fig. 2. Number of dams built in the Soap Creek watershed per decade and the cumulative total storage capacity of the dams; the NID database documents only those dams built up to the year 2013

runoff storage in the basin. The storage capacity of the dams in the catchment ranges from 23,436 to 15,591,210 m^3. The mean and median storage capacity of the dams are 1,321,934 and 498,326 m^3, respectively. Of these dams, 77 are built for flood control, 57 are built for fire protection, livestock, or small fish ponds, and the rest are built for recreational and other purposes.

The Soap Creek watershed is monitored by four stream stage sensors installed by the Iowa Flood Center (IFC) at the University of Iowa. There are no USGS stream gauging sites in the watershed. The existing IFC stream stage sensors were installed in November 2012 and can only report water level (stage) information because there is yet no stage-discharge relationship (rating curve) available for these sites. The short period of record of streamflow at these gauging sites means that the watershed is essentially ungauged and, as a result, an observation-based empirical analysis of the role of these spatially distributed small dams on flood frequency is impossible. As a result, a continuous simulation approach is adopted, simulating the watershed with and without the dams using a physically based distributed hydrologic model and two types of rainfall inputs: a 10,000-year-long sequence of spatially uniform hourly rainfall generated using a stochastic rainfall simulator, and the Stage IV hourly radar-rainfall data (Lin and Mitchell 2005) that is available since 2002. The components of the continuous simulation experiment are discussed in detail in the subsequent sections.

Rainfall Data

The Soap Creek watershed is covered by the nationwide Stage IV radar-rainfall product, which is available from 2002 onward at an approximately 4-km spatial and an hourly temporal resolution. This means that the radar-rainfall data are only available for the past 13 years, which limits their application to flood frequency estimation. Nevertheless, the watershed was simulated using the available radar-rainfall data to conduct a first-order analysis of the flood frequency effects of the spatially distributed small dams.

The limited length of the available radar-rainfall data requires looking for an alternative source of rainfall data to conduct the long simulation experiments. To this end, a stochastic point rainfall generator that is based on the widely used Bartlett-Lewis rectangular pulse (BLRP) model (Rodriguez-Iturbe et al. 1987) is selected. The model, which belongs to the family of Poisson cluster processes, assumes that a given storm system is a temporal superposition of a random number of storm cells that have random intensity and duration. The model has the following structure: Storm origins arrive in a Poisson process of rate λ and last for a random duration that is exponentially distributed with parameter γ. During the lifetime of each storm, a random number of storm cells arrive in a Poisson process of rate β and each cell lasts for a duration that is drawn from an exponentially distribution with parameter η. Each storm cell has a constant intensity that is drawn from an exponential distribution with parameter μ and terminates at the end of the storm duration. In this study, a modified version of the model called the modified Bartlett-Lewis pulse (BLP) model (Cowpertwait et al. 2007), which was introduced to improve many of the limitations of earlier stochastic rainfall models including the representation of dry periods, is used. There are other stochastic rainfall models (e.g., Burton et al. 2008; Ravazzani et al. 2014; Tarpanelli et al. 2012; Veneziano and Iacobellis 2002; Willems 2001) in the literature that can also be used to undertake a similar study.

The parameters of the rainfall model were fitted using an observed rainfall time series that was obtained from a rain gauge that is located in the small town of Downing, Missouri (Rain Gauge COOP:232318). Even though this rain gauge site is located approximately 50 km from the centroid of the Soap Creek watershed, it is the closest rain gauge site that has the longest high-resolution rainfall observation. The station has 43 years of 15-min. resolution rainfall data. Fig. 3 shows the comparison between the observed and simulated mean monthly rainfall depth, standard deviation, and lag 1 autocovariance for the hourly and daily rainfall accumulation periods. This shows that the rainfall model reasonably reproduces the observed rainfall statistics. Finally, the fitted BLRP stochastic rainfall model is used to generate a 10,000-year hourly rainfall time series.

Hydrologic Model

In this study, a distributed rainfall-runoff model that has been developed at the Iowa Flood Center was chosen. The model is based on the partitioning of the landscape to hillslope and channel link units as discussed in Mantilla and Gupta (2005). The individual hillslope channel link unit constitutes two hillslopes and a single channel that collects surface and subsurface flow from the two adjacent hillslopes. Accordingly, each hillslope channel link unit serves as the control volume at which the mass and momentum

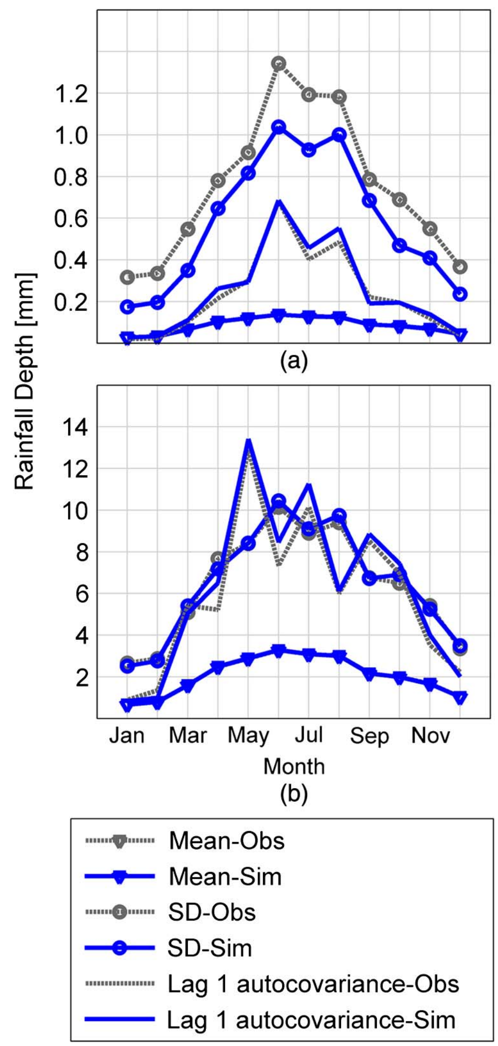

Fig. 3. Comparison of the observed and simulated mean monthly rainfall depth, standard deviation, and lag 1 autocovariance for the (a) hourly; (b) daily rainfall accumulation periods

Downloaded from ascelibrary.org by Univ of Iowa Libraries on 03/02/17. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Univ of Iowa Libraries on 03/02/17. Copyright ASCE. For personal use only; all rights reserved.

conservation equations are solved. The version of the model that is used in this study is described in detail in Ayalew et al. (2014b). The model is known to reasonably reproduce observed streamflow across a range of spatial scales in various watersheds in the state of Iowa (Ayalew et al. 2014a, b, 2015a).

The topographic parameters of each hillslope channel link unit, which are used as input to the rainfall-runoff model, are obtained from a 30-m digital elevation model (DEM) that the USGS provides through its National Map Viewer web service (USGS 2017). The DEM of the watershed was processed using *CUENCAS-GIS* (Mantilla and Gupta 2005). The software *CUENCAS-GIS* has the capability to extract the drainage network, which is shown in Fig. 1, and the associated hillslope and channel link parameters. This extraction process has resulted in 18,131 hillslope channel link pairs at which scale rainfall and model parameters are assigned. This allows for the application of spatially variable rainfall, hillslope, and channel link parameters. As discussed previously, both spatially uniform and spatially variable rainfall inputs and a constant runoff coefficient value of 0.5 were used. The constant runoff coefficient scheme was chosen to isolate the effect of small ponds on peak flows from those associated with spatial and temporal variability of antecedent conditions due to differences in soil moisture.

The rainfall-runoff model has the capability of handling spatially distributed storage dams simulation. The model can either take in the design parameters of the dam that can be used to automatically calculate the storage-discharge relationship using hydraulic principles or directly take in a preprocessed storage-discharge relationship. The outflow from a given dam is then calculated as a function of the storage in the dam. For this study, the storage-discharge relationship for each of the 133 dams was obtained from the corresponding design reports that are archived by the Soap Creek Watershed Board. An additional required step is to identify the location of each of the dams in the drainage network because of small discrepancies between the actual river network and the network computed by the DEM-based algorithms. This step was completed manually.

All the dams are assumed to be empty at the beginning of the simulation. The first year of the 10,000-year-long continuous simulation was used as a spin-up period. The water level in each of the dams for the remaining years is a function of the antecedent inflow sequence and the storage-discharge relationship of each of the dams. This means that the initial water level in each of the dams before the onset of the annual maximum peak discharge event is a purely random variable that not only varies in time but also from one dam to another. As such, depending on the antecedent inflow sequence and the storage-discharge relationship of the dams, the initial water level before each flood event could vary from zero to full capacity.

Results

Impacts of Small Dams on Stationarity of Peak Discharges

The assumption that the hydroclimate has been stationary and will continue to remain so in the future is commonly made in both at-site and regional flood frequency analysis techniques. Whether or not this assumption is valid in the face of the changing climate and how to address it in flood frequency estimation has been under debate with opinions varying from stationarity is dead to stationarity is immortal (e.g., Galloway 2011; Lettenmaier et al. 1994; Lins and Cohn 2011; Mallakpour and Villarini 2015; Milly et al. 2008, 2005; Montanari and Koutsoyiannis 2014; Stedinger and Griffis 2011; Villarini and Smith 2010). On the other hand, there is more consensus on the effect of land-use change on flood frequency (e.g., Brath et al. 2006; Bronstert et al. 2002; Crooks and Davies 2001; Hollis 1975; Konrad 2003; Niehoff et al. 2002; Villarini et al. 2009). Depending on the nature of the land-use changes in a particular catchment, flood susceptibility could increase or decrease. An increase in impervious area due to urbanization, for example, will amplify the peak discharge (Hollis 1975; Konrad 2003), whereas the restoration of wetlands can attenuate flood peaks (e.g., Hillman 1998). The construction of spatially distributed small dams is yet another type of land-use change that can influence flood frequency, whether or not such dams are designed explicitly for flood-control purposes. This section asks the question: is the stationarity assumption valid in those catchments that are regulated by spatially distributed small dams?

To investigate how spatially distributed small dams affect the peak discharge distribution as a function of time, the following three assumptions were made: First, the statistics describing the intensity, duration, and space-time structure of rainfall have remained unchanged over time. Second, the storage capacities of the dams have not been affected by sedimentation and hence remain the same over time. And third, there has been no land-use and land-cover change in the watershed except the construction of the small dams. The first assumption was enforced by using the same rainfall model parameters while generating the point rainfall time series that was used to undertake the continuous simulation experiment. The remaining two assumptions are imposed by making the relevant parameters, such as the runoff coefficient and hillslope overland flow velocity, in the rainfall-runoff model time-invariant.

Using the preceding assumptions, five scenarios were simulated: the watershed with no dams, with 33 dams, with 66 dams, with 99 dams, and with all 133 dams that were built in the watershed until the year 2013. The subsets were selected randomly from the 133 dams. The systematic increase of the number of dams is intended to mimic the growing number of dams in the catchment as a function of time. Fig. 4 shows the peak discharge distribution at the catchment outlet resulting from the five scenarios. It can be seen that the peak discharge distribution is significantly affected by the spatially distributed small dams and, as expected, the peak flood magnitude corresponding to a given exceedance probability decreases with increasing number of dams. Moreover, a significant peak discharge reduction is observed as the number of dams increases from 99 to 133. This jump is because substantial storage

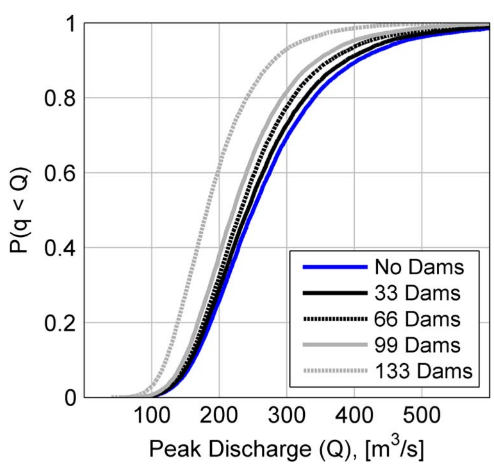

Fig. 4. Comparison of the cumulative distribution function of peak discharges simulated under different watershed regulation scenarios

capacity is added with the last 34 dams. The respective total storage capacity of the 33, 66, 99, and 133 dams is 10, 20, 25, and 41 Mm^3. This shows that there is a bigger jump in the total storage capacity of the dams with the total storage capacity nearly doubling as the number of dams increases from 99 to 133. This is because several of the dams in the final group of 34 are relatively large.

The previous discussion is qualitative. Even though the cumulative distribution function plots corresponding to the simulated scenarios appear to be different, it is important to ascertain that they indeed come from different peak discharge distributions, a result that will invalidate the stationarity assumption currently used in practice. To this end, the two-sample Kolmogrov-Smirnov test is conducted to check whether or not the simulated peak discharge corresponding to the scenario where the watershed is regulated by 33, 66, 99, or 133 dams comes from the same distribution that gives the simulated peak discharge corresponding to the no-dam scenario. The test results reject the null hypothesis that the regulated peak discharges come from the same distribution as the unregulated peak discharges at the 95% confidence level. This result confirms that the stationarity assumption may not be a valid assumption in catchments that are regulated by spatially distributed small dams.

Moreover, the results in this section indicate that these small dams will undoubtedly affect outcomes of studies that have been looking into trends in the annual maximum peak discharge. For example, Mallakpour and Villarini (2015) analyzed historical annual maximum peak discharges from the central United States, including Iowa, over the 1962–2011 time period and concluded that there is no evidence of an increasing trend of the flood magnitude. Their study ignored the flood attenuation effects of the spatially distributed small dams that have been built over the same period. Other similar studies (e.g., Eash et al. 2013) also ignore the flood attenuation effect of the spatially distributed small dams and it may be the case that a possible increasing trend of annual maximum peak discharges due to increases in extreme rainfall or changes in land use could have been offset by the system of geographically distributed small dams. These issues should be addressed in future studies.

Scale-Dependent Effects of Small Dams on Flood Frequency

This section evaluates how the spatially distributed small dams affect the flood frequency across a range of spatial scales in the watershed. To this end, the simulation results that are driven by a stochastically generated 10,000-year-long hourly point rainfall time series that is applied uniformly over the watershed is used. The simulation experiment was configured in such a way that all 133 dams are included in the hydrologic model. The model outputs the simulation results at 24 systematically selected locations in the watershed (Fig. 1). These locations correspond to subcatchments whose drainage areas range between 2 and 660 km^2. Finally, the Weibull plotting position formula is used to calculate the exceedance probabilities of the regulated and unregulated annual maximum peak discharges at all 24 locations. Some example results are shown in Fig. 5, which shows the regulated and unregulated flood frequency curves at three representative locations in the watershed. These results show that the spatially distributed small dams significantly affect the simulated peak discharge over a range of exceedance probabilities.

Another interesting insight depicted in Fig. 5 is that the difference between the regulated and unregulated peak discharges is negligible for exceedance probabilities of greater than 0.5 and it increases with decreasing exceedance probabilities down to 0.001. However, the difference between the two sets of peak discharges appears to decrease with decreasing exceedance probabilities of less than 0.001 as less and less storage capacity is available in the dams with increasing flood magnitudes. Other relevant studies of flood frequency modification by single dams have shown that the difference between the regulated and unregulated peak discharges increases with decreasing exceedance probability up to a certain point, after which it starts decreasing (Ayalew et al. 2013; Nehrke and Roesner 2004), which confirms that this artifact of the regulated flood frequency curve is also applicable to the case of streamflow regulation by a network of small dams.

The results presented in Fig. 5 do not show how the effect of the spatially distributed small dams on flood frequency changes with catchment spatial scale. To address this issue, the percentage peak discharge reduction due to the 133 spatially distributed small dams is calculated at all 24 locations where regulated and unregulated streamflow simulation results are available. These locations are shown in Fig. 1. The results are presented in Fig. 6, which shows how the percentage peak discharge reduction changes with drainage area for the 2- and 100-year recurrence intervals (T_r). It can be seen that the effect of the spatially distributed small dams on the peak discharge generally decreases with increasing catchment

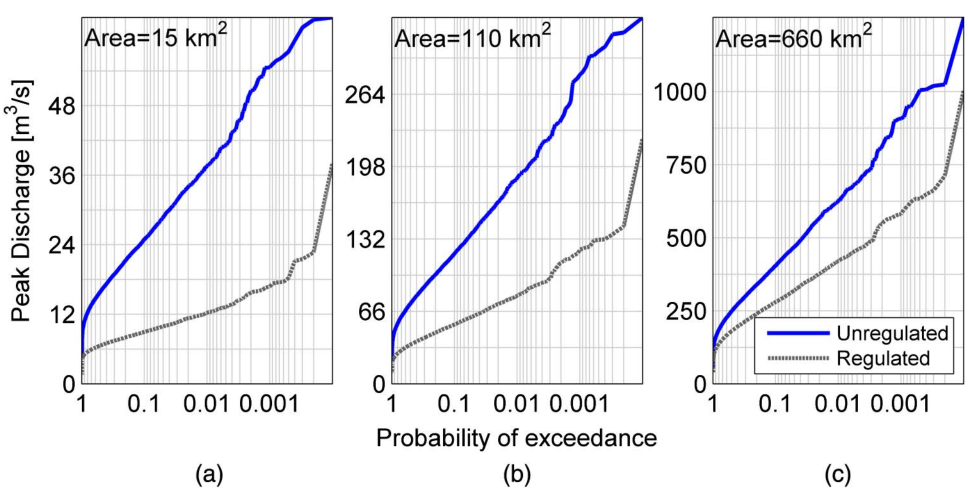

Fig. 5. Regulated and unregulated flood frequency curves at three randomly selected spatial scales in the watershed; (c) depicts the flood frequency curve comparison at the outlet of the catchment

Downloaded from ascelibrary.org by Univ of Iowa Libraries on 03/02/17. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Univ of Iowa Libraries on 03/02/17. Copyright ASCE. For personal use only; all rights reserved.

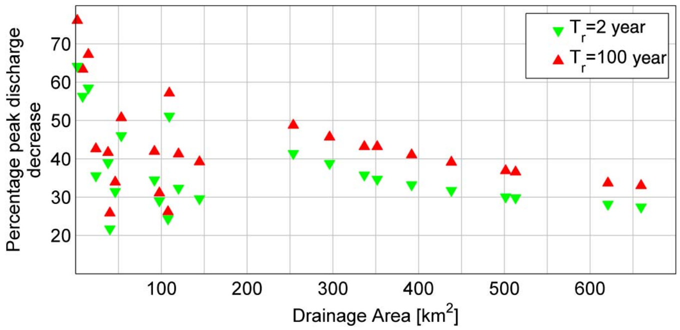

Fig. 6. Percentage peak discharge reduction as a function of drainage area for the 2- and 100-year recurrence intervals; the peak discharges are observed at the 24 sampling points shown in Fig. 1

spatial scale. The simple reason is that, as the drainage area increases, the proportion of subcatchments that are regulated by the spatially distributed small dams decreases. In other words, the ratio of the total storage capacity of the dams to the volume of runoff generated in a given catchment decreases with increasing catchment spatial scale. This is shown in Fig. 7 using the combined specific reservoir storage capacity, which is defined as the ratio of the total storage capacity of dams in a given catchment to its drainage area as a proxy. It can be seen that the effect of the spatially distributed small dams on the peak discharge increases as the total storage capacity of the dams increase relative to the drainage area. It can also be seen in Fig. 6 that there is significant scatter in the percentage peak discharge reduction for drainage areas less than 150 km^2. However, a similar scatter is not apparent in Fig. 7, which indicates that the combined specific reservoir storage capacity is a good indicator of their effect on the flood peak reduction.

The preceding results clearly show how the percentage peak discharge reduction is controlled by the total storage capacity in the watershed and confirms a similar result reported in Smith et al. (2015). An additional question is to test how much storage capacity was available in the basin before the rainfall event that resulted in the annual peak discharge arrived in the watershed. This was achieved by checking the storage state of each dam before the arrival of the annual maximum peak discharge. The results, which are not shown here for the sake of brevity, indicate that, on average, 99% of the storage capacity of the dams was available. The results also showed that there are four dams whose available storage capacity was at, on average, 50, 75, 81, and 85%. A close inspection of these four dams revealed that their orifice (outlet) was elevated above the bottom of the dam and hence there was always a certain amount of water that is left stagnant behind the dam. These results suggest that, with the exception of the four aforementioned dams, the dams' outflow characteristics are such that interevent storage is minimal.

Continuous Simulation Using Spatially Variable Rainfall

How the spatially distributed small dams affect the flood frequency as a function of catchment spatial scale was shown in the previous section. The results were obtained using a stochastically generated point rainfall time series under the assumption that rainfall is uniform in space. While insightful results were obtained under this assumption, the results can be questionable because rainfall is also variable in space and, as a result, the spatially distributed small dams may regulate the streamflow response differently. Wright et al. (2014), for example, show that the spatial distribution of rainfall can play an important role in flood frequency, even in small watersheds. Hence, confirmation is needed about whether or not the results obtained under an assumption of spatially uniform rainfall will hold true when a spatially and temporally variable rainfall is used as an input. This issue is addressed by using the Stage IV radar-rainfall data.

The watershed is simulated using the Stage IV radar-rainfall data, which are available nationally since 2002. The region has experienced significant flooding over this time period, with the historical flood event of 2008 that affected the state of Iowa being a standout event (Smith et al. 2013). Examination of the past 107 years of annual maximum peak discharge observed at the outlet of the Des Moines River basin at Keosauqua (USGS 05490500), which includes the Soap Creek watershed as one of its subcatchments, shows that 5 of the top 14 annual maximum peak discharges were observed since 2007. This makes the past decade an interesting time window for flood-related hydrologic studies in the basin.

The watershed was simulated with no dams and with the spatially distributed 133 small dams, using the Stage IV radar-rainfall data as input. The results are presented in Fig. 8. Because only 13 years of Stage IV radar-rainfall data are available, peak discharges with recurrence intervals of 2 and 10 years were calculated. However, peak discharges corresponding to these recurrence intervals may be larger than usual because, as discussed previously, the last decade has seen a frequent occurrence of extreme peak discharge events in the watershed as can be inferred from peak discharges observed at the outlet of the Des Moines River basin,

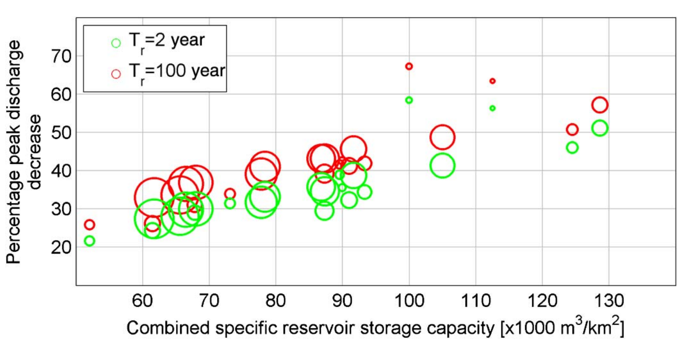

Fig. 7. Percentage peak discharge reduction as a function of the combined specific reservoir storage capacity that is calculated at 24 systematically selected locations that represent different spatial scales in the watershed; the size of the circles in the plot indicate the relative size of the drainage area at the 24 locations shown in Fig. 1

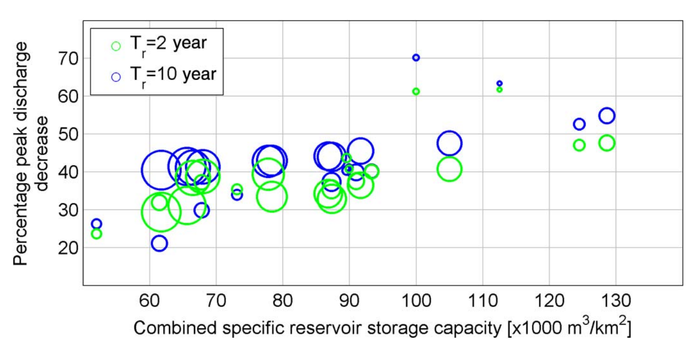

Fig. 8. Percentage peak discharge reduction as a function of the combined specific reservoir storage capacity that is calculated at different spatial scales in the watershed; the size of the circles in the plot indicate the relative size of the drainage area at the 24 locations shown in Fig. 1

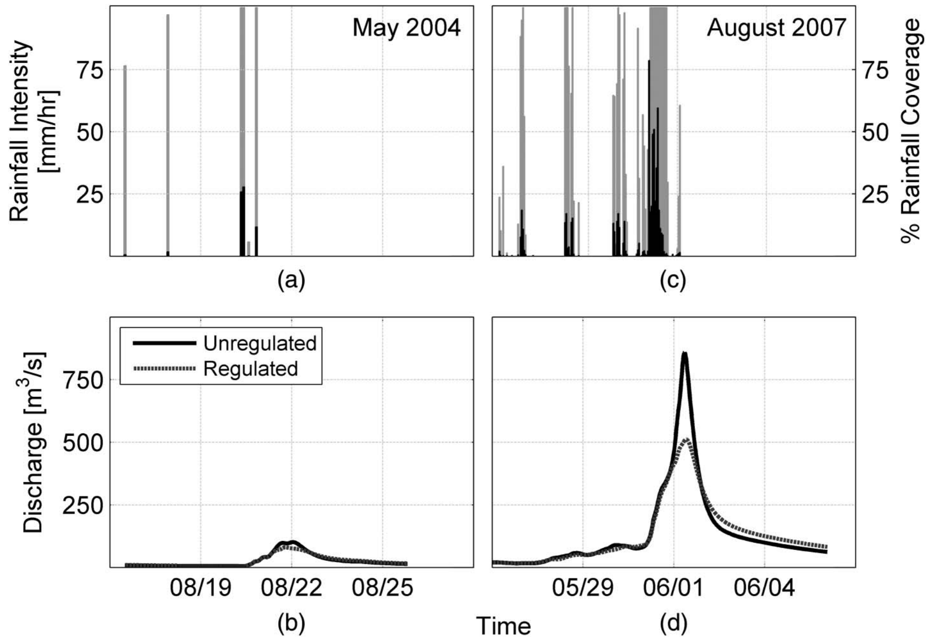

Fig. 9. (a and c) Rainfall time series (black bars) along with the percentage areal rainfall coverage (gray bars); (b and d) simulated regulated and unregulated streamflow at the outlet of the catchment for the rainfall events shown in (a) and (c), respectively

Downloaded from ascelibrary.org by Univ of Iowa Libraries on 03/02/17. Copyright ASCE. For personal use only; all rights reserved.

which is located approximately 30 km downstream of the junction where it is joined by the Soap Creek. This means that the peak discharges of 2- and 10-year recurrence intervals may not correspond to the peak discharges that were simulated using the point rainfall time series that are presented in the previous section. It can be seen in Fig. 8 that the percentage peak discharge reduction increases as the combined specific reservoir storage capacity increases. Irrespective of the discrepancy in the estimated recurrence intervals, these results are strikingly similar to the results presented in Fig. 7, which were obtained under the assumption of spatially uniform rainfall.

Considering the medium size of the watershed, it may be the case that the annual maximum peak discharges observed in the watershed are a result of rainfall events that cover the entire basin. This may explain the apparent similarity between the results obtained using spatially uniform and spatially variable rainfall inputs. To investigate this further, the rainfall events that correspond to each of the 13 annual maximum peak discharges observed at the catchment outlet between 2002 and 2014 were examined. Fig. 9 shows plots of the rainfall time series corresponding to the smallest (May 2004) and the largest (August 2007) annual maximum peak discharge observed at the outlet over the 13-year period. It can be seen in Figs. 9(a and c) that higher intensity rainfall events cover the entire basin (gray bars in Fig. 9). These and additional results from the analysis of the rest of the data set show that the rainfall events that generated the annual maximum peak discharge tend to cover the entire watershed.

It is shown in so far how the spatially distributed small dams affect the flood frequency across a range of spatial scales in the study watershed. A remaining question of interest is to examine the utilization of the storage capacity of the small dams during the rainfall events that led to the annual maximum peak discharge at the outlet of the watershed. To address this issue, the instantaneous peak storage each dam attained during the event that corresponds to the annual maximum peak discharge observed at the outlet was selected. The peak storages of all 133 dams are then summed. This information is used to estimate the percentage of the combined total storage capacity of dams used to store runoff, which is calculated as the ratio of the summation of the peak storages to the summation of the storage capacity of each dams. Recall that the combined storage capacity of the 133 dams is approximately 41×10^6 m^3. The results shown in Fig. 10 show that the utilization of the combined storage capacity of the dams increases as a function of the peak discharge observed at the catchment outlet, which is expected. What is striking is that, during the largest peak discharge event that occurred in the watershed over the past 13 years, i.e., during the August 2007 event, only approximately 41% of the combined total storage capacity of the 133 dams is utilized. This indicates the significant potential these spatially distributed small dams possess in attenuating extreme flood events. The existing small dams in the Soap Creek watersheds do not have active control structures such as gates or valves. Therefore, they should be considered as passive storage. A system of dams with active control, if properly operated, would likely produce further attenuation of the flood peaks. Operating such a system requires skillful quantitative precipitation forecasting. Consideration of such a system is outside the scope of this paper.

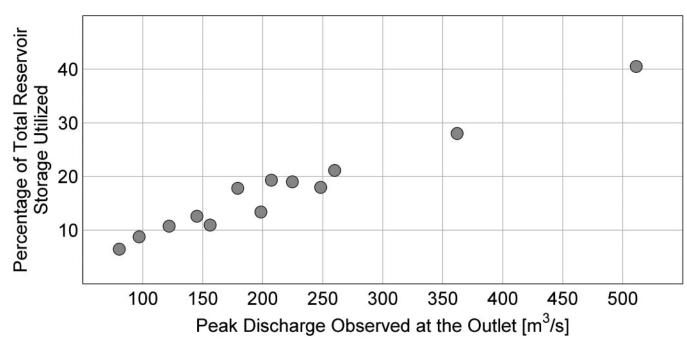

Fig. 10. Percentage utilization of the total reservoir storage capacity in the watershed as a function of the annual maximum peak discharge simulated at the outlet for the years between 2002 and 2014

Downloaded from ascelibrary.org by Univ of Iowa Libraries on 03/02/17. Copyright ASCE. For personal use only; all rights reserved.

While the results summarized previously provide some insight into the flood mitigation potential of these spatially distributed small dams, the flood risk resulting from a cascade failure of these dams is a possibility. These dams could fail for various reasons including overtopping. In order to evaluate the frequency at which these dams could potentially fail due to overtopping, whether or not the storage capacity of the dam is exceeded during the event that led to the annual maximum peak discharge is checked. The results show that the relative frequency of overtopping varies from dam to dam (location to location) and ranges from 0–0.16% with an average of 0.03%. That is, on average, of the 10,000 annual maximum peak discharges that were simulated, only three led to overtopping of the dams. Considering that all overtopping events do not necessarily lead to dam failure, the potential for a cascade failure due to overtopping of a network of small dams discussed in this study appears to be low. However, it is still a possibility that warrants an in-depth investigation, which is beyond the scope of this study.

Conclusions

This study investigated how a system of spatially distributed small dams attenuate the peak discharge across a range of spatial scales using the 660-km^2 Soap Creek watershed that is located in southeastern Iowa. The watershed is regulated by more than 144 small dams whose storage capacity range from 23,436 to 15,591,210 m^3. The investigation is based on a continuous hydrologic simulation of the streamflow regulation impact of 133 small dams for which complete design information is available and is driven by two types of rainfall inputs: a stochastically generated 10,000-year-long sequence of hourly point rainfall-time series and 13 years of Stage IV hourly radar-rainfall data. The main results are summarized as follows:

- The spatially distributed small dams play a significant role in attenuating the peak discharge across a range of spatial scales and exceedance probabilities in the watershed. As a result, they significantly affect the peak discharge distribution. Based on the simulation of the increasing number of small dams in the watershed that are built over time, the results showed how the peak discharge distribution changes with time, invalidating the peak discharge stationarity assumption that is central to regional and at-site flood frequency estimation methods.
- The percentage peak discharge reduction due to the spatially distributed small dams is negligible for exceedance probabilities greater than 0.5 and it increases with decreasing exceedance probabilities down to 0.001. However, the percentage peak discharge reduction appears to decrease with exceedance probabilities less than 0.001. These exceedance probabilities should not be taken at face value because they are based on an uncalibrated model of the watershed. As stated in the "Study Watershed" section of the paper, calibration of the hydrologic model was not possible due to lack of streamflow gauging stations in the basin and it remains one of the limitations of this study.
- The effect of the spatially distributed small dams on the flood frequency is scale-dependent, with the effect decreasing as the drainage area increases. A closer examination of the simulation results reveal that the decreasing effects of the dams on flood frequency with increasing drainage area is due to the observed reduction in the combined specific reservoir storage capacity that is defined as the ratio of the total storage capacity of the dams to the drainage area that they regulate, which also decreases as the drainage area increases in the downstream direction.
- Results from the simulation of the watershed using the Stage IV radar-rainfall data indicate that the proportion of the combined storage capacity of the dams that is used to store event runoff increases with increasing peak discharge magnitude at the outlet. The simulation results also show that only approximately 41% of the combined storage capacity of the 133 dams was used during the August 2007 flood event, which is the highest peak discharge that is simulated at the outlet of the watershed for the period between 2002 and 2014. The actual state of storage in the distributed dams during this event is not available. Nevertheless, these results indicate that ignoring the system of spatially distributed small dams in hydrologic models that are being used in real-time flood forecasting operations could lead to the overestimation of flood risk.

The present study is not without limitations, including the assumption of spatially uniform rainfall. Even though the results obtained under this assumption were confirmed using 13 years of radar rainfall data, future studies will benefit from the use of stochastic rainfall models that are capable of reproducing the spatiotemporal variability of rainfall. Moreover, the assumption that the storage capacity of the dams remains constant over time is an additional limitation because the storage capacity can be significantly affected by sedimentation over time. The interplay among the decreasing storage capacity of the dams due to sedimentation and the construction of new dams across the watershed along with other land-use and land-cover changes calls for a comprehensive study of the problem. Moreover, the dams addressed here are passive storage. A similar investigation of the flood frequency effects of active storages coupled with the spatiotemporal variability of rainfall could reveal new insights. Additionally, there is also a possibility of cascade failure of the network of small dams, which could exasperate the flood risk in extreme situations and needs to be investigated in greater detail. These questions are reserved for future studies.

Acknowledgments

The authors would like to thank the Iowa Flood Center (IFC) at the University of Iowa for the financial support of this study.

References

Ayalew, T. B., Krajewski, W. F., and Mantilla, R. (2013). "Exploring the effect of reservoir storage on peak discharge frequency." *J. Hydrol. Eng.*, 10.1061/(ASCE)HE.1943-5584.0000721, 1697–1708.

Ayalew, T. B., Krajewski, W. F., and Mantilla, R. (2014a). "Connecting the power-law scaling structure of peak-discharges to spatially variable rainfall and catchment physical properties." *Adv. Water Resour.*, 71(0), 32–43.

Ayalew, T. B., Krajewski, W. F., and Mantilla, R. (2015a). "Analyzing the effects of excess rainfall properties on the scaling structure of peak discharges: Insights from a mesoscale river basin." *Water Resour. Res.*, 51(6), 3900–3921.

Ayalew, T. B., Krajewski, W. F., and Mantilla, R. (2015b). "Insights into expected changes in regulated flood frequencies due to the spatial configuration of flood retention ponds." *J. Hydrol. Eng.*, 10.1061/(ASCE)HE.1943-5584.0001173, 04015010.

Ayalew, T. B., Krajewski, W. F., Mantilla, R., and Small, S. J. (2014b). "Exploring the effects of hillslope-channel link dynamics and excess rainfall properties on the scaling structure of peak-discharge." *Adv. Water Resour.*, 64, 9–20.

Bradley, A. A., and Potter, K. W. (1992). "Flood frequency-analysis of simulated flows." *Water Resour. Res.*, 28(9), 2375–2385.

Brath, A., Montanari, A., and Moretti, G. (2006). "Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty)." *J. Hydrol.*, 324(1–4), 141–153.

Bronstert, A., Niehoff, D., and Burger, G. (2002). "Effects of climate and land-use change on storm runoff generation: Present knowledge and modelling capabilities." *Hydrol. Processes*, 16(2), 509–529.

Burton, A., Kilsby, C. G., Fowler, H. J., Cowpertwait, P. S. P., and O'Connell, P. E. (2008). "RainSim: A spatial-temporal stochastic rainfall modelling system." *Environ. Modell. Software*, 23(12), 1356–1369.

Collier, M., Webb, R. H., and Schmidt, J. C. (1996). *Dams and rivers: A primer on the downstream effects of dams*, DIANE Publishing, Collingdale, PA.

Cowpertwait, P., Isham, V., and Onof, C. (2007). "Point process models of rainfall: developments for fine-scale structure." *Proc. R. Soc. A: Math. Phys. Eng. Sci.*, 463(2086), 2569–2587.

Crooks, S., and Davies, H. (2001). "Assessment of land use change in the Thames catchment and its effect on the flood regime of the river." *Phys. Chem. Earth. Part B*, 26(7-8), 583–591.

Eash, D. A., Barnes, K. K., and Veilleux, A. G. (2013). "Methods for estimating annual exceedance-probability discharges for streams in Iowa, based on data through water year 2010." *USGS Scientific Investigations Rep. 2013-5086*, USGS, Reston, VA.

Emerson, C., Welty, C., and Traver, R. (2005). "Watershed-scale evaluation of a system of storm water detention basins." *J. Hydrol. Eng.*, 10.1061/(ASCE)1084-0699(2005)10:3(237), 237–242.

Friedman, J. M., Osterkamp, W. R., Scott, M., and Auble, G. (1998). "Downstream effects of dams on channel geometry and bottomland vegetation: Regional patterns in the great plains." *Wetlands*, 18(4), 530–545.

Galloway, G. E. (2011). "If stationarity is dead, what do we do now?" *J. Am. Water Resour. Assoc.*, 47(3), 563–570.

Goldman, D. M. (2001). "Quantifying uncertainty in estimates of regulated flood frequency curves." *Proc., Bridging the Gap Meeting the World's Water and Environmental Resources Challenges*, ASCE, Reston, VA, 1–13.

Graf, W. L. (2006). "Downstream hydrologic and geomorphic effects of large dams on American rivers." *Geomorphology*, 79(3–4), 336–360.

Hillman, G. (1998). "Flood wave attenuation by a wetland following a beaver dam failure on a second order boreal stream." *Wetlands*, 18(1), 21–34.

Hollis, G. E. (1975). "The effect of urbanization on floods of different recurrence interval." *Water Resour. Res.*, 11(3), 431–435.

IACWD (Interagency Advisory Committee on Water Data). (1982). *Guidelines for determining flood flow frequency: Bulletin 17B*, U.S. Water Resources Council, Washington, DC.

Inbar, M. (1990). "Effect of dams on mountainous bedrock rivers." *Phys. Geogr.*, 11(4), 305–319.

Konrad, C. P. (2003). "Effects of urban development on floods." USGS, Tacoma, WA.

Laurenson, E. M. (1973). "Effect of dams on flood frequency." *Flood investigation*, Vol. II, USGS, Washington, DC.

Lettenmaier, D. P., Wood, E. F., and Wallis, J. R. (1994). "Hydro-climatological trends in the continental United States, 1948-88." *J. Clim.*, 7(4), 586–607.

Ligon, F. K., Dietrich, W. E., and Trush, W. J. (1995). "Downstream ecological effects of dams." *Biosci.*, 45(3), 183–192.

Lin, Y., and Mitchell, K. E. (2005). "The NCEP Stage II/IV hourly precipitation analyses: Development and applications." *19th Conf. on Hydrology*, American Meteorological Society, Boston.

Lins, H. F., and Cohn, T. A. (2011). "Stationarity: Wanted dead or alive?" *J. Am. Water Resour. Assoc.*, 47(3), 475–480.

Liu, Y., et al. (2014). "Assessing effects of small dams on stream flow and water quality in an agricultural watershed." *J. Hydrol. Eng.*, 10.1061/(ASCE)HE.1943-5584.0001005, 05014015.

Magilligan, F. J., Nislow, K. H., and Graber, B. E. (2003). "Scale-independent assessment of discharge reduction and riparian disconnectivity following flow regulation by dams." *Geology*, 31(7), 569–572.

Mallakpour, I., and Villarini, G. (2015). "The changing nature of flooding across the central United States." *Nature Clim. Change*, 5(3), 250–254.

Mamede, G. L., Araújo, N. A. M., Schneider, C. M., de Araújo, J. C., and Herrmann, H. J. (2012). "Overspill avalanching in a dense reservoir network." *Proc. Natl. Acad. Sci.*, 109(19), 7191–7195.

Mantilla, R., et al. (2012). "Simulation of a distributed flood control system using a parallel asynchronous solver for systems of ODEs." *Applied simulation and modelling/777: Artificial intelligence and soft computing*, ACTA Press, Calgary, AB, Canada.

Mantilla, R., and Gupta, V. K. (2005). "A GIS numerical framework to study the process basis of scaling statistics in river networks." *IEEE Geosci. Remote Sens. Lett.*, 2(4), 404–408.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., and Stouffer, R. J. (2008). "Stationarity is dead: Whither water management?" *Sci.*, 319(5863), 573–574.

Milly, P. C. D., Dunne, K. A., and Vecchia, A. V. (2005). "Global pattern of trends in streamflow and water availability in a changing climate." *Nature*, 438(7066), 347–350.

Montaldo, N., Mancini, M., and Rosso, R. (2004). "Flood hydrograph attenuation induced by a reservoir system: analysis with a distributed rainfall-runoff model." *Hydrol. Processes*, 18(3), 545–563.

Montanari, A., and Koutsoyiannis, D. (2014). "Modeling and mitigating natural hazards: Stationarity is immortal!" *Water Resour. Res.*, 50(12), 9748–9756.

Nehrke, S. M., and Roesner, L. A. (2004). "Effects of design practice for flood control and best management practices on the flow-frequency curve." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(2004)130:2(131), 131–139.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., and Williams, J. R. (2011). "Soil and water assessment tool theoretical documentation version 2009." Texas Water Resources Institute, College Station, TX.

Niehoff, D., Fritsch, U., and Bronstert, A. (2002). "Land-use impacts on storm-runoff generation: Scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany." *J. Hydrol.*, 267(1–2), 80–93.

Peter, S. J., de Araújo, J. C., Araújo, N. A. M., and Herrmann, H. J. (2014). "Flood avalanches in a semiarid basin with a dense reservoir network." *J. Hydrol.*, 512, 408–420.

Ravazzani, G., Gianoli, P., Meucci, S., and Mancini, M. (2014). "Assessing downstream impacts of detention basins in urbanized river basins using a distributed hydrological model." *Water Resour. Manage.*, 28(4), 1033–1044.

Rodriguez-Iturbe, I., Cox, D. R., and Isham, V. (1987). "Some models for rainfall based on stochastic point-processes." *Proc. R. Soc. Lon. Ser.-A*, 410(1839), 269–288.

Rodriguez-Iturbe, I., and Rinaldo, A. (1997). *Fractal river basins: Chance and self-organization*, Cambridge University Press, Cambridge, U.K.

Smith, B. K., Smith, J. A., Baeck, M. L., and Miller, A. J. (2015). "Exploring storage and runoff generation processes for urban flooding through a physically based watershed model." *Water Resour. Res.*, 51(3), 1552–1569.

Smith, J. A., Baeck, M. L., Villarini, G., Wright, D. B., and Krajewski, W. (2013). "Extreme flood response: The June 2008 flooding in Iowa." *J. Hydrometeorol.*, 14(6), 1810–1825.

Stedinger, J. R., and Griffis, V. W. (2011). "Getting from here to where? Flood frequency analysis and climate." *J. Am. Water Resour. Assoc.*, 47(3), 506–513.

Tarpanelli, A., Franchini, M., Brocca, L., Camici, S., Melone, F., and Moramarco, T. (2012). "A simple approach for stochastic generation of spatial rainfall patterns." *J. Hydrol.*, 472, 63–76.

Thomas, N. W., Arenas Amado, A., Schilling, K. E., and Weber, L. J. (2016). "Evaluating the efficacy of distributed detention structures to reduce downstream flooding under variable rainfall, antecedent soil, and structural storage conditions." *Adv. Water Resour.*, 96, 74–87.

USACE (U.S. Army Corps of Engineers). (2010). "Des Moines river regulated flow frequency study." Rock Island District, Rock Island, IL.

USACE (U.S. Army Corps of Engineers). (2013). "National inventory of dams." Alexandria, VA.

USGS. (2017). "Data download and visualization services." ⟨http://viewer.nationalmap.gov⟩ (Jan. 23, 2017).

Downloaded from ascelibrary.org by Univ of Iowa Libraries on 03/02/17. Copyright ASCE. For personal use only; all rights reserved.

Veneziano, D., and Iacobellis, V. (2002). "Multiscaling pulse representation of temporal rainfall." *Water Resour. Res.*, 38(8), 1311–1313.

Villarini, G., and Smith, J. A. (2010). "Flood peak distributions for the eastern United States." *Water Resour. Res.*, 46(6), W06802.

Villarini, G., Smith, J. A., Serinaldi, F., Bales, J., Bates, P. D., and Krajewski, W. F. (2009). "Flood frequency analysis for nonstationary annual peak records in an urban drainage basin." *Adv. Water Resour.*, 32(8), 1255–1266.

Willems, P. (2001). "A spatial rainfall generator for small spatial scales." *J. Hydrol.*, 252(1–4), 126–144.

Williams, G. P., and Wolman, M. G. (1984). "Downstream effects of dams on alluvial rivers." *Professional Paper*, USGS, Washington, D.C.

Wright, D. B., Smith, J. A., and Baeck, M. L. (2014). "Flood frequency analysis using radar rainfall fields and stochastic storm transposition." *Water Resour. Res.*, 50(2), 1592–1615.

Downloaded from ascelibrary.org by Univ of Iowa Libraries on 03/02/17. Copyright ASCE. For personal use only; all rights reserved.