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Long-term, process-based, continuous simulations for a cluster of six smaller, nested rangeland watersheds near Tombstone, AZ (USA): Establishing a baseline for event-based runoff and sediment yields

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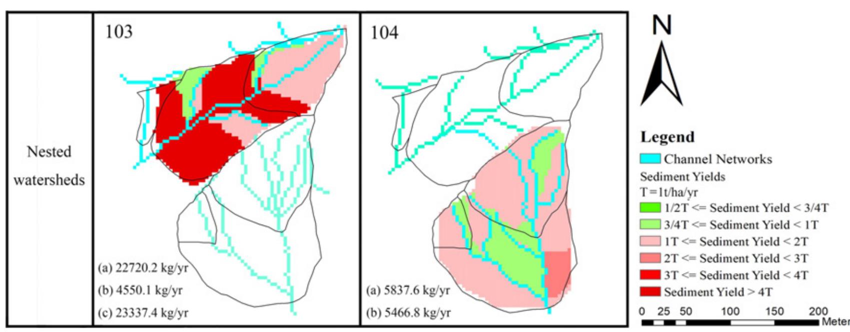
HIGHLIGHTS

- Process-based GeoWEPP validation for six neighboring, nested watersheds
- Simulations compared to runoff and sediment yields for various time periods
- Validation based on short-term parameterization and long-term verification
- Effects of topography and temporal climate were evaluated
- Results are baseline for soil redistribution and climate changes research

GRAPHICAL ABSTRACT



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ABSTRACT

Accurately predicting long-term, process-based runoff and sediment yields measured at the outlet of even small watersheds can be challenging. The assessments following careful parameter determination enable establishing a baseline for local land management to assess policy implementations and rehabilitation especially under climate or land use/cover changes. Process-based, continuous models have demonstrated their advantage of representing event-based hydrological responses at smaller spatial and temporal scales. In this study, the Geospatial interface for the Water Erosion Prediction Project (WEPP) is validated for a series six, neighboring, nested subwatersheds (101 to 106) at Lucky Hills, Walnut Gulch Experimental Watershed (WGEW), Tombstone, Arizona (USA). The primary objective of this study is to assess short-term parameterization and long-term verification and simulation validation of GeoWEPP based on 55 years of runoff and sediment yields for six subwatersheds. The effective hydraulic conductivity (K_{eff}) parameter is adjusted based on runoff observed in watershed 101 using a research-grade 1 m-Digital Elevation Model (DEM). The performance of runoff simulated generated by an aggregated 5 m-resolution DEM lead to better results in contrast to using the original 1 m- or aggregated 3 m-resolution. Since there are no sediment yield observations for that watershed, the similar sized, neighboring watershed 102 and a publicly available DEM were used to parameterize critical shear. The short-term verification of K_{eff} as well as the long-term verification of K_{eff} and critical shear stress indicate that both parameters generated based on one subwatershed can be used to accurately predict the runoff in all other watersheds in the study area. However, the results have a tendency to slightly over-estimate runoff, and become more significant with the distance from the rainfall and runoff gauges for the watershed that was used for the K_{eff} parameter estimation. For sediment yields, the results indicate that the short-term parameterization

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of shear stress based on one watershed can potentially lead to significantly different results for neighboring watersheds. The results are the baseline for spatially distributed shear stress and channel erosion parameter validation and impact assessment for future climate and land use changes.

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1. Introduction

While many challenges remain in attaining the goal of accurately predicting related parameters, including surface runoff, sediment yield, etc., measured at the outlet of a large watershed (Vente et al., 2007), information gleaned from watershed hydrology-erosion models can be considerably helpful as a guide to local land management, policy implementations, and restoration and rehabilitation (Maalim et al., 2013). Precise estimations of soil losses as well as runoff and sediment yields, however, are urgently needed for assessing disturbances in rural watersheds (Pacheco et al., 2014) as well as the development of future conservation strategies (Saghafian et al., 2014), respectively. Predictions of surface runoff and sediment quantities have been enabled through the development of a number of simulation models to assess watersheds or to plan a measurement strategy for watersheds without measurements.

Based on the work of Narumani and Yu, soil erosion models can be classified in the following categories: a) they can either be classified as empirical or process-based models according to the calculation principles (Narimani et al., 2017), or b) classified as lumped or distributed models according to the model construction in space and time (Yu et al., 2009). The list of empirical models includes the famous Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1958), the Revised/Modified USLE model (Renard et al., 1991), the Erosion Potential Method (EPM) (Gavrilovic, 1972), the Pacific Southwest Interagency Committee (PSIAC) model (PSIAC, 1968), the Modified PSIAC (MPSIAC) model (Mansouri and Bagherzadeh, 2012), and the United States Bureau of Land Management (US-BLM) model. On the other side the list of process-based models includes models such as the Erosion-Productivity Impact Calculator (EPIC) (Williams, 1990) and the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995). These process-based models have relatively more advantages compared to simple empirical models: they are able to simulate more detailed spatial and temporal process dynamics of net soil loss with more accurate extrapolation to ungauged sites and have an enhanced ability to predict sediment yield (Flanagan and Nearing, 1995; Maalim et al., 2013). Process-based parameters such as hydraulic conductivity and critical shear are parameterized based on a smaller subset of observations, then verified on an equally sized subset of observations and then verified on an independent set of observations of a nearby location.

The classification of lumped models includes the Water Atmosphere Vegetation Energy and Solutes (WAVES) model (Slavich et al., 1998), the Soil and Water Integrated Model (SWIM) (Krysanova et al., 1998) and the Soil Plant Atmosphere Continuum (SPAC) model (Lamsal et al., 1998). In contrast distributed models considering more adequately the variability of spatial hydrological parameters and could better simulate the spatial and temporal variable hydrological responses across a range of scales (Yu et al., 2009).

The main objective of this study is to analyze the parameterization, verification and validation of a detailed, process-based, distributed model for a set of six, nested watersheds with uniquely available long-term data on runoff and sediment yield data. The results created a comprehensive data set and a valid baseline model simulation to assess past spatially distributed soil redistribution within these watersheds as well as assess the impact of future climate and land use/land cover change scenarios.

2. Material and methods

2.1. The semi-distributed, process-based soil Erosion model WEPP

The Water Erosion Prediction Project (WEPP), used in this study, is a process-based, semi-distributed parameter, one-dimensional, continuous model founded on the fundamentals of hydrology, erosion mechanics, plant growth, and open channel hydraulics (Flanagan and Nearing, 1995; Meghdadi, 2013). The model was designed for two approaches: a hillslope and a watershed version, which can be used to model spatial and temporal distributions of net soil loss and sediment deposition along a representative hillslope, or across a distributed, watershed on a single event or a time series under different environmental conditions, respectively (Flanagan and Nearing, 1995). It allows the selection of appropriate measures for soil conservation and for soil erosion control (González-Arqueros et al., 2017). Several factors determine the response from soil to water, including climate, winter processes, irrigation, infiltration, overland flow hydraulics, water balance, plant growth, residue decomposition, soil parameters, hillslope erosion and deposition, watershed channel hydrology and erosion processes, and the watershed impoundment component, all of which are important to simulate the detailed processes of how soil erosion condition may change due to the influence of various factors. The WEPP model has been applied to various regions of the world for quantifying soil erosion (Maalim et al., 2013), creating scenarios under different climate conditions, land management and soil groups (González-Arqueros et al., 2017; Narimani et al., 2017). It is suitable to study systematic environmental variations and their response to hydrological changes (Yu et al., 2009). However, as a process-based model with great accuracy simulating soil erosion condition considering properties and processes at fine spatial and temporal scales, WEPP has an extensive requirement for data (Renschler, 2003).

2.2. The distributed, geospatial Interface of the WEPP model (GeoWEPP)

The use of Geographic Information Systems (GIS) technology enables process models to be applied to environmental problems outside the scales for which they were developed (Renschler, 2003). GeoWEPP is a user-friendly geo-spatial interface for the WEPP model that combines the process model with ArcGIS (Renschler, 2003) enabling researchers and practitioners alike to utilize a complex process-based model for land management decision-making. It was also developed to overcome the limitation of WEPP with the advanced characteristics of GIS (Yu et al., 2009). GeoWEPP provides a platform for processing and generating digital data outputs at a watershed scale and the visualization of the production of soil erosion and the deposition of sediments in a time series (Renschler, 2003). It allows input parameters for WEPP to be well-prepared by processing publicly available data sources to the required inputs for WEPP watershed simulation (Renschler, 2003), which in turn provides an excellent tool to simulate the runoff and sediment yields at a watershed scale. The GIS-based GeoWEPP has emerged as an important tool in soil erosion studies, especially at the watershed scale, and has made a contribution to the development of appropriate soil conservation strategies (Meghdadi, 2013).

GeoWEPP has been used to study soil erosion conditions in study areas within the United States, such as Le Sueur watershed in Minnesota (Maalim et al., 2013). It has also been used as the tool to study soil erosion in many study areas around the world, including simulating sediment yields in the Orcan Creek Watershed in Kahramanmaras, Turkey (Yüksel et al., 2008), Agatsuma Watershed in Japan, the Teotihuacan Valley in Central Mexico (González-Arqueros et al., 2017), as well as the Kasilian watershed (Meghdadi, 2013) and the Lighvanchai watershed (Narimani et al., 2017) in Iran. Comparing simulation results between current and pre-settlement land use was performed in the Le Sueur watershed in Minnesota, USA (Maalim et al., 2013), while the comparison between pre-Hispanic periods and modern times was performed using GeoWEPP in the Teotihuacan Valley in Central Mexico (González-Arqueros et al., 2017).

2.3. The long-term study area: Walnut Gulch, AZ (USA)

The Walnut Gulch Experimental Watershed (WGEW) is a 150 km^2 major tributary of the upper San Pedro River, entering it from the east (31° 42′N, 110°03′W; see Fig. 1) (Osterkamp, 1955). The mean annual temperature at WGEW is approximately 18 °C, with an average monthly maximum temperature of 35 °C occurring in June, and an average monthly minimum temperature of 2 °C in December. Two thirds of the annual precipitation falls during the monsoon season from July through September, and much of the remainder is concentrated in the winter months of December through February. The watershed is

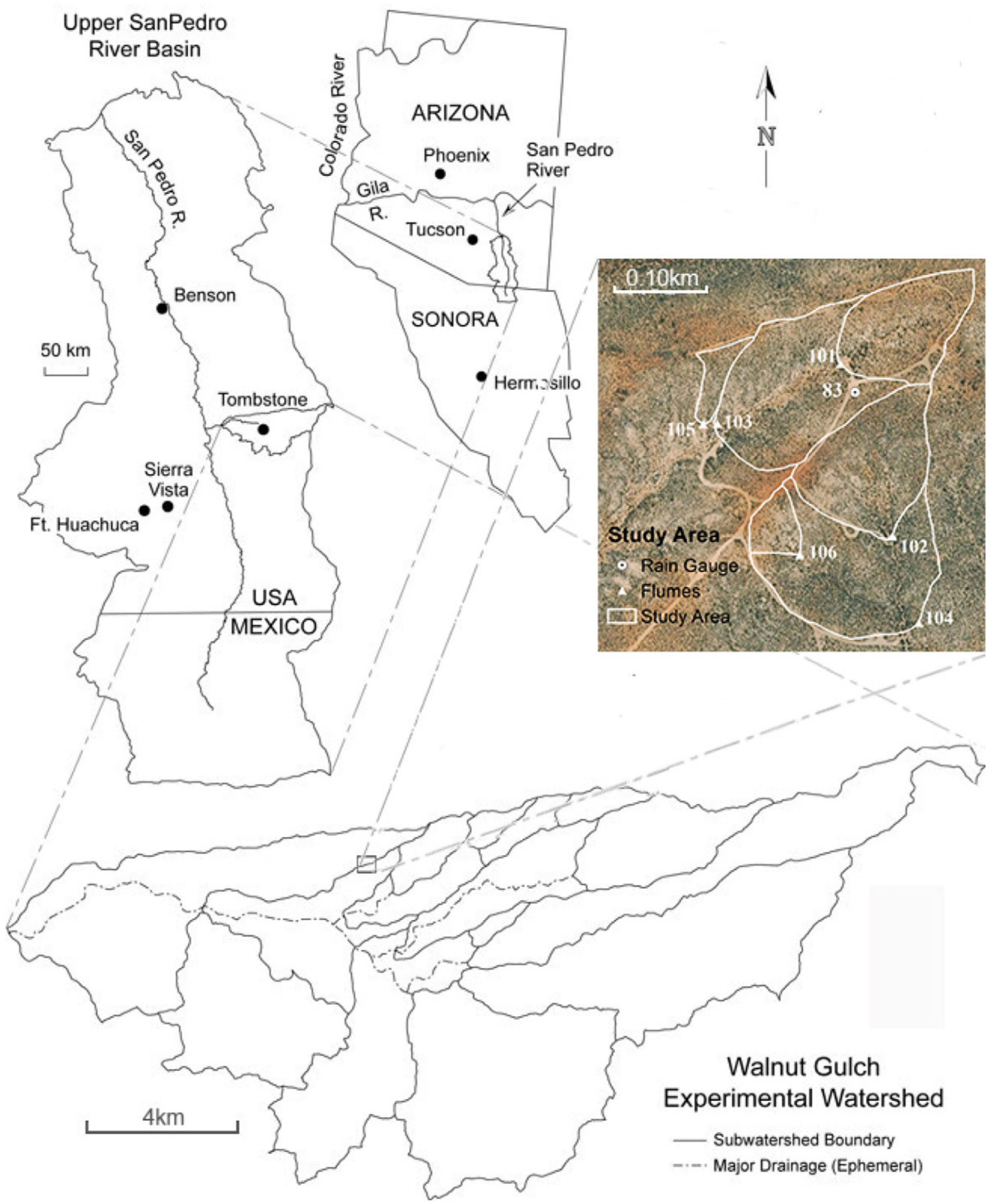

Fig. 1. Location of the study area in the Walnut Gulch Experimental Watershed, modified based on USDA (2007), with image of vegetation in WGEW, most of the landscape consisting of scattered shrubs (Minkowski, 2012).

dominated by brush and grass covered rangeland found throughout the semi-arid southwest and it is a transition zone between the Chihuahuan and Sonoran Deserts (Nichols and Renard, 2007). Soils were formed on alluvial fans and are characterized by shallow A horizon underlain by deep argillic and calcic horizon (Polyakov et al., 2016). Primary land use includes grass and shrub, with remaining land use of cattle grazing, mining, limited urbanization, and recreation. Part of the watershed had been seriously overgrazed during the last two centuries and it was invaded by desert shrubs dominating the lower two thirds of the watershed; the remaining upper part of the watershed is dominated by desert grasses. The watershed is assumed to be representative of the black grama desert shrub vegetation complexes of southeastern Arizona, southwestern New Mexico, northeastern Sonora and parts of northern Chihuahua, Mexico (Renard et al., 2008) (Fig. 1). It has been identified as a watershed with unique rainfall-runoff characteristics of semiarid regions. Nearing et al. (2007) found that sediment concentrations and total event sediment yields were related to storm-runoff characteristics, and statistical relationships were developed to estimate sediment yields for events with missing data.

2.4. The high resolution nested watershed cluster: Lucky Hills, AZ (USA)

The Lucky Hills is a 47-ha, shrub-dominated, creosote bush and acacia subwatershed located within the WGEW. It has been identified as a typical environment on WGEW (Fig. 1) (Canfield and Goodrich, 2003). Two Walnut Gulch supercritical flumes (WGSF) (Stone et al., 2008), flume 101 and 103, have been operational since 1963 in the Lucky Hills area. The study area includes six subwatersheds, starting from three flumes within the Lucky Hills (Flume 101,103, 105), and three flumes at the south of the Lucky Hills (Flume 102,104, 106) (Fig. 1). The six subwatersheds are numbered as watershed 101–106, corresponding with the flume number inside each subwatershed. Watershed 105 and 106 are smaller watersheds, with areas of 0.22-ha and 0.34-ha, respectively. Watersheds 101 and 102 are larger watersheds, with areas of 1.29-ha and 1.46-ha, respectively. Watershed 103 and 104 are nest watersheds, with watershed 101 nested in watershed 103, and watershed 102 and 106 nested in watershed 104. The areas of watershed 103 and 104 are 3.68-ha and 4.53-ha, respectively.

Among the subwatersheds, 102, 103, 104 are drained by well-developed, incised channel networks that efficiently deliver eroded particles to the watershed outlets. Watersheds 105 and 106 are relatively smaller in size without highly incised channels or toe-slope areas of noticeable deposition and sediment storage (Nearing et al., 2007). The elevation ranges from about 1354 m to 1376 m above sea level. The major soil is Luckyhills-McNeal Sandy Loam (Ustochreptic Calciorthids) and is mainly gravelly sandy loam with a high fraction of fragmented rocks (Ritchie et al., 2005). The vegetation is mainly shrub-dominated land cover with Acacia, Tarbush, and Creosote (Ritchie et al., 2005). Canopy cover in Lucky Hills during the rainy season is approximately 25%, and the ground area is mainly covered with rock and bare soil (Nearing et al., 2007). The Lucky Hills watershed is classified as rangeland, which has historically served as grazing land for cattle and horses. The shrubland was severely eroded by the early 1900s because it experienced overgrazing from 1880 to 1930 (Nearing et al., 2007). The overgrazing has been prevented by the local residents, since the watershed has been fenced off since 1963, although smaller herbivores may still graze within the watershed (Minkowski, 2012). Long-term average precipitation at Lucky Hills is 350 mm per year (Fig. S1 (Supplementary information)), and potential evapotranspiration is 260 mm per year, which is approximately 7.5 times the annual precipitation (Becker et al., 2018).

Except for individual events in 1982 and 1984 as part of a erosion model comparison study (Nearing et al., 2005), simulating runoff and sediment yields using GeoWEPP for Lucky Hills have not been validated for long-term, continuous simulations in a systematical manner to all possible spatial and temporal scales of surface runoff, sediment yield and soil redistribution.

2.5. Model performance measures: The Nash-Sutcliffe efficiency (NSE)

Traditionally, the correlation coefficient and standard error of estimate have been used to measure the fitness of a model. However, the correlation coefficient can be a poor estimator of goodness of fit because of model bias (McCuen et al., 2006). The correlation coefficient assumes that the model being tested is unbiased, but a fitted power model can be significantly biased in contrast (McCuen et al., 1990). Nash and Sutcliffe (1970) proposed an alternative goodness-of-fit index, Nash-Sutcliffe Efficiency (NSE), which overcomes the limitation of the traditional correlation coefficient.

$$\mathrm{NSE} = 1-\frac{\sum_{1=1}^{n}(\hat{y}_i-y_i)^2}{\sum(y_i-\overline{y})^2} \tag{1}$$

in which y_i= simulated values, $\hat{y}_i$ =observed values, $\overline{y}$ =mean of the observed values, and n= sample size.

If the predictions of a linear model are unbiased, then the NSE will lie in the interval from 0 to 1. For biased models, the NSE index may actually be algebraically negative. The NSE index can be applied to a variety of model types, which indicates its flexibility as a goodness-of-fit statistic (McCuen et al., 2006). For hydrological models values with NSE > 0.5 are considered a good fit (Moriasi et al., 2007).

The first objective of this study is to simulate 55 years of runoff and sediment yields of six subwatersheds using GeoWEPP. Input parameters are set and adjusted based on one subwatershed using the research-grade 1 m-DEM with no sediment yield measurements records for runoff, and one subwatershed using the publicly available 1 m-DEM and with sediment yield records available. Simulation results are then validated for other subwatersheds. A 22-year short-term analysis on the basis of previous research and a 53-year long-term analysis are performed for the surface runoff, as well as a 20-year short-term analysis for sediment yields of all available watershed outlets. Simulation performance in these six small, nested watersheds is compared and the differences between watersheds are detected.

2.6. Observed data preparation: Climate, runoff and sediment yields

For the six Lucky Hills watersheds, measured records, including runoff and sediment yields, were obtained from the South Western Research Center (SWRC) Data Access Project to validate the model performance. Observed precipitation records are obtained from rain gauge 83, which was installed in 1963 within the nested watershed 101 of the study area and they can be accessed from South Western Research Center (SWRC) Data Access Project. Rain gauge 83 has recorded most events and events with peak 30-min rainfall intensity rate higher than 22 mm/h, and the highest total precipitation amount among all the rain gauges located in WGEW (Lu and Renschler, 2020). The precipitation data is break point data, which contains more than one precipitation depth record for each single event. There are break points for each event, with a precipitation depth following each break point. Other climate data, including daily maximum and minimum temperature, solar radiation, wind velocity, wind directions and dew-point temperature can be obtained in the WEPP application.

There are six flumes, flume 101 to 106, located in the study area (Fig. 1). Information about the flumes is shown in Table S1 (Supplementary Information). Records for 1963 to 1999 are analog data, while records for 2000 to 2017 are digital. Observed runoff data from 1963 to 1986 is available for watershed 101, and observed runoff data from 1962 to 2017 is available for watershed 102 to 104. Observed runoff data from 1965 to 2017 is available for watershed 105 and 106. There is no observed sediment yield data available for watershed 101, and there are 20 years of observed sediment yield data from 1998 to 2017 for watershed 102, 22 years of observed sediment yield data from 1996 to 2017 for watershed 104 to 106, and 23 years of observed sediment yield data from 1995 to 2017 for watershed 103. Watersheds 102 to 106 are equipped with Santa Rita or Smith Flume, while watersheds 105 and 106 are equipped with H-Flume (see Table S1 (Supplementary Information)). The Santa Rita or Smith Flumes were designed in the way that flow accelerates to supercritical velocities to ensure that sediment was not deposited in the flume bottom (Nearing et al., 2007). Flow stage was measured with a standard stilling well and float. Sediment was sampled by an automatic traversing slot sampler, which took a depth-integrated sample at specified time intervals within a flow event. The sampling process begins when the flow path is above a particular threshold. The H flumes collected depth-integrated samples with automatic pump samplers. There is a difference between the two kinds of sampler. The H flumes can sample only up to about 6.4 mm particles, while the Santa Rita or Smith Flumes can sample up to 13 mm diameter material (Nearing et al., 2007).

Based on the availability of observation data a sequence of consecutive steps was developed in order to estimate and adjust the hydraulic conductivity and the critical shear parameters, respectively (see Fig. 2). After the parameter verification a long-term verification was performed for both parameter settings.

2.7. GeoWEPP input data preparation

2.7.1. Digital elevation models

For the six watersheds near Tombstone, two more recent DEMs are available. The research-grade 1 m-LiDAR DEM (ARS DEM) data provided by Dr. Mark Nearing and Dr. Mary Nichols of the USDA – Agricultural Research Service, which was created in 2003, covers watershed 101 and 103 (Fig. 3a). The publicly available 1 m-DEM data (USGS DEM) obtained from United States Geological Survey, which was created in 2015, covers the entire WGEW area and was extracted to smaller areas that cover the watershed 103 (see Fig. 3b) and the other watersheds at Lucky Hills (Fig. 3d).

The difference between the two DEMs mentioned above is shown in Fig. 3c. For the majority of watershed 103, there is a relatively higher elevation in 2015, which is relatively equally distributed, compared to the elevation in 2003. The area with a decrease in elevation from 2003 to 2015 is concentrated on the area that is close to the main channel in watershed 103, while the area with no significant elevation change (change < 0.25 m) is concentrated on areas near the tributaries to the main channel. According to USDA-ARS researchers at the WGEW (Mary Nichols, personal communication), the 2015 USGS DEM is not as accurate and the direct comparisons of elevation values are considered problematic, because most of the uphill or mid-hill sections of the watershed would be expected to have lower elevations due to expected sheet and interrill erosion. According to Ritchie et al. (2005), the erosion and deposition value of 1 t/ha/year would result in an average of 0.135 cm of reduction in elevation per year due to erosion, which indicates that there should be a reduction in elevation for 1.35 cm in 10 years or 7.425 cm in 55 years.

To get the most accurate simulation results for runoff and sediment yield in the study area, simulations for watershed 101 and 103 are performed using the 2003 ARS DEM, and simulations for watershed 102, 104, 105 and 106 are performed using the 2015 USGS DEM. Simulations for watershed 101 and 103 are also performed using the USGS DEM to detect the relationship between results generated by the two DEMs. Both DEMs are also aggregated into 3 m- and 5 m-resolution for further study.

2.7.2. Watershed delineation

GeoWEPP integrates the WEPP model and TOPAZ (TOpography PArameteriZation) software via ArcGIS. A DEM provides the required input data for the delineation of the watershed and sub-catchments extraction. The channel network is defined using TOPAZ based on the steepest down slope path, considering eight adjacent cells of each pixel (Garbrecht and Martz, 1997). The channel network can be adjusted by changing values of Mean Source Channel Length (MSCL) and Critical Source Area (CSA). The MSCL defines the shortest channel length and the CSA is the minimum drainage area (Garbrecht and Martz, 1997). Sub-catchments are explicitly defined based on the channel network and prepared for further processing (Flanagan and Nearing, 1995).

The watershed outputs are generated as grid layers representing sediment yields as the relationship to a Target Soil Loss (TSL). The runoff and sediment yield simulated results for each event are listed in text files or in grid outputs. Text files indicate average annual rainfall and number of storms, total runoff, soil loss, and sediment yield for each subwatersheds and for the entire watershed (Yüksel et al., 2007).

2.7.3. Climate file

The climate file for the observations at Weather Station 83 consists of 10 columns, including day, month, year, the number of daily break point (nbrkpt), daily maximum and minimum temperature (tmax, tmin), as well as solar radiation (rad), wind velocity (w-vel), wind directions (w-dir) and dew-point temperature (dew). Daily break point precipitation data from 1963 to 2017 is obtained from rain gauge 83, which was installed in 1963 within the nested watershed of the study area and can be accessed from South Western Research Center (SWRC) Data Access Project. Daily maximum and minimum temperature, solar radiation, wind velocity, wind directions and dew-point temperature within the same time period are obtained from the nearest climate station located in Tombstone, AZ. Data above are formatted to a Breakpoint Climate Data with 55 years of climate records following the standard formats (Zeleke et al., 2019).

For each day with precipitation records, the break point precipitation is formatted into two columns, the time and precipitation, under the general climate information of the day. The time is described as the hour and the percentage of the minutes of a break point, divided by a colon, followed by the corresponding precipitation at the break point. The number of break points in each day is listed as the fourth column. For those days with no precipitation, the number of break points is 0.

2.7.4. Soil and management/vegetation files

The soil model parameters for the Lucky Hills-McNeal Sandy Loam (Breckenfeld, 1995) illustrated in Table S2 (Supplementary Information) were initially developed for selected individual events in 1982 and 1984 (Nearing et al., 2005). Minkowski (2012) adjusted two

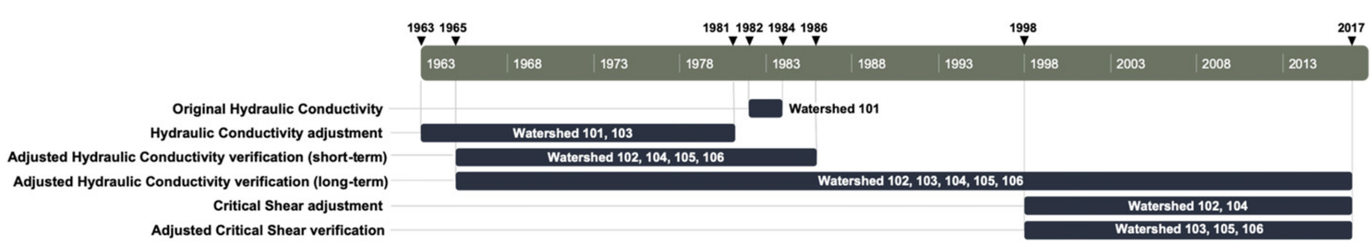

Fig. 2. Timeline for parameter adjustment and verification.

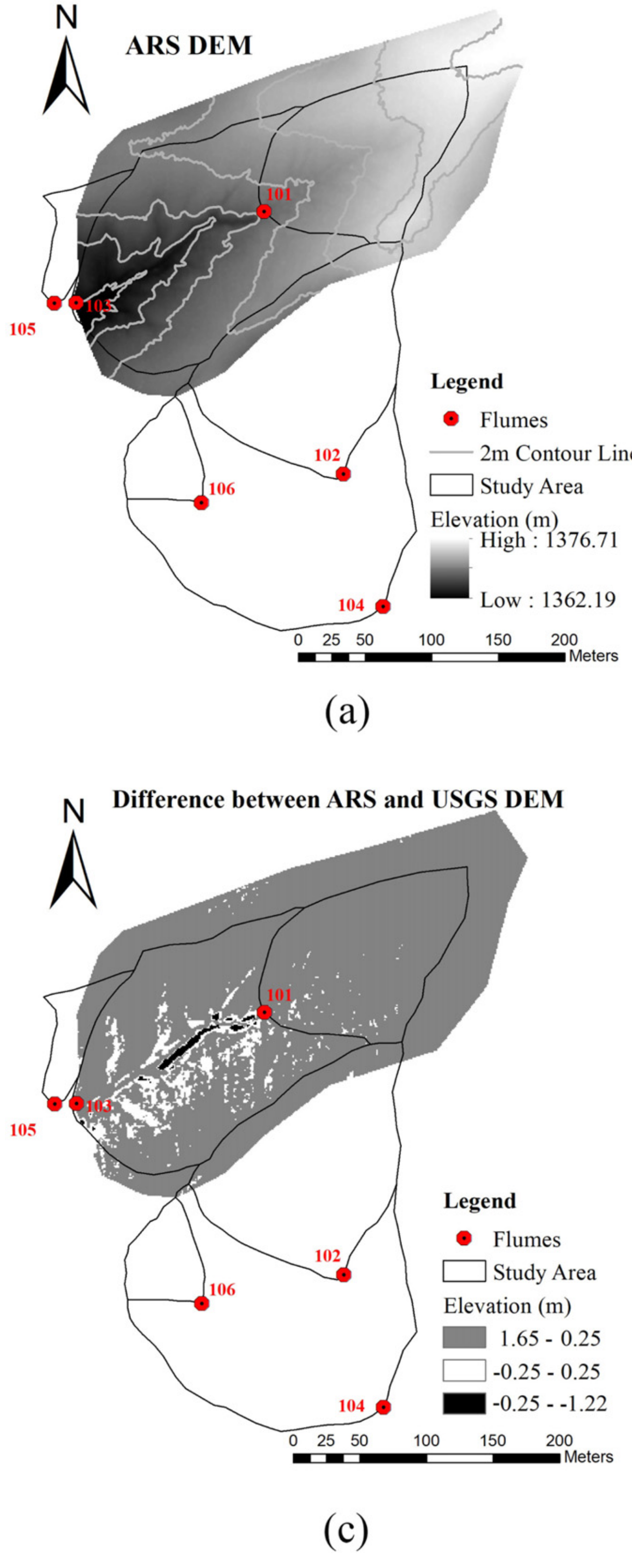

Fig. 3. DEM with 2 m contour lines in the study area. Darker color represents higher elevation: (a) ARS DEM covering watershed 101 and 103, (b) USGS DEM covering watershed 101 and 103, (c) difference between ARS and USGS DEM, and (d) USGS DEM covering watershed 101 to 106. For (c), white areas within the watershed represents areas within a ±25 cm-margin of difference, grey represents a different of >25 cm in elevation, and black represents a difference of more than -25 cm in elevation.

parameters - hydraulic conductivity and shear stress to reflect the hydrologic and sediment yield responses, respectively – for a continuous, but short-term simulation over three years (see original hydraulic conductivity for 1982–1984 in Fig. 2).

The main goals of this paper is to estimate and validate those two same main parameters, but for much longer-time periods within in a cluster of nested, neighboring watersheds. Fig. 2 lists the series of consecutive steps in this paper to a) adjust the effective hydraulic conductivity (K_{eff}) model parameter in GeoWEPP to have acceptable NSE indices for the nested watersheds 101 and 103 for the longest possible time period (1963–1986) and then consequentially b) verify for all six watersheds the adjusted hydraulic conductivity parameters for a shorter, 22-year (1965–1986) and c) a longer, 52-year time period (1965–2017).

Minkowski (2012) – as Nearing et al. (2005) - determined K_{eff} based on storm season data from 1982 to 1984 as 3.7 mm/h. This value is used as the initial K_{eff} watershed 101 to adjust K_{eff} for the other five watersheds (Fig. 4; non-dashed arrows). After the focus on adjusting the hydrologic parameterization of the model, the adjustment of the critical shear parameter was based on the nested watershed 102 and 104 for the longest possible, 20-year time period from 1998 to 2017 and d) verified for the other watersheds 103, 105 and 106 (Fig. 4; dashed arrows). For this study, there is the assumption, that there is no spatially distribution of soil and vegetation parameters within in the Lucky Hills watersheds. The vegetation parameter file representing for those of creosote and whitethorn vegetation, was the same one that was put together for a soil erosion model comparison study (Nearing et al., 2005).

2.7.5. GeoWEPP model application

Required input data, including the DEM, soil, land use in the same resolution are selected to generate an ArcMap project using the GeoWEPP interface. The critical source area (CSA) and the minimum source channel length (MSCL) adjusted to meet the identified channels in the watershed 101. According to the composition of the soil in the study area, the channel parameters were set as gravel. There are two orders of channels for all watersheds except watershed 104, which has three orders of channels. The outlet points of each watershed are

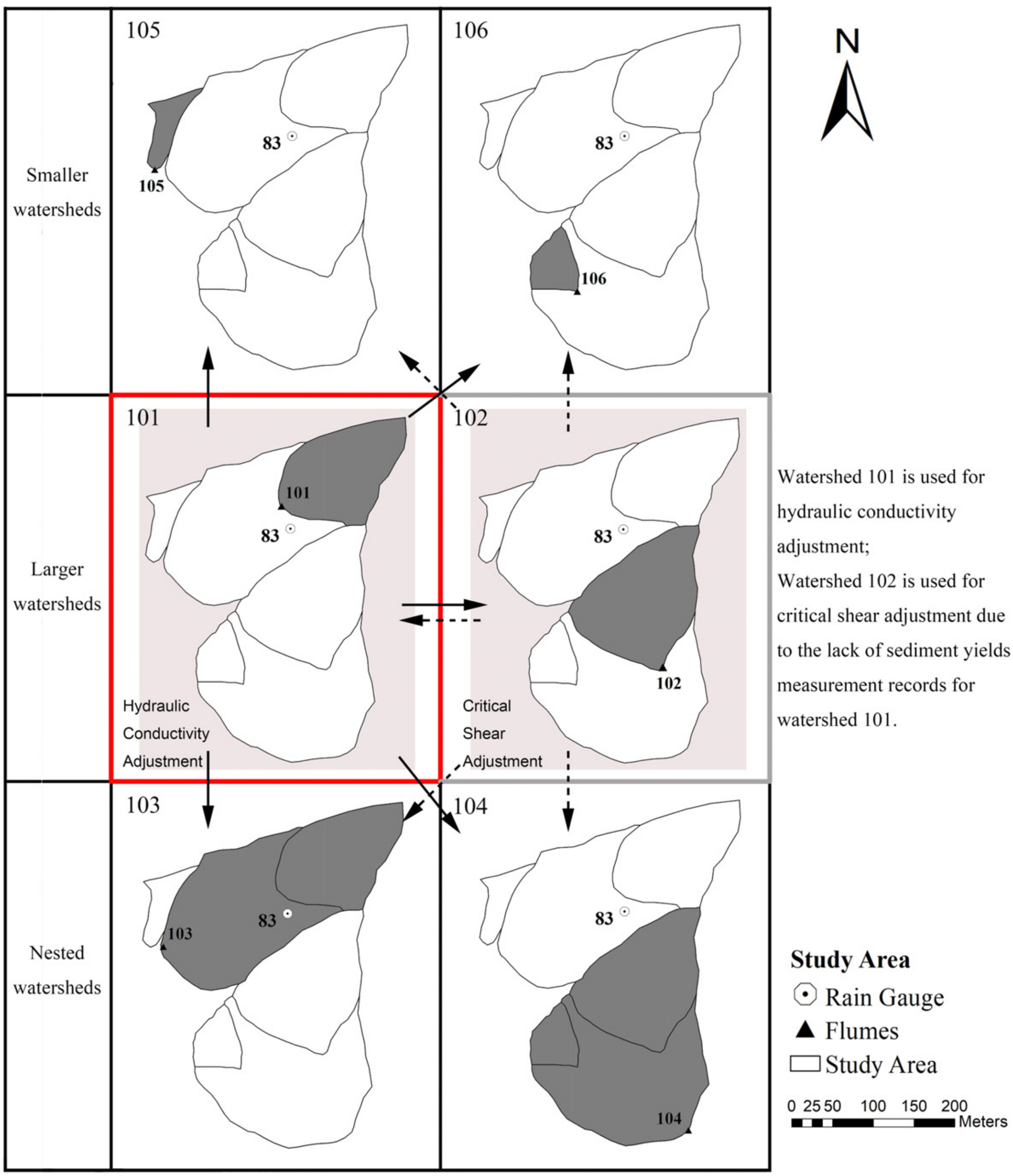

Fig. 4. Watershed 101 and watershed 103 as the basic watershed for hydraulic conductivity (non-dashed arrow) and critical shear (dashed arrow) adjusted parameter estimation and verification, the remaining watersheds as the watersheds for parameter validation (as indicated by the arrows).

specified based on Google Earth images and the satellite basemap of ArcMap, combining with the shapefile of subwatersheds obtained from the SWRC Data Access Project. The sub-catchments of each watershed are defined based on the outlet points. The data above are accepted and then input into GeoWEPP with the climate data to generate the erosion patterns for 55 years for 1963 to 2017 using the watershed method. Both the general information about the soil erosion patterns, runoff and sediment yield by events are simulated and output as text files. A map of the average annual sediment yields for GeoWEPP generates each watershed with the target value T of 1 t/ha/year to highlight four classes of sediment yields below T in green and multiples of T in red.

2.8. Event classifications: Rainfall, runoff and sediment yield events

For the simulated events, there are a small number of events without corresponding observed runoff records, which is probably for the reason that the amount of runoff in an event might be too small to be collected and recorded. ***Significant events*** are defined based on precipitation. According to Goodrich et al. (2008), significant rainfall events should be defined as rainfall events with precipitation over 25 mm/h. Due to the limitation that there are only 24 years of observed data for watershed 101 for 1963 to 1986, and there are no observed data available before 1965 for watersheds 105 and 106, two sets of analysis are performed: a short-term analysis (22 years) for watershed 101 for 1965 to 1986, and a long-term analysis (53 years) for watersheds 102 to 106 for 1965 to 2017 (see Fig. 2).

At Lucky Hills, watershed 101 is nested in watershed 103, and watersheds 102 and 106 are nested in watershed 104. To account for *events with transmission losses between two outlet measurement points*, positive balance, zero balance and negative balance events can be defined (see Table 1), e.g. by comparing the observed runoff by events in watershed 101 and 103, watershed 102 and 104, as well as watershed 106 and 104. Taking watershed 101 and 103 as the example, if watershed 101 has smaller runoff than watershed 103 in the same event, which indicates that there is more surface runoff contributing to the downstream between watershed 101 and 103, the event is defined as a positive balance event. There are smaller transmission loss events due to smaller infiltration between 101 and 103 in comparison with what are contributed through the hillslope, which lead to more runoff downstream. Similarly, if watershed 101 has approximately the same runoff compared to watershed 103 in the same event (difference < 0.01 mm), which indicates that there is the same surface runoff contributes to downstream between watershed 101 and 103, the event is defined as a zero balance event. There are equal transmission loss events due to larger infiltration between 101 and 103 in comparison with what are contributed through the hillslope, which lead to the same runoff downstream. If watershed 101 has larger runoff compared with watershed 103, which indicates that there is less surface runoff contributes to the downstream, the event is defined as a negative balance event. There are larger transmission loss events due to larger infiltration between 101 and 103 in comparison of what are contributed through the hillslope, which lead to less runoff downstream. The same classification process (Table 1) is performed to define the event type in watershed 102, 104, and 106. Since watershed 105 is an individual subwatershed and is not nested in any larger watershed, the event type in this watershed cannot be classified and is not included in the analysis.

Table 1
Event classification criteria (taking watershed 101 and 103 as example).

Event type	Criteria (runoff in mm)	Situation
Positive balance event	W 101 < W 103	More surface runoff contributing to the downstream between watershed 101 and 103 than transmission losses.
Zero balance event	W 101 ≈ W 103	Same surface runoff contributing to the downstream between watershed 101 and 103 than transmission losses.
Negative balance event	W 101 > W 103	Less surface runoff contributing to the downstream between watershed 101 and 103 than transmission losses.

3. Results and discussion

The following chapters illustrate the results in accordance with the consecutive steps indicated in Fig. 2.

3.1. Original and adjusted effective hydraulic conductivity (K_{eff})

Simulations of runoff in watershed 101 from 1982 to 1984 and from 1963 to 1986 are performed using this soil file and the 1 m-ARS DEM, and the validation of the results is shown in Fig. 5a. For the simulation of runoff from 1982 to 1984, the relationship between the observed and simulated runoff is $y = 0.9396x$. The coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE) between the observed and simulated runoff is 95.45% and 93.84%, respectively. The model efficiency is high, which indicates that the simulated runoff is highly representative for that relative short time period.

However, for the simulation of runoff events from 1963 to 1981, the relationship between the observed and simulated runoff is $y = 1.2677x$. The R^2 and NSE are much lower with 69.87% and 38.71%, respectively. The runoff is over-estimated and the model efficiency is relatively low. If event outliers with a difference of >20 mm between the simulated runoff and the observed runoff are removed, the R^2 and NSE are slightly better, but still far from being acceptable. This might be caused by the significant increase of precipitation from 1982 to 1984 compared with the time period before 1982 (compare Fig. S1 (Supplementary information)), and thus K_{eff} might be different between 1963 and 1981 and 1982 to 1984. To simulate long-term runoff and sediment yields in the study area accurately, K_{eff} needs to be adjusted to fit over a longer time period.

According to NRCS (2019), the saturated hydraulic conductivity (K_{sat}) of the main soil type in Lucky Hills is between 15.228 and 50.796 mm/h for gravelly sandy loam. Using values within this range, resulted in the simulation for runoff in watershed 101 from 1963 to 1981 is $y = 0.9597x$ with a R^2 of 84.18%, and NSE of 82.90% (Fig. 5b). After the adjustment, the relationship between the simulated and observed runoff from 1982 to 1984 is $y = 1.0492x$ with a R^2 of 84.67%, and NSE of 84.45% (Fig. 5b). This model with adjusted K_{eff} fits much better for both time periods from 1963 to 1981 and from 1982 to 1986. Applying the adjusted K_{eff} to simulate runoff in watershed 103 downstream from 101 for the entire time period of 1963 to 1986 results in $y = 1.1736x$ with a R^2 of 84.14%, and a NSE of 70.65%. Thus, the K_{eff} has been adjusted successfully and is used in the next steps of this modeling study.

3.1.1. Impact assessment of DEM resolution

The channel networks and sub-catchments for watershed 103 generated by the input data in 1 m, 3 m and 5 m using the ARS DEM and USGS DEM are shown in Fig. S2 (Supplementary information)on the left and right side, respectively. With the decrease of the input data's resolution, the generated channel networks become shorter. There is no significant difference between the channel networks generated by the 1 m-ARS DEM (Fig. S2 a.1 (Supplementary information)) and 1 m-USGS DEM (Fig. S2 a.2 (Supplementary information)). For the channel networks generated by the 3 m-DEMs, the one generated by the USGS DEM (Fig. S2 b.2 (Supplementary information)) failed to include the channel at the south of the main channel compared with the one generated by the ARS DEM (Fig. S2 b.1 (Supplementary information)), which leads to a shorter channel length for the one generated by the USGS

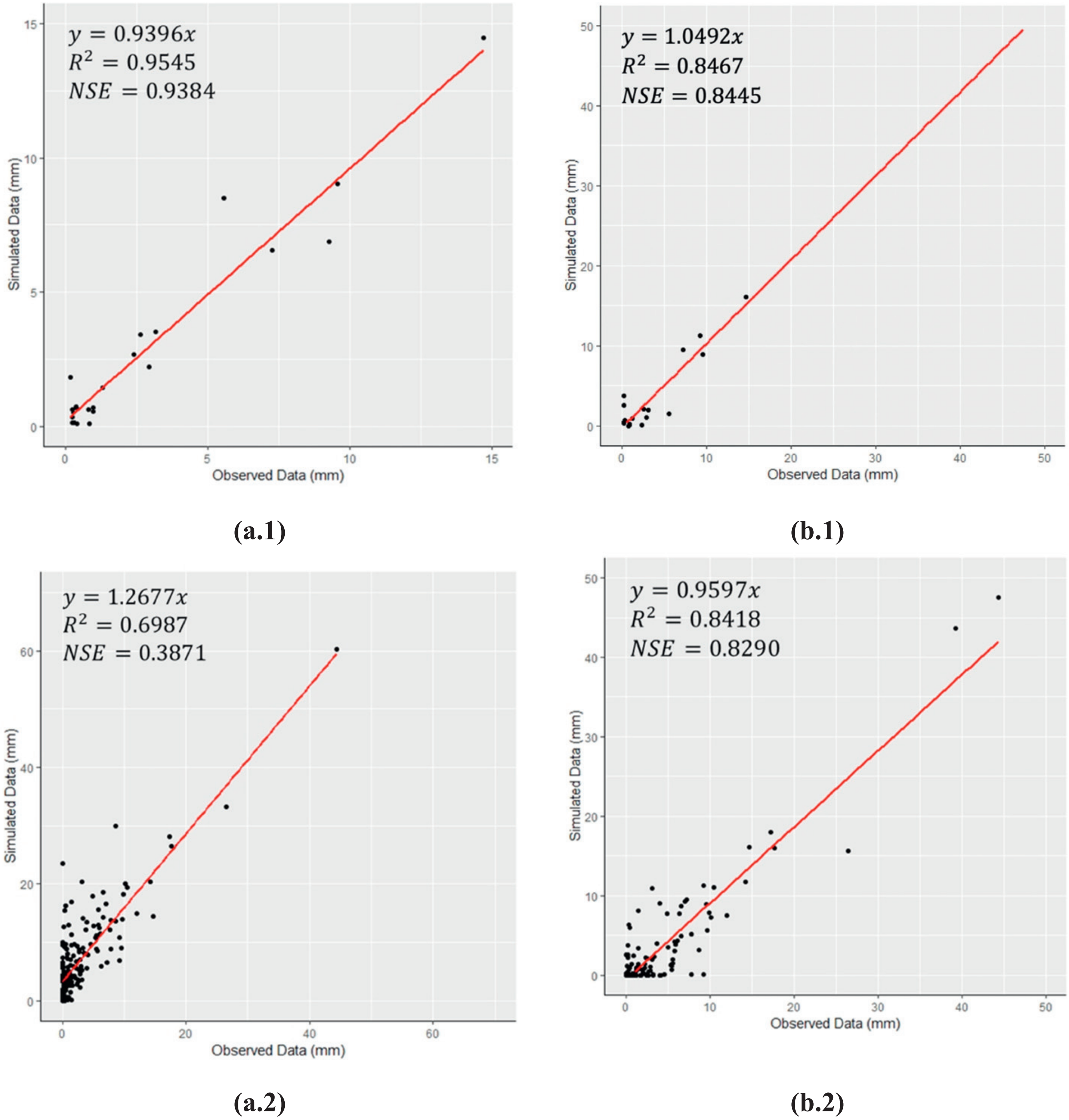

Fig. 5. Runoff simulation performance for watershed 101 for 1982–1984 (a.1) and 1963–1981 (a.2) using the originally estimated hydraulic conductivity (Minkowski, 2012) (a); for 1982–1984 (b.1) and 1963–1981 (b.2) using the adjusted hydraulic conductivity (b) and 1 m ARS DEM (unit in mm). All of the relationships between simulated and observed runoff are significant (Pr(>|t|) < 0.001).

DEM. For the channel networks generated by the 5 m-DEMs, the one generated the USGS DEM (Fig. S2 c.2 (Supplementary Information)) has more channels compared with the one generated by the ARS DEM, particular the channel at the south of the main channel for the one generated by the USGS DEM. In addition, the number of sub-catchments decreases with the decrease of resolution.

Table 2 shows the simulation performance for watershed 101 for 1963 to 1986 and watershed 103 for 1963 to 2017 using the ARS DEM in 1 m, 3 m and 5 m-resolution. All event results, include those that are with observed runoff over 0.1 mm and significant events with precipitation rates larger than 25 mm per hour, have acceptable R^2 above 78%, and NSE above 73%. Comparing the result performances generated by input data in different resolutions, it can be seen any runoff simulation event results using the input data in 5 m-resolution have NSE above 82% for watershed 101 and 81% for watershed 103.

Generally, simulation using input data in 5 m-resolution seems to result in more accurate results at the scales of 1.29 ha and 3.68 ha for watershed 101 and 103 respectively. It seems that using a higher resolution DEM for GeoWEPP is not necessarily required in this research area. The information represented by data in a higher resolution might be too

Table 2
Runoff simulation performance for watershed 101 for 1963–1986 and watershed 103 for 1963–2017 using the ARS DEM in 1 m, 3 m and 5 m-resolution: (a) All simulated events with observed record, (b) events with observed runoff over 0.1 mm, and (c) significant events (events with precipitation rate larger than 25 mm/h). All of the relationships between simulated and observed runoff are significant (Pr(>|t|) < 0.001).

Watershed	Year	Resolution	Range	Number of events	Estimate	R^2	NSE
101	1963–1986	1 m	(a)	99	0.9340	0.8091	0.7874
			(b)	91	0.9441	0.8076	0.7834
			(c)	34	0.9244	0.8239	0.8180
		3 m	(a)	145	0.8917	0.8065	0.7668
			(b)	117	0.9067	0.8008	0.7567
			(c)	12	0.8886	0.7833	0.7693
		5 m	(a)	118	0.9597	0.8418	0.8290
			(b)	106	0.9680	0.8406	0.8261
			(c)	34	0.9570	0.8611	0.8590
103	1963–2017	1 m	(a)	333	1.2389	0.8848	0.8024
			(b)	301	1.2495	0.8826	0.8082
			(c)	38	1.2387	0.8945	0.7897
		3 m	(a)	212	1.1682	0.8144	0.7956
			(b)	203	1.1837	0.8225	0.8015
			(c)	34	1.0880	0.7951	0.7316
		5 m	(a)	213	1.0748	0.8216	0.8518
			(b)	206	1.0880	0.8296	0.8473
			(c)	35	1.0870	0.7892	0.8175

noisy leading potentially to a higher accumulated error. This follows the argument of Charrier and Li (2012) observing that LiDAR DEMs with a lower resolution could be more appropriate for delineating watershed, since higher resolutions are more sensitive to micro-topographic variations. According to these results, the analysis of using K_{eff} for verification in the other watersheds are performed using the 5 m-DEM input data for GeoWEPP.

3.1.2. Impact assessment of DEM difference

To assess the impact of using either the 2003 ARS DEM or the 2015 USGS DEM, the simulation performances of watershed 101 and 103 with both DEM datasets in 5 m-resolution are compared (Table 3). According to the comparison of simulated runoff generated, estimates using the USGS DEM are generally a bit higher compared with those using the more accurate ARS DEM for either watershed. The difference is more significant for the larger watershed 103 compared with watershed 101, and the difference explains the general over-estimation of the runoff in the six watersheds simulated using the USGS DEM in the next step.

3.1.3. Long-term analysis of accumulated runoff

Accumulated runoff for all six watersheds using 5 m-USGS DEM for 1965 to 1986 illustrate that simulated accumulated runoff for 104 is overestimated while others have more balanced appearance of under and overestimated event totals over the 22-year period (Fig. S3 (Supplementary information)). Runoff simulation performances for watershed 101 to 106 using the 5 m-USGS DEM are shown in Fig. 6 for all simulated observed events (1965 to 1986 and 1965–2017). NSE are all higher than 71% for either time period, except for the larger watershed 104 with a lower NSE of 69% for 1965 to 1986 and a very low NSE of 28% for 1965 to 2017.

Looking closer at the results for the relative small number of significant events – where most of the sediment yield is produced – has usually higher NSE values with >75% for all watersheds in comparison to all events with observed records of events (except of 106; see Table 4). Overall, runoff is over-estimated for the larger nested watersheds 103 and 104 by 16 to 25%, while the smaller watersheds have an estimate of −3% to +3% (except for the small watershed 106 with an underestimation ranging from 15 to 19% (Table 4).

Table 3
Runoff simulation performance for watershed 101 and 103 using 5 m-ARS DEM and 5 m-USGS DEM for 1963–1986: (a) All simulated events with observed record, (b) events with observed runoff over 0.1 mm, and (c) significant events (events with precipitation rate larger than 25 mm/h). All of the relationships between simulated and observed runoff are significant (Pr(>|t|) < 0.001).

Watershed	DEM	Range	Number of events	Estimate	R^2	NSE
101	ARS	(a)	118	0.9597	0.8418	0.8290
		(b)	106	0.9680	0.8406	0.8261
		(c)	34	0.9570	0.8611	0.8589
	USGS	(a)	157	0.9875	0.8447	0.8291
		(b)	127	1.0060	0.8440	0.8238
		(c)	12	1.0128	0.8633	0.8621
103	ARS	(a)	213	1.0748	0.8216	0.8518
		(b)	206	1.0880	0.8296	0.8473
		(c)	35	1.0870	0.7892	0.8175
	USGS	(a)	414	1.1498	0.8448	0.8279
		(b)	310	1.1817	0.8412	0.8178
		(c)	36	1.2204	0.8640	0.8155

3.1.4. Runoff by event type

In order to assess the impact of transmission losses in the watershed, one can look at the comparison of positive, zero or negative balance events (see Table 1). The simulation performance based on these types of events in nested watersheds between 101 and 103, 102 and 104, as well as 106 and 104 using the 5 m USGS DEM for 1965 to 1986 and 1965 to 2017 are shown in Table 5. For negative balance events (more transmission losses in channel section between runoff gages), NSE has the maximum value of 88.95% for watershed 102 and the minimum value of 26.71% for watershed 104. For the time period 1965 to 1986, the negative balance events for all thee pairs of nested watersheds have all NSE higher than 71.31%, but overestimation by >20% for 103 and 104. In contrast for the longer time period of 1965 to 2017, only negative balance events for 102 and 104 have NSE of >78% while the others are below 52%. For zero balance events (more or less the same observed runoff downstream and upstream), NSE for the shorter the 1965 to 1986 are higher than 68.22% for 103 and 104. For positive events (more runoff at the downstream gauge than upstream), NSE is higher than 72.5% for 103 and 104 (except when comparing with 106 upstream). This spatially distributed analysis enables one to see which simulations of contributing parts of the nested watershed does a better hydrologic simulation than the downstream simulation (See Table 5).

3.2. Critical shear parameter estimation and sediment yields simulations

In this final step of this study, critical shear parameter adjustments and verification are assessed (see Fig. 2). Utilizing observation from

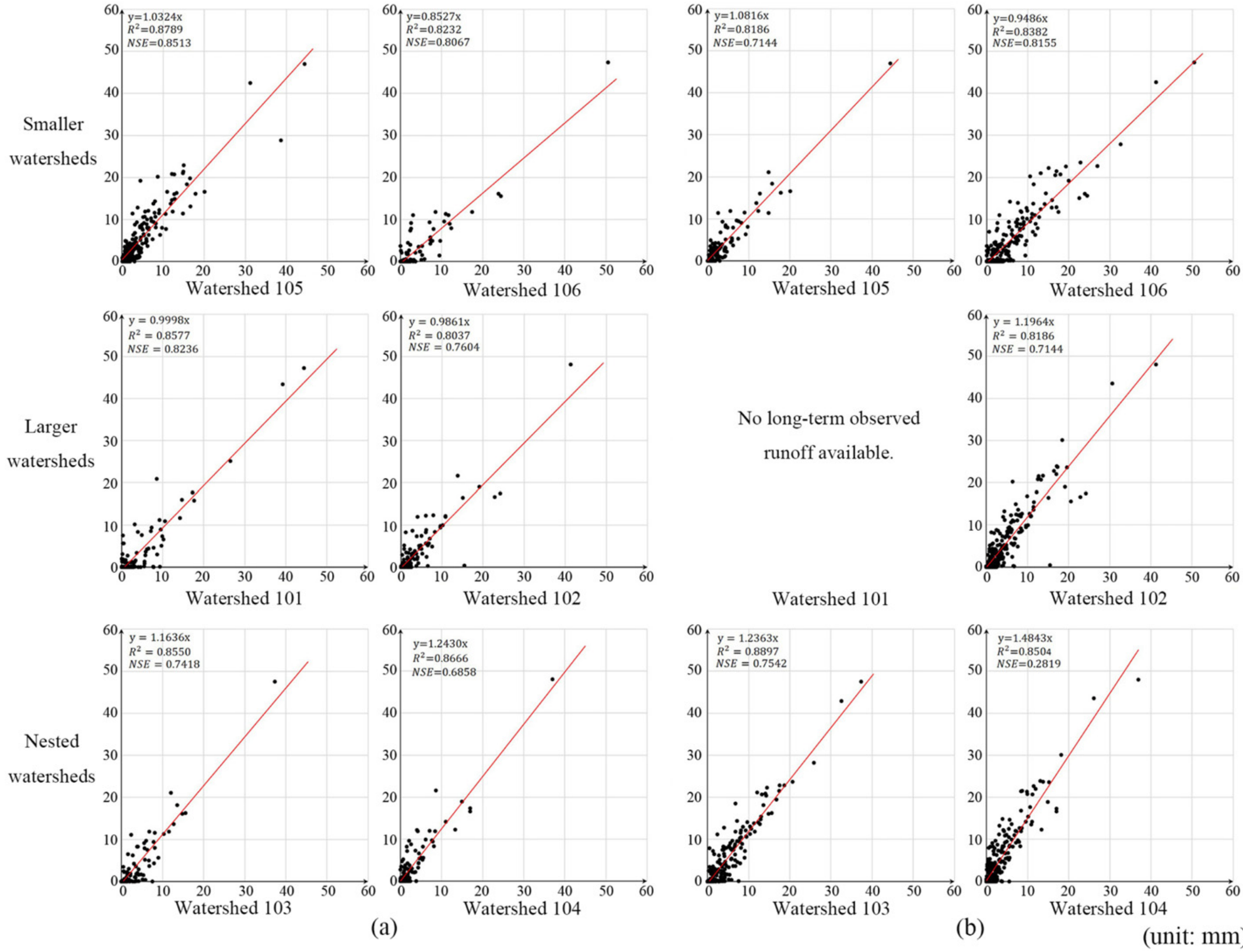

Fig. 6. Runoff simulation performance for watershed 101–106 for 1965–1986 (a) and for 1965–2017 (b) using 5 m USGS DEM. *x*-axis represents years, *y*-axis represents accumulated runoff (mm), each point represents an event. All the relationship between simulated and observed runoff are significant (Pr(>|t|) < 0.001).

Table 4
Runoff simulation performance for watersheds 101 to 106 using 5 m-USGS DEM for 1965–1986 sorted by the increasing area of watersheds. (a) All simulated events with observed record, (b) events with observed runoff over 0.1 mm, and (c) significant events (events with precipitation rate larger than 25 mm/h). All the relationship between simulated and observed runoff are significant (Pr(>|t|) < 0.001).

Watershed	Type	Watershed 105				Watershed 106			
		Number of events	Estimate	R^2	NSE	Number of events	Estimate	R^2	NSE
Smaller watersheds	(a)	113	1.0324	0.8789	0.8513	102	0.8527	0.8232	0.8067
	(b)	112	1.0323	0.8785	0.8507	93	0.8629	0.8271	0.8045
	(c)	11	0.9957	0.8812	0.8682	11	0.8135	0.8246	0.7789
	Type	Watershed 101				Watershed 102			
		Number of events	Estimate	R^2	NSE	Number of events	Estimate	R^2	NSE
Larger watersheds	(a)	139	0.9998	0.8577	0.8236	118	0.9861	0.8037	0.7604
	(b)	112	1.0045	0.8559	0.8121	107	0.9886	0.7973	0.7493
	(c)	10	1.0128	0.8633	0.8621	10	1.0290	0.8490	0.8443
	Type	Watershed 103				Watershed 104			
		Number of events	Estimate	R^2	NSE	Number of events	Estimate	R^2	NSE
Nested watersheds	(a)	187	1.1636	0.8550	0.7418	158	1.2430	0.8666	0.6858
	(b)	131	1.1903	0.8504	0.7121	110	1.2422	0.8555	0.6546
	(c)	10	1.2204	0.8640	0.8155	8	1.1740	0.8529	0.7581

Table 5
Runoff simulation performance for watershed 102 to 106 using 5 m USGS DEM for 1965–2017. (a) All simulated events with observed record, (b) events with observed runoff over 0.1 mm, and (c) significant events (events with precipitation rate larger than 25 mm/h). For 22 years event classification (1965–1986), (d) negative balance events, (e) positive balance events, and (f) zero balance events. For 53 years event classification (1965–2017), (g) negative balance events, (h) positive balance events, and (i) zero balance events. All the relationship between simulated and observed runoff are significant (Pr(>|t|) < 0.001).

Watershed	Type	Watershed 105				Watershed 106			
		Number of events	Estimate	R^2	NSE	Number of events	Estimate	R^2	NSE
Smaller watersheds	(a)	225	1.0816	0.8186	0.7144	221	0.9486	0.8382	0.8155
	(b)	223	1.0816	0.8178	0.7130	209	0.9553	0.8374	0.8107
	(c)	35	0.9957	0.8812	0.8682	34	0.8135	0.8246	0.7789
		Individual watershed, event classification is not available.				Comparing watershed 106 and 104			
	(d)					81	0.8640	0.8442	0.8166
	(e)					14	1.0548	0.6850	0.6999
	(f)					14	0.7321	0.5624	0.5111
	(g)					191	1.0126	0.5358	0.5280
	(h)					20	0.9612	0.8385	0.8256
	(i)					15	0.7641	0.5764	0.5213
	Type	Watershed 101				Watershed 102			
		Number of events	Estimate	R^2	NSE	Number of events	Estimate	R^2	NSE
Larger watersheds	(a)	No long-term observed runoff available.				279	1.1964	0.8163	0.6233
	(b)					268	1.1972	0.8127	0.6138
	(c)					36	1.1356	0.7896	0.6903
		Comparing watershed 101 and 103				Comparing watershed 102 and 104			
	(d)	56	1.0338	0.8631	0.7774	91	0.9932	0.8272	0.8895
	(e)	39	0.9797	0.6277	0.6768	11	1.0217	0.6870	0.6821
	(f)	17	1.1029	0.5143	0.4816	4	1.0497	0.4882	0.5788
	(g)	No long-term runoff for watershed 101 available for comparison.				263	0.9612	0.8120	0.7835
	(h)					54	0.7641	0.9882	0.9814
	(i)					34	1.0126	0.7621	0.6735
	Type	Watershed 103				Watershed 104			
		Number of events	Estimate	R^2	NSE	Number of events	Estimate	R^2	NSE
Nested watersheds	(a)	414	1.2363	0.8897	0.7542	365	1.4843	0.8504	0.2819
	(b)	310	1.2594	0.8841	0.7241	277	1.4795	0.8353	0.1983
	(c)	36	1.2204	0.8640	0.8155	36	1.1740	0.8529	0.7581
		Comparing watershed 101 and 103				Comparing watershed 104 and 106			
	(d)	95	1.2373	0.8636	0.8309	124	1.2430	0.8820	0.7131
	(e)	86	1.0668	0.8422	0.8388	49	1.4134	0.7987	0.2712
	(f)	6	1.0180	0.6980	0.6822	14	0.5326	0.8597	0.7714
	(g)	No long-term runoff for watershed 101 available for comparison.				288	1.4987	0.8670	0.2671
	(h)					95	1.3047	0.7170	0.7250
	(i)					26	0.8300	0.8416	0.7134
		Unavailable				Comparing watershed 104 and 102			
	(d)					108	1.2627	0.8992	0.7298
	(e)					14	0.9390	0.9629	0.9163
	(f)					4	1.0544	0.9889	0.9805
	(g)					266	1.5080	0.8735	0.2826
	(h)					92	0.8965	0.8218	0.7839
	(i)					36	1.0450	0.9884	0.9816

Negative balance events: less surface runoff contributes to the downstream between watershed 101and 103, 102 and 104, 106 and 104.
Positive balance events: more surface runoff contributes to the downstream between watershed 101 and 103, 102 and 104, 106 and 104.
Zero balance events: same surface runoff contributes to the downstream between watershed 101 and 103, 102 and 104, 106 and 104.

1998 to 2017 and the 5 m USGS DEM, the soils critical shear parameter are adjusted for 102, then verified for 104, before they are validated for 103, 105 and 106 (Fig. 4). Please note that there is no observed sediment yield record for watershed 101.

Table 6
Sediment yields simulation performance for watershed 102 to 106 for 1998–2017 using the original critical shear value.

Watershed	Number of events	Estimate	R^2	NSE
105	48	2.6234	0.7856	0.2060
106	67	2.0759	0.6992	0.4246
102	45	4.8372	0.6992	0.2968
103	77	1.0239	0.7017	0.6957
104	60	2.0221	0.7313	0.4888

3.2.1. Original critical shear parameter

The analysis is performed for the sediment yields simulation in watershed 102 to 106 for 1998 to 2017 using the soil file provided by Minkowski (2012) (Table S2 (Supplementary Information)). The model simulated sediment yields in watershed 103 accurately, with the R^2 and NSE as 70.17% and 69.57%, respectively (see Table 6). However, for watershed 102, 104, 105 and 106, the sediment yields are highly over-estimated with the estimate value of >100%, and the NSE is below 49% for all simulated events with observed records. It indicates that the soil property in watershed 103 is likely different from watershed 102, 104, 105 and 106.

The property that affects sediment yields and soil erosion rates in the soil file is critical shear. Thus, critical shear was adjusted for watershed 102, and then applied to 104, 105 and 106. For watershed 103, the

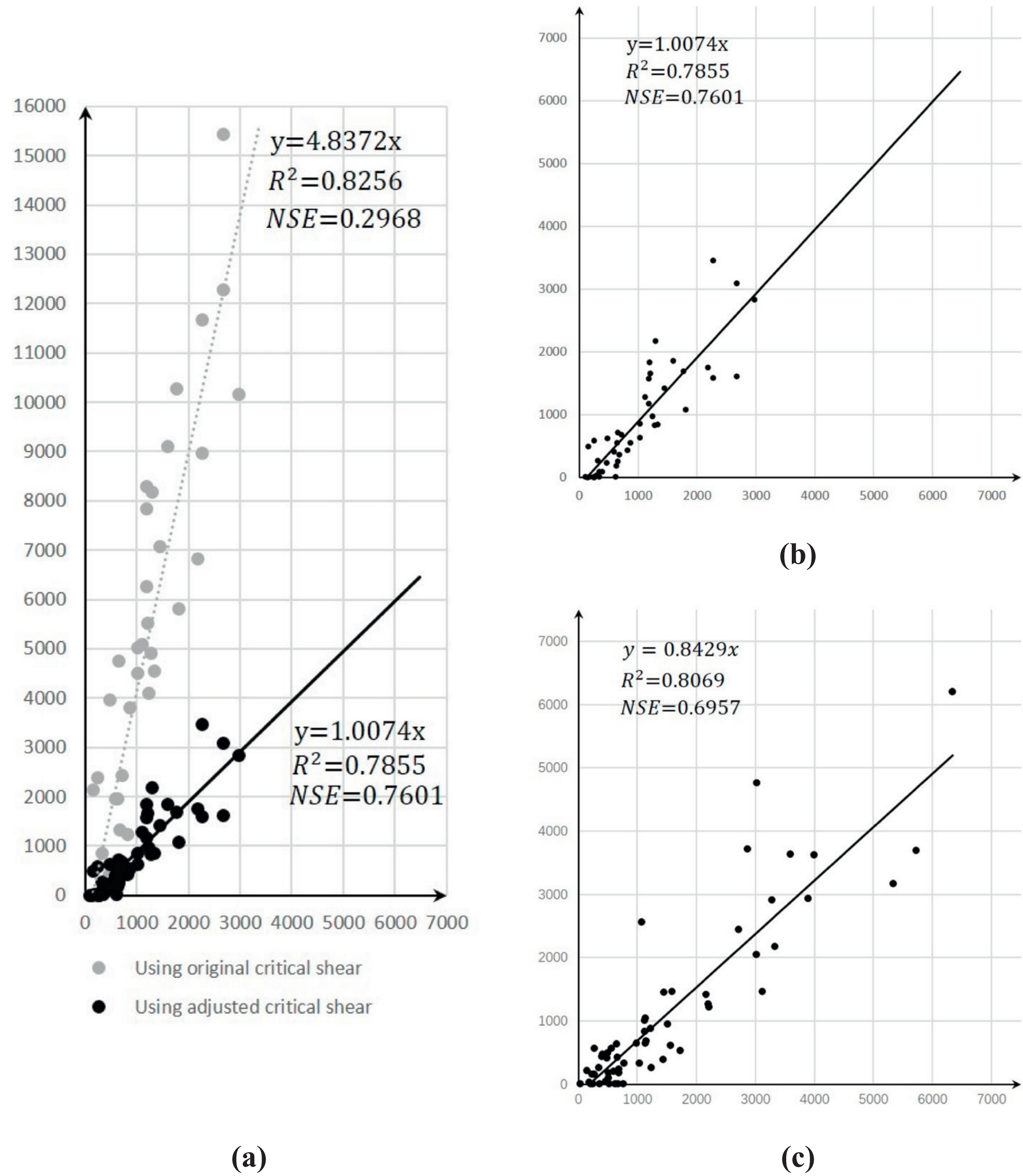

Fig. 7. Sediment yields simulation performance for watershed 102 using the soil file with the original critical shear and the adjusted critical shear value (a), watershed 102 using the adjusted critical shear value (b), and watershed 104 using the adjusted critical shear value for 1998–2017 (unit in kg).

critical shear was set as 3.1 pa. While the same critical shear leads to the highly over-estimated results for watershed 102, 104, 105 and 106, critical shear in these four watersheds was increased so that the sediment yields generated by the model would be decreased. Watershed 102 is used as the basic watershed to adjust the critical shear so that the NSE can reach above 70% and that the sediment yields can be accurately predicted. Fig. 7a and b shows simulation performance for watershed 102 for 1998 to 2017 using the soil file with the adjusted critical shear value and the original critical shear value. For watershed 102, the simulated sediment yields generated by the adjusted critical shear are generally 1.0074 times the observed sediment yields in the 20 year period. The R^2 is 78.55%, the NSE is 76%. This model with the adjusted critical shear fits for watershed 102.

The soil file with the same critical shear is used to simulate the runoff in watershed 104 for 1998 to 2017. The relationship between the observed runoff and the simulated runoff is $y = 0.8429x$, the R^2 is 80.69%, and the NSE is 69.57% (Fig. 7c). Thus, the critical shear has been adjusted successfully and the soil input data with the adjusted critical shear is used for the simulations of the other watersheds.

3.2.2. Adjusted critical shear parameter

The soil file with the same critical shear value is used as the input file for the sediment yields simulation of watersheds 103 to 106 for 1998 to 2017, and the simulation performances for the six watersheds are shown in Table 7. It shows that the same critical shear value is successfully adjusted to watershed 102, 104, 105 and 106 with NSE of 66.87% or higher, but leads to significantly under-estimated sediment yields for watershed 103 and an unacceptable, negative NSE. According to the former section, it's reasonable to assume that watershed 103 has a different critical shear for its soils from watershed 102, 104, and 106.

Sediment yield distributions in the six watersheds are shown in Fig. 8. The sediment yields in watershed 103 are significantly larger than other watersheds, with the largest area that has the sediment yields > 1 t/hectar/year for the years 1989–2017 (using the original critical shear), in contrast of watershed 104 with 1/4th of the sediments produced by 103 even though they have similar size watershed. Watershed 102 and 106 contribute roughly about 50% and 5% of sediment yield to its nested watershed outlet 104. Overall, the distribution of sediment yield increases dramatically with the increase of the area of the watersheds.

4. Discussion

It is critical to parameterize and adjust hydraulic conductivity and critical shear soil parameter files in the study area. to obtain the best simulation results. The estimate and Nash-Sutcliffe Efficiency values are critical in adjusting and validating the performance of results. The impact of input data's resolution, different DEM input, 22-year short-term and 53-year long-term analysis for runoff, as well as 20-year analysis for sediment yields were analyzed and illustrate how the simulation outcomes determine the design of the steps to parameterize the model and how to spatially-distribute the assessment of the results.

Runoff values are generally over-estimated in the nested watersheds and slightly under-estimated in the larger watersheds, having the best simulation performance with higher accuracy for smaller watersheds. This is usually the case since the downstream comparisons are not as sensitive to spatial distributed differences in soils when assessing smaller upstream areas. In addition, the distance from watershed 104 to watershed 101, which is the watershed where the weather station 83 is located (see Fig. 4) plays a bigger role the further one uses the data to use in the watershed simulations. The adjustment of K_{eff}, greatly improved the simulation results. However, overall, it's reasonable to assume that the landscape condition, including soil property, land cover, or climate, might be different in watershed 104 compared to 103 across the watershed divide. The trend of over-estimation is the most significant for nested watershed, followed by larger watershed. Runoff values in smaller watersheds lead to the better results.

For positive, zero and negative balance events, watershed 103 and 104 have the best simulation results. Generally, negative balance events are over-estimated, especially in watershed 102, while positive balance events are relatively under-estimated comparing to negative balance events. The NSE for zero balance events in watershed 101 and 106 are below 60%, which might be cause by the small number of events used to be validated, while the NSE for zero balance events in 104 is extremely high (above 98%).

The runoff simulation results using input data in three different resolutions (1 m, 3 m and 5 m) shows that input data in 5 m resolution leads to a better simulation performance comparing to the input data in 1 m and 3 m resolution. It indicates that a set of input data in higher resolution is not a necessity for the simulation of runoff and sediment yields using GeoWEPP in this study. The runoff in watersheds 101 to 106 are simulated and the results show that the uniform input parameters obtained based on a single watershed can be extended and applied to a larger area, although the model efficiency may decrease by the distance from the extended watershed to the watershed that the parameters are fitted. Runoff is mainly over-estimated, but it's reasonable when taking the difference between the results generated by two DEMs into consideration. Events are classified based on the relationship between runoff of the nested watersheds. The patterns of the runoff simulation performance analyzed by event types can be detected. Generally, small events are over-estimated, and large events are relatively under-estimated comparing to the small events. Equal events have relatively poor model efficiency except for watershed 102 and 104.

5. Conclusion

For the Lucky Hills nested watersheds, 55 years of runoff and sediment yields of six subwatersheds located in the Walnut Gulch Experimental Watershed, Tombstone, southern Arizona, are simulated using GeoWEPP. The model efficiency of sediment yields for watershed 103 for 1998–2017 using the original critical shear value is relatively high, while the sediment yield in watersheds 102, 104, 105, and 106 in the

Table 7
Sediment yields simulation performance for watershed 102 to 106 for 1998 to 2017: (a) using original critical shear, (b) using adjusted critical shear. All the relationship between simulated and observed sediment yields are significant (Pr(>|t|) < 0.001) except watershed 103(b).

Watershed	Type	Watershed 105				Watershed 106			
		Number of events	Estimate	R^2	NSE	Number of events	Estimate	R^2	NSE
Smaller watersheds	(a)	51	2.6234	0.7856	0.2060	69	2.0759	0.6992	0.4246
	(b)	48	1.0340	0.7636	0.6687	67	0.8761	0.7760	0.7524
Watershed	**Type**	**Watershed 101**				**Watershed 102**			
		Number of events	Estimate	R^2	NSE	Number of events	Estimate	R^2	NSE
Larger watersheds	(a)	No observed sediment yields available.				45	4.8372	0.6992	0.2968
	(b)					44	1.0074	0.7855	0.7601
Watershed	**Type**	**Watershed 103**				**Watershed 104**			
		Number of events	Estimate	R^2	NSE	Number of events	Estimate	R^2	NSE
Nested watersheds	(a)	77	1.0239	0.7017	0.6957	67	2.0221	0.7017	0.4888
	(b)	68	0.2008	0.6917	−20.2013	60	0.9123	0.7979	0.7733

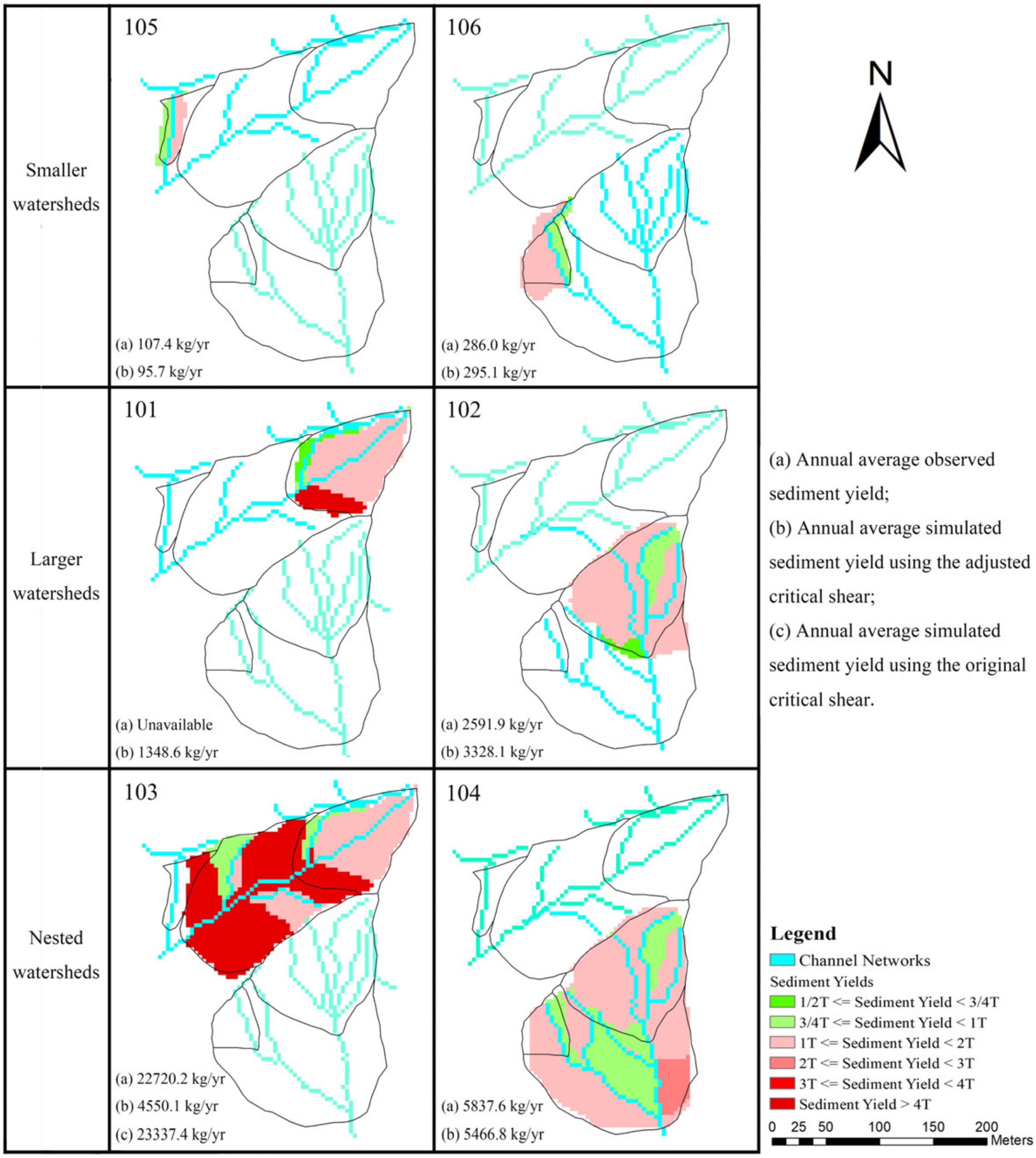

Fig. 8. Sediment yields (tonnes/ha/year) distribution for watershed 101–106 for 1998–2017. T represents the tolerance value as 1 t/ ha/year.

same time period using the same soil file is highly over-estimated. It indicates that the soil property might be different in watershed 102, 104, 105 and 106 from watershed 103. The critical shear is adjusted based on watershed 102 and validated based on watershed 104. The soil file with the same critical shear is used as the input data for watershed 103 to 106. The simulation results show that the adjusted critical shear value leads to a fit model for watershed 102, 104, 105 and 106, but leads to a significantly under-estimated result for watershed 103. Considering the fact that the original soil parameter file leads to an acceptable sediment yields simulation result for watershed 103, one comes to the conclusion that watershed 103 might have a different soil property from watershed 102, 104, 105 and 106.

Accurately simulating runoff and sediment yields has been an important guide to local land management, policy implementations, and restoration and rehabilitation. Process-based models have relatively more advantages comparing to simple empirical models when analyzing in the spatial and temporal scale, as well as an enhanced ability to predict sediment yield (Flanagan and Nearing, 1995; Maalim et al., 2013). WEPP is a process-based, semi-distributed parameter, one-dimensional, continuous model founded on the fundamentals of hydrology, erosion mechanics, plant growth, and open channel hydraulics (Flanagan and Nearing, 1995; Meghdadi, 2013). GeoWEPP is a user-friendly geo-spatial interface for WEPP model that combine the process model with ArcGIS. It extends the range for WEPP and provides an excellent tool to simulate the runoff and sediment yields at a variety of watershed scales.

6. Future research

The baseline parameterization for the soils in regard to effective hydraulic conductivity and critical shear has been created. The various differences of sediment delivery from different parts of the nested watersheds as well as available soil redistribution observations based on a 137 Cesium study in watershed 101 and 103 can be now assessed and validated in more detail. After that one has to critically evaluate the parameter settings for the first and second order channel parameterization especially in regard to erodibility. This research is currently on going and will be published in the near future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

CR: Conceptualization; CR & HZ: Data curation; CR & HZ: Formal analysis; CR: Methodology; CR: Project administration; CR: Software; CR: Supervision; CR & HZ: Validation; CR & HZ: Visualization; CR & HZ: Roles/Writing - original draft; CR & HZ: Writing - review & editing.

Color options

All figures should be printed without colors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.137089.

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