

PREDICTED CHANGES IN SHORT-TERM RAINFALL INTENSITIES AND RUNOFF AT THE IPOLTICA RIVER BASIN

¹ Gabriel FÖLDES*, ² Silvia KOHNOVÁ, ³ Marija Mihaela LABAT
⁴ Kamila HLAVČOVÁ

^{1,2,3,4} Department of Land and Water Resources Management, Faculty of Civil Engineering
Slovak University of Technology Bratislava, Radlinského 11, 810 05 Bratislava
e-mail: ¹gabriel.foldes@stuba.sk, ²silvia.kohnova@stuba.sk, ³marija.labat@stuba.sk,
⁴kamila.hlavcova@stuba.sk

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Abstract: The paper focuses on the impact of climate change on runoff in the Ipolica River basin in northern Slovakia. The analysis is divided into two parts: the first part contains an analysis of predicted changes in short-term rainfall intensities at the Liptovská Teplička climatological station; the second part is focused on the impact of runoff on a small mountainous river basin. The predicted short-term rainfall intensities were analyzed using the Community Land Model, which is a Regional Climate Model. The analysis was performed in durations of 60 to 1440 minutes for a warm period. The focus was aimed at comparing changes in rainfall characteristics, especially changes in seasonality, the scaling exponents, and design values. The second part focuses on the impact of changes in short-term rainfall on changes in runoff. The estimation of predicted runoff changes was provided for the period 2070 - 2100. These results were compared with the results from actual observations. The design floods were calculated using the Soil Conservation Service - Curve Number method. The results show that the runoff will be affected by climate change. Hence, it is important to reevaluate the land use management and practices at the Ipolica River basin.

Keywords: Short-term rainfall, Seasonality, Design values, Regional climate scenario, Runoff, Curve numbers

1. Introduction

Short-term rainfalls have become one of the most common natural hazards in recent decades across Europe. Extreme flash floods caused by intensive rainfall have seasonal

* Corresponding Author

characteristics and mainly occur in the summer months. The floods cause considerable economic damage and also threaten human lives. These hydrological extremes have also been observed in Slovakia and have affected the hydrological methods, which need to be improved. For successful hydrological management, these extreme events and their effects need to be known [1].

These problems across Europe and the world are reflected in the large numbers of studies dealing with the seasonality of rainfalls, Intensity-Duration-Frequency (IDF) analysis, the use of regional climate models to analyze and estimate design rainfall intensities like projected changes in rainfall seasonality and dry spells in a high greenhouse gas emissions scenario [2], flash floods in urban areas in the Reggio Calabria (Italy) region [3], future changes in extreme precipitation estimated in Norwegian catchments [4], pooled frequency analysis for IDF curve estimation [5], and regionalization of rainfall IDF using a simple scaling model [6]. In Slovakia and the Czech Republic there are also many authors dealing with this problem and their studies show, e.g. possible changes in the precipitation regime in Slovakia due to air pressure and circulation changes in the Euro-Atlantic area until 2100 [7] and trends in the characteristics of sub-daily heavy precipitation and rainfall erosivity [8], [9]. There are also several studies that deal with problems caused by intensive rainfall and hydrological problems caused by climate change like a simulation of the progress of a flood on the River Gidra [10], a hydrological-hydraulic assessment of proposed flood protection measures [11], and an assessment of soil water erosion in the Myjava hill land with the application of a physically-based erosion model [12].

This article is focused on an assessment of changes in short-term rainfall intensities and the impact of climate change on runoff. The changes in runoff are presented as changes in design floods. The design floods have been calculated using the Soil Conservation Service - Curve Number (SCS-CN) method and the design rainfall intensity values from the Liptovská Teplička station. In the first part of the paper, predicted changes in short-term rainfall intensities were analyzed as seasonality and scaling exponent changes followed by an estimation of the design values of rainfall intensities. The periods analyzed for the future changes in the rainfall intensities were historical (1960-2000), actual observations (1995-2009) and the future (2070-2100). The second part is focused on predicted change in runoff caused by climate changes for the period from 2070 to 2100, which have been calculated and analyzed. The design values of the short-term rainfall were divided from the actual observations using a simple scaling method. The predicted climate change is represented by data from the Regional Climate Model (RCM) scenario for the period 2070-2100.

2. SRES scenarios

The United Nations Intergovernmental Panel on Climate Change (IPCC) created a Special Report on Emissions Scenarios (SRES) [13], which contain scenarios that have been developed for a description of the relationships between the forces driving emissions and their evolution into climate change by the end of the 21st century. The main element of the SRES scenarios is the forces driving emissions. The driving forces include: demographic developments, socio-economic developments, technological

changes, and environmental developments. The development of these driving forces is very uncertain. For this reason, the IPCC created four narrative storylines that represent different developments in the driving forces, which can be positive or negative. These four narrative sets or families are called the A1, A2, B1, and B2 (*Fig. 1*) scenarios. The data in this paper are based on the A1 storyline. The A1 storyline describes a world with very rapid economic growth, a peak in the global population that will be reached by the middle of the 21st century, and new and efficient technologies that will rapidly be introduced. The A1 scenarios have three subgroups that describe alternative technological changes in the energy system. The subgroups are: A1FI - intensive fossil energy sources, A1T - non-fossil energy sources, and A1B - a balance across all the sources [14].

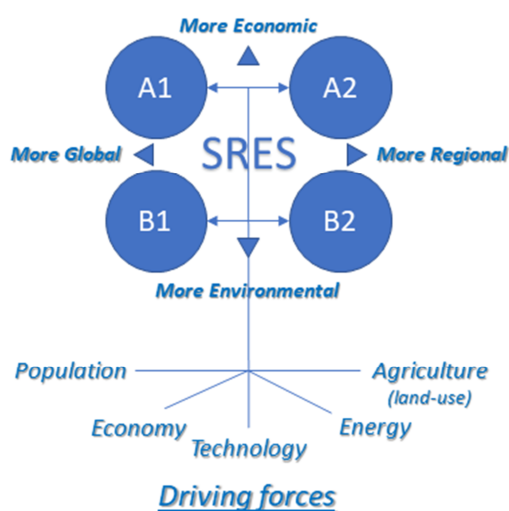


Fig. 1. Storyline Schemes of the SRES Scenarios, on the basis of [14]

2.1. CLM Scenario

The Community Land Model (CLM) was created as a collaborative project between scientists from the Terrestrial Sciences Section (TSS) and the Climate and Global Dynamics Division (CGD) at the National Center for Atmospheric Research (NCAR) and the Community Earth System Model (CESM), the Land Model, and the Biogeochemistry Working Groups in the USA (Boulder, Colorado). The model formalizes and assesses ecological climatology concepts. Ecological climatology is a multidisciplinary structure. It is used to understand the impacts of changes in vegetation on the climate that are caused by humans and nature. It studies physical, chemical, and biological processes by which terrestrial ecosystems influence and are influenced by the climate on various spatial and temporal scales. The main theme is that terrestrial

ecosystems are important determinants of the climate through their energy, water, chemical elements, and trace gases. The main parts of model are surface heterogeneity, bio-geophysics, the hydrological cycle, biogeochemistry, ecosystem dynamics, and the human dimension. The CLM addresses several aspects that allow for the study of two-way interactions between human activities in the countryside and the climate, changes in land cover/land use, agricultural practices, and urbanization [14]-[16].

3. Methodology

Several methods have been used in this paper for the detection of changes in rainfall characteristics. For estimating seasonality changes, Burn's vector method was used. The scaling exponents were derived using the simple scaling method. For the estimation of design floods, the SCS-CN methodology was used.

3.1. Seasonality changes using Burn's vector method

Burn's vector method [17] is used to estimate seasonality; it is often used to estimate the occurrence of extreme seasonal phenomena. This method describes the variability of the date when the maximum rainfall occurs, so that the direction of the vector corresponds to the expected day of the occurrence during the year, while its length describes the variability around the expected date of the occurrence. The date of occurrence (D) represents the average position of an event that is plotted in polar coordinates per unit circle. First, the vector orientation to indicate when the maximum value for the given year occurred was calculated. The position of the event's occurrence is shown in a unit circle by an angle we define as:

The date of occurrence D_i of the extreme event in the angular value θ_i :

$$\theta_i = D_i \frac{2\pi}{365}, \quad (1)$$

The abscissa x and ordinate y of Burn's vector are calculated as:

$$x = \frac{1}{n} \sum_{i=1}^n \cos(\theta_i), \quad (2)$$

$$y = \frac{1}{n} \sum_{i=1}^n \sin(\theta_i). \quad (3)$$

The orientation of Burn's vector θ is calculated as:

$$\theta = \tan^{-1}\left(\frac{y}{x}\right). \quad (4)$$

The seasonal concentration index r can be calculated as:

$$r = \sqrt{x^2 + y^2}. \quad (5)$$

The orientation of the vector can have a value from 0, which corresponds with the 1st of January to 2π , which corresponds with the 31st of December. The seasonal concentration index can have a value between 0 and 1; 0 means that the occurrences are uniformly distributed throughout the year, while the 1 means that the occurrence happens every year on the same date. The results are interpreted in Burn's diagrams.

3.2. Simple scaling

A simple scaling method is used to process rainfall data for a period of time shorter than one day. Simple scaling determines the design values for duration shorter than one day and for a selected time period by using daily rainfall records that are commonly available. Applying simple scaling to the relationship between the IDF properties of the precipitation is possible. Determining the scaling properties of precipitation is based on the general shape of the following IDF formula [18]:

$$i = \frac{a(T)}{b(d)}, \quad (6)$$

where i is the rainfall intensity; $a(T)$ is the return period function T ; and $b(d)$ is the duration function of the rain given by the formula:

$$b(d) = (d + \theta)^\eta, \quad (7)$$

where θ, η are parameters (determined by the estimation $\theta > 0, 0 < \eta < 1$).

Simple scaling for the scaling of the statistical moments was applied in this paper. The scaling exponents could be estimated with a linear regression from the slope between the logarithmic moment values and the scaling parameters for the different order of the moments. If there is a linear dependence between the scaling exponent and the moment order, it is a scaling exponent of the first order. This property is referred as 'wide sense simple scaling'. The following formula is used for deriving the scaling coefficients [19]:

$$E[I_{\lambda d}^n] = \lambda^{\beta_n} E[I_d^n], \quad (8)$$

where I_d is the maximal mean precipitation intensity with d return period; λ is the scaling parameter; $\beta_n = n\beta$ represents the scaling exponent of the n -th order.

3.3. The soil conservation service - curve number

The SCS-CN is used in ungauged rural catchments where there are no measurements/observations of direct flows for estimating the volume of the direct surface runoff characteristics of small basins [20]. This method is used not only to predict the direct surface runoff volume for a given rainfall event, but also to estimate the volume and peak rate of the surface runoff [20]. The Curve Number (CN) is the main parameter in this model, and it is based on an empirical study of runoff in small watersheds and hill slopes [21]. For this study, the values of the main CN parameter,

which depends on land surface characteristics and hydro-soil conditions, were selected from the CN table values [22]. As it was shown in Mishra and Singh [23], the SCS-CN method is based on a water balance equation (Eq. 9) and two hypotheses, Eq. (10) and Eq. (11):

$$P = Ia + F + Q, \quad (9)$$

$$\frac{Q}{P - Ia} = \frac{F}{S}, \quad (10)$$

$$Ia = \lambda \cdot S, \quad (11)$$

where P is the total rainfall [mm]; Ia is the initial abstraction [mm]; F is the cumulative infiltration excluding Ia [mm]; Q is the direct runoff [mm]; λ is the initial abstraction coefficient [-], and S is the maximum potential retention or infiltration [mm].

This method allows for the calculation of a peak flow Q_{\max} by calculating the time concentration t_c (the time that it takes the rainfall to get from the furthest point of the basin to its river mouth), the design rainfall intensity H_z , the depth of runoff H_0 , and the flood wave volume V . When applying the CN method to calculate design floods in the Ipolica river basins, the design rainfall was used as an input rainfall, and the initial abstraction coefficient was equal to zero. The probabilistic properties of CN values in Slovakia were analysed in [24].

4. Data analysis

The data used in the analysis of future changes in short-term rainfall intensities were created by a CLM simulation and were provided by Martin Gera from Comenius University in Bratislava, Department of Astronomy, Physics of the Earth, and Meteorology [25]. The RCM used consists of rainfall intensities for two time periods for a historical period (1960-2000) and for a future period (2070-2100). The analysis was made for durations from 60 minutes up to 1440 minutes. The RCM scenario selected for the simulation of the climate was the SRES A1B scenario, which is a semi-pessimistic scenario with a predicted increase in the global temperature of about 2.9 °C by the year 2100. This scenario relates well to the current processes in the atmosphere. The results were then compared to the actual measured data in hourly time steps, which was provided by the Slovak Hydrometeorological Institute for the 1995-2009 period. For the estimation of the design floods, the SCS-CN method was used, which needed the Corine Land Cover land use map (Fig. 2) [26].

The area of interest is the Ipolica River basin, located in the Liptovský Mikuláš district in the Low Tatras National Park (Fig. 2). The Ipolica River basin with an area of 86.25 km² is a left tributary of the Čierny Váh River. The Liptovská Teplička climatological station is located 903 m a. s. l. The area belongs to a slightly warm climatic area with a mountain climate and low temperature inversions. The location of the station is presented in Fig. 2.

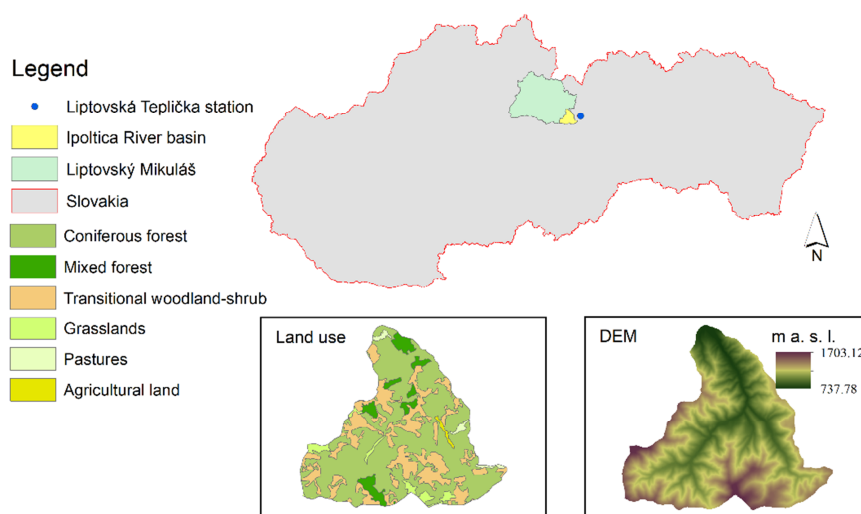


Fig. 2. Location of the Ipolica River basin and Liptovska Teplička station, land use map and Digital Elevation Model (DEM)

5. Results

The first step in the study was to analyze the future changes in seasonality in the occurrence of rainfall maxima. The results were presented in Burn's diagrams (Fig. 3). The extremes occurred in the month of July for each period. The actual measured data 1995-2009 (red) shows the occurrence of the maximal events at the Liptovská Teplička station in the first half of July for precipitation duration of 60 minutes; in the rest of the durations, the actual measured data showed in the occurrence in the second half of July. The CLM simulation shows the occurrence in the last days of June or early July for the historical period of 1960-2000 (light blue). For the future period of 2070-2100 (blue), the simulation shows a similar tendency of the occurrence of the maxima as the actual observations shows. The shift between the actual and future scenarios is about 1 week in the 60, 120, and 1440-minute durations. The highest shift from the actual observations is in the 180 and 240-minute durations, where the shift is about 12 days to the earlier period of the month. The results are shown in Fig. 3.

The next step was to evaluate the changes in the values of the design rainfall. To derive the design values of the rainfall, the scaling exponents were used. For the estimation of the scaling exponents, a scaling approach based on the scaling of the statistical moments was applied. The relationship between the log-transformed values of the moments of various orders and various rainfall durations are presented in Fig. 4.

The results from the simple scaling are shown in Table I. The scaling exponent values have a decreasing tendency for the future. It is suggested that this could be caused by less extreme events that are predicted to occur during the future period. On the other hand, they do not indicate that the future IDF curves would be lower, in spite of this fact due to the increase of daily precipitation totals in the future; the downscaled

rainfall intensities are finally higher. They also confirmed the fact that the downscaled design values of the short-term rainfall depths are radically higher than they are now shown in *Fig. 5*.

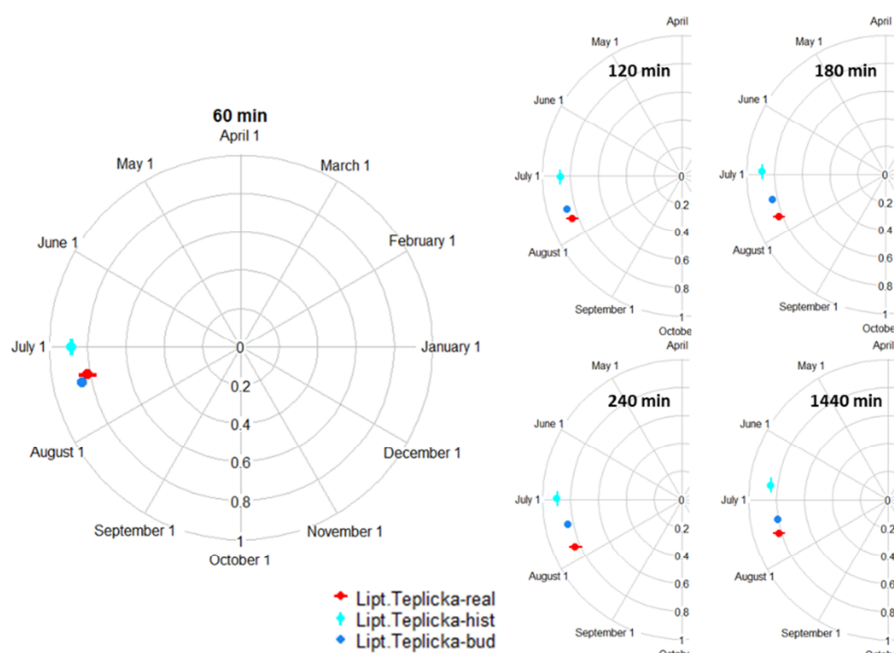


Fig. 3. Burn's diagram for 60 min. duration

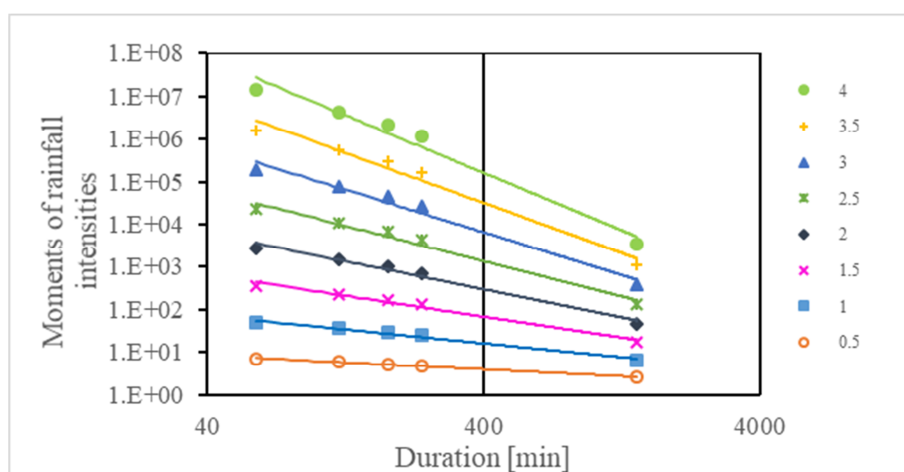
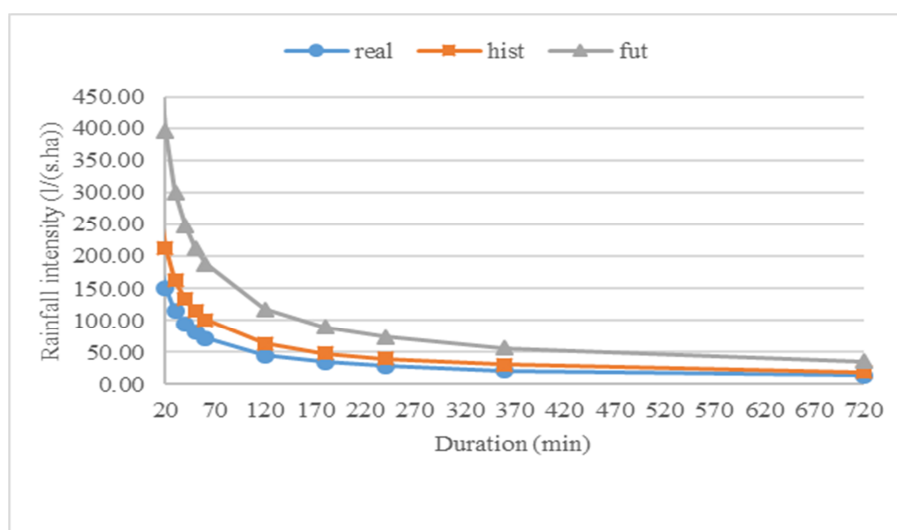


Fig. 4. Log-transformed values of the moments of various orders against various rainfall durations at the Liptovská Teplica climatological station for the future period 2070-2100.

Table I

Scaling exponents for the stations analyzed for the historical and future periods

Station	Period		
	Actual (1995-2009)	Historical (1960-2000)	Future (2070-2100)
Liptovská Teplička	0.762	0.669	0.6228

Fig. 5. IDF curves for the Liptovská Teplička climatological station for the future period (2070-2100) and periodicity $P=0.01$

The final step was to compare the impact of climate change on the changes in the design floods (Q_N). The design floods were calculated for return periods (N) of 10, 20, 50, and 100 years, by first using the design values of the rainfall intensities for the actual period divided by the actual measured data (total rainfall), and then by using the future predictions of rainfall data created by the CLM simulation (2070-2100 period). These rainfall intensity values were determined by interpolation for the time of concentration $t_c=84.32$ min. The calculations and results of the estimation of the design floods using the design values of the rainfall intensities for the actual period are shown in Table II. The calculations and results of the estimation of the design floods using the downscaled data from the future scenario are shown in Table III.

From the results, it is expected that the design floods will increase by 60% in the case of the return period of 10 years, by 96% in the case of the return period of 20 years, by 143% in the case of the return period 50 of years, and by 175% in the case of the return period of 100 years.

Table II

Estimation of the design floods for the Ipolica River basin
using the actual design values of rainfall

N [year]	$P_{N,tc}$ [mm]	Weighted average CN value [-]	Q_N [m ³ .s ⁻¹]
10	29.32	58.10	47.17
20	31.78		54.77
50	34.69		64.38
100	36.65		71.21

Table III

Estimation of the design floods for the Ipolica River basin
using the design values of rainfall intensities from the future scenario

N [year]	$P_{N,tc}$ [mm]	Weighted average CN value [-]	Q_N [m ³ .s ⁻¹]
10	38.40	58.10	75.64
20	46.63		107.54
50	57.60		156.63
100	65.49		196.02

6. Conclusion

This study presents the results of an analysis of the predicted changes in the short-term rainfall intensities combined with an estimation of changes in runoff due to climate change in a small mountainous river basin in northern Slovakia. The analysis was performed using the CLM regional climate scenario data and Corine Land Cover maps. The main focus was on changes in the seasonality, the design values of the short-term rainfall at Liptovská Teplička climatological station, and the estimation of design floods at the Ipolica River basin. The Ipolica River basin is situated in the northern part of Slovakia in the Low Tatras National Park.

An analysis of the short-term rainfall intensities was performed for actual, historical and future time periods and for durations of 60 minutes up to 1440 minutes of short-term rainfall. The actual measured data and data from the RCM simulation were analyzed. The main results can be summarized as follows:

- Changes in seasonality that will shift between 1 week for the 60, 120, and 1440-minute durations and about 2 weeks for the 180 and 240-minute durations;
- The design values for the future have higher values than in the actual period for all durations;
- There will be a shift to an earlier period for the occurrence of extreme rainfalls;
- The design values for the future have higher values than in the actual period;

- The average difference between the actual and future short-term rainfall intensities is about 89%.

From the results of the runoff estimations, it is expected that the design floods will increase from around 60% (in the case of the return period of 10 years) up to 175% (in the case of the return period of 100 years).

As the results show, the changes in the land use and also the change in the rainfall intensities will have a big impact on the runoff; it will be necessary to re-evaluate the principles of water management in the area in the future. In the headwater parts of the analyzed catchment the reforestation should be done with combination of flood and erosion protection measures on small mountainous creeks and gullies, which should be based mainly on the application of nature based flood protection measures as check dams of small water ponds.

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