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Numerical Modeling of Extreme Flash Flood in Yalta in September 2018

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Abstract
The paper considers the results of numerical modeling of the extreme flash flood in Yalta on September 6, 2018, which led to a number of negative socio-economic consequences. The flood occurred as a result of extreme rainfall on the Ai-Petri plateau, Yalta and Gurzuf yailas. The purpose of the study was to obtain and analyze the quantitative characteristics of flash floods based on modern methods of numerical modeling of hydrological processes. To achieve it, the WRF-Hydro hydrological model with a spatial resolution of 90 m was adapted to the territory of Crimea. The atmospheric forcing fields for WRF-Hydro were based on the verified convective-resolving WRF simulations. Quantitative characteristics of surface runoff and channel discharge of mountain rivers were obtained, and hydrographs of discharge at their mouths were constructed. It is noted that the main inflow into the rivers occurs in the upper reaches in the area of the plateau and mountain slopes, and this is true both for the total surface and channel runoff. The channel discharge is characterized by a sharp rise and a gradual decrease in time; within 9 hours from the start of the rainfall, most of the moisture reached the mouths of the rivers. The maximum calculated discharge values for the Derekoika (6 m^3/s) and Uchan-Su (8 m^3/s) Rivers are less than historical peaks, but they are in good agreement with typical discharge estimates during extreme flash floods in the warm season. The significant channel discharge is also reproduced for other rivers of the southern coast of Crimea, in particular for the Avunda River.

Keywords: hydrological modeling, Crimea, precipitation, flash flood, WRF-Hydro

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Численное моделирование экстремального ливневого паводка в Ялте в сентябре 2018 года

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Аннотация
В работе рассмотрены результаты численного моделирования случая экстремального ливневого паводка в Ялте 6 сентября 2018 г., приведшего к ряду негативных социо-экономических последствий. Паводок произошел в результате выпадения экстремального количества осадков на плато Ай-Петри, Ялтинской и Гурзуфской яйлах. Цель исследования состояла в получении и анализе количественных характеристик ливневого паводка на основе современных методов численного моделирования гидрологических процессов. Для ее достижения к территории Крыма была адаптирована гидрологическая модель *WRF-Hydro* с пространственным разрешением 90 м. В качестве входных полей данных использовались верифицированные результаты расчета по атмосферной модели *WRF* с конвективно-разрешающим шагом по пространству. Получены количественные характеристики поверхностного стока и руслового расхода горных рек, построены гидрографы расхода в их устьях. Отмечено, что основной приток в реки происходит в верховьях в районе плато и горных склонов, причем это верно как для общего поверхностного, так и для руслового стока. Русловый расход характеризуется резким подъемом и постепенным по времени снижением, за 9 ч с момента начала ливня бóльшая часть влаги достигла устьев рек. Максимальные рассчитанные значения расхода для Дерекойки (6 м^3/с) и Учан-Су (8 м^3/с) меньше, чем пиковые значения, наблюдавшиеся в прошлые периоды, однако они хорошо согласуются с типичными оценками расхода при экстремальных ливневых паводках в теплое время года. Значимый русловый расход воспроизводится и для прочих рек Южного берега Крыма, в частности для р. Авунды.

Ключевые слова: гидрологическое моделирование, Крым, осадки, экстремальный ливневый паводок, *WRF-Hydro*

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Introduction

The mountainous regions of the Black Sea region are characterized by shower-type atmospheric precipitation, which causes extreme floods on rivers, called *flash floods* in the English-language literature [1]. These are short-term, but extremely intense phenomena, bringing significant socio-economic damage. A flood is known on the rivers of the southern coast of Crimea on June 19–20, 1987, as well as floods in the 1960s, when historical maximums of water flow were recorded on the Derekoika and Uchan-Su (Vodopadnaya) Rivers in Yalta. In June 2021, according to the data from gauging stations, the discharges of these rivers exceeded the norm by 3.4–6.0 times and set new records. The water level at that time rose by more than one and a half meters: on June 18, 2021, the water level rose by 167 cm on the Derekoika River, and by 163 cm on the Vodopadnaya River. Hundreds of houses were damaged in Yalta, 117 streets are in need of major repairs or reconstruction. Global warming makes this problem even more urgent due to the increase in the frequency and intensity of rainstorms in the region. It is known that in other regions the forecast of such hazardous phenomena based on hydrological numerical models [2] has been introduced into operational practice, while in Crimea this issue has been bypassed. Adaptation, testing and evaluation of the reproducibility of such extreme hydrological phenomena in the Crimean territory is a very relevant scientific and applied task. The purpose of this study was to obtain and analyze the quantitative characteristics of the flash flood in Yalta in September 2018 based on the use of modern methods of numerical modeling of hydrological processes.

Materials and methods

In modern conditions, it is possible to use numerical models of river runoff to determine the probability of occurrence of extreme flush floods and construct scenarios for their development. In particular, the WRF-Hydro model has been adapted for Crimea. This model consists of four main blocks: models of the earth's surface, surface water, groundwater and channel runoff.

Input data

As input data with a discreteness of 1 hour in time and 900 m in space, the following results of calculations using the WRF atmospheric model with the ARW dynamic core[1)] with a convective-resolving step in space are used: shortwave and longwave radiation, specific humidity and air temperature at a height of 2 m, atmospheric pressure at the surface, wind speed component at a height of 10 m, quantity of precipitation, properties of the underlying surface (share of vegetation, LAI (Leaf Area Index)). The description of the numerical experiment and the WRF model configuration is given in [3, 4]. The terrain data is generated based on the HydroSHEDS data from the Shuttle Radar Topography Mission satellite instrument with a resolution of 90 m [5]. Since the fallout of extreme precipitation and the occurrence of a flash flood are fast processes, the WRF-Hydro calculation was performed for an interval of one day. The initial time point of the calculation was taken to be 6 hours from the beginning of precipitation, as in earlier works on the rivers of this region [6].

NOAH Land Surface Model

In the NOAH one-dimensional model of the land surface with a spatial resolution of 900 m, based on the radiation-heat balance equation, the vertical fluxes and the heat and moisture content of the soil are calculated. Taking into account the properties of the underlying surface, data on vegetation and soil porosity, the following are calculated: the amount of moisture retained by the forest canopy, direct evaporation from the soil surface and vegetation cover, transpiration, surface and subsurface

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[1)] Skamarock, W.C, Klemp, J.B., Dudhia, J., Gill, D.O., Liu, Z., Berner, J., Wang, W., Powers, J.G., Duda, M.G. et al., 2019. *A Description of the Advanced Research WRF Model*. Version 4. NCAR/TN-556+STR. Boulder: NCAR, 148 p. doi:10.5065/1dfh-6p97 runoff, moisture flow into the soil. The depth of the soil layers in WRF-Hydro can be set manually, while the total depth of the soil column and the thickness of the individual soil layers are constant throughout the model area. In our case, in a two-meter soil column in WRF-Hydro, four layers of soil are used with a thickness from top to bottom of 100, 300, 600 and 1000 mm. The land cover classification is given according to the USGS or MODIS Modified IGBP product; the soil classifications are provided by the STATSGO database with a step of 1 km [7].

After calculating NOAH, the model variables (excess infiltration (surface runoff), depth of accumulated water and soil moisture) are interpolated from the low-resolution grid (900 m) to the high-resolution grid (90 m) and fed to the groundwater and surface water modules. The underground runoff occurs on a coarse grid, while ground runoff occurs on a fine grid. WRF-Hydro then calculates the groundwater depth according to the depth of the upper subsurface saturated soil.

Underground runoff

In WRF-Hydro, the underground lateral runoff is calculated before surface runoff to ensure that exfiltration from fully saturated grid cells is added to the excess infiltration calculated by the land surface model, which ultimately updates the surface head value for surface runoff. The mass balance for each cell at the model time step Δt can be calculated from the change in groundwater level Δz:

$$\Delta z = \frac{1}{\varphi_{(i,j)}} \frac{Q_{net(i.j)}}{A} \Delta t,$$

where φ is soil porosity; A is cell area; Q_{net} is horizontal flow of saturated underground moisture for a cell i, j:

$$Q_{net(i,j)} = h_{i,j} \sum \gamma_{x(i,j)} + h_{i,j} \sum \gamma_{y(i,j)},$$

where $h_{i,j} = \left(1 - \frac{z_{i,j}}{D_{i,j}}\right)^{n_{i,j}}$ and $\gamma_{x,y(i.j)} = -\left(\frac{w_{i,j} Ksat_{i,j} D_{i,j}}{n_{i,j}}\right) \cdot \beta_{x,y_{(i,j)}}$.

Here z is groundwater level; D is soil thickness; $Ksat$ is saturated hydraulic conductivity; n is the parameter that determines the rate of decrease of $Ksat$ with depth (= 1 at present); w is cell width specified for a regular grid; β is groundwater level slope (calculated as the ratio of the difference in groundwater depth between two adjacent grid cells to the grid step).

This method considers the soil as a single homogeneous column. Therefore, the change in groundwater depth needs to be re-mapped to the soil layers of the land surface model. Considering the timescale of groundwater movement and the limitation in the model structure, there is considerable uncertainty in the time required for the proper “acceleration” of groundwater systems.

Surface runoff

At the next stage, surface runoff is determined. Hydraulic gradients are approximated as the slope of the groundwater level between adjacent grid cells using the D8 steepest descent method [8]. A fully non-stationary, explicit finite-difference diffusion wave formulation [9] with a later modification by Ogden is a way of representing land runoff that occurs when the depth of water in a grid cell exceeds the retention depth. As in [9], the continuity equation for a ground-based one-dimensional flood wave is combined with a diffusion wave formulation of the momentum equation. To account for friction, the Manning equation is used, indicating the roughness coefficient for surface runoff. This coefficient was obtained from [10] and compared with land cover classifications.

For terrain scales ranging from 30 to 300 m, the diffuse wave formulation is a simplification of the more general Saint-Venant equations for shallow water. The two-dimensional continuity equation for a flood wave flowing around the land surface has the following form:

$$\frac{\partial h}{\partial t}+\frac{\partial q_l}{\partial l}=i_e,$$

where h is surface current depth; i_e is excess infiltration; q_l is unit flow in the direction of the steepest descent l, calculated using the Manning equation $q_l = \alpha_l h^{\beta}$, where $\beta = \frac{5}{3}$; $\alpha_l = \frac{S_{fl}^{1/2}}{n_{OV}}$; n_{OV} is surface roughness factor (adjustable parameter); S_{fl} is friction slope in the direction of l, calculated from the momentum equation for the direction l: $S_{fl} = S_{ol} - \frac{\partial h}{\partial l}$, where S_{ol} is the slope of the terrain in the direction l; $\partial h/\partial l$ is change in the depth of the water surface in the direction l.

Channel runoff

WRF-Hydro has additional modules for representing flow processes in river channels. The inflow into the river network is a unidirectional process, i.e. it is always positive with respect to the channel element. If the runoff layer in the grid cells labeled “channel” exceeds the local depth of retained waters, then excess runoff volume is transferred from the surface water model to the channel model.

As a rule, inflow into the channel is based on the calculation of the mass balance. Water is directed to the channel when the stored water depth of the channel grid cells exceeds the set retention depth. The depth of the water stored in any grid cell is a combination of local excess infiltration, the amount of water entering the grid cell from surface runoff, and exfiltration from groundwater. Each cell of the channel network is represented in the form of a trapezoid, as shown in Fig. 1.

The channel side slope (z), bottom width (B_w) and roughness (n) are currently set by default as functions of the Strahler flow order. Flow order is a positive integer used in geomorphology and hydrology to indicate the level of branching

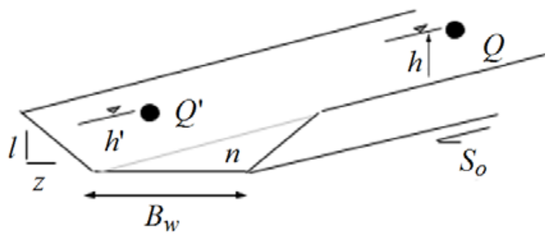


Fig. 1. Channel scheme. S_o – channel slope; z (m) – side slope; B_w (m) – bottom width

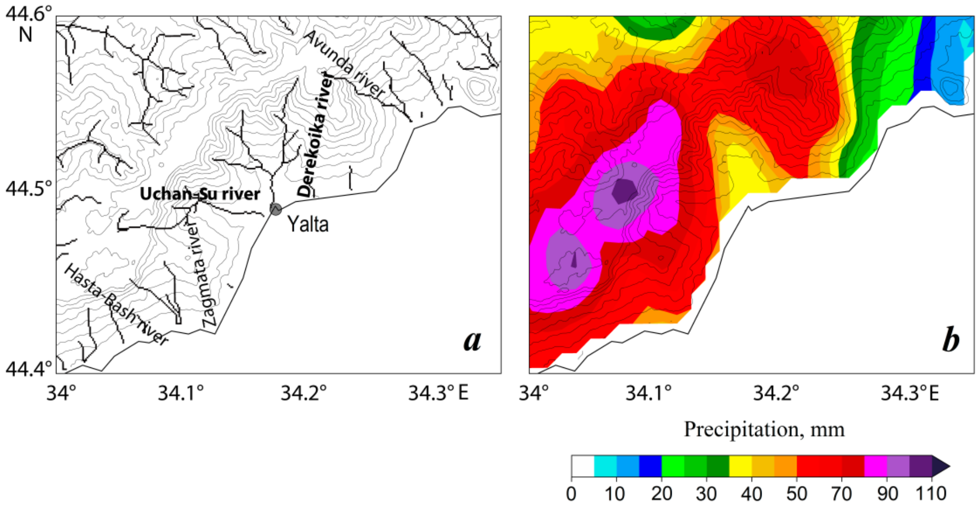
in a river system. Strahler's method sets the lowest order (number 1) starting from headwaters, which is the highest point. Each segment of a stream or a river is treated as a node in a tree. When two streams of the same order merge, they form a stream of the next order. When streams of lower order merge into a stream of higher order, the stream orders do not change. Note that the definition of channel runoff parameters as a function of flow order is correct for relatively small watersheds (as in our case), but not for large regions.

Channel cells receive horizontal inflow from surface runoff, which is effectively unidirectional. Thus, when a river overflows its banks, the flood areas are not explicitly reproduced in WRF-Hydro. To integrate the equations of the diffusion wave flow, the Newton-Raphson solution of the first order is used. Unlike land flood waves, channel flood waves have much greater flow depths and wave amplitudes, which can potentially lead to large momentum gradients and strong acceleration of the propagating wave. To correctly reproduce such flood waves, it is necessary to correctly set the time steps of the model in order to satisfy the Courant conditions. In WRF-Hydro, the diffuse wave module for channel runoff uses a variable time step: the initial value of the time step is set equal to the time step of the surface runoff model. This step is, in turn, a function of the grid step (in our case, 5 s). If during model integration the Newton-Raphson convergence criteria for upstream and downstream flow rates are not met, the time step of the channel model is halved and the scheme for solving the Newton-Raphson equation is repeated [2)].

Results

Fig. 2, *a* shows the channel network of the WRF-Hydro model according to the data on a finite difference grid with a resolution of 90 m. The main attention is paid to the runoff of the Uchan-Su and Derekoika rivers, which flow into the Yalta Bay. Fig. 2, *b* shows the precipitation field for September 6, 2018, used as input. Most of the daily precipitation fell from 06:00 to 09:00 UTC. The maximum amount of precipitation was noted on the Ai-Petri plateau and the Yalta Yaila (about 100 mm). In the area of the Gurzuf Yaila, which belongs to the catchment

[2)] Gochis, D., Barlage, M., Cabell, R., Dugger, A., FitzGerald, K., McAllister, M., McCreight, J., RaieeiNasab, A., Read, L. et al., 2020. *The WRF-Hydro Modeling System. Technical Description*. Version 5.1.1. NCAR Technical Note. 107 p. Available at: https://ral.ucar.edu/sites/default/files/public/projects/wrf_hydro/technical-description-user-guide/wrf-hydro-v5.1.1-technical-description.pdf [Accessed: 10 September 2022].

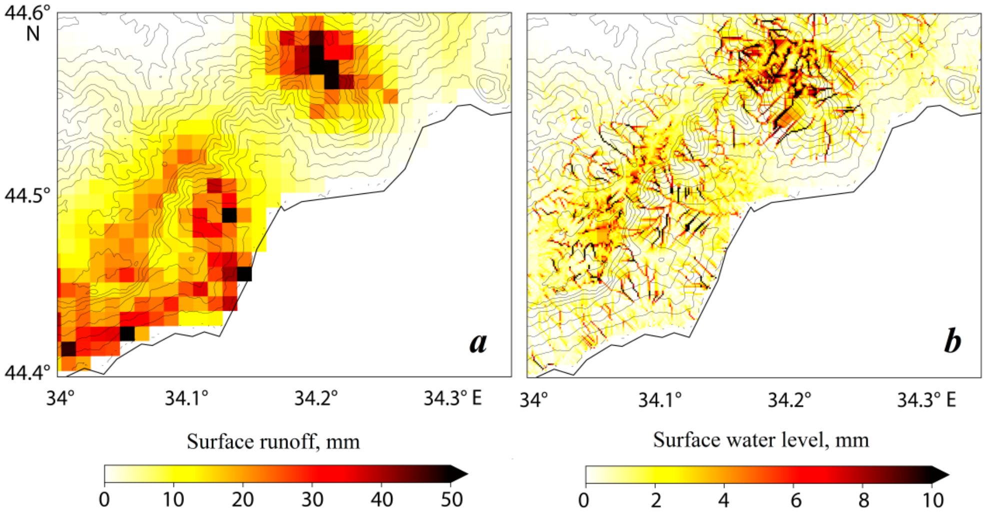


F i g . 2 . Channel network of WRF-Hydro model (*a*) and precipitation amount for 6 September 2018 based on WRF model (*b*)

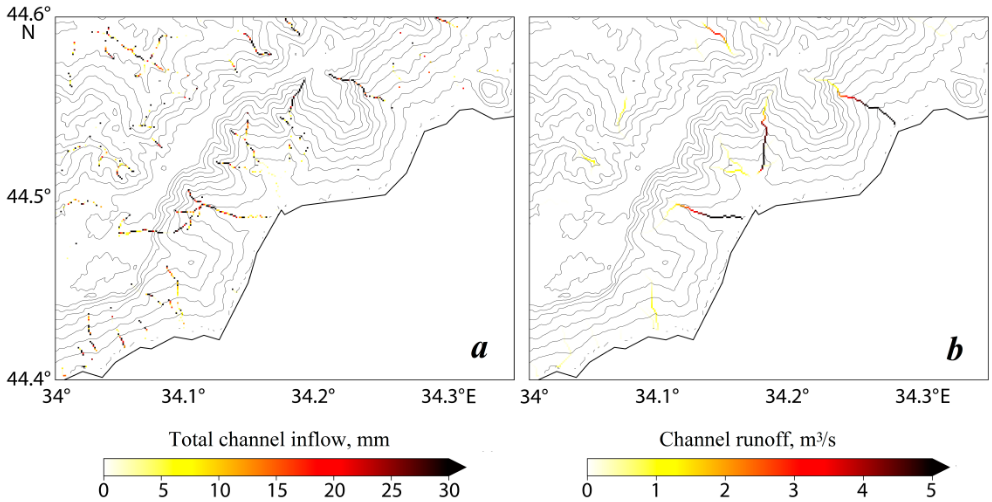
area of the Derekoika River, about 70 mm of precipitation fell. Precipitation estimates were obtained from the data of the WRF model and were verified using observational data at meteorological stations and radar measurements [3].

Fig. 3 shows that the main inflow into the rivers occurs in the upper reaches in the area of the Ai-Petri plateau and mountain slopes, where the total runoff for 12 hours exceeds 30 mm, or even 40 mm, and the surface water level is above 10 mm. In the lower reaches, the total runoff for 12 hours is less than 20 mm, and the level is less than 2 mm. The maximum values of the fields of total surface runoff correspond to the maximum values of precipitation at the Ai-Petri and Gurzuf Yaila. In the level fields, the maximum values are noted in the area of the Gurzuf Yaila, where precipitation fell somewhat later than on the Ai-Petri. Let us note that the proportion of moisture that enters the surface runoff and is transferred for calculation to the surface moisture distribution module is calculated using the NOAH land surface model and is determined by a number of tuning parameters depending on the properties and moisture content of the soil. In turn, the value of the surface moisture level on a finer 90-meter grid is calculated in the surface runoff module and is mainly determined by the relief.

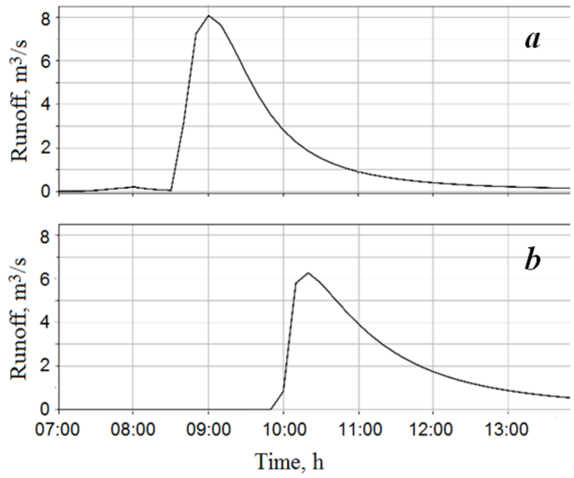
Let us consider the total inflow into the channels calculated by the model and the values of the channel discharge. As well as surface runoff, the total inflow into the channels for 12 hours (Fig. 4, *a*) in the upper reaches of the rivers exceeds 30 mm, and in the lower reaches does not even reach 5 mm. According to the channel discharge modeling results at 09:00 on September 6, 2018 (Fig. 4, *b*), most of the moisture had almost reached the mouths of the rivers by that moment. As a result of the already noted earlier precipitation on the Ai-Petri, the maximum channel discharge for the Uchan-Su is also reproduced earlier than for the Derekoika. Significant (> 5 m^3/s) channel discharge is also reproduced for the Avunda River near Gurzuf.



F i g . 3 . Total surface runoff for 12 h on 6 September 2018 (*a*) and the surface water level at 8:00 UTC (*b*)



F i g . 4 . Total channel inflow for 12 h on 6 September 2018 (*a*) and channel runoff at 9:00 (*b*)



F i g . 5 . Runoff at the mouths of the Derekoika (*a*) and Uchan-Su (*b*) Rivers for 6 September 2018

The maximum channel discharge of the Uchan-Su (8 m^3/s) and Derekoika (6 m^3/s) (Fig. 5) is less than the peak discharge values observed in the past, but it is in good agreement with typical estimates of discharge during flash floods during the warm season [11, 12]. Discharge is characterized by a sharp rise and a gradual decrease over time. The absence of discharge during the time preceding the onset of the flood is associated with a short "acceleration" model period. Let us note that our discharge estimates for the Derekoika River are slightly lower than those obtained in another work using the Hydrograph model, where the discharge estimate exceeded the maximum observed values (14.9 m^3/s) [13]. This result seems to be due to the lower total precipitation in the WRF-Hydro model input.

Conclusion

As a result of numerical modeling of the flash flood in Yalta on September 6, 2018, using WRF-Hydro, quantitative characteristics of surface runoff and channel discharge of mountain rivers on the Southern coast of Crimea were obtained. The flood occurred as a result of extreme rainfall on the Ai-Petri plateau. The WRF-Hydro model was adapted to the territory of the Southern Coast of Crimea and integrated with a spatial resolution of 90 m. The use of input data from the WRF atmospheric model with a convective-resolving spatial step made it possible to take into account the structure of precipitation and reproduce the main characteristics of the flood. As a result of the work, quantitative characteristics of surface runoff and channel discharge of mountain rivers were obtained. The maximum channel discharge of the Derekoika (6 m^3/s) and Uchan-Su (8 m^3/s) rivers is less than the peak discharge values observed in the past and obtained in other works, however, it is in good agreement with typical discharge estimates during flash floods in warm seasons.

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Anatolii E. Anisimov – problem statement, model simulations, qualitative and quantitative analysis of the results, critical analysis and improvement of the text

All the authors have read and approved the final manuscript.