OPTIONS FOR ADAPTATION OF URBANIZED AREAS TO CLIMATE CHANGE INDUCED EXTREME RAINFALLS

T. Metelka[1*], T. Janu[1], J. Sebek[1]

[1]Department of Climate Change Adaptation, Aquaprocon, Dukelskych hrdinu12, Prague 7, Czechia
tomas.metelka@aquaprocon.cz; tana.janu@aquaprocon.cz; josef.sebek@aquaprocon.cz

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ABSTRACT:

The impacts of the climate change progress in a form of heavy cloudbursts, have been being reported over the course of last decade from many world cities. The consequences of this phenomenon are causing damages to urban infrastructure and private properties, and they affect urban transport as well as other primary city functions. In this respect we should ask question, if and to which extent can our society be protected against these extreme hydrological processes. The paper focuses on current adaptation possibilities of cities and settlements to mitigate the impact of extreme heavy storms resulting in sudden flash floods, regardless of the location and elevation of the particular place. The impact of such cloudbursts on urban drainage performance in the city of Prague is analysed by means of coupled 1D and 2D simulation model supported by DEM and GIS technology as well as services of Google Maps. The influence of climate change in terms of growing rainfall intensities is assessed by an indicator called „Climate Factor". The authors present that the only way of adapting cities to these rainfall extremes is based on a proper management of rainfall water outflow on the catchment surface.

1. INTRODUCTION – CLIMATE CHANGE CHALLENGES FACING OUR SOCIETY

The impacts of the climate change progress have been gradually recognized in places both inside and outside central Europe in the last decade (IPCC, 2022). Shift in expert and public opinion is observed as a consequence of growing intensity of climate change induced phenomena in this region. This includes water scarcity and droughts, growing summer and winter temperatures, increase of strong winds, growing intensities of extreme precipitation and occurrence of heavy cloudbursts across Europe (Larsen et Al., 2009). The society is beginning to ask whether the governments are ready for these impending climate change affects.

The phenomenon of extreme precipitation (so called heavy cloudburst rainfalls) has been carefully observed (WMO, 2021) and investigated by the urban drainage expert society as one of fundamental climate change impacts. There is a question, to what extent are the current drainage networks capable of coping with heavy cloudbursts and, in other words, to what extent is the overall urban drainage system prepared for expected changes in the precipitation patterns over the next 30 to 50 years.

2. URBAN DRAINAGE SERVICES UNDER CLIMATE CHANGE

The prevailing part of European drainage networks was built more than 100 years ago. The natural migration of population in a course of subsequent decades caused substantial population growth in the cities which caused an increase in the drainage network capacity requirements. In parallel, the needs for improved quality of drainage and protection of the natural environment have taken gradually place in mind of local inhabitants. All these requirements generate ongoing pressure on the current urban drainage systems. At the same time, it is impossible to make the complete reconstruction of old drainage networks in the city centres because of the extremely high cost

and location, mostly in the historical hearts of the city. This urban water environment is nowadays subjected to the impacts of the climate change in terms of long periods of droughts followed by arrivals of heavy cloudburst rainfalls. Therefore, there is a question, how and to what extent can society face these kinds of climate change impacts?

The answer is not simple. First, it is necessary to clarify the nature of the climate change induced cloudburst phenomenon. It is a natural process occurring already for some time, though getting stronger and having more visible impacts in more than last ten years. The core of this process is based on gradual growth of rainfall intensity and change in rainfall patterns. As scientists claim, "the smaller rainfall intensities will not increase much while big rainfall intensities will grow a lot". In practice, this means that we can expect more frequent heavy cloudburst events in the near future, which will overload existing drainage networks and will cause rainfall induced urban floods in the cities.

It should be noted, that combined drainage networks have been designed to assure the safe drainage for rainfall with two years return period (to clarify this one could approach rainfall return period the same way as it goes for phenomenon of floods – statistically occurring once in two years). In reality, the real drainage network capacity is around ten years rainfall. However, any bigger size rainfall cannot get safely drained and the rainfall excess will stay on surface. This runoff water then flows gravitationally respecting the surface morphology without any other influence to the downstream. It causes flooding of properties, blocks urban transport and endangers the key city infrastructure (historical sites, hospitals, subways, backbone transportation paths, etc.). The reports form many world cities then prove the growing number of such heavy cloudbursts. The situation will most probably worsen in the near future.

At this stage, local and governmental representatives need to start urgently thinking about how to adapt the drainage systems

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* Corresponding author

(Climate-ADAPT, 2016) and how to change the current drainage services to make the urban infrastructure protected as there is no question of "if" but "when" an extreme cloudburst hits the city.

2.1 Climate change impact on precipitation extremes

The climate change impact on increasing rainfall intensities and subsequent flash floods has been being observed in many world cities during the last years. In consequence, the municipality in Prague took an initiative in assessing the expected long-term impact of heavy rainfalls induced by the climate on the urban drainage system in Prague. The study was elaborated by Aquaprocon company in cooperation with Czech University of Life Sciences Prague.

The key project objective was focussed on the development of "Climate Factor" (CF) indicator (Gregersen at al., 2014) for the territory of Prague valley. CF is defined as multiplicator of rainfall intensities defined for target time horizon and selected locality. The actual value of CF is then calculated from global and regional climate model results. In this case eight regional climate model (RCM) results were used to apply a non-stationary regional extreme model, results disaggregation and subsequent cluster analysis. The RCM model results were selected for climate development scenario defined by expected Representative Concentration Path (RCP) of carbon dioxide. The scenario RCP 8,5 was finally used as realistic development scenario of future development of society. The Climate Factor was calculated for three-time horizons (2050, 2080 and 2100) and distinct return periods and durations of rainfalls as defined by Intensity-Duration-Frequency curve (IDF). The method of the frequency analysis was applied together with the Generalised Extreme Value distribution (GEV) to generate IDF tables for both current and future time horizons. The results are presented in Table 1.

CF 2050						
N	2	5	10	20	50	100
T						
10	1.13	1.16	1.17	1.17	1.18	1.18
15	1.11	1.13	1.14	1.15	1.16	1.16
30	1.09	1.11	1.12	1.13	1.14	1.14
60	1.08	1.1	1.11	1.11	1.12	1.12
90	1.07	1.09	1.1	1.11	1.11	1.11
CF 2080						
N	2	5	10	20	50	100
T						
10	1.24	1.28	1.3	1.31	1.32	1.33
15	1.2	1.24	1.26	1.27	1.29	1.3
30	1.16	1.2	1.22	1.24	1.25	1.26
60	1.13	1.17	1.19	1.2	1.21	1.22
90	1.12	1.16	1.18	1.19	1.2	1.2
CF 2100						
N	2	5	10	20	50	100
T						
10	1.3	1.36	1.38	1.4	1.42	1.43
15	1.25	1.31	1.34	1.35	1.37	1.38
30	1.2	1.26	1.29	1.31	1.32	1.33
60	1.17	1.22	1.24	1.26	1.27	1.28
90	1.16	1.21	1.23	1.24	1.25	1.26

Table 1. CF values for distinct return period (N) and duration (T) of rainfall intensity grouped for three time horizons.

The table presents the Climate Factor values for distinct return period (N) and duration (T) of rainfall intensity grouped for three time horizons oy year 2050, 2080 and 2100. The assessment of the expected cloudburst extremality as impact of the climate change for the target years 2050, 2080 and 2100 horizons in the area of the Prague valley shows the increase of rainfall intensities in average between 15% (for 2050) and 35% (for 2100). Indeed, expected increase in rainfall intensities will result in increase of surcharge in the drainage networks and ultimately will lead to the surface flooding and damage of the urban infrastructure as observed in other urban areas.

2.2 Potential of city adaptation to extreme precipitation

The occurrence of heavy cloudburst rainfalls was experienced in several European cities during recent years (Copenhagen in 2011, Ankara in 2018, Germany 2021 etc.). The lessons learned from these catastrophic events (WMO, 2021) clearly show the fact that there is no secure place in front of these extremes. The only way to protect the city is to adapt the city drainage system. The fundamental idea behind the adaptation measures is focussed on the need to modify the urban surface to the capacity which the sewer cannot efficiently drain. The reason is that such extreme runoff water amount and the fundamental reconstruction (increase of drainage capacity) of the urban drainage network is not realistic. The modification of the urban landscape is aiming to redirect the surface runoff to the locations causing minimum damages and thus to protect the urban infrastructure and its basic functions. This is done by means of so called blue-green infrastructure (BGI).
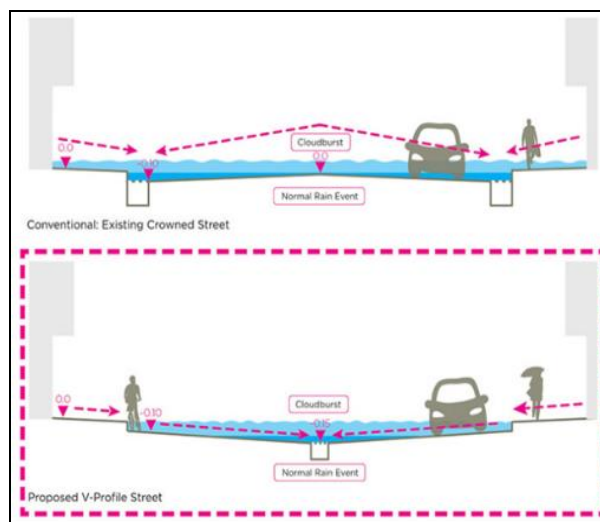

Figure 1. Conceptual road cross section Classical (up), cloudburst (down).

There are several typical adaptation measures designed as technical means for reducing and mitigating the surface runoff, e.i., cloudburst roads, detention streets, green streets and/or central retention areas. Green streets are designed usually in the upstream catchment locations, while cloudburst roads in the downstream part of the area with detention streets in between. The cloudburst road is recognised by „V" cross section shape with elevated curbs (Figure 1). This road is primarily designed for surface runoff drainage from cloudburst events. The water is directed to the middle of the road to protect the surrounding buildings. The central retention areas (parking depressions, parks, etc.) are designed, if it is possible, along the cloudburst roads to reduce the dimensions of the cloudburst road.
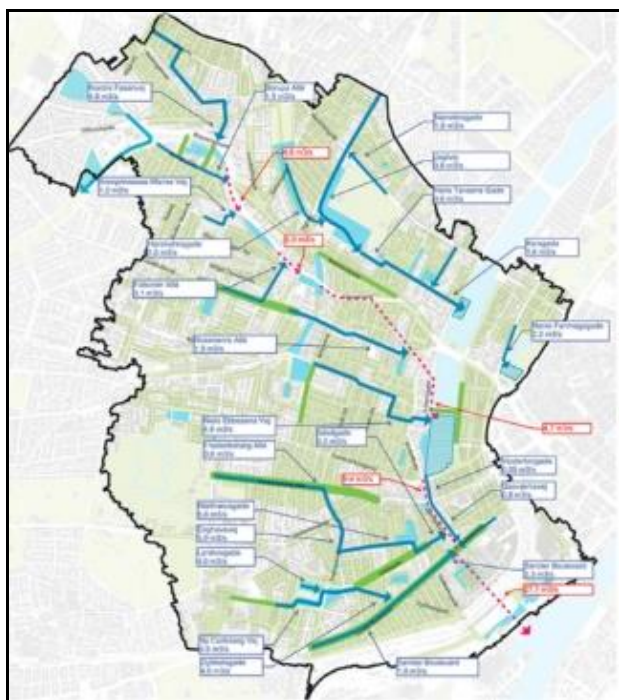
Figure 2. Conceptual cloudburst plan for Copenhagen city

Once these cloudburst adaptation measures are to be implemented in urbanized areas they are usually designed as multipurpose structures to serve also other urban purposes in parallel with cloudburst flood protection. These are typically places for free time activities, meeting places; it allows to increase biodiversity, to change the local micro-climate, etc. The use of such a free space enables the area to be secured for 99% of time as cloudburst extremes are relatively rare events and will contribute to the concept of future "liveable cities" in 21th century.

Copenhagen is presented here as an example of one of the most progressive cities adapting its infrastructure to the impact of the climate change. Copenhagen was heavily flooded by a cloudburst event on 2 July 2011 (with total rainfall volume of 150 mm in 2 hours). The city was completely paralyzed for several hours, and the direct losses amounted to 800 mi. EUR. This devastating experience was the reason why Copenhagen municipality decided to elaborate the city cloudburst adaptation plan (Figure 2) to prevent such a situation in the future (Copenhagen Cloudburst Management Plan, 2011). At present, the cloudburst adaptation plan is developed and there are approximately 300 detailed design projects under this adaptation plan. Some of the measures are already being implemented. Copenhagen is the right example of a growing number of cities taking into account seriously the approaching climate change impacts.

2.1 Role of predictive modelling and remote sensing data

The assessment of the cloudburst flooding and disaster mitigation measures can be achieved by means of modern technology of predictive modelling using remote sensing and GIS technologies. Specifically for this case, the use of coupled one (1D) and two (2D) dimensional hydrological and hydrodynamic simulation model is combined with power of geographical information system (GIS) and with technology of point clouds and digital elevation modelling of relief (DEM).

On top of that, the application of satellite imagery and Google Maps visualisation technology makes the full understanding of the site possible.

The performance of current drainage system with and without proposed adaptation measures is assessed and verified by means of hydrological and hydrodynamic simulation models. These models are developed as a virtual copy of the real world (twins) and they are capable of simulating distinct hydrological situations in the urbanised areas comprising the drainage network performance, drainage performance of local river networks and performance of the urban landscape during surface flooding.

Figure 3. Example of city cloudburst flood as simulated by 2D model (Copenhagen)

The ArcGIS and/or QGIS suite is applied for combining the model results (maps, animations) with real world data (cadastre maps, landscape data maps, orthophotos, etc.) and for data publishing and plotting. In addition, the spatial queries and processing tools are fundamental tools for the data pre and post processing.

Digital terrain elevation model data represent key data source for the development of 2D simulation model. As such, the quality of DEM in the urbanised area is the key issue for trustable 2D model results. The orthogonal 1x1m grid is used or alternatively triangular irregular network (TIN) with special care spent on definition of sharp edges (buildings, sidewalks) and as precise as possible Z coordinate. The distinct DEM data warehouses are currently available (e.g. USGS) to build up the DEM and 2D model worldwide. The technology of Google Maps visualisation (Street View) then serves as a unique information source on local land cover, terrain details and changes to be applied locally in DEM, as well as for the verification of flood extent and depth simulation results.

According to the knowledge of the authors, there are no significantly different approaches used for the assessment of extreme rainfalls in urbanized areas. As the topic of city cloudburst adaptation is rather complex, coupled 1D and 2D simulation models seem to be a proper means of helping the drainage performance assessment and proposal of alleviation measures. In our case, we make use of MIKEURBAN simulation model provided by DHI software vendor. Indeed, there are other simulation tools available on the market (e.i. InfoWorks ICM from INNOVYZE) capable in providing adequate analysis, but the overall approach is rather similar. Alternatively, simple 1D simulation model approach can also be applied for simplified assessment cases. However, this approach is lacking full understanding of complex sewer and surface

water exchanges during rainfall events. There is the "flood screening" approach applied in Sweden with only 2D model use and postprocessed rainfall data. This approach is based on a simplified assumption of the sewer network capacity corresponding to 10 years rainfall. The excess precipitation is then applied to a 2D simulation model without a drainage network, to assess the extent of local flooding once the drainage network is fully surcharged.

3. BOHNICE COLLECTOR STUDY CASE

The district of Bohnice is located in the northern part of Prague. The local landscape is characterised by flat plateau in the northern part of Bohnice with a concrete housing estate for approx. 20 000 inhabitants followed by a steep slope with an elevation difference approximately equal to 100 meters above the Vltava riverbank. The drainage network in the area follows the landscape and drains the urban water from the housing estate down to wastewater treatment plans at the Vltava River.

The drainage performance of the combined sewer network in Bohnice suffered from frequent functional failures during heavy rainfalls causing release of a stormwater from the combined sewer network on the surface. The current situation will further worsen in future due to increasing intensities of heavy rainfalls, which is why it calls for urgent solution. The overloaded network fails primarily at the location of drop manhole at the upper slope edge where insufficient flow capacity exceeds and storm water releases on the surface. The storm water then follows the slope and flows downhill to the Vltava River while causing damages on urban infrastructure and private properties. The purpose of the study (Cloudburst Alleviation Study for District "Bohnice" Urban Drainage System, 2021) was then focussed on proposal of alleviation measures to minimise the surface runoff from heavy rainfalls and in consequence to minimise subsequent damage at downstream part of this urban catchment.

Figure 4. Photo documentation of cloudburst damage

3.1 Approach and methodology

The principal approach used for evaluation of the Bohnice collector ("Bohnicky sberac") drainage network was based on technology of simulation modelling. DHI MIKE Urban simulation tool was used for 1D flow simulation in the drainage systems while the surface runoff water flow was simulated by the MIKE21 simulation tool. Combination of both tools was the must in this particular case to make sure that the mutual exchange of water between the pipeline network and surface during the simulation works. This objective was achieved by wrapping both tools under the umbrella of MIKE Flood tool. The specific spatially oriented tasks were performed by means of the ESRI ArcGIS toolbox. The catchment delineation, network topology construction, visualisation of model results and development of final map products were elaborated by this tool. The grid based on a digital elevation model with 1meter grid size was also assessed and finally processed by ArcGIS. The landscape details were analysed by the Google "Street View" technology.

The surface runoff processes show important differences in their behaviour under the conditions of extreme rainfalls. As the rainfall intensity is high the pervious areas get saturated with the rainfall and consequently the runoff is observed not only in impervious areas but also on those originally pervious. At some moment during the extreme rainfall, the whole catchment begins to contribute to the generation of the urban runoff. This fact needs to be also respected in the simulation model. That is why additional model adjustments are necessary while preparing the model setup for running the extreme rainfall simulations. This can be accomplished by several ways, i.e., by precise definition of all surface types and their initial losses. Once the initial loss is filled up, particular surface begins to contribute as an impervious surface (Figure 5). Another option is based on extending the sub-catchments layer with adequate contribution form pervious areas. The runoff from pervious areas is then defined by initial loss. These model adjustments are necessary to make sure the catchment response to cloudburst event is not underestimated.
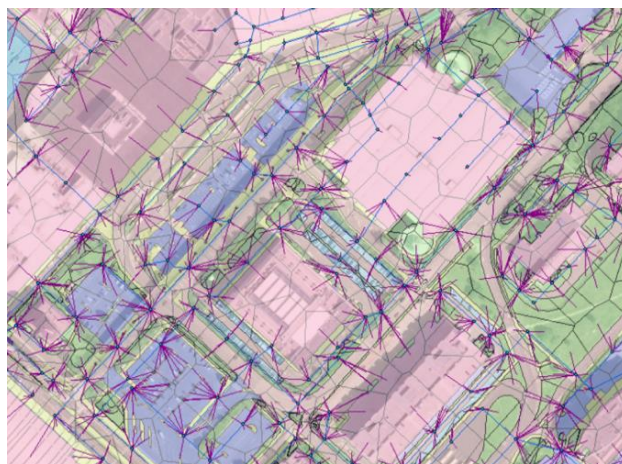

Figure 5. Example of precise definition of all surface types for rainfall runoff simulation

The stormwater management measures are applied as one of the potential options for the urban runoff reduction of. These measures are designed on local Standards (CSN 75 9010 and TNV 75 9011) for the 30 minutes rainfall intensity with the 10 years return period. All measures are designed in appropriate

places (dominantly in the parcels owned by the city). The adaptation measures on the surface (cloudburst roads, detention streets, etc.) are designed according to experience from the adaptation of Copenhagen.

3.2 Model building and calibration

The drainage network simulation model was built based on 1D simulation model MIKE Urban provided by the client. This model was adopted to account for simulation of extreme rainfalls by applying the method of the sub-catchment layer duplication for pervious areas (see Chapter 3.1,). Surface runoff simulation model MIKE21 was built using a DEM of the area of interest with 1x1m grid resolution. Both models were coupled into one simulation environment my means of the MIKE Flood simulation tool. The coupling was performed for all manholes in 1D model and respective grid points in 2D model. The final model setup was capable in running both surface and pipeline models in parallel with mutual exchange of water from the drainage network to the surface and back.
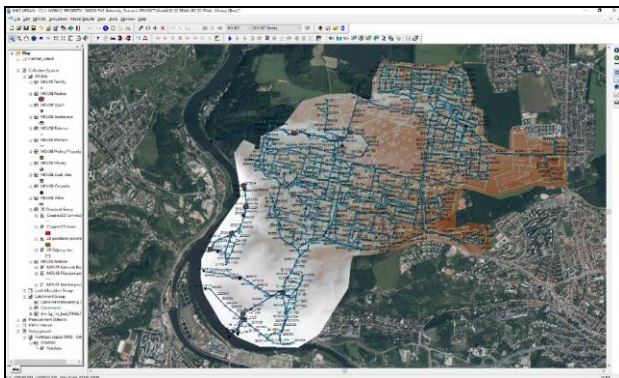

Figure 6. Final setup of simulation model MIKE Urban

The model was calibrated for the most recent and at the same time the most devastating rainfall event from August 14, 2020. This cloudburst rain parameters (duration 63 minutes, total sum 66 mm, average intensity 174 l/s/ha) were estimated as higher than 100 years rainfall with 60 minutes duration (154 l/s/ha).
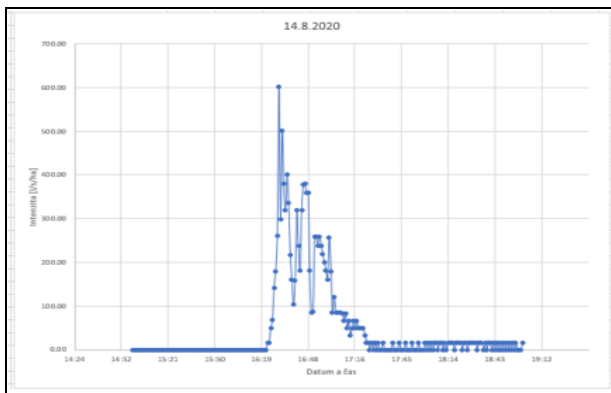

Figure 7. Cloudburst rainfall from 14.8.2020

Figure 8 Calibration site "Jiri Janda" for rainfall event from 14.8.2020 – during dry weather (top) and cloudburst (bottom)

The model calibration was performed at the location downstream of a problematic drop manhole causing the spill of water on the surface. The street ("Jiri Janda") got completely flooded (Figure 8) from the drainage network with an estimated maximum flow between 6 and 7 m^3/s and maximum height above 33 cm. These parameters were used to calibrate model performance under these extreme rainfall conditions.

The model was verified on the flood extent data provided by Prague ZOO. As Prague ZOO is located downstream of the problematic drop manhole and water outflow from the drainage network. The ZOO was hit by a flood wave what allowed to carefully document the flood from 14 August.2020 for insurance purposes. The ZOO flood map was then therefore used to verify the surface flood results provided by the simulation model (Figure 9). In parallel, several other locations were photo-documented or recorded by local inhabitants. This information helped to perform the final model rectification.
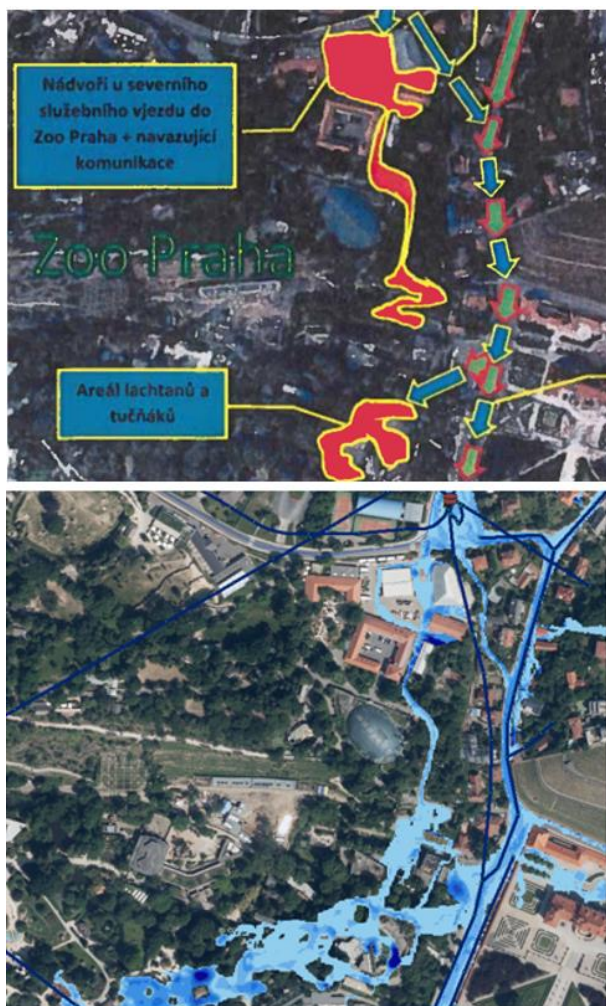
Figure 9. Verification of flood extent (bottom) based on recorded data (top)

3.3 Definition of scenarios

A number of alleviation options (Figure 10) was proposed and discussed with the client to reduce the flow in the drainage network and to mitigate the spill of stormwater on the surface during heavy rainfalls. These options comprise local stormwater management (SWM) measures on the surface of Bohnice concrete housing estate, reconnection of drainage network with redirection of stormwater flow to one branch while helping to decrease the stormwater load in second one. It also includes designing the new combined sewer overflow to relief the surcharge in the network, to increase the pipeline diameter and develop pipe retention structures, to reconstruct the problematic drop manhole and increase the discharge capacity in this manhole, etc. These alleviation options were grouped into four alternative scenarios. All scenarios were modelled and analysed including the investment cost assessment.

Figure 10. Setup of potential alleviation options for assessment

3.4 Project results

Finally, the combination of the drop manhole reconstruction and increase of the capacity discharge from 4 to 6 m^3/s together with a network reconnection and a cloudburst road were assessed as the winning scenario. This scenario will increase the drainage system safety from the current approximately 2 years return period rainfall to the future 10 to 15 years return period rainfall. The runoff from a heavier rainfall exceeding the pipe capacity is then proposed to be handled on surface by introducing cloudburst road and system of cloudburst road measures (to redirect surface water flow to desirable location) to carry the excess of water safely through the city down to the river Vltava. The proposed scenario was also assessed as the best option in the cost-benefit analysis, and as such it was finally delivered to the client (Figure 11) shows the flood extent before (yellow colour) and after (blue colour) the implementation of proposed scenario four.
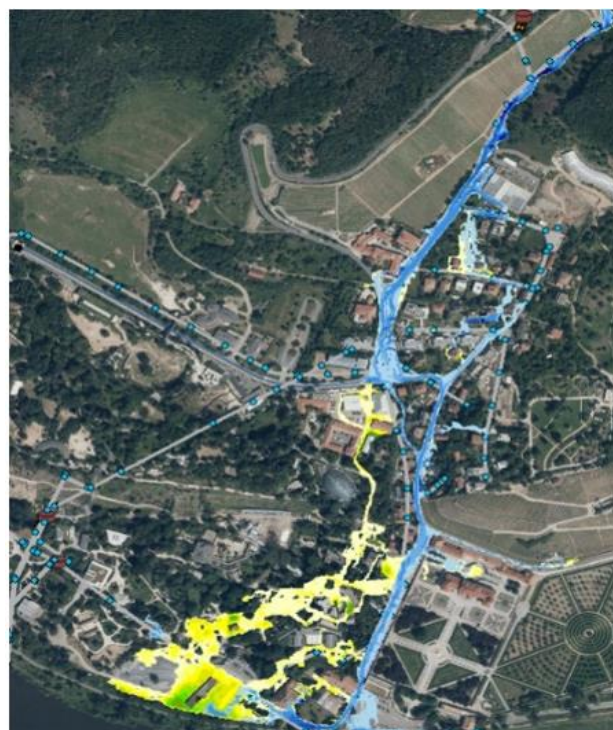

Figure 11. Original (yellow) and final flood extent for proposed scenario

4. SUMMARY AND CONCLUSIONS

This elaborated project represents one of first steps at a long-term city adaptation strategy to the impacts of the climate change. Heavy rainfalls will occur more frequently in the near future and classical drainage options will be not sufficient to assure adequate drainage standards of urban areas. The development of cloudburst roads on surface combined with other flood mitigation options seem to be a relevant solution for urbanised areas to avoid damages on infrastructure and serious problems of the city transport.

The project results proved that the modern technology was found as a key driver for this kind of new solution in the urban infrastructure. A coupled 1D and 2D simulation model was built, calibrated and used to assess proposed alleviation scenarios. Flood extent, depth and hazard maps were developed using the GIS (ArcGIS) technology. Remote sensing data were used for a successful project completion including digital terrain data, satellite imagery, land cover maps, etc. Technology of Google Maps (Street View) was applied as a fruitful tool for understanding of the local landscape conditions.

At present many water engineering projects are obliged to incorporate impacts of the climate change into their project design and performance parameters. The year of 2100 is generally used as target time horizon for designed structures. The same holds for extreme rainfall events. Use of the Climate Factor indicator is presented in the paper as one of the practical ways on how to handle the impact of the climate change for cloudburst project cases.

In the Czech Republic, the phenomenon of climate change and heavy cloudbursts has been being discussed already for several years. The capital is preparing a launch of the city cloudburst adaptation plan as an integral part of the overall city climate change adaptation strategy. Several pilot projects were elaborated to verify and prove the methods and techniques used for the city adaptation programme. At the same time, the local legislation is under revision in incorporate approaches and technical details of surface adaptation measures for a new design. The climate change phenomenon is approached seriously also in other countries of Europe as there is no question of "if" but "when" a cloudburst extreme will hit a city.

5. ACKNOWLEDGEMENTS

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