METHODOLOGY FOR THE DEVELOPMENT OF FLOOD HAZARD MAPS AND FLOOD RISK MAPS FOR AREAS EXPOSED TO FLOODING IN THE EVENT OF DAM FAILURE – PART II

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BDOT10k	Topographic Database at a scale of 1:10 000
CZSW	Central Administration of the Prison Service
DSM	Digital Surface Model (Polish abbreviation “NMPT”)
DTM	Digital Terrain Model (Polish abbreviation “NMT”)
DWSM	Digital Water Surface Model (Polish abbreviation “NMPW”)
FHA	Flood hazard area (Polish abbreviation “OZP”)
FHM	Flood Hazard Maps (Polish abbreviation “MZP”)
FRM	Flood Risk Maps (Polish abbreviation “MRP”)
GDOŚ	General Directorate for Environmental Protection
GIOŚ	Chief Inspectorate of Environmental Protection
GIS	Geographic Information System
GUGiK	Head Office of Geodesy and Cartography
GUS	Central Statistical Office
IGW	Water management instruction of the reservoir
IMGW-PIB	Institute of Meteorology and Water Management - National Research Institute
KG PSP	National Headquarters of the State Fire Service
MaxPP	Maximum water damming level of the reservoir
MKiDN	Ministry of Culture and National Heritage
MPHP10k	Map of Hydrographic Division of Poland at a scale of 1:10 000
MS	Ministry of Justice
NFZ	National Health Fund
NID	National Heritage Board
NOBC	System of Address Identification of Streets, Real Estates, Buildings and Dwellings
NPP	Normal water damming level of the reservoir
PFRA	Preliminary Flood Risk Assessment (Polish abbreviation “WORP”)
PGW WP	State Water Holding Polish Waters
PIG-PIB	Polish Geological Institute - National Research Institute
PIS-GIS	State Sanitary Inspection – Chief Sanitary Inspectorate
PZGiK	National Geodetic and Cartographic Database
RBMP	River Basin Management Plan (Polish abbreviation “PGW”)
RZGW	Regional Water Management Authorities
UW	Voivodeship Offices
WIOŚ	Voivodeship Inspectorate for Environmental Protection

1. INTRODUCTION

1.1. LEGAL GROUNDS

In order to conduct proper assessment of flood risk and develop methods of flood risk management as well as to reduce adverse effects of floods in EU countries, Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks was developed, hereinafter referred to as the “Floods Directive”. This Directive requires Member States to develop planning documents constituting the basis for taking measures aimed at reducing the adverse consequences of floods for human health and life, economic activity, the environment and cultural heritage.

The provisions of the Floods Directive were implemented into the Polish legal system by the Act of 5 January 2011 amending the Water Law and certain other acts (Journal of Laws of 2001 No. 32, item 159), which entered into force on 18 March 2011.

In accordance with Article 11, item 1, point 1 of the above mentioned act, the implementation of the Floods Directive in the first planning cycle (in 2010 - 2015) was performed by drawing up:

- preliminary flood risk assessment (PFRA) by 22 December 2011;
- flood hazard maps (FHMs) and flood risk maps (FRMs) by 22 December 2013 (the maps were published and submitted to the administrative authorities on 15 April 2015);
- flood risk management plans (FRMP) for river basins by 22 December 2015 (Regulation on flood risk management plans of 18 October 2016).

The Act of 20 July 2017 - The Water Law (Journal of Laws 2021, item 624 as amended), hereinafter referred to as the "Water Law Act", which entered into force on 1 January 2018, retains the validity of the aforementioned planning documents (Article 555, section 2, points 4, 5, 7 and 9) and requires their review every 6 years and, if necessary, updating. The deadlines for such reviews and updates are as follows:

- preliminary flood risk assessment (PFRA) by 22 December 2018;
- flood hazard maps (FHMs) and flood risk maps (FRMs) by 22 December 2019;
- flood risk management plans (FRMP) for river basins by 22 December 2021.

Pursuant to Article 171, item 9 of the Water Law Act, flood hazard maps and flood risk maps may be reviewed and, if necessary, updated more frequently than every 6 years, but if such an update is made, it should be repeated in accordance with the principle expressed in item 8, i.e. within the deadlines resulting from the Floods Directive.

The Water Law Act (in Articles 169 - 171) sets forth the general scope and manner of drawing up flood hazard maps and flood risk maps as well as the procedure for their evaluation and approval.

Detailed requirements for map preparation are contained in the Regulation of the Minister of Maritime Economy and Inland Navigation of 4 October 2018 on the development of flood hazard maps and flood risk maps (Journal of Laws 2018, item 2031), hereinafter referred to as the "Regulation”.

Pursuant to Article 171, item 1 and Article 240, item 2, point 6 of the Water Law Act, draft flood hazard maps and draft flood risk maps are developed by the Polish Waters in agreement with the relevant voivodes.

The aforementioned legal provisions (the Flood Directive, the Water Law Act and the Regulation) are the basis for the preparation of the methodology for the development of flood hazard maps and flood risk maps.

As required under the Floods Directive, flood hazard maps and flood risk maps are prepared for the areas and types of floods indicated in the preliminary flood risk assessment. As a result of the review and update of PFRA in 2018, areas of potential significant flood risk were identified, i.e. areas where a significant flood risk exists or is likely to occur, including the following types of floods:

1) fluvial flood - associated with the flooding of land by waters originating from rivers, streams, mountain streams, canals, lakes - in two scenarios:
    a) natural exceedance,
    b) destruction of flood embankments;
2) flood from the sea water - associated with flooding of the area by sea waters, including estuarial river sections and coastal lakes - in two scenarios:
    a) natural exceedance,
    b) destruction of storm control dykes;
3) flood from artificial water bearing infrastructure - associated with flooding of the area in the event of dam failures.

Under task 1 of the Project: “Review and update of flood hazard maps and flood risk maps", the "Methodology for the development of flood hazard maps and flood risk maps in the 2nd planning cycle" was developed, which relates to fluvial floods (hereinafter referred to as the "Methodology for fluvial floods").

The flood hazard maps and flood risk maps for floods from the sea are developed by the directors of maritime authorities on the basis of a separate methodology.

However, this methodology relates to the development of flood hazard maps and flood risk maps for floods from artificial water bearing infrastructure and covers the scenario of dam failure.

1.2. METHODOLOGICAL BASIS

This methodology was prepared on the basis of the following documents:

- **"Methodology for the analysis of flood hazards caused by dam failure with a height of H ≥ 15m. Project PL0456 "Flood hazards caused as a result of dam failure". Contractor: RZGW in Cracow, IMGW, Cracow, 2011**;
- Methodology for the development of flood hazard maps and flood risk maps in the 2nd planning cycle (version 7.0). Contractor: IMGW-PIB, ARCADIS Sp. z.o.o., Warsaw, 2019 – hereinafter referred to as the Methodology for fluvial floods.
- Methodology for the development of flood hazard maps and flood risk maps for areas exposed to flooding in the event of dam failure (version 5.0). Contractor: MGGP S.A., Cracow, 2020 – hereinafter referred to as the Methodology part I.

The first one was the basis for the designation of floodplain zones and floodplain depth zones for the cases of failures of 7 dams included under FHMs and FRMs development.

The second of the above mentioned methodological documents was the basis for defining "technical" requirements as regards the scope and form of FHMs and FRMs for the scenario of dam failure and, to a limited extent, additions to methodological provisions.

The third document takes into account modifications in relation to the document dated 2011, applied in dam failure modelling for the above mentioned 7 reservoirs i.e: Besko, Chańcza, Świnna Poręba, Przeczyce, Słup, Mietków and Dobromierz (IMGW-PIB, 2017a, 2017b, 2017c, 2017d); RZGW in Cracow, IMGW-PIB, 2011; Radoń R. et al., 2012). This is a methodical document referring only to those facilities.

This Methodology is a document that comprehensively describes the method of development of FHMs and FRMs for the scenario of dam failure for all 26 dams identified in the review and update of the preliminary flood risk assessment.

1.3. PRODUCT QUALITY CONTROL

Product control is carried out in accordance with the "Procedure and criteria for product quality control" adopted in the project entitled: "Review and update of flood hazard maps and flood risk maps".

2. CONTENTS OF FHMs AND FRMs FOR THE SCENARIO OF DAM FAILURE

Flood hazard maps and flood risk maps are developed for areas of potential significant flood risk identified in the preliminary flood risk assessment i.e. areas where a significant flood risk exists or is likely to occur.

In the case of floods from dam failure, in the review and update of the preliminary flood risk assessment, the areas of potential significant flood risk were determined for selected dammed reservoirs.

Pursuant to Article 169, item 2, point 3, letter c of the Water Law Act, flood hazard maps should show: **areas including those exposed to flooding in the event of dam failure.**

Pursuant to the Regulation (par. 5, item 2), flood hazard maps are developed separately for each of the flood hazard areas referred to in Article 169, item 2 of the Water Law Act.

Pursuant to par. 5, item 3 of the Regulation, flood hazard maps with water flow velocity are not developed for floods from artificial water bearing infrastructure, as this provision only applies to floods from rivers. Therefore, only flood hazard maps with water depths are developed for areas that are exposed to flooding in the event of dam failure.

Flood hazard maps show, inter alia, the following elements:

1) flood hazard area;
2) water depths;
3) maximum elevation of water level below the dam;
4) flood embankments;
5) top of flood embankment elevation in cross sections, which were used in hydraulic modelling;
6) chainage of modelled water courses;
7) dams;
8) location of dam failure.

Flood hazard maps show the depths of water in categories that determine the degree of hazard to people and the manner of impact on buildings, according to the Regulation:

– h ≤ 0.5 m – means low hazard to people and buildings;
– 0.5 m < h ≤ 2 m - means medium hazard to people due to the possibility of evacuation to higher floors of buildings, but high due to material damage;
– 2 m < h ≤ 4 m - means high hazard to people, but very high due to material damage; not only ground floors but also upper floors of buildings may be flooded;
– h > 4 m - means very high hazard to people and very high hazard of total material damage.

For the areas of flood hazard, for which flood hazard maps were made, pursuant to Article 170 of the Water Law Act, flood risk maps are developed.

The scope of flood risk maps for areas covering also areas exposed to flooding in the event of dam failure is the same as the scope presented on flood risk maps for fluvial floods. It is only necessary to adjust the names of the maps and the contents of the legend while taking into account the elements specific to this scenario.

Flood risk is defined in Article 16, item 48 of the Water Law Act and means the combination of probability of occurrence of a flood and the potential adverse effects of a flood on human life and health, the environment, cultural heritage and economic activity.

Flood risk maps specify the values of potential flood losses and show structures at risk of flooding in the case of a flood with a certain probability of occurrence. Those are structures that allow for the assessment of flood risk to human health and life, the environment, cultural heritage and economic activity, meaning the groups for which the adverse effects of floods should be reduced in accordance with the objectives of the Floods Directive.

For this purpose, flood risk maps show:

1) estimated number of residents who are likely to be affected by the flood;
2) types of economic activities carried out in flood hazard areas;
3) installations which, if flooding occurs, may cause significant pollution of individual natural elements or the environment as a whole;
4) the presence of:
    a) water abstractions, water abstraction protection zones or protected areas of inland water bodies,
    b) bathing waters,
    c) Natura 2000 areas, national parks and nature reserves;
5) in justified cases:
    a) areas where floods may occur, accompanied by the transport of large quantities of sediment and debris,
    b) potential sources of water pollution.

The detailed scope and requirements for the development of flood hazard maps and flood risk maps, as well as the scale of those maps, are set forth in the Regulation. The detailed description of map contents is also provided later herein.

3. DESCRIPTION OF FLOOD SCENARIOS

This methodology refers to the development of FHMs and FRMs for the scenario covering areas exposed to flooding in the event of dam failure.

In the Water Law Act, the scenario of dam failure was considered as a separate scenario, in addition to areas with a certain probability of flooding. Thus, it was not determined for which probability of flooding it should be developed. Flows with a medium (1%) and high (10%) probability of occurrence, taking into account the method of disposing of water discharges from the reservoir, as described in water management instructions, do not cause a sudden increase in the reservoir filling level, which could be dangerous for the facility and lead to its failure. In view of this the scenario of dam failure is developed only for scenario of extreme events referred to in Article 169, item 2, point 1 of the Water Law Act and Article 6, item 3, point a) of the Floods Directive.

The development of this scenario envisages the analysis of its various variants depending on the type and class of the civil structure, the structure of the facility (including outlet works) and information about its technical condition. The aim of the aforementioned analysis is to develop the most unfavourable scenario in terms of the size of the area exposed to flooding in the event of dam failure.

The methodological basis for hydraulic modelling is the Methodology for the analysis of flood hazards caused by failures of dams with a height of H ≥ 15 m. Project PL0456 "Flood hazards resulting from dam failures". Contractor: RZGW in Cracow, IMGW, Cracow, 2011. The passages in italics are taken from the aforementioned methodology.

3.1. RULES FOR CREATING VARIANTS OF FAILURE

"*Variants of failure define the initial conditions and course of the very phenomenon consisting in the failure of a structure. Due to the types of dam structures that we have in Poland, they should be divided into two basic groups:*

- *variants for concrete dams;*
- *variants for earth dams.*

The above division results from basic differences in the structure of those facilities and thus different causes and course of a failure. In this division, the first group includes stone dam, and the second group includes rockfill dams.

The determination of initial conditions comes down to specifying the place where the dam damage begins as well as the accepted process (overflow, burst, loss of stability) leading to the failure of a dam. The consequence of such failure is uncontrolled drainage of the given reservoir. The reservoir is drained through a hole in the dam. Many models are used to predict the formation of such hole. In practice, it comes down to choosing one of several models implemented in the software used." (RZGW in Cracow, 2011).

This methodology assumes the use of Dambreak Str. module from MIKE 11 software by DHI.

"The models of such hole require the following parameters: dimensions of the dam and the reservoir and the initial shape of the hole. For earth dams, the physical characteristics of the soil in the dam body are also necessary". (RZGW in Cracow, 2011).

The development of probable failure variants requires obtaining data concerning the structure and technical parameters of dams and reservoirs, as discussed in Chapter 4.2.

"When developing a failure variant for the dam, the following factors should be considered regardless of its structure:

- *hydrological conditions in the sub-basin above the reservoir;*
- *the filling level of the reservoir;*
- *damage to or inadequate flow capacity of the outlet works."* (RZGW in Cracow, 2011).

The aforementioned factors are described below (Chapters 3.2-3.4). They may lead to a failure as a result of damage to the dam body or water overflowing the crest of the dam (Chapters 3.5, 3.6).

"When creating variants of such failure, the following must also be taken into account:

- rules of reservoir control - rules resulting directly from the instructions on water management in the facility (standard) and their variants of modifications, e.g. illustrating the rules of reservoir operation in the event of failure of some of the outlet works (bottom outlets, overflow flaps, etc.) or related to a specific (special) type of conducting water management as regards the reservoir, consisting e.g. in maximum suspension of water discharges from the reservoir;
- synchronisation of the time of inflow culmination and the time of facility failure - i.e. the coincidence or time shift between the time when the culmination of flood wave reaches the reservoir and the time when the dam failure begins." (RZGW in Cracow, 2011).

These issues are described in the chapter on hydraulic modelling (Chapter 5.1).

3.2. HYDROLOGICAL CONDITIONS IN THE SUB-BASIN ABOVE THE RESERVOIR BEFORE FAILURE

"The hydrological conditions should be considered in the context of flood operation mode of the reservoir, as failures occur most often in conditions of high inflows to reservoirs and their considerable filling, which translates directly into the intensity of filtration phenomena that can cause leaks in the body, as well as the theoretical possibility of dangerous water damming level in reservoirs, which can lead to their overfilling in some cases." (RZGW in Cracow, 2011).

In the case of efficient outlet works, a hypothetical hydrograph of inflow to the reservoir should be determined for the peak flow exceeding the control flow for which the flow capacity of outlet works is designed. In the event of failure of those works, it is recommended that hypothetical flood waves with a maximum flow equal to the extreme design flow for the analysed facility should be taken into account in the development of failure variants. According to the Regulation of the Minister of the Environment of 20 April 2007 on technical conditions to be met by hydro-engineering structures and their location, the probability of occurrence of control flows depends on the class of structures and ranges from 0.02 to 0.5%. When determining hypothetical flood waves, the recommendations formulated in the methodology for the calculation of maximum flows and rainfall (SHP, 2017) should be followed.

3.3. FILLING LEVEL OF RESERVOIR BEFORE FAILURE

"The basic initial filling levels of reservoir before its failure, both in the case of failure variant due to overflowing the crest of the dam as well as due to hydraulic rupture, should be as follows:

– *normal water damming level (NPP);*
– *maximum water damming level (MaxPP).*

The normal water damming level corresponds to the normal operation mode of the damming structure, allowing all functions performed by the reservoir to be fulfilled. It is assumed that the simulated flood wave takes place abruptly, giving no time to lower the water level in the reservoir. On the other hand, the adoption of the maximum water damming level corresponds to the situation in which after the first flood wave, which was dealt with properly by the reservoir, before lowering of the water level to a normal water damming level, another flood wave occurs." (RZGW in Cracow, 2011).

As part of the development of FHMs and FRMs, the initial filling level of the reservoir, the failure of which is under consideration, is assumed to be MaxPP.

3.4. FLOW CAPACITY OF OUTLET WORKS

"Too low flow capacity of outlet works may result from the fact that the simulated flood flows exceed the maximum values for which they were designed. It is also possible that floodgates or exhaust mechanisms fail. Such failure of floodgates may occur before the commencement of or during a flood wave. Too low flow capacity causes faster filling of the reservoir and water overflowing the crest." (RZGW in Cracow, 2011).

While creating the variants of failures, the failure of outlet works should be assumed in order to take into account the situation of water overflowing the dam top. The failure of outlet works can be simulated indirectly by modifying the rules of reservoir control. If the hypothetical wave for the extreme design flow does not cause water to overflow the dam top and thus a failure process, a modification of control rules should be carried out by reducing the flow down to 50% and if this does not cause a failure either, then the outflow from the reservoir should be completely reduced.

3.5. IDENTIFICATION OF POSSIBLE VARIANTS OF CONCRETE DAM FAILURE

"Dam failures are usually caused by many factors. Data on more than 150 failures that have occurred in the world since the beginning of the 20th century have been compiled by ICOLD - International Commission on Large Dams (Storożyńska K., 2000). They show that in the case of concrete dams, the main causes of failures are problems related to their foundation, especially internal erosion of the ground (21%) and its insufficient shear strength (21%). Additional causes of many failures are malfunctions of outlet works or their low flow capacity (22%). The causes of 20% of failures were not discovered." (RZGW in Cracow, 2011).

When developing failure variants for concrete dam, damage to the dam body and water overflowing the crest of the dam should be considered, taking into account the aforementioned causes i.e.:

– hydrological conditions in the sub-basin above the reservoir;
– the filling level of the reservoir;
– damage to or inadequate flow capacity of the outlet works.

3.5.1. Damage to dam body

"The main causes of concrete dam failures are problems with their foundation and, as a result, loss of stability resulting in collapse or displacement of parts of the structure. Through the resulting hole, the

reservoir is emptied in an uncontrolled manner. The destruction of the dam occurs suddenly on a large part of the valley and, in the case of arch dams, often over the entire width of the valley. The process of creating a hole takes several minutes.

When developing a failure variant of concrete dam that consists of independent concrete sections sealed on the expansion joints, one or more sections can collapse and move down the valley. The variant of pushing out one or more sections is also likely. The level of damage can be adopted at the level of the largest weakening of the concrete body caused by the location of structural chambers necessary for the operation of the dam or at the place where concreting was suspended due to winter conditions.

The damage initiation time can be connected with the maximum flood wave reaching the reservoir, the maximum water level in the reservoir resulting from the flood wave or water overflowing the crest of the dam. The time of hole formation is 5 to 10 minutes." (RZGW in Cracow, 2011).

3.5.2. Water overflowing the crest of the dam

"Water overflowing the crest of the dam is most often caused by natural phenomena such as flood waves, the occurrence of which may possibly be combined with a malfunction of outlet works in the reservoir.

Water overflowing the crest of the dam can also be caused by damage to the dam located above in the valley. In case of a cascade form, it is recommended to develop a failure variant for the whole cascade. In case of considerable distance between the two structures, a failure variant of the structure located below can be created, taking into account the hydrograph of the inflow to the reservoir caused by the failure of the dam located above.

Water overflowing the crest of concrete dam may or may not be combined with damage to the dam body. When developing failure variants, the purpose of which is to determine the maximum area of flooding caused by the dam failure, it is recommended to create a variant that combines overflowing the crest with damage to the body of the dam." (RZGW in Cracow, 2011).

3.6. IDENTIFICATION OF POSSIBLE VARIANTS OF EARTH DAM FAILURE

"In the case of earth dams, the main causes of failures include: water overflowing the crest of the dam and internal erosion of the body. Both of these causes generally lead to uncontrolled washing out of the soil of the dam body, the course and development of which over time depends on the momentary conditions of water flow through the damaged section of the dam body as a result of gradual self-emptying of the reservoir and on the structure and geotechnical parameters of the soil constituting the earth body. In the case of such facilities, both possibilities of failures should be considered independently.

The set of variants for earth dam failure should refer to both above mentioned main causes of failures and result from the analysis of factors having a direct impact on its character, size and course. These factors, in the case of earth dams, include also those described in the previous chapters:

- *hydrological conditions in the sub-basin above the reservoir before failure;*
- *the filling level of the reservoir before failure;*
- *flow capacity of outlet works;*

and, as described below:

– *shape, size and location of a hole (determined by commonly used calculation methods and analysis of the structure of dam body)."* (RZGW in Cracow, 2011).

3.6.1. Shape, size and location of a breach

"The determination of the predisposed place of dam body damage should result from identification of dam body structure, including location of elements such as anti-filtration screens in the body, location of the outlet and spillway works in relation to the earth body and analysis of dam body geometry (changes in longitudinal and transverse geometry may be places of potential weakening of the soil embedded in the dam body in a situation of increase in the gradient of filter pressures). At this stage, it is necessary to review the existing technical documentation of the facility and get acquainted with the results of its technical inspection.

In case of failure variant as a result of water overflowing the crest of the dam, it is generally recommended to take the line located in the middle of the dam body as the axis of the hole resulting from the body washout. For earth structures with outlet and spillway section built into the dam body - dividing the earth body into two sections, the axis of the hole is proposed to be taken in the middle of the right- or left-side earth body length. The decision as to which side of the earth body may be more exposed to washout should result from the identification of the structure of the facility and its available technical documentation.

In addition, in the event of possible lowering of the dam body crest elevation, such places should also be treated as sensitive areas where overflow and washout may occur in the first place.

Regardless of the above, for every earth structure with built-in elements such as e.g.: outlet and spillway sections, overflow sections, or other concrete or reinforced concrete structures with walls directly in contact with the earth body, the potential location of the damage site (the formation of a hole) also at the contact point of these elements should be considered. In such a case, the list of possible failure variants can be extended to include variants covering e.g. simultaneous damage to the earth body at its contact point with the outlet and spillway section and in its central part.

For variants involving dam failure as a result of piping failure*, resulting in ground suffosion and as a consequence (generally) also in the formation of a hole, it is recommended to take, similarly as in the case of failures caused by overflow, places lying in the transverse axis of the earth body (or one of its sides in the case of separating the earth body with an outlet and spillway section) or places located at the contact point of concrete sections with the earth body ground. In the vertical reference frame, the elevation of the rupture point should be taken in the line of the edge of the downstream slope base of the dam or in the bottom of the ditch collecting water from seepage. In justified cases, consideration should be given to taking into account additional height levels of the rupture as well as additional locations of possible damage in the horizontal layout of the structure. This applies to places where the geometry of the earth body has changed (e.g. bench of downstream slope) and other sensitive places, resulting from technical documentation for the dam body or observations of seepage through the body - recorded by the control and measuring equipment located on the facility (inspection gallery)."* (RZGW in Cracow, 2011).

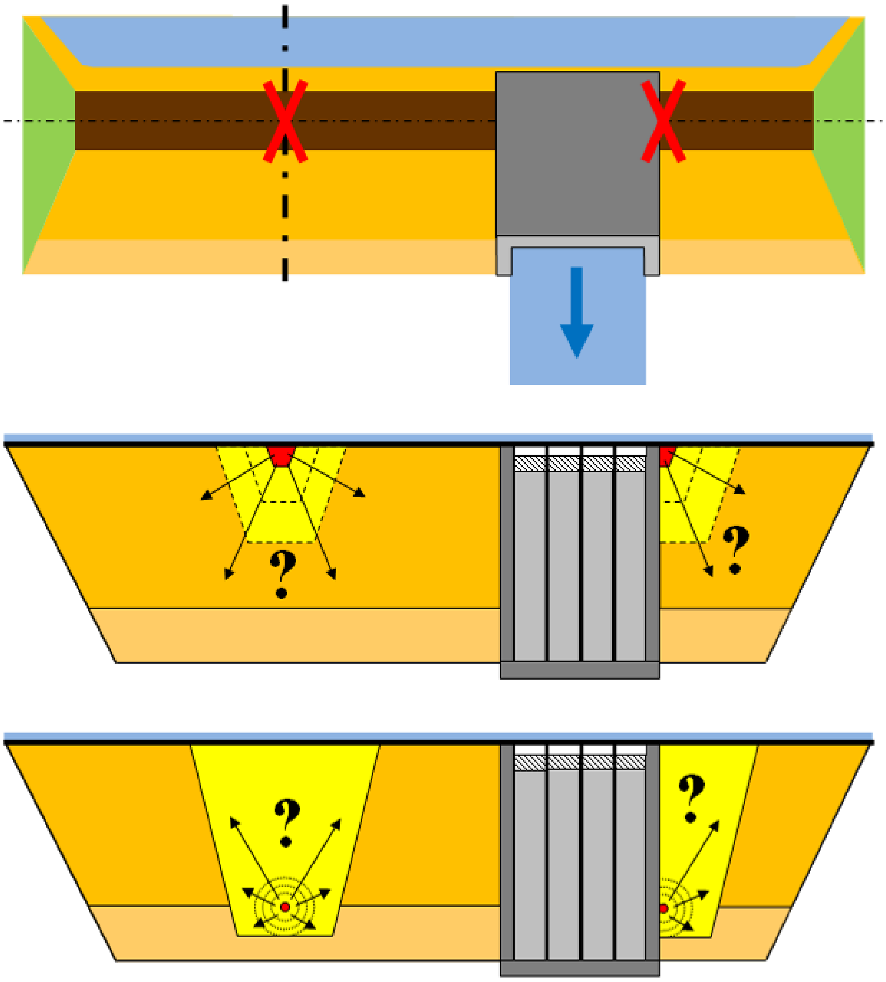

Figure 1. Examples of locations of places where damage to earth dam body occurs in the event of water overflowing the crest of the dam or hydraulic rupture and ground suffosion (RZGW in Cracow, 2011)

"In both cases of failures, it is recommended to adopt the trapezoidal or rectangular shape of the hole. The maximum possible width of the hole should be determined on the basis of empirical formulas commonly used in the literature, based on historical analyses of earth dam failures (e.g. Froehlich, MacDonald & Langridge-Monopolis, Von Thun & Gillette, etc.)." (RZGW in Cracow, 2011).

It is recommended to adopt the maximum possible width of a hole based on averaged results of formulas.

"The dynamics of the processes leading to hydraulic rupture and ground suffosion, as well as the rate of the cross-sectional growth of the hole in dam body - resulting from water overflowing the crest and gradual washing out of the body or as a result of hydraulic rupture - can be determined by means of model calculations based on the erosion formulas implemented in the hydrodynamic models (e.g. the Engelund-Hansen formula in MIKE 11 Dambreak Str. module), which are based on basic geotechnical parameters of the soil, such as e.g. grain diameter, specific gravity, porosity, shear strength, etc." (RZGW in Cracow, 2011).

"In the case of both basic types of failures (i.e. rupture and overflowing the crest), it is recommended to introduce in the dam profile the so-called limiting cross-section which allows us to limit the maximum size of the hole. The line of the bottom of such a cross-section should be adopted at the level of the base of the earth body of the dam or e.g. at the boundary of the layers constituting the rock substrate under the dam. The lateral limitation of the cross-section should be formed by the natural slope of the valley into which the dam body is built, or e.g. the walls of outlet and spillway sections." (RZGW in Cracow, 2011).

3.7. NUMBER OF ANALYSED VARIANTS

"The set of variants of dam failure (in the form of the so-called matrix of variants) may include theoretically unlimited number of variants, resulting from the combination of many different initial factors like: initial filling level of the reservoir, hydrological conditions in the catchment or the direct cause of the failure and the associated location and parameters of the piping failure or the hole." (RZGW in Cracow, 2011).

For practical reasons, it is assumed that two variants of failure will be developed for each facility, where the direct cause of failure will be the subject of each variant. In the case of cascade reservoirs, when analysing the variants of failure for the upper reservoir, failure of the lower reservoir is also analysed, assuming similar variants of failure as for the upper reservoir, but without assuming that the capacity of outlet works will be limited. The rules for constructing those variants are given below.

<u>Parameters of variants for individual reservoir:</u>

- hydrological conditions:
  - upper boundary condition - hypothetical wave according to Strupczewski for $Q_{extreme\ design}$ from the water management instruction;
  - lateral inflows - as in the scenario with $Q_{0.2\%}$ for rivers (time relations of peak wave occurrence as for the scenario with 0.2%);
  - if it is necessary to take into account the recipient of the watercourse on which the analysed reservoir is located - it is possible to adopt the boundary conditions for the recipient as for the scenario with 10%, taking into account the recommendation to maintain consistency of boundary conditions for different reservoirs in one river section (this possibility is aimed at avoiding excessive areas of failure on embanked sections of watercourses for which the scenario with Q0.2%, determined on the basis of steady flow model, results in maximum elevations close to the elevations of the embankment tops);
- initial filling level of the reservoir: MaxPP;
- characteristics of outlet works: failure (limitation of discharge capacities so as to achieve overflow);
- direct cause of the failure:
  - variant 1 - overflowing the dam top (earth dams) / damage to one section of the dam body (concrete dams);

- variant 2 - piping failure (earth dams) / damage to several sections of the dam body (concrete dams).

For earth dams, where due to the technical parameters of the dam and reservoir, it is not possible for water to overflow the dam top, only the variant of piping failure of the dam body is considered. Such a situation may occur when the elevation of the front dam top is significantly higher than the elevation of the side dam tops[1] or when the reservoir or the dam has a permanent and uncontrolled spillway with the flow exceeding the maximum flow for the extreme design wave[2].

<u>Reservoirs in a cascade - failure of the upper reservoir:</u>

- upper reservoir - 2 variants as for individual reservoir;
- lower reservoir - 1 or 2 variants assuming dam failure according to the following assumptions:
  - upper boundary condition - outflow from upper reservoir;
  - other hydrological conditions as for individual reservoir;
  - initial filling level - MaxPP or NPP, depending on the assessment of how the reservoirs in cascades are fed and on the rules of facility control (in a situation when the lower reservoir is fed with significant inflows and/or the water management instruction takes into account earlier replenishment of flood reserve in the lower reservoir, it is recommended to adopt NPP, in the remaining cases MaxPP);
  - characteristics of outlet works - nominal (operational devices);
  - direct cause of the failure:
    - variant 1 - overflowing the dam top (earth dams) / damage to one section of the dam body (concrete dams);
    - variant 2 - none (earth dams) / damage to the dam body (concrete dams); the variant of piping failure on the lower reservoir is not considered as the subject of analysis here is the failure of the upper reservoir. Water overflowing the dam top of the lower reservoir considered under variant 1 is an unavoidable consequence of the upper reservoir failure, while the chance of simultaneous occurrence of conditions for 2 piping failures in the cascade reservoirs within the same event is negligible;
- cascade - 2 - 4 variants as above.

<u>Reservoirs in a cascade - failure of the lower reservoir:</u>

- scenario for the lower reservoir as for individual reservoir without considering the upper reservoir.

If there is more than one reservoir on one watercourse, but the distance between the reservoirs is significant, they are not considered as a cascade. In this case, the simulation of upper reservoir failure assumes an initial filling level of NPP in the lower reservoir and functioning outlet works. The failure of

[1] e.g. Dębe and Koronowo reservoirs
[2] e.g. Otmuchów reservoir

the lower reservoir, in one variant i.e. overflowing, is considered only if the wave resulting from the upper reservoir failure leads to the overflow of the lower reservoir.

No failure variants are assumed for compensating reservoirs. For these reservoirs, only water overflowing the dam top is considered without modelling of the failure.

"After model calculations have been carried out and comparative analysis of obtained results, one the most unfavourable variant is selected in terms of the range of maximum flooding, which will be the basis for developing flood hazard areas and consequently flood hazard maps and flood risk maps in the valley below the dam." (RZGW in Cracow, 2011). The selection criterion is the surface area of FHAs. As a basis for the scenario of dam failure, the variant resulting in the largest surface area of FHAs is selected.

4. PREPARATION OF INPUT DATA FOR FHMs AND FRMs

For the purposes of development of FHMs and FRMs, it is recommended that data older than a few years should not be used without prior verification, as well as verification measurements. Each flood wave may cause changes in the course of the river and the shape of its bed. It is also necessary to check how the valley's structure and road infrastructure have changed and whether new flood embankments have been built or existing ones have been modernised. Chapters 4.1 to 4.4 below describe the requirements for key input data for the development of FHM, while Chapter 4.5 summarises all the input data needed to develop FHMs and FRMs, together with information on the institutions that are the source of these data and the formats in which they occur.

4.1. SURVEYING DATA

4.1.1. Cross-sections (of river valleys)

Cross-sections of river valleys should cover the entire river valley, i.e. the riverbed (cross-section of channel) and both floodplains (left and right) - the cross-section through floodplains. The part of the measurement concerning the riverbed should be made directly in the field (typical cross-section of riverbed) and the part of cross-section of fiver valley including floodplains - based on the latest available digital terrain model (DTM).

When preparing FHMs for the scenario of dam failure, it is required to use materials used for the development of FHMs for the watercourse on which the analysed dam is located.

When developing or lengthening cross-sections of river valleys, the requirements of the Methodology for the development of FHMs and FRMs in the 2nd planning cycle (for fluvial floods) should be taken into account.

4.1.2. Civil engineering structures

For the purpose of building a hydraulic model, it is necessary to conduct a survey of civil engineering structures located on the watercourses covered by the study i.e:

- bridges (including bridges and footbridges);
- hydro-engineering structures (including dams, weirs and barrages).

When preparing FHMs for the scenario of dam failure, it is required to use materials used for the development of FHMs for the watercourse on which the analysed dam is located.

When conducting an additional survey of civil engineering structures, the requirements of the Methodology for the development of FHMs and FRMs in the 2nd planning cycle (for fluvial floods) should be taken into account.

4.1.3. Flood embankments

For the purpose of building a hydraulic model, it is necessary to conduct a survey of flood embankments located on the watercourses covered by the study. When preparing FHMs for the scenario of dam failure, it is required to use materials used for the development of FHMs for the watercourse on which the analysed dam is located.

When conducting an additional survey of civil engineering structures, the requirements of the Methodology for the development of FHMs and FRMs in the 2nd planning cycle (for fluvial floods) should be taken into account.

4.2. DATA ON DAMS COVERED BY THE ELABORATION OF MAPS

Information about dam is collected with a view to developing probable failure variants and obtaining data allowing for their simulation. The set of necessary data depends on the software used and general assumptions made in terms of mapping of the facility.

In each case, data should be collected about the location of the dam, its structure, discharge devices and the ground on which it is founded. For all types of dams (earth dams, concrete dams), the basic data on the body are the length, the lowest ordinate of the foundation, the elevation of the crest, the width of the crest and its shape. In case of concrete dam, the additional data are the number and size of concrete sections, and in case of earth dams, the parameters of the soil from which the body is made, the parameters and type of body sealing and protection of slopes as well as their inclination. The required data concerning the discharge devices are their shape, location in the dam body and, above all, the curves of discharge capacity, depending on the water level in the reservoir and the location of floodgates.

For the development of failure variants, valuable information can be found in the as-built documentation of the structure. Before the development of such variants, it was also worthwhile to get acquainted with the assessments of technical and safety condition of the structure as well as with the results of the performed tests, recommended to be performed as part of conducted assessments.

A very important element of the developed hydrodynamic model is the model of the reservoir which is emptied as a result of the failure. The best sources of information about the reservoir geometry are the results of bathymetric measurements. It is necessary to obtain the curve of reservoir storage - i.e. the relation between the reservoir storage and the water level in the reservoir - allowing for a detailed reservoir storage calibration. To prepare variants of failures, characteristic damming levels and corresponding reservoir storage capacities are also required.

A simulation of the reservoir operation requires that the rules for controlling the outflow from the reservoir be specified, therefore the data defining these rules should be obtained, allowing for saving them in the hydrodynamic model. Such rules of control make the size of the outflow from the reservoir dependent upon such parameters as: inflow to the reservoir, current position of the water level and operating conditions (operation during low water periods, normal operation, flood watch, flood operation).

If there is another reservoir in the valley below, analogous data must be obtained for that reservoir. The results of failure simulation must determine whether the reservoir located below is able to safely take over the flood wave resulting from the failure of the dam located above or whether it is going to fail.

All necessary data concerning dams and reservoirs are in the possession of administrators or owners of those structures. It is also possible to use materials used for the development of FHMs for the watercourse on which the analysed dam is located.

4.3. HYDROLOGICAL AND METEOROLOGICAL DATA

Hydrological data are necessary to calibrate and verify the developed hydrodynamic models and formulate boundary conditions.

The scope of collected data depends on whether "raw" hydrological data are obtained and calculations are made by the authors of the study, or whether calculations made by other experts are used, e.g. materials used for the development of FHMs for the watercourse on which the analysed dam structure is located. In the case of source data development, data should be obtained to determine the characteristics described below.

To calibrate and verify the model, hydrographs of water levels and flows for at least two historical flood waves are needed. The calibration and verification of the model is performed according to the readings of water level gauges located on the modelled watercourse. For correct determination of boundary conditions, for the same historical flood waves, hydrographs of water levels and flows for the remaining water level gauges located in the valley are needed. If there is no water level gauge closing the modelled river section, a river network model is created, consisting of the modelled river and a recipient limited by water level gauges located above and below the place where it falls into the modelled river recipient. Hydrographs of water levels and flows for the aforementioned flood waves are also needed for those water level gauges.

A correctly identified and verified model allows us to perform calculations implementing the developed variants of failures. The most probable conditions for the occurrence of a failure are the operation of the structure during an extreme flooding. Therefore, hypothetical hydrographs of flows calculated for flows with a certain probability of exceedance are also needed. The selection of hypothetical flood wave should be guided by the requirement that conditions for hydraulic rupture or dam washout as a result of water overflowing the dam crest occur (point 3). The choice of method should be based on the guidelines provided in the “Update of the methodology for the calculation of maximum flows and rainfall with specific probability of exceedance for controlled and uncontrolled catchments and identification of models of the transformation of rainfall into runoff” (SHP, 2017). Report on FHMs and FRMs completion for the case of dam failure should include information on which method has been used for the specific reservoir.

The model considers inflow from controlled rivers (with gauges) as a point inflow. This requires the calculation of the hydrograph of flow at the point of inflow to the modelled river. Inflow from rivers not covered by water level gauge monitoring is taken into account as inflow from differential sub-basins, distributed along the analysed segments of the main river as a result of applying interpolation or extrapolation methods, depending on available hydrological data. In order to determine the tributaries referred to above, it is necessary to obtain data on the area of sub-basin at characteristic points of the valley. The development of reservoir model requires the acquisition of information on all tributaries flowing to the reservoir.

During the development of hydrological data, it is possible to use materials used for the development of FHMs for the watercourse on which the analysed dam is located.

In the case of data development, it is necessary to take into account the requirements of the Methodology for the development of FHMs and FRMs in the 2nd planning cycle (for fluvial floods)[3]. According to the above mentioned methodology, hydrological calculations are carried out on the basis of input data obtained from IMGW-PIB, which include:

- daily sums of precipitation from the last 30 years from stations located in the area of the analysed sub-basin;
- hyetographs of historical precipitation, which have caused the two largest floods in the last 30 years with the available time step (hour, day);
- maximum annual flows in the last 30 years minimum for the water level gauge stations on the watercourses for which FHMs and FRMs will be developed;
- hydrographs of water flows and water levels and rating curves for at least 2 largest flood waves that have occurred in the last 30 years - for the purposes of model calibration and verification.

Hydrological data necessary for river flow modelling in channels and floodplains for all types of hydraulic modelling include the following for controlled sub-basins:

- hydrological characteristics of water level gauge stations (river name, water level gauge station name, kilometre, area of sub-basin, zero ordinate of water level gauge) and their geographical coordinates;
- values of flows with a given probability of exceedance for the adopted flood scenarios calculated for water level gauge stations;
- the coincidence of maximum flows on the main river and its tributaries;
- rating curves for water level gauge stations for two largest flood waves in the last 30 years;
- hydrographs of flows for two selected historical highest flood waves;
- hydrographs of hypothetical wave flows.

In the case of uncontrolled sub-basins, hydrological data include:

- maximum flows for given probabilities of exceedance;
- hypothetical hydrographs for given probabilities of exceedance.

[3] For three out of 26 reservoirs covered by this methodology (i.e. Besko, Chańcza and Świnna Poręba reservoirs), the flood ranges were determined before the Methodology for the development of FHM and FRM in the 2nd planning cycle (for fluvial floods) was developed.

4.4. DIGITAL ELEVATION MODEL

4.4.1. Digital terrain model (DTM)

One of the basic data necessary for the development of FHM is the digital terrain model (DTM). The digital terrain model is one of the key elements used at the stage of developing the hydrodynamic model of the valley below the dam reservoir and it also allows for streamlining the process associated with generating depth distribution in flooded areas, significantly shortening the time of map development. It also enables the development of cross-sections of valleys of one-dimensional models. It should be remembered that in the course of activities aimed at preparation of digital terrain model for the purposes of its use in works related to the analysis of dam failure phenomenon and the transformation of flood wave in the valley below, it should be made more detailed by introducing the results of geodetic measurements of linear (such as dykes or road embankments) or cubature structures, which may significantly affect the range and velocity of the wave. A digital terrain model can be expressed by information in the form of a regular grid - a fixed spatial grid (e.g. GRID).

DTM is an element of the national geodetic and cartographic database. Collection of information and keeping of the national geodetic and cartographic database as well as making data available are the responsibilities of the Chief Land Surveyor of Poland. DTM is saved in the form of text files containing coordinates (X, Y in the PL-1992 system; Z in the Kronsztadt 86 system) of points in a regular grid with a spatial interval of 1 meter as well as in the form of a raster with the same spatial resolution. The information about terrain ordinates were interpolated on the basis of point cloud obtained from laser scanning (LIDAR). The maximum average height error is 0.2 m. The individual DTM data files correspond with their range to the map sheets in “1992" rectangular plane coordinate system at a scale of 1:5 000.

For urban areas, the average measurement density is 12 points/m^2 (standard II). The area coverage of individual DTM files developed on the basis of LIDAR point cloud corresponds spatially to the sheets in PUWG 1992 rectangular plane coordinate system at a scale of 1:1 250 (area 0.5 × 0.5 km). For the remaining area, the average density is 4 or 6 points/m^2 (standard I), in the same coordinate system but at a scale of 1:2 500 - the area for one sheet is approximately 1 × 1 km.

4.4.2. Digital Surface Model (DSM)

The Digital Surface Model (DSM), like DTM, is the result of processing a cloud of measurement points acquired from laser scanning. The average height error for data is determined by the standard in which the input material was made, with the maximum error value of up to 0.2 m. Individual DSM files correspond with their range to the sheets in “1992” rectangular plane coordinate system at a scale of 1:5 000. Selected DSM fragments are used in 2D modelling to update DTM in terms of obtaining actual heights of buildings.

4.5. LIST OF DATA FOR THE DEVELOPMENT OF FHMs AND FRMs

In addition to the key data described in Chapters 4.1 to 4.4, it is also necessary to obtain additional data for the development of FHMs and FRMs. The tables below contain a complete set of required data in both categories (key data and additional data). The data for the development of flood hazard maps are listed in Table 1 and the data for the development of flood risk maps are listed in Table 2.

Table 1. List of input data necessary for the development of FHM

No.	Data	Name of institution/Database	Format	Data update
1	Orthophotomaps (pixel field size: 0.5 m; 0.25 m, 0.1 m)	Head Office of Geodesy and Cartography	tif	2010-2018
2	National Register of Boundaries and Areas of Territorial Division Units of Poland (PRG)		shp	2018
3	National Register of Geographical Names (PRNG)		shp	2018
4	Topographic Database BDOT10k		shp	2018
5	Digital Terrain Model (DTM) and Digital Surface Model (DSM)		xyz, asc, tif, las, TIN	2010-2018
6	Map index 1:10 000		shp	nd
7	Hydrological and meteorological data	Institute of Meteorology and Water Management - National Research Institute	docx, xlsx, pdf, tif , jpg and other	1956-2016 (most of the stations)
8	Hydraulic models developed for fluvial floods for rivers with reservoirs	State Water Holding Polish Waters		
9	Map of Hydrographic Division of Poland MPHP10k			
10	Updated instructions for water management in reservoirs		docx, xlsx, pdf, tif , jpg and other	
11	Design/as-built documentation for reservoirs		docx, xlsx, pdf, tif , jpg and other	
12	Data on flood control dykes			
13	Channel cross sections of rivers and civil engineering structures (Geodetic data - direct field measurement)		shp, xlsx, jpg and other	2018

Table 2. List of data necessary for the development of FRM

No.	Data	Name of institution/Database	Format	Data update
1	Population	GUS/ System of Address Identification of Streets, Real Estates, Buildings and Dwellings (NOBC) GUS/ Local Database	xlsx, txt, docx, shp, pdf xlsx	2018 2018
2	Address points	GUGiK/Geoportal/Dictionary services	xml	2018
3	Residential buildings and facilities of particular social importance (hospitals, schools, kindergartens, nurseries, hotels, shopping centres, nursing homes, care homes, hospices, prisons, correctional facilities, detention centres, police units, firefighting units, border guard units)	GUGiK/BDOT10k database	shp	2018
4	Care homes, nursing homes	Voivodeship Office (UW)	shp, xlsx, docx	2018
5	Hospices	National Health Fund (NFZ)	xlsx	2018
6	Penitentiaries, custodies	Central Board of Prison Service (CZSW)	xlsx	2018
7	Correctional facilities	Ministry of Justice	xlsx	2018
8	Groundwater abstractions	PIG PIB PGW WP (Identification of pressures*)	xlsx, shp	2019 2018
9	Surface water abstractions	GUGiK/BDOT10k database PGW WP (Identification of pressures)	shp shp	2018 2018
10	Protection zones of water abstractions	PGW WP	shp	2018
11	Bathing waters	PIS-GIS	shp	2018
12	Boundaries of Natura 2000 areas, including boundaries of special areas of bird protection and special areas of habitat protection	General Directorate for Environmental Protection (GDOŚ)	shp	2018
13	Boundaries of national parks	General Directorate for Environmental Protection (GDOŚ)	shp	2018
14	Boundaries of nature reserves	General Directorate for Environmental Protection (GDOŚ)	shp	2018
15	Fixed monuments	National Heritage Board (NID)	shp	2018
16	Sites on the UNESCO World Heritage List	National Heritage Board (NID)	shp	2018
17	Extermination monuments	The Act, Regulations of Ministry of Culture and National Heritage	pdf	2019
18	Open-air museums and museums listed in the National Register of Museums	Ministry of Culture and National Heritage	xlsx	2018
19	Libraries forming the national library resources	Regulation of Ministry of Culture and National Heritage	pdf	2019
20	Archives forming the national archive resources	Ministry of Culture and National Heritage	pdf	2018
21	Zoos	GUGiK/BDOT10k database	shp	2018
22	Industrial plants	GUGiK/BDOT10k PGW WP (Identification of pressures)	shp shp	2018 2018
23	Industrial plants with high and increased risk of major industrial failure	Chief Inspectorate of Environmental Protection (GIOŚ)	xlsx xlsx, docx, pdf, rtf pdf	2018 2018 2018

No.	Data	Name of institution/Database	Format	Data update
		Voivodeship Inspectorate of Environmental Protection (WIOŚ) National Headquarters of the State Fire Service (KG PSP)		
24	IPPC installations (register of installations with integrated permits)	register of installations with integrated permits	xlsx	2018
25	Cemeteries	GUGiK/BDOT10k database	shp	2018
26	Landfills	GUGiK/BDOT10k database PGW WP (Identification of pressures) Voivodeship Inspectorate of Environmental Protection (WIOŚ)	shp shp shp, xlsx, mdb, docx, pdf	2018 2018 2018
27	Sewage treatment plants	Voivodeship Inspectorate of Environmental Protection (WIOŚ) PGW WP (Identification of pressures) GUGiK/BDOT10k database	shp, xlsx, pdf shp shp	2018 2018 2018
28	Sewage Pumping Stations	GUGiK/BDOT10k database	shp	2018
29	Flood losses	Consortium of IMGW-PIB/ARCADIS/MGGP	shp	2019
30	Cities	GUGiK/BDOT10k database	shp	2018
31	Land use	GUGiK/BDOT10k database	shp	2018

** Identification of pressures in water regions and river basins, 2018 (works carried out for PGW WP)*

5. METHODOLOGY FOR THE DEVELOPMENT OF FHMs

Regulation on the development of FHMs and FRMs (§Par. 9, item 1) stipulates that flood hazard areas (FHA) defined as areas referred to in Article 169, item 2 of the Water Law Act, including point 3, letter c, are determined on the basis of water level ordinates obtained as a result of mathematical hydraulic modelling.

The methodological basis for hydraulic modelling is the Methodology for the analysis of flood hazards caused by failures of dams with a height of H ≥ 15 m. Project PL0456 "Flood hazards resulting from dam failures". Contractor: RZGW in Cracow, IMGW, Cracow, 2011. The passages in italics are taken from the aforementioned methodology.

5.1. METHODOLOGY FOR HYDRAULIC MODELLING

The analysis of the course of dam failure and the transformation of wave caused by this phenomenon in the valley below should be based on model studies. Hydroinformatics tools allow us, in a relatively simple way, to carry out modelling for the entire complex process related to the passage of flood wave through the reservoir, the destruction of the dam and the transformation (in the valley below) of the hydrograph created as a result of such failure. This modelling is the basis for the determination of flood hazard areas in the valley below the facility and the analysis of the effects of the whole phenomenon.

"Due to the complexity and integrity of calculations of dam body washout due to the overflow of water over the top of the dam or piping failure with further calculations of wave transformation in the valley below the dam - it is recommended to perform them preferably in one hydrodynamic model covering all aspects of the dam failure process - from the formation of the phenomenon itself, through its development, to the effects of such failure." (RZGW in Cracow, 2011). This solution should be applied in the event of building a model of failure "from scratch".

In case of having models for basic scenarios, they should be used after appropriate adjustment (supplementing the reservoir model with Dambreak Structure, extension of cross-sections, modification and/or addition of floodplains, etc.). The calculations based on these models can be carried out while keeping the division of the analysed fragment of the hydrographic network into sections as in the basic scenarios or, after their integration, within one model.

5.1.1. Hydrodynamic model of dam failure

"The hydrodynamic model of dam failure should allow for mapping of the reservoir basin and geometry of the dam body, introduction of rules for controlling the outlet from the reservoir (in case of facilities with controlled floodgates) and, most of all, allow for the implementation of adopted variants of failure, i.e. allow for defining (in the dam section) of the hydraulic structure of "dambreak" type, described by geometrical, geotechnical and time parameters." (RZGW in Cracow, 2011).

5.1.1.1. Mapping of reservoir basin and dam shape

"The description of the shape of water reservoir basin closed by the body of the dam, for which it is planned to carry out simulation calculations of its failure, is performed using a hydrodynamic model.

Bathymetric measurements are the best sources of cross-sections - allowing for the most accurate representation of the shape of reservoir basin. The method of reservoir basin description on the basis of bathymetry is also a method which allows for mapping of the so-called backward wave generated in the reservoir during a sudden outflow of water through a hole (this phenomenon applies especially to facilities with concrete structure, the failures of which usually happen very quickly). Therefore, this method is recommended in the first place.

The greater the number of cross-sections describing the reservoir, the more accurately the reservoir will be mapped. It is assumed that the intervals between the cross-sections are about 500 m but during the determination of cross-section locations, it is necessary to take into account at the same time the need to map the horizontal shape of the reservoir basin, i.e. e.g. possible sudden changes in reservoir width, bays and branches.

If there are no current and representative bathymetric measurements, there are ways of mapping the reservoir storage in the hydraulic model by means of e.g. one design point (cross-section), where the whole information about the reservoir storage is implemented in the form of storage curve (or curve of flood area).

Regardless of the way the geometry of the reservoir basin is described, it is necessary to calibrate the reservoir storage in detail at a later stage of the works. Such calibration should be the result of iterative calculations on constant flow values (constant inflow to the reservoir) and it is necessary for correct transformation of the flood wave through the reservoir. As a standard curve of the reservoir storage, the curve contained in the instructions for water management currently valid for the facility should be adopted, or - in case of significant changes in reservoir storage (e.g. silting up of the basin) - the updated curve, determined on the basis of bathymetric measurements.

Calibration calculations must be made at least for the characteristic water levels: NPP, MaxPP, and for the level corresponding to the elevation of dam crest (it is suggested to perform calibration calculations for the reservoir filling levels every 1.0 m in active storage including flood storage zone). Maximum differences in the calculated levels of the water level in the reservoir in relation to the actual ordinates (reservoir storage curve) should not exceed 10 cm at each level.

The implementation of the dam shape, especially the shape and ordinates of its crest is another obligatory element for the creation of hydraulic model of its failure. This activity determines the possibility of taking into account in the calculations the volume of water overflowing the dam's crest, which is particularly important in variants of this type of failure. It can be carried out in different ways - depending on the type of software used (hydraulic model). However, most often the implementation of the dam shape takes place in the cross-section editor or directly in the module responsible for the simulation of facility's failure (usually as a wide crest overflow).” (RZGW in Cracow, 2011).

5.1.1.2. Rules for controlling outflows from the reservoir

“The proper mapping of the reservoir's operation principles is particularly important in the case of simulation of dam failure in flood conditions. In this case, we are dealing with the inflow of flood wave (hypothetical or real) of cubic capacity (defined in the hydrograph) into the reservoir and the correct algorithm of the rules for disposing of the outflow depending on the current inflow and the

water level in the reservoir becomes of great importance. In such situations, the wave volume intercepted by the reservoir, which results directly from the relations between the inflow, water level in the reservoir and the outflow adopted in the so called instructions for water management in the facility, in many cases determines the occurrence of the very phenomenon of facility failure. This applies especially to a failure caused by water overflowing the dam crest, which, according to the assumption itself, can only take place if the water level in the reservoir reaches (and exceeds) the crest elevation. On the other hand, the possibility of reaching such a crest elevation depends on two basic factors: the cubic capacity and shape of the flood wave and the rules for controlling the outflow from the reservoir, written in the instructions. For this reason, the inclusion of the latter in the hydraulic model created especially for the analysis of dam failure is an indispensable element. Moreover, the dynamics of the reservoir operation, resulting from the rules contained in the instructions, translates directly into changes in the water level in the reservoir, and these in turn into the gradient of filtration pressures in the body, which determine the process of formation and development of suffosion phenomena." (RZGW in Cracow, 2011).

5.1.1.3. Model of dam failure

"Having built a hydraulic model, based on a calibrated current reservoir storage curve and describing: reservoir basin, dam body geometry and water management principles, it is necessary to start implementing the model of the failure itself. The basis for this stage of works is a previously prepared set of variants. Assumptions adopted in particular variants as to hydrological conditions, reservoir filling level and parameters of simulated dam damage, as well as other - additional variables, should be "translated" into the mathematical language of the model and implemented in the calculation structure responsible for failure mapping. Such implementation is carried out in a special module designed to describe the "dambreak" phenomenon. It consists in introducing design parameters concerning:

- *the level of dam crest and its length;*
- *the inclusion in calculations of the so-called cross-section limiting the maximum size of damage to dam body;*
- *the location of damage to the body (location of the hole - in the case of earth dam or a damaged section of the dam - in the case of concrete dam) in relation to the dam;*
- *the geometry of damage (maximum width at the bottom, target bottom ordinate, inclination of side walls);*
- *the coefficients of resistance to the flow of water through the damaged part of dam body;*
- *the moment or conditions that determine the start of dam failure process (e.g. failure when the reservoir reaches a certain level of damming, failure when the flood wave culminates in the reservoir, failure at a certain moment - date, hour, minutes and seconds);*
- *the way in which the phenomenon of formation and spatial development of damage is described (e.g. time series - in the case of damage to concrete dams, time series or erosion formulas - in the case of damage to earth dams);*
- *the causes that initiate failure (overflowing the crest, hydraulic rupture);*
- *the filling level of the reservoir before failure.*

In case of simulation of earth dam failure using erosion formulas, it is also necessary to determine the basic physical and mechanical characteristics of the soil of dam body. Such characteristics generally include: grain diameter, specific gravity, porosity, shear strength, and, in the case of failures caused by hydraulic rupture, additionally, for example, the roughness of fissure walls initiating the suffosion process.

Moreover, due to the necessity to define the initial boundary conditions for the calculations of hole formation or hydraulic rupture fissure over time, it is necessary to define the initial parameters of these structures i.e. the initial width and ordinate of the hole bottom in the dam body or the initial diameter of rupture fissure and its ordinate or also e.g. the ratio of the diameter of rupture fissure to the thickness of the soil layer of the body above it - as a condition for the formation of the hole as a result of rupture and suffosion. At this point, it should be noted that when mapping this type of failures in earth facilities, the occurrence of protection made of boards on the upstream slope of the dam, elements protecting against waves on the dam crest or other permanent protection measures which have no direct impact on the course of phenomena occurring in the soil of the body is usually omitted.

Some models simulating an earth dam failure additionally allow us to determine the percentage volume of soil retained in the dam profile as a result of sudden collapse of the soil caused by a rupture and the formation of a hole." (RZGW in Cracow, 2011).

Mentioned above the phenomena of hydraulic rupture and formation of a hole or damage of a section in the case of concrete dam can be simulated using model Mike 11 with CONTROL STRUCTURE module (enables simulation of rules for reservoir control) and DAMBREAK STRUCTURE module (enables simulation of dam damage/destruction).

For the proper operation of the failure module (dambreak) mapped in the hydraulic model, it is necessary to ensure that the following conditions are met:

- the flow capacity of the reservoir cross-sections located above the dam must ensure the minimum flow rate necessary to sustain and develop the process of failure,
- the elevations of the bottom of reservoir cross-sections cannot slow down the process of failure.

It is therefore important that the filling level curve of the reservoir is correctly calibrated in its full filling level.

5.1.2. Hydrodynamic model of the valley below the dam

5.1.2.1. Diagram of the valley

"The route of the one-dimensional model describing the dam failure should be marked along the river valley and not, as is the case with the traditional hydraulic model created for delineating flood hazard areas, along the axis of the watercourse, taking into account all its meanders. Such an approach is forced by the significant depths of water in the valley (a dam failure causes a rapid emptying of the water reservoir) many times greater than the amounts that can occur in the event of natural flooding caused by heavy rainfall. The direction of flow will therefore not be determined by the river axis but by the overall topography of the valley. Schematisation should focus on taking

into account those features of the river valley that will influence the transformation of extreme flows, with neglecting insignificant details like small embankments, meanders and bends. Schematisation should be performed in a way that at the same time allows for later calibration of the model based on historical waves, so that the model in terms of historical flows, in the initial and final phase of the simulation, is able to properly transform the wave caused by the dam failure while maintaining the overall shape of the valley.

In the case of two-dimensional model based on DTM, the situation is different - calculations are performed on a calculation grid. Therefore, it is not necessary to calculate the route of the model - this process is performed automatically during calculations." (RZGW in Cracow, 2011).

5.1.2.2. Cross-sections

"Cross-sections are the basic and most important input elements to the construction of one-dimensional model of wave transformation resulting from dam failure. Their proper determination is a condition for the proper transfer of the volume of water masses flowing out intensively from a rapidly widening hole down the river valley. Cross sections should be located perpendicularly to the main direction of the valley i.e. perpendicularly to the course of contour lines on the main slopes limiting the river valley from its right and left side. It should be remembered that the beginning and the end of cross-sections should have the same ordinate and be elevated high enough above the river valley to avoid artificial narrowing of the flow field and rapid swelling of water and incorrect results as a consequence. Depending on the available input materials, cross sections can be performed entirely by means of direct field measurements or as a combination of field measurements of the river bed and adjacent areas with floodplains generated on the basis of digital terrain model." (RZGW in Cracow, 2011).

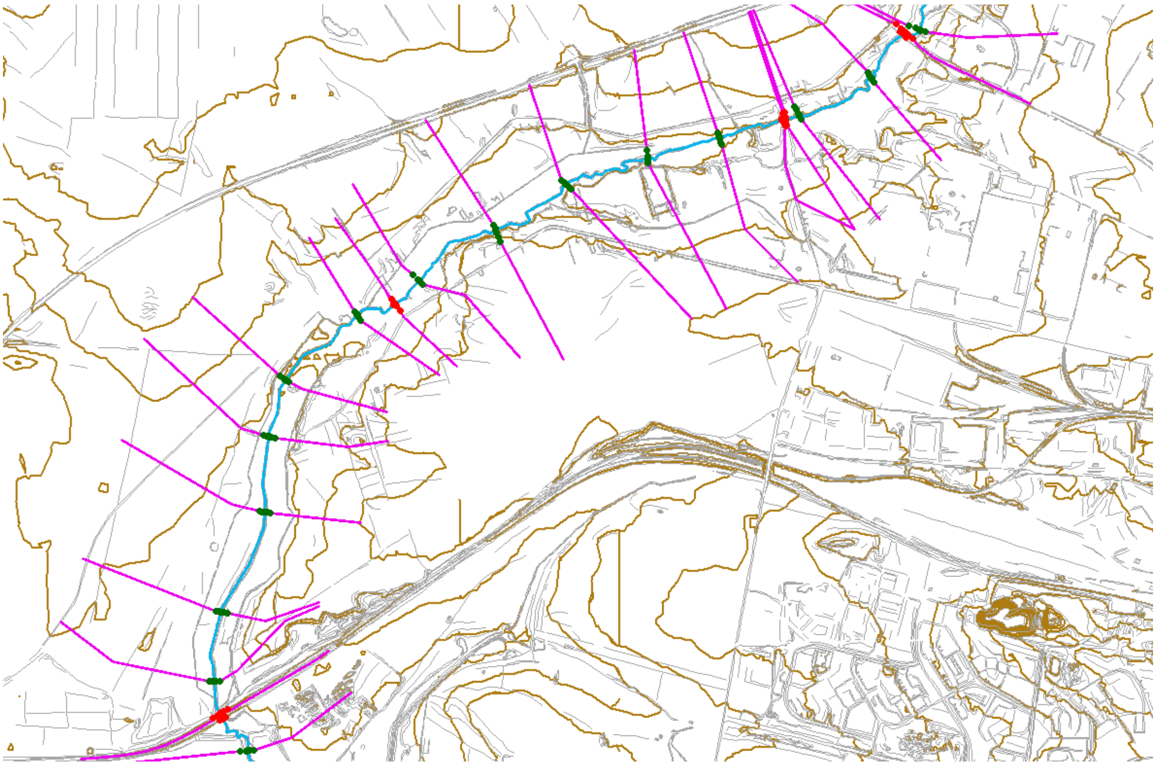

Figure 2. Example of cross section locations in a river valley (RZGW in Cracow, 2011)

"In the case of two-dimensional models, there are no cross-sections and the calculations (as mentioned in the section concerning the valley diagram) are based on DTM grid. In the case of hybrid models that combine elements of one-dimensional and two-dimensional modelling i.e. for which flows, velocities and filling levels in the river channel (i.e. for relatively small areas in terms of analysis of dam failure phenomenon) are calculated with the use of 1D model, while the transformation in the rest of the valley is carried out with the use of 2D modelling, it is important to properly connect the cross-sections from 1D model with the calculation grid of the two-dimensional model. In this type of models, the contact of cross-sections with the digital terrain model is a critical place which may have a negative impact on calculation results. Therefore, it is very important that the points that are common to the cross-sections of 1D model with the 2D model grid have identical altitudes. The fulfilment of this condition prevents oscillations during the calculations and increases the stability of the model." (RZGW in Cracow, 2011).

5.1.2.3. Identification of hydraulic parameters

"The key hydraulic parameter for the flood wave transformation models that determines the correct calculation results is the roughness coefficient (flow resistance). However, in the case of models built for the purposes of dam failures, the selection of the value of this parameter is the main element of uncertainty affecting the quality of calculation results. In the case of river models, there are many studies that indicate typical values of roughness coefficients for both river channels and floodplains. In the case of dam failure, the velocities and flow values are so high and the amounts of carried and dragged material are so significant that flooded areas cannot be treated as typical floodplains, which makes it impossible to determine the values of roughness coefficients in a standard way. As

mentioned above, in the case of dam failures, there is not only the flow of water in the valley (especially in the section immediately below the damaged facility) but also the flow of a significant amount of various material (parts of the dam, stones, gravel, sand, mud, trees, cars, parts of houses, civil engineering structures and fences, etc.). Thus, the resistance of the substrate will change dynamically as individual large elements fall, roll and stop, thus losing the kinetic energy of the flood wave. As the front of the wave moves below the damaged dam, the values of the roughness coefficient will therefore decrease and come close to the values that are typical for particular types of land development. In view of the facts described above, it is recommended to divide the valley area into two parts (based on successive approximations):

- *the part immediately below the dam where the flow rate, velocities and depths are so high that everything in the river current is expected to be destroyed; for this part of the valley, the value of the roughness coefficient should be defined as one global value along the entire cross-section and adopted with a very high value of 0.10 - 0.15 (for "n" according to Mannig);*
- *the part where a significant drop in velocity and depth is observed and the wave can be treated as a typical flood wave with low probability of exceedance; for this part of the valley, the roughness coefficient values should be selected based on typical hydraulic tables (e.g. according to Ven Te Chow).*

At the stage of model development, for the purposes of its calibration and verification based on hydrographs of historical floods, the roughness coefficient values should be selected based on typical hydraulic tables (e.g. according to Ven Te Chow)." (RZGW in Cracow, 2011).

5.1.2.4. Civil engineering structures

"Civil engineering structures include bridges (bridges and culverts) and hydro-engineering structures (dams, weirs, barrages, etc.). When river models are developed for the purpose of delineating flood hazard areas caused by natural floods, it is very important that all such structures be included in the model as they can significantly affect the transformation of flood wave in the riverbed and floodplains and affect the calculation results as a consequence. The situation is different in the case of models created for the analysis of dam failure phenomenon. In this case, due to the rapid course of the phenomenon associated with the outflow of huge masses of water through the failed dam, it should be taken into account that some structures will be destroyed and skip their implementation in the model, bearing in mind the appropriate increase in the roughness coefficient. When choosing which structures should be included in the model, it is necessary to perform simulation in the absence of all structures and check the results obtained, especially in terms of velocity and depth. When analysing the results, it is worthwhile to include the following three criteria:

- *"Pressure criterion". Will the structure withstand a flood wave carrying large amounts of different material? It is suggested not to introduce civil engineering structures into the model over a distance not exceeding 5 km due to the considerable destructive force of the carried material.*
- *"Depth criterion". Is the structure significant in relation to the predicted water depth and, therefore, is it worth including it in the model? For structures covered with a layer of water higher than their height, it can be assumed that they will not affect the calculation results.*

– *"Velocity criterion". If the depth criterion shows grounds for including the structure in the model, aren't flow velocities so high that the structure hasn't a chance to resist the wavefront? It is suggested to introduce into the model only those structures where the average velocity of the moving wave does not exceed 5 m/s (despite meeting the "Depth criterion").*

The above criteria indicate how to approach the selection process of civil engineering structures to be included in the hydraulic model. Due to different geomorphological conditions of particular river valleys where water reservoirs are located, they should be treated as indicators. At the stage of creating the model and related implementation of civil engineering structures, field investigation and expert knowledge will be additionally necessary to finally decide which structures should be included in the model.

In the case of civil engineering structures which, after previous analysis, should be included in the model, they should be implemented based on geodetic measurements, the principles of which are described in Chapter 4.1.2 hereof. Such implementation should be carried out according to the conditions and requirements of 1D modelling tools on the basis of commonly used methods, such as: the combination of culvert and spillway, Water Surface Profile (WSPRO) method, through direct solution of the energy equation with the use of iterative method, based on the energy conservation principle or using e.g. equations of Yarnell, D'Aubuisson, Nagler and others." (RZGW in Cracow, 2011).

5.1.2.5. Boundary conditions and determination of failure extent

"In a hydraulic model, it is necessary to establish boundary conditions limiting the modelling area. In each model, there are upper and lower boundary conditions and optionally internal boundary conditions in the form of concentrated or distributed tributaries. Upper boundary conditions are defined in the form of hydrographs of flows or water levels (ordinates). These conditions must be established for all upper watercourse sections included in the model. Lower boundary conditions, closing the model depending on the modelling assumptions, can be either a water level hydrograph (elevations) or a rating curve. In the case of a model for dam failure, the upper boundary condition is the outflow hydrograph created as a result of failure (where the models for dam failure and model of wave transformation in the riverbed below are built separately) or the inflow hydrograph (with the integrated model)." (RZGW in Cracow, 2011).

When using models built for basic scenarios, the models may also include sections of watercourses located above the reservoir. In this case, a small flow is introduced as an upper boundary condition so that the model along its entire length is filled with water and does not generate errors. Lateral inflows above the reservoir, concentrated and distributed, should be eliminated and the hypothetical wave with peak flow equal to the extreme design flow for the analysed structure should be introduced in the first cross-section of the reservoir basin or another nearby cross-section.

The hydrological situation in the catchment below the reservoir is not very important for the extent of flooding in the section directly below the reservoir, since a dam failure results in a flood wave many times higher than the wave flowing into the reservoir, but as the distance from the dam increases, concentrated and dispersed lateral inflows become more important in this context. In order to avoid a situation in which the extent of flooding resulting from dam failure is determined by lateral inflows, it is assumed that the inflows below the reservoir will be adopted and they will be identical to those for the scenario of low probability of fluvial floods (wave with a probability of exceedance 0.2%). This solution allows us to define a criterion for the extent of dam failure scenario by comparing it to the scenario with 0.2%. The stop criterion is the situation when the maximum water level for the scenario of dam failure in the calculation cross-section of the model differs by less than 30-50 cm from the water level for the scenario with 0.2%. The criterion of 50 cm is applied to reservoirs in areas where mountain and highland watercourses prevail, with more indented valleys, where changes in flows result in larger changes in water levels than in lowland rivers. It is recommended to apply this criterion for the following water regions: Upper Oder, Middle Oder, Little Vistula, Upper-Western Vistula and Upper-Eastern Vistula. For the remaining areas of the country, the criterion of 30 cm is recommended. When analysing the differences between the scenario with Q0.2% and BP scenario and determining the boundary cross-section defining the extent of the failure, the differences of maximum elevations of the water level in the river channel and on the downstream faces are taken into account. In the situation when lateral inflows according to the scenario with 10% (cf. chapter 3.7) are assumed for the recipient of the watercourse on which the analysed reservoir is located, the extent of the failure is defined in the same way as for lateral inflows according to the scenario with 0.2% i.e. by relating the maximum water level for the scenario of dam failure to the water level for the scenario with 0.2%.

The extent of the failure determined according to the aforementioned criteria is then adjusted to the boundaries of the map sheets at the stage of delineation of FHAs (cf. chapter 5.2).

5.1.2.6. Calibration and verification

"In the case of the hydrodynamic model (non-steady flow), the calibration is performed for a specific flood wave for which the time and spatial distribution of flows and water levels is known. It consists in determining the parameters of the model in such a way as to obtain, compliant with the historical flood wave, a design distribution of water levels in the longitudinal profile of the river, with the correct boundary conditions in the form of flow hydrographs. This compliance comes down to obtaining consistent hydrographs of water levels, both in terms of value and time at calibration points (with known historical values).

The verification of the model is carried out on a flood wave different from the flood wave for which calibration was performed. It consists in the assessment of the compliance of historical and design hydrographs at the same points and based on the same model parameters for which calibration was performed.

Calibration and verification can be carried out for controlled watercourse i.e. the one on which a water level gauge station is located. Additional condition necessary for proper calibration and verification is the location of control water level gauge on the section covered by the hydraulic model.

In the case of hydraulic models created for the purpose of the analysis of flood wave transformation caused by dam failure, the process of calibration and verification of the model is performed only for the purpose of checking the general principles of its operation i.e. to determine whether the model properly transforms the flows down the valley and whether the relation between the values of water *levels and flows at individual control points (water level gauges) is maintained. It should be remembered that the flows caused by dam failures are many times higher than the flows associated with typical floods caused by rainfall. Therefore, calibration of the model for such high flows is not possible due to the lack of appropriate historical waves.*

To assess the quality of model verification and calibration, it is proposed to rely on the following parameters:

- *correlation coefficient (R);*
- *special correlation coefficient (R_s);*
- *total squared error (CBK);*
- *error of culmination level (ΔH_{max});*
- *error of culmination flow (ΔQ_{max});*
- *culmination dislocation (Δt_{max});*
- *error of flood wave volume (ΔV_{max}).*

The ***correlation coefficient*** *should be determined for water levels from the following formula, where: h_o – observed level, h_c - design level:*

$$R = \frac{N\sum_{i=1}^{N} h_{o(i)} \cdot h_{c(i)} - \sum_{i=1}^{N} h_{o(i)} \cdot \sum_{i=1}^{N} h_{c(i)}}{\left\{\left[N\sum_{i=1}^{N} h_{o(i)}^2 - \left(\sum_{i=1}^{N} h_{o(i)}\right)^2\right]\left[N\sum_{i=1}^{N} h_{c(i)}^2 - \left(\sum_{i=1}^{N} h_{c(i)}\right)^2\right]\right\}^{1/2}}$$

The correlation coefficient should be determined for flows from the following formula, where: Q_o – observed flow, Q_c– design flow:

$$R = \frac{N\sum_{i=1}^{N} Q_{o(i)} \cdot Q_{c(i)} - \sum_{i=1}^{N} Q_{o(i)} \cdot \sum_{i=1}^{N} Q_{c(i)}}{\left\{\left[N\sum_{i=1}^{N} Q_{o(i)}^2 - \left(\sum_{i=1}^{N} Q_{o(i)}\right)^2\right]\left[N\sum_{i=1}^{N} Q_{c(i)}^2 - \left(\sum_{i=1}^{N} Q_{c(i)}\right)^2\right]\right\}^{1/2}}$$

The criterion for determining compliance measures for the correlation coefficient:

- *$0.95 < R \le 1.00$ excellent*
- *$0.80 < R \le 0.95$ very good*
- *$0.70 < R \le 0.80$ good*
- *$0.60 < R \le 0.70$ quite good*
- *$0.00 < R \le 0.60$ unsatisfactory*

The ***special correlation coefficient*** *should be determined for water levels from the following formula, where: h_o – observed level, h_c - design level:*

$$R_s = \left[\frac{2\sum_{i=1}^{N} h_{o(i)} \cdot h_{c(i)} - \sum_{i=1}^{N} h_{c(i)}^2}{\sum_{i=1}^{N} h_{o(i)}^2} \right]^{1/2}$$

The special correlation coefficient should be determined for flows from the following formula, where: Q_o – observed flow, Q_c - design flow:

$$R_s = \left[\frac{2\sum_{i=1}^{N} Q_{o(i)} \cdot Q_{c(i)} - \sum_{i=1}^{N} Q_{c(i)}^2}{\sum_{i=1}^{N} Q_{o(i)}^2} \right]^{1/2}$$

The criterion for determining compliance measures for the special correlation coefficient:

–	*$0.95 < R_s \le 1.00$*	*excellent*
–	*$0.85 < R_s \le 0.95$*	*very good*
–	*$0.70 < R_s \le 0.85$*	*good*
–	*$0.60 < R_s \le 0.70$*	*quite good*
–	*$0.00 < R_s \le 0.60$*	*unsatisfactory*

*The **total mean squared error** should be determined for water levels from the following formula, where: h_o – observed level, h_c - design level:*

$$CBK = \frac{\left[\sum_{i=1}^{N} \left(h_{o(i)} - h_{c(i)} \right)^2 \right]^{1/2}}{\sum_{i=1}^{N} h_{o(i)}} \cdot 100\%$$

The total mean squared error should be determined for flows from the following formula, where: Q_o – observed flow, Q_c - design flow:

$$CBK = \frac{\left[\sum_{i=1}^{N} \left(Q_{o(i)} - Q_{c(i)} \right)^2 \right]^{1/2}}{\sum_{i=1}^{N} Q_{o(i)}} \cdot 100\%$$

The criterion for determining compliance measures for the total mean squared error:

–	*0.0 ≤ CBK [%] < 3.0*	*excellent*
–	*3.0 ≤ CBK [%] < 6.0*	*very good*
–	*6.0 ≤ CBK [%] < 10.0*	*good*
–	*10.0 ≤ CBK [%] < 25.0*	*quite good*
–	*25.0 ≤ CBK [%]*	*unsatisfactory*

*The **error of culmination level** should be determined for water levels as the difference between the ordinates of the maximum value of the design and observed hydrograph.*

The criterion for determining compliance measures for the error of culmination level:

- $0\ cm \leq (\Delta H_{max}) < 5\ cm$ — *excellent*
- $5\ cm \leq (\Delta H_{max}) < 10\ cm$ — *very good*
- $10\ cm \leq (\Delta H_{max}) < 15\ cm$ — *good*
- $15\ cm \leq (\Delta H_{max}) < 20\ cm$ — *quite good*
- $20\ cm \leq (\Delta H_{max})$ — *unsatisfactory*

*The **error of culmination flow** should be determined for flows as the difference between the maximum value of the design and observed hydrograph.*

The criterion for determining compliance measures for the error of culmination flow:

- $0\ \% \leq (\Delta Q_{max}) < 3\ \%$ — *excellent*
- $3\ \% \leq (\Delta Q_{max}) < 6\ \%$ — *very good*
- $6\ \% \leq (\Delta Q_{max}) < 10\ \%$ — *good*
- $10\ \% \leq (\Delta Q_{max}) < 25\ \%$ — *quite good*
- $25\ \% \leq (\Delta Q_{max})$ — *unsatisfactory*

*The **culmination dislocation** should be determined for water levels as the displacement in time of the maximum value of the design and observed hydrograph.*

The criterion for determining compliance measures for the culmination dislocation:

- $0\ h \leq (\Delta t_{max}) < 0.5\ h$ — *excellent*
- $0.5\ h \leq (\Delta t_{max}) < 1.0\ h$ — *very good*
- $1.0\ h \leq (\Delta t_{max}) < 1.5\ h$ — *good*
- $1.5\ h \leq (\Delta t_{max}) < 2.0\ h$ — *quite good*
- $(\Delta t_{max}) \leq 2.0\ h$ — *unsatisfactory*

*The **error of flood wave volume** should be determined for flows as the difference between the volume of the design and observed wave.*

The criterion for determining compliance measures for the error of flood wave volume:

- $0\ \% \leq (\Delta V_{max}) < 3\ \%$ — *excellent*
- $3\ \% \leq (\Delta V_{max}) < 6\ \%$ — *very good*
- $6\ \% \leq (\Delta V_{max}) < 10\ \%$ — *good*
- $10\ \% \leq (\Delta V_{max}) < 25\ \%$ — *quite good*
- $(\Delta V_{max}) \leq 25\ \%$ — *unsatisfactory*

In the event of calibration, for each criterion it is recommended that the model should be given at least 'good' rating and in the event of verification - at least 'quite good'." (RZGW in Cracow, 2011).

If calibrated and verified models, developed for the basic scenarios, are used in the simulations of the process of dam failure, a new calibration and verification process is not required.

5.2. PROCESSING OF MODELLING RESULTS AND DELINEATION OF AREAS EXPOSED TO FLOODING IN THE EVENT OF DAM FAILURE

"The final result of the calculations simulating the failure of dam is the delineation of the flood hazard area (FHA) together with the determination of water depth distribution." (RZGW in Cracow, 2011).

FHA and water depth zones, in characteristic categories (Chapter 2), can be determined, using one or two-dimensional models. Hybrid models are also used in practice, they combine one-dimensional models with two-dimensional models. Two-dimensional models are usually used in urban areas where, due to high population density, the greatest threats to human health and life occur.

"The designation of FHA to show the extent of dam failure involves the creation of digital water surface model (DWSM) based on hydraulic modelling. Combining the digital water surface model with the digital terrain model in GIS systems allows us to determine the flooded areas and the distribution of water depth.

The principles of creating DWSM depend on the digital model used in the calculations. In one-dimensional models, in which the result of calculations is the water level which is the same for the entire cross-section, the determined valley and riverbed cross-sections are applied as linestrings with known X, Y coordinates and the calculated elevation of water level for the given cross-section. The resulting set of contour lines is transformed into DWSM in GIS systems. In the case of calculations performed with the use of two-dimensional models, DWSM is the direct result of calculations." (RZGW in Cracow, 2011).

Flood hazard areas generated in GIS systems are visualised on orthophotomaps in order to facilitate the interpretation of hazard caused by the dam failure. When analysing the developed FHAs, attention should be paid to areas that have been designated as flooded areas and are not in contact with the main flood zone. This may be due to the accuracy of DTM or result from incorrect assumptions at the stage of creation of the hydraulic model. Such areas should be subject to expert interpretation and, if found to be incorrect, excluded from the flood hazard areas.

The procedure for the delineation of FHAs and depth zones, based on GIS software, includes the following steps:

1) Generation of digital water surface model (DWSM) raster and water depth raster.
2) Verification of water depth raster.
3) Delineation of flood hazard areas and depth zones.
4) Reconciliation of flood hazard areas at the interfaces of modelled areas.
5) Final verification of water depth zones and flood hazard areas.

A detailed description of the aforementioned procedure is included in the Methodology for fluvial floods.

The final determination of the extent of dam failure is also performed during the process of delineation of FHAs. The extent defined by the boundary cross-section, determined on the basis of stop criterion (cf. chapter 5.1.2.5) is extended to the boundaries of the map sheets in the meridional or latitudinal alignment (cf. Figure 3). An exception to this rule is when the extent of failure ends at the river mouth. The boundary of failure extent in this case is the recipient into which the river flows.

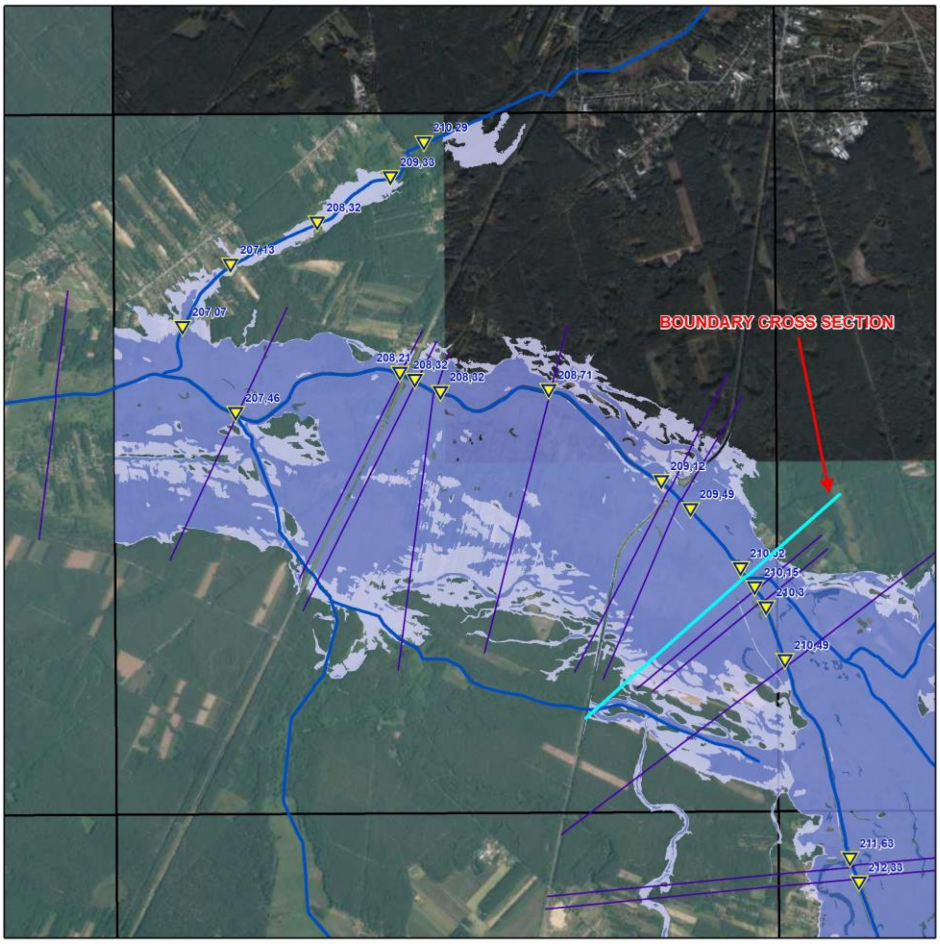

Figure 3. Adjusting the extent of the dam failure to the borders of the map sheet - an example for the Poraj reservoir

6. METHODOLOGY FOR THE DEVELOPMENT OF FRMs

According to the Water Law Act (Article 170, item 1), flood risk maps are developed for flood hazard areas.

According to the Regulation, flood risk maps present the potential negative consequences associated with flooding by specifying:

- negative consequences on human life and health;
- types of economic activities;
- protected areas;
- facilities that pose threats to the environment in the event of a flood, including those that may also have a negative impact on human health;
- cultural heritage areas and sites;
- value of potential flood losses.

Flood risk maps for the scenario of dam failure should be made in accordance with the "Methodology for fluvial floods".

However, the specific nature of the scenario of dam failure should be taken into account in terms of, among others, map names, legend content, database structure and catalogue structure.

7. FHMs AND FRMs SPATIAL DATABASES

7.1. DATABASES

FHMs and FRMs spatial databases for the scenario of dam failure are prepared in *.shp format in EN-1992 rectangular flat coordinate system. In addition, a version of the database in ESRI geodatabase format should be prepared, together with tools for migration between data formats.

FHMs and FRMs database for areas exposed to flooding in the event of dam failure will constitute a separate database but with a structure coherent with other types of floods (attribute and directory structure, file naming). Differences in structure and nomenclature are only due to the specific nature of data and information in this scenario.

FHM and FRM database includes:

1) Reference layers:

- watercourses and canals;
- other watercourses;
- surface waters;
- roads;
- railway lines;
- voivodeship;
- district;
- commune;
- sheets of maps at a scale of 1:10 000 for PL-1992.

2) Layers of flood hazard maps:

- flood hazard area for the scenario of dam failure;
- water depth;
- maximum water level;
- location of dam failure;
- dams;
- top of flood embankment elevation in cross-sections;
- flood embankments;
- chainage.

3) Layers of flood risk maps:

- land use with calculated potential flood losses;
- land use;
- buildings;
- industrial plants;
- water abstractions;
- protection zones of water abstractions;
- bathing waters;
- forms of nature conservation;
- areas of cultural heritage;
- objects of cultural heritage;
- zoos;

- cemeteries (potential sources of pollution);
- landfills (potential sources of pollution);
- wastewater treatment plants and wastewater pumping stations (potential sources of pollution);
- cities.

Information about the current version of FHMs and FRMs sheet (e.g. 2019v1, 2022v1) is included in the layer containing division of map sheets (at a scale of 1:10 000).

A detailed description of the attribute structure of FHMs and FRMs database for the scenario of dam failure, layer names, layer types, layer description, data source and attributes (field name, field type, description, attribute source) are included in Annex no. 1

The internal catalogue structure of the database in shp format for areas exposed to flooding in the event of dam failure is analogous to the structure for fluvial floods.

7.2. METADATA

For all spatial data generated in the project, metadata should be prepared in accordance with the INSPIRE Directive and European Commission reporting guidelines from the Floods Directive.

The scope of metadata according to the INSPIRE profile has been defined (under the "Methodology for fluvial floods") for all types of floods on the basis of the following documents:

- INSPIRE Metadata Implementing Rules: Technical Guidelines based on EN ISO 19115 and EN ISO 19119 v1.3, 2013;
- Technical Guidelines for implementing dataset and service metadata based on ISO/TS 19139:2007 v2.0.1, 2017;
- Data Specification on Natural Risk Zones – Technical Guidelines v3.0, 2013;
- Floods Directive GIS Guidance – Guidance on the reporting of spatial data to WISE, 2020.

According to the above scope, the metadata should be prepared separately for:

1) FHMs and FRMs database - according to the current INSPIRE metadata profile - for the following sets:
    a) MZP
    b) MZP_WZ
    c) MZP_BP*
    d) MRP_RL
    e) MRP_RL_WZ
    f) MRP_RL_BP*
    g) MRP_RS
    h) MRP_RS_WZ
    i) MRP_RS_BP*

    *metadata related to flood hazard maps and flood risk maps prepared in the scenario of dam failure.

2) Data sets from INSPIRE Annex III - according to the current INSPIRE metadata profile (only for fluvial floods and floods from the sea):

a) FHA_low
b) FHA_medium
c) FHA_high
d) FRZ_low
e) FRZ_medium
f) FRZ_high

3) A report for the European Commission on the review and updating of flood hazard maps and flood risk maps (applies to all types of floods).

The data sets indicated in section 1 (highlighted with *) should be described with metadata in xml format, grouped thematically by river basins. The xml format of the metadata is described in the "Methodology for fluvial floods".

It is required to prepare indexes (for FHMs and FRMs in cartographic version) in *.shp format, containing sheets with assigned information about the type of data and their spatial range, dates of source data, type of model used and the Contractor (Table 3, Table 4).

In addition, it is required to prepare indexes of FHMs and FRMs timelines, for river sections and 1:10 000 map sheets.

7.2.1. Index of flood hazard maps for the scenario of dam failure

- Layer: Skorowidz_MZP_BP;
- Layer type: polygons;
- Description: map sheets with FHM on a map at a scale of 1:10 000 in PL-1992 coordinate system;
- Data source: aMZPiMRP.

Table 3. Attribute structure of the index of flood hazard maps

Attribute	Field type	Description	Attribute source
GODLO	T(22)	Map sheet identification number in 1992 system	GUGIK
WSP_LG	T(254)	Coordinates [X;Y] of the upper left corner of the sheet	GUGIK
WSP_LD	T(254)	Coordinates [X;Y] of the lower left corner of the sheet	GUGIK
WSP_PG	T(254)	Coordinates [X;Y] of the upper right corner of the sheet	GUGIK
WSP_PD	T(254)	Coordinates [X;Y] of the lower right corner of the sheet	GUGIK
WYKONAWCA	T(38)	Contractor	aMZPiMRP
KL_MOD	T(5)	Type of model used	aMZPiMRP
AKT_BDOT	T(50)	Date of BDOT	aMZPiMRP
AKT_NMT	T(50)	Date of DTM	aMZPiMRP
UWAGI	T(254)	Notes	aMZPiMRP
MZP_BP	T(50)	Name of flood hazard map with water depth	aMZPiMRP

7.2.2. Index of flood risk maps for the scenario of dam failure

- Layer: Skorowidz_MRP_BP;
- Layer type: polygons;
- Description: map sheets with FHM on a map at a scale of 1:10 000 in PL-1992 coordinate system;
- Data source: aMZPiMRP.

Table 4. Attribute structure of the index of flood risk maps

Attribute	Field type	Description	Attribute source
GODLO	T(22)	Map sheet identification number in 1992 system	GUGIK
WSP_LG	T(254)	Coordinates [X;Y] of the upper left corner of the sheet	GUGIK
WSP_LD	T(254)	Coordinates [X;Y] of the lower left corner of the sheet	GUGIK
WSP_PG	T(254)	Coordinates [X;Y] of the upper right corner of the sheet	GUGIK
WSP_PD	T(254)	Coordinates [X;Y] of the lower right corner of the sheet	GUGIK
WYKONAWCA	T(38)	Contractor	aMZPiMRP
KL_MOD	T(5)	Type of model used	aMZPiMRP
AKT_BDOT	T(50)	Date of BDOT	aMZPiMRP
AKT_NMT	T(50)	Date of DTM	aMZPiMRP
UWAGI	T(254)	Notes	CONTRACTOR
MRP_RL_BP	T(50)	Name of flood risk map - potential adverse consequences on human life and health and the value of potential flood losses	aMZPiMRP
MRP_RS_BP	T(50)	Name of flood risk map - potential adverse consequences on the environment, cultural heritage and economic activity	aMZPiMRP

8. CARTOGRAPHIC VERSION OF FHMs AND FRMs

The cartographic versions of FHMs and FRMs for the scenario of dam failure are developed in the form of raster files, broken down into sheets corresponding to the sheets of topographic maps at a scale of 1:10 000, in EN-1992 rectangular flat coordinate system.

Such cartographic versions are prepared in the following formats:

- pdf (version with description outside the frame);
- geotiff (map content, without information outside the frame).

Cartographic versions of FHM and FRM are made for the following types of maps:

1) flood hazard maps in one thematic set:
   a) flood hazard map with water depth - presenting flood hazard areas with four water depth zones (with limit values of 0.5m; 2m; 4m);
2) flood risk maps in two thematic sets:
   a) flood risk map - potential adverse consequences for human life and health and the value of potential flood losses,
   b) flood risk map - potential adverse consequences for the environment, cultural heritage and economic activity.

A list of all types of cartographic versions of flood hazard maps and flood risk maps is presented in the table below (Table 5).

Table 5. Types of cartographic version of flood hazard maps and flood risk maps

No.	Map title	Name of file with cartographic version [map sheet id_ scenario_version]	Example
1	FLOOD HAZARD MAP WITH WATER DEPTH AREAS EXPOSED TO FLOODING IN THE EVENT OF DAM FAILURE	Map sheet id_ ZG_BP_reservoir_ version_file type. extention	N33060Aa1_ZG_BP_Besko _2022v1.pdf N33060Aa1_ZG_BP_Besko _2022v1_GEOTIFF.tif
2	FLOOD RISK MAP - POTENTIAL ADVERSE CONSEQUENCES FOR HUMAN LIFE AND HEALTH AND THE VALUE OF POTENTIAL FLOOD LOSSES AREAS EXPOSED TO FLOODING IN THE EVENT OF DAM FAILURE	Map sheet id_ RL_BP reservoir_ version_file type. extention	N33060Aa1_RL_BP_Besko _2022v1.pdf N33060Aa1_RL_BP_Besko _2022v1_GEOTIFF.tif
3	FLOOD RISK MAP - POTENTIAL ADVERSE CONSEQUENCES FOR THE ENVIRONMENT, CULTURAL HERITAGE AND ECONOMIC ACTIVITY AREAS EXPOSED TO FLOODING IN THE EVENT OF DAM FAILURE	Map sheet id_ RS_BP reservoir_ version_file type. extention	N33060Aa1_RS_BP_Besko _2022v1.pdf N33060Aa1_RS_BP_Besko _2022v1_ GEOTIFF.tif

A detailed description of all types of maps, including titles and file names, can be found in Annex no. 2: *Description of the cartographic version of flood hazard maps and flood risk maps for the scenario of dam failure*.

9. LIST OF ANNEXES

Annex no. 1. Attribute structure of the digital version of flood hazard maps and flood risk maps for areas exposed to flooding in the event of dam failure.

Annex no. 2. Description of the cartographic version of flood hazard maps and flood risk maps for the scenario of dam failure.

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