

Refining zoning of artificially-drained mine subsidence areas: relative elevation models and hydrological hazard frameworks as decision support tools for spatial planning and mitigation of flood-related geohazards and risks

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Abstract

The extraction of minerals is the main reason for the permanent maintenance of forced flows of surface and ground waters in mining areas. When natural water flows are restored the inundated areas most often may be many times larger than the existing ones. This requires rethinking of existing land use in artificially-drained mining areas by using tailor-made spatial planning policy to address future changes in water conditions. The main goal of this paper is to show that in such areas the current prevalent practice of classical hydrological modeling using the base flood translates into inadequacies in spatial planning policies. To accurately model the hydrological hazard in such areas, water equal to or greater than the 500-year flood as well as other flood-related geohazards and risks must be taken into consideration. The current practice and omissions can now be precisely updated and satisfied by the author's site-specific decision support tools, namely (1) hydrological hazard frameworks based on (2) relative elevation models. Regardless of the restoration of natural water flows, these tools conceptualize, simplify and optimize spatial planning and environmental policies for mitigation of flood-related geohazards and risks in artificially-drained mine subsidence areas and constitute the key research finding of this paper.

Keywords: Artificial Drainage, Decision Support Tool, Geohazards, Mining Impacts, Mitigation Strategies, Spatial Planning

Introduction

One of the effects of mineral extraction is artificial drainage of the environment. This is caused by transfer of water from underground and open-pit mines by means of pumping. After potential restoration of natural water flow, the resulting inundated areas will most often be many times larger than the existing ones. In hydrology, this qualitative transformation of the water environment is referred to as a hydrological hazard (HH) caused by surface and ground waters.

In artificially-drained mining areas (MAs), classical hydrological modelling usually assumes the existence of water facilities and at least partial drainage of the surface and rock mass by pumping. By definition, this means that most classical hydrological modeling does not take into account the real HH but only the flood risk, the scale of which is reduced due to artificial drainage.

This gap in hydrological practice translates into inadequacies in spatial planning policies in MAs under the HH and other flood-related geohazards and risks. These omissions can now be precisely addressed and filled by the author's recently published method and tools.

Data and Method

The detailed subject of this analysis may be a digital elevation models (DEM) of the MSA surface and/or a situational contour map that project the analyzed state of a surface relief (archival or current or forecasted). Additionally, the hydrogeological documentation of mineral deposits is analyzed.

The innovative relative elevation model method (REM method) of assessing and managing the HH in artificially-drained MSAs is used.

REM method differs from classical hydrological and hydraulic modeling by introducing six specific principles of hydrological hazard analyses and determinant hydrometric reference points that together define the totality of man-induced damage to the water environment at the assessed moment. These six principles are listed below:

- 1) The assumption that the subject matter of assessment and management of the HH and inundation is a single mine subsidence area (MSA) in which the mining-induced damage to the water environment can generally be attributed to a single responsible entity, regardless of the ongoing water regime;
- 2) A-priori assumption and subsequent simulation of the restoration of quasi-original water conditions (QOWCs) without taking into consideration any hydrotechnical drainage works by using the normal hydrometric reference point as a basis for REM to identify the totality of damage to the water environment;
- 3) A-priori assumption and subsequent simulation of the restoration of QOWCs while simultaneously taking into consideration all needed mitigation (hydrotechnical and reclamation) works in as many artificially-drained MBs as desired by using the conditional hydrometric reference point as a basis for REM in order to ultimately stop and/or reduce forced pumping;
- 4) The range of permanent inundation under normal water conditions is determined by the constancy of normal water surface levels in the lower sections of the watercourse beds above their outflows from the MSA (the hydrometric reference points are determinant factors for identification of permanent inundation inside the MSA);
- 5) A priori assumption of the worst-case flood scenario based on 500-year and/or greater flood wave culminations to determine occasional flooding (the hydrometric reference point are determinant factors for identification of occasional inundation inside the MSA.
- 6) A-priori assumption of the occurrence of other flood-related geohazard effects caused by mining, such as sinkhole subsidence, that may amplify each other (inside the MSA, *the hydrometric reference points* are determinant factors for identification all flood-related geohazards).

By the term mine subsidence area (MSA), the author understands those parts of the rock mass and the surface in the vicinity of exploited deposits, in particular those parts subject to continuous and discontinuous deformations, as currently legally defined in terms of range and intensity.

QOWCs denote the natural conditions after cessation of pumping, completion of groundwater rebound and the hypothetical restoration of the full hydraulic relationship between ground and surface waters after deactivation of all water facilities (e.g., breaking levies).

In separate catchment areas of the significant watercourses draining the MSA, catchment studies are carried out on their state and environmental changes by means of newly formulated water components of the MSA water environment. These catchment and MSA-specific components allow the identification of the dynamically changed, current, past and/or future characteristic water surface levels and ranges of inundation (hydrological hazard frameworks; HHFs) after restoration of QOWCs in mining-disturbed surface relief areas (Figure 1). Due to these six principles, most of the method's components of the MSA water environment are innovative and modeled in specific ways, even though its terminology seems

to be typical in hydrology (Ignacy, 2019, 2021). They are discussed below and shown in figures.

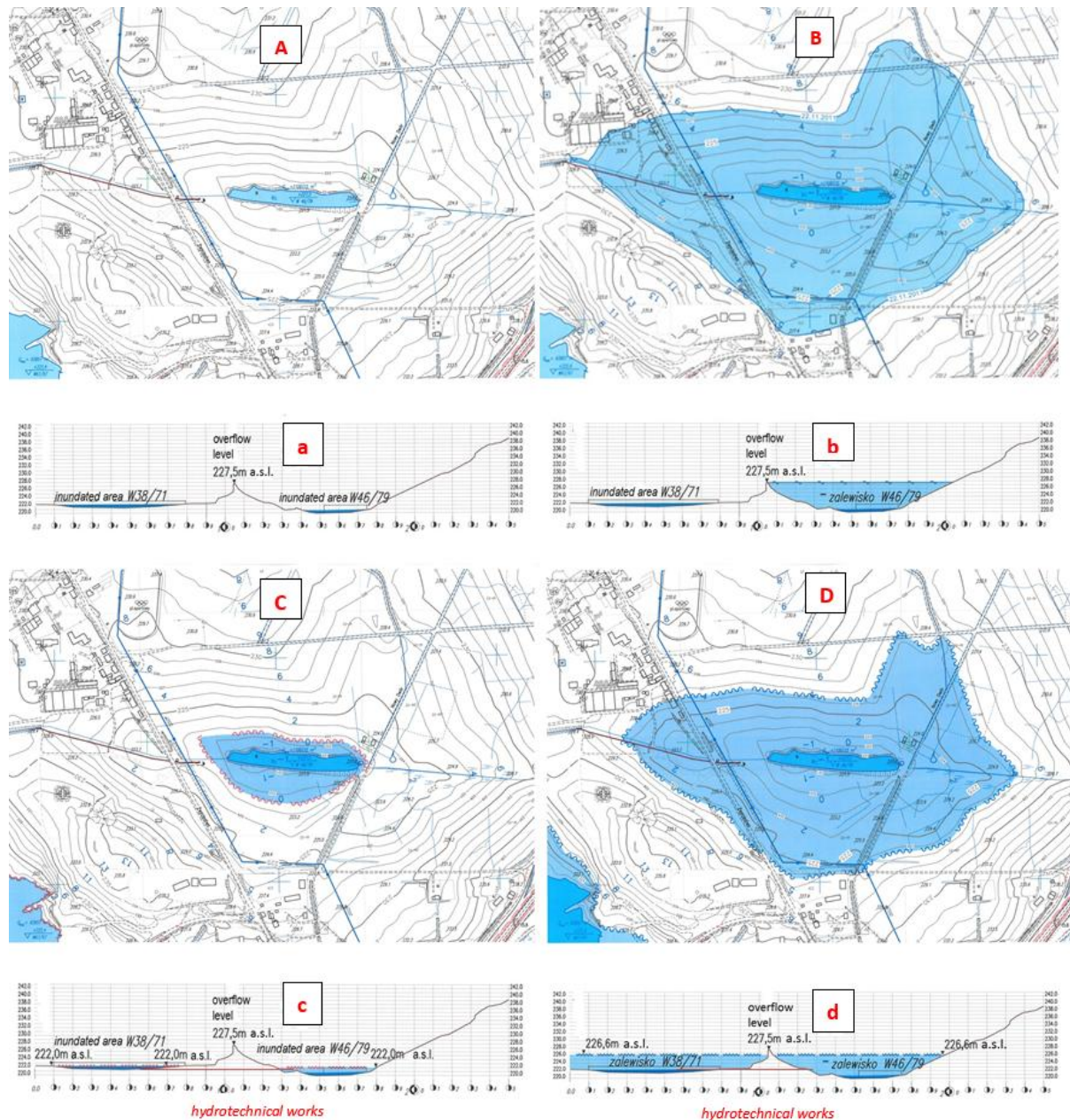


Fig. 1. Spatial schematic diagram of four site-specific hydrological hazard frameworks (levels/ranges of inundation) identified in each artificially-drained morphological basins as of 2011 – case study of the Krywaldzki stream basin in the “Szczygłowice” MSA (50°12'03"N 18°38'50"E); Legend: catchment-specific hydrological hazard frameworks: A, a – the existing inundated area under artificial drainage; B, b – the boundary of artificially-drained area or the closed basin lake C, c – the boundary of potential backwater (after pumping closure and carrying out intended hydrotechnical works required for limiting the extent of the hydrological hazard); D, d – the boundary of extreme flood water level (after carrying out intended hydrotechnical works required for limiting the extent of the hydrological hazard); blue numbers on maps – relative elevation models of the MSA surface; 222.0m a.s.l. – elevation of normal hydrometric reference point; 226.6m a.s.l. – elevation of the extreme flood water level.

The most significant and innovative concept of REM method is the hydrometric reference point. This is located at the intersection of MSA boundary and the axis of the significant

watercourse draining the MSA (Fig.2). On the MSA boundary, there is usually no subsidence. Therefore, such hydrometric reference points can become determinant factors for identifying catchment-specific permanent and occasional inundations inside MSA.

The key innovation of the REM method is the adoption of hydrometric reference points, either normal (designation “ZN 222.0” in Fig. 2) or conditional, as the base-level for catchment-specific digital elevation models (DEMs) named by the author as relative elevation models (REMs; brown contour lines and numbers in Fig. 2) of the MSA surfaces. This makes possible time-dependent and flood-related modeling of the water environment of separate catchments inside the MSA. After restoration of QOWCs and completion of hydrotechnical works, negative relative elevations of the appropriately determined REMs directly indicate the depth of potential future reservoirs (designation “-1” in the upper right corner of Fig. 2).

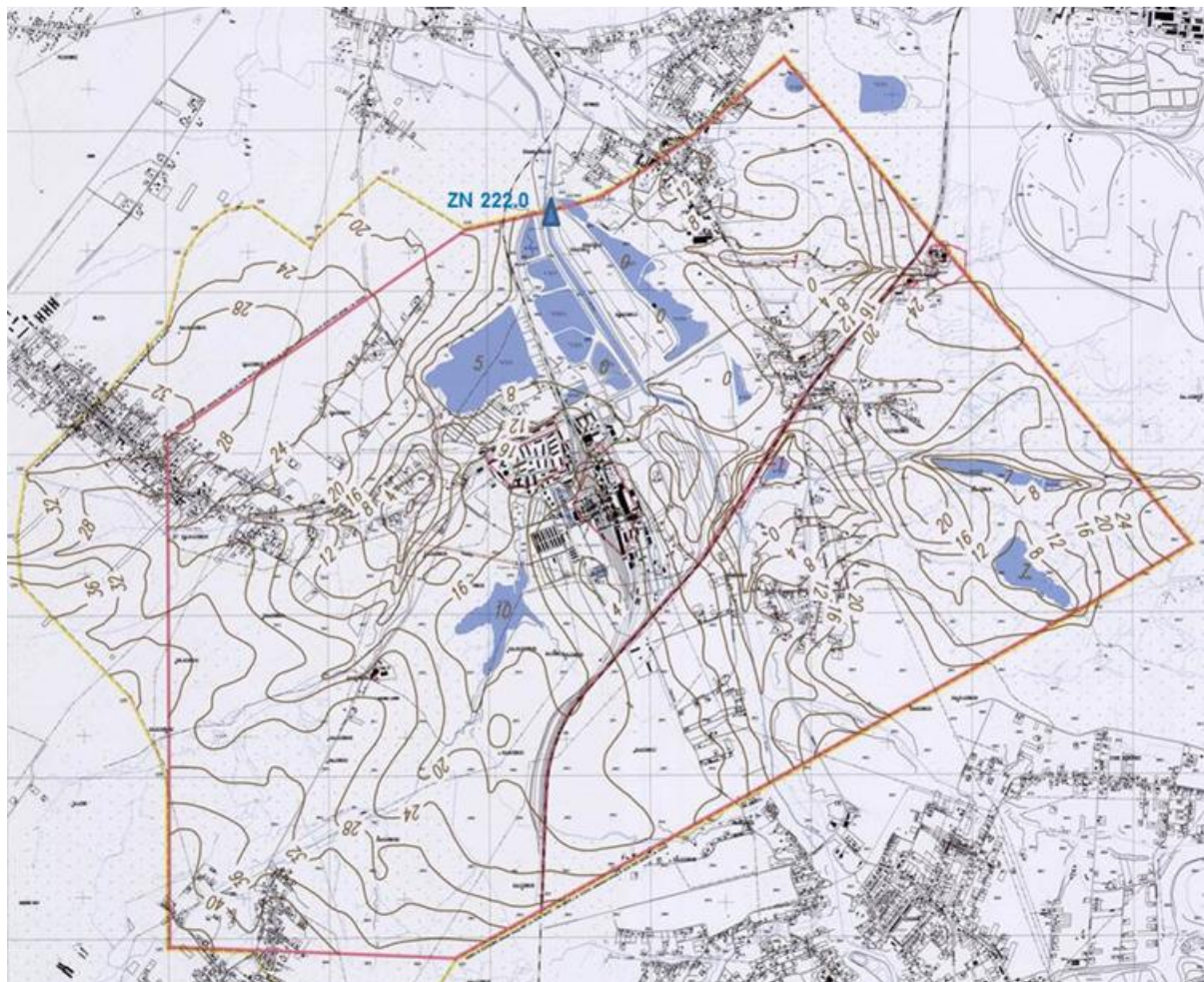


Fig. 2. Relative elevation model of the “Szczygłowice” MSA as of 2009 (50°12'03"N 18°38'56"E); Legend: brown numbers and contour lines – relative elevation models of the MSA surface; ZN 222.0 – the normal hydrometric reference point; blue color – existing inundated areas.

In the REM method, a four-level scale is proposed for zoning MSAs (Fig. 3). HHFs projected on a spatial hydromorphological map of the MSA most often become the boundaries of HH categories of mining areas. The highest Category IV HH refers to permanent flooding of MSAs (designation No. 9 in Fig. 3). The lowest Category I HH refers to mining areas in which there were no or only insignificant transformations of the water environment (designations No. 11 in Fig. 3).

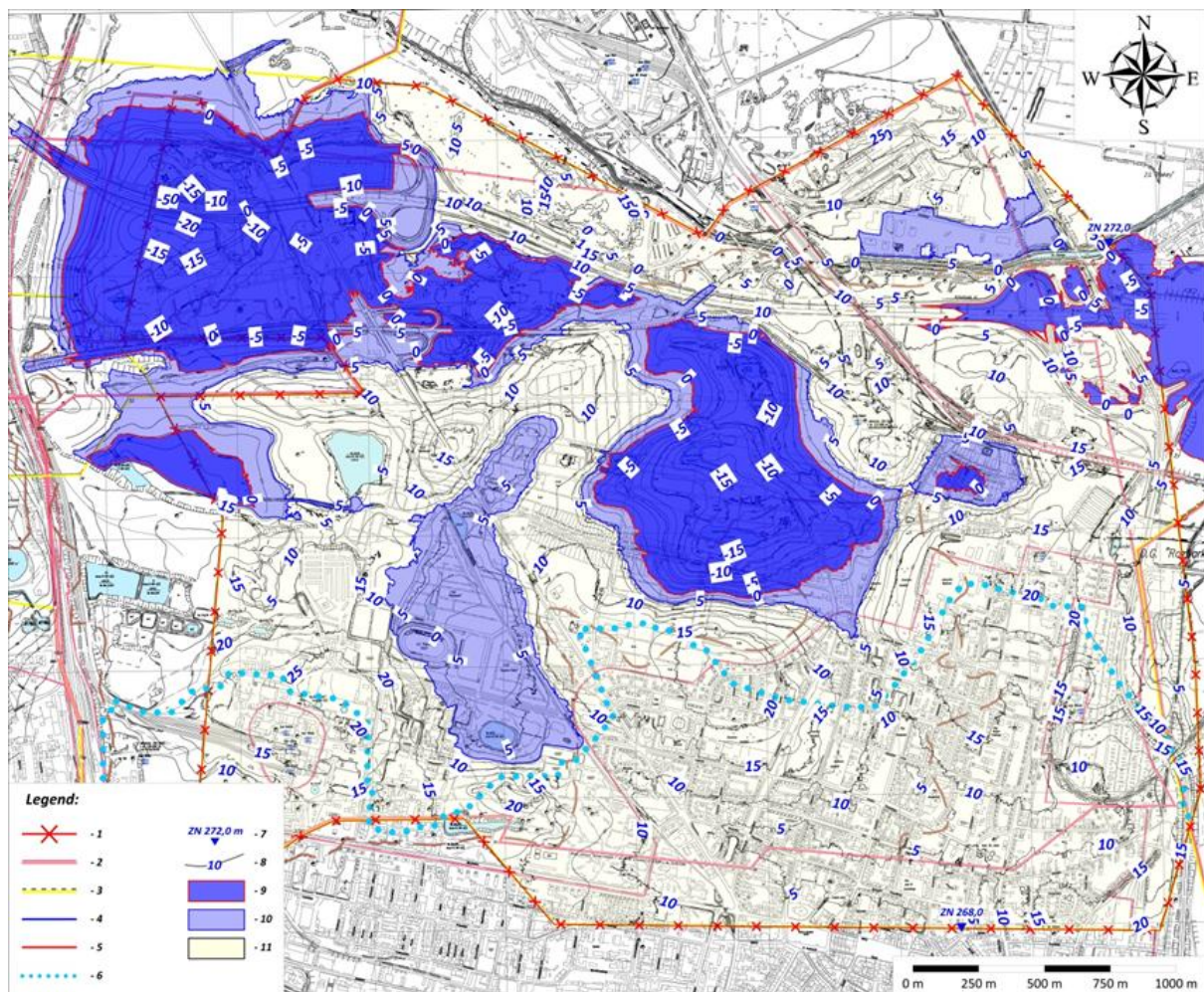


Fig. 3. Spatial hydromorphological map of a fragment of the "Bytom-Centrum I" mine subsidence area as of 2020 (50°22'19" N 18°53'18" E) indicating extremely negative (-22m) relative elevations of its surface; Legend: 1 - boundary of the closed-down part of the mine subsidence area, 2 - the boundary of mining area, 3 - the boundary of mine subsidence area, 4 – the closed basin lake, 5 – the boundary of potential backwater, 6 – the watershed, 7 – ZN 272.0 m a.s.l. - the normal hydrometric reference point, 8 – relative elevations of the mine subsidence area surface (above hydrometric reference point), 9 - mining areas under Category IV hydrological hazard, 10 - mining areas under Category II hydrological hazard, 11 - mining areas under Category I hydrological hazard.

Results

Comparison of time-dated spatial hydromorphological maps of the MSA (Fig. 3 and Fig. 4) indicating time-oriented REMs and HHFs allows evaluation of the different attributes of potential reservoirs (e.g., increases in ranges, depths and categories of the HH), caused by the activities of respective entities.

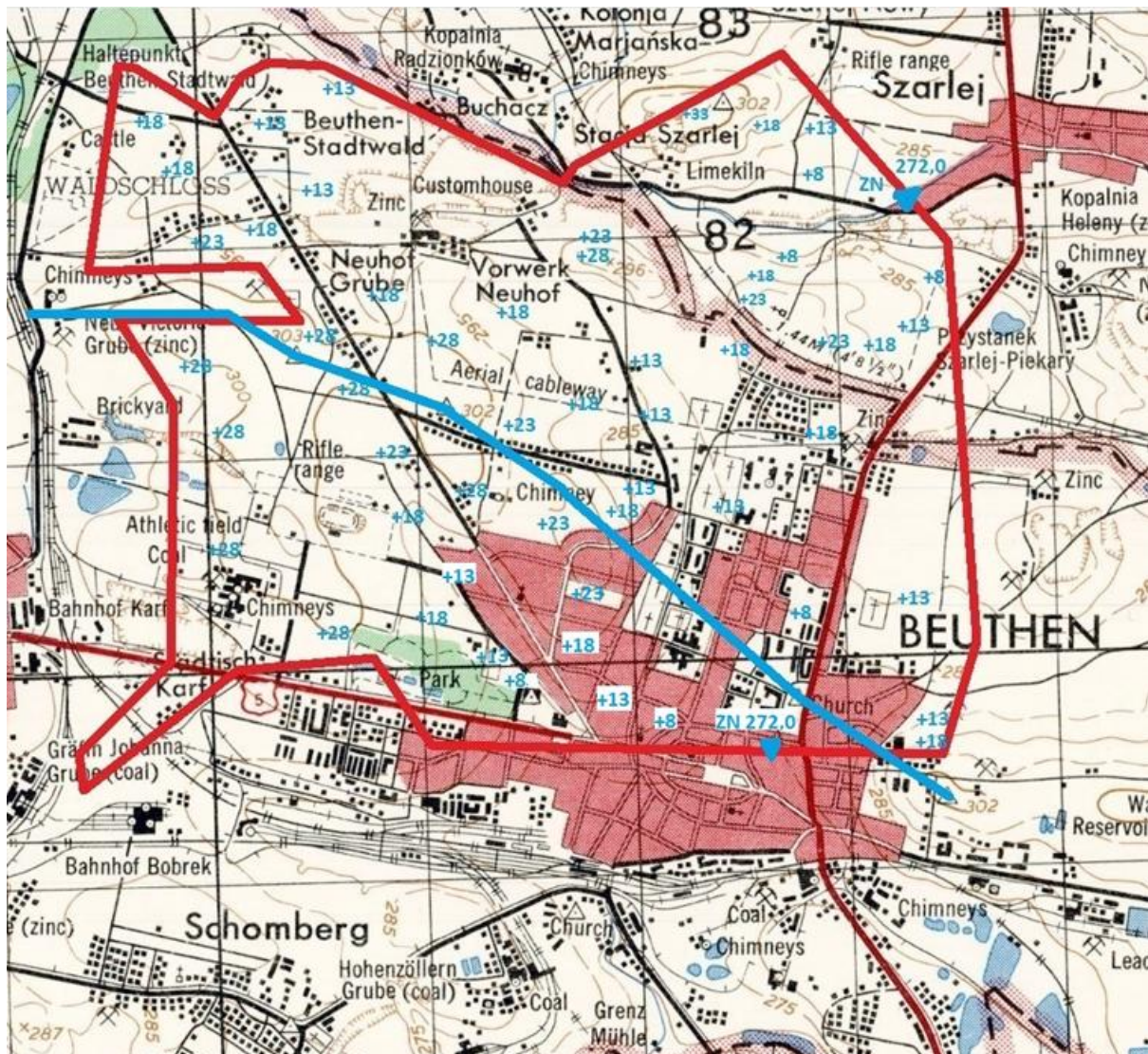


Fig. 4. Spatial hydromorphological map of the "Bytom-Centrum I" mine subsidence area as of 1939 (50°22'19" N 18°53'18" E; prepared by Corps of Engineers of US Army) indicating large positive values (+28) of relative elevations of its surface and absence of areas threatened by flooding; Legend: red line – boundary of the closed-down part of the mine subsidence area; blue line – the watershed; ZN 272,0 – the normal hydrometric reference point; +18 (blue numbers) – relative elevation of the mine subsidence area surface (above the hydrometric reference point).

In mining and post-mining areas, the HH is the result of restoration of natural water flows during the process of mine closures. It is up to policy makers to determine the desirability and feasibility of the restoration of free flows of water based on perceived socio-economic and environmental needs. Currently, urban development of areas under the HH is now permissible because today's planning procedures rarely if ever acknowledge the possibility of future restoration of free water flows in such areas.

In the Polish Upper Silesian Coal Basin, due to the lack and/or rarity of consideration of the real HH in MSAs, more and more land threatened by flooding is still being developed. Therefore, more and more surface structures and facilities are and will remain under the HH and other flood-related geohazards and risks (Fig. 5). There are many reasons for the above (Ignacy, 2024, 2025).

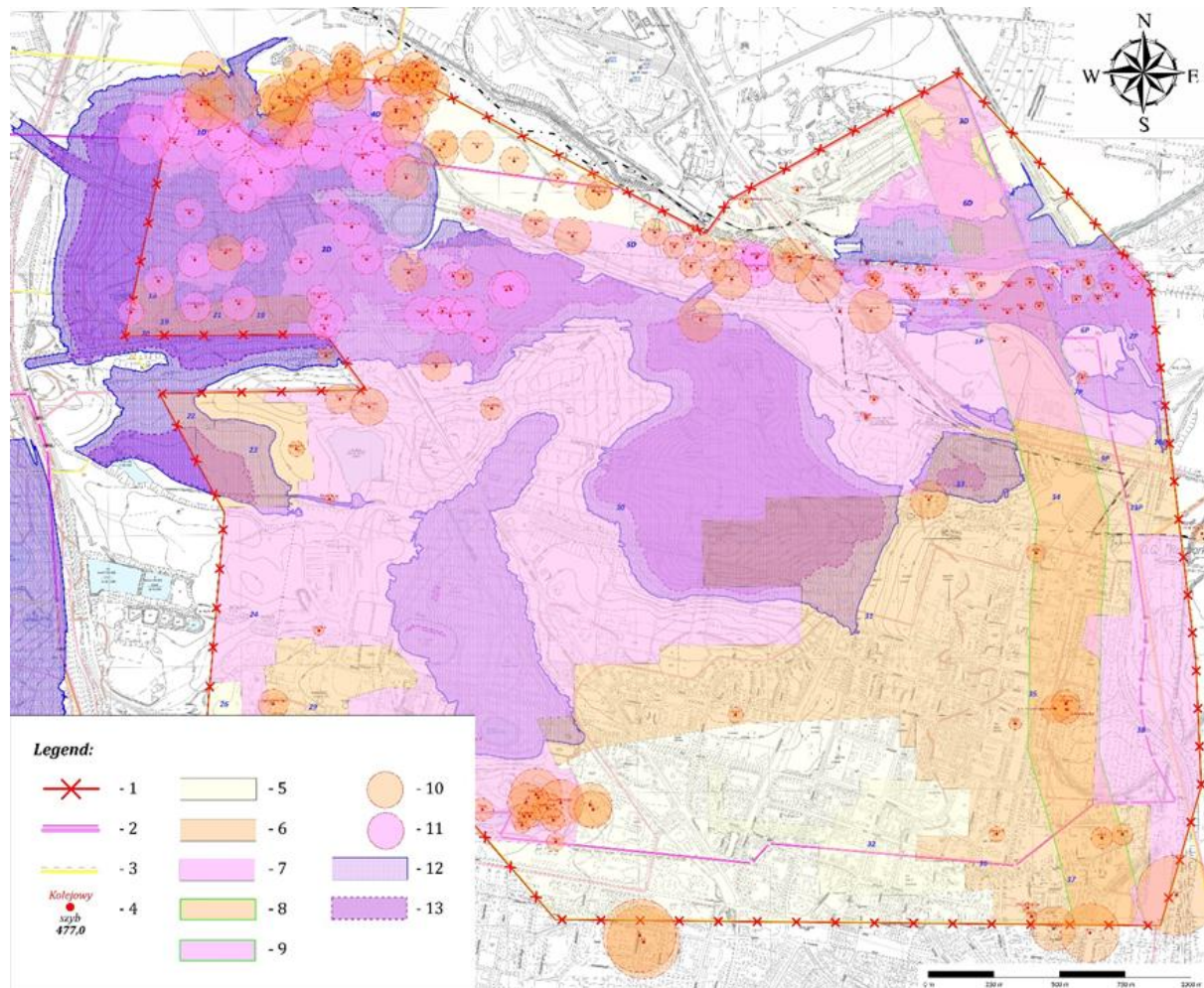


Fig. 5. Map of the suitability of land for development for the “Bytom – Centrum I” mine subsidence area (50°22'19" N 18°53'18" E) plotted based on the expert report prepared by the Central Mining Institute in 2020 (Ignacy & Gruchlik, 2021). Legend: 1 – boundary of the part of the mine subsidence area currently being closed, 2 – boundary of the mining area, 3 – boundary of the MSA, 4 – mine shaft connected to the surface, 5 – area transformed to a low degree, suitable for development, 6 – transformed area, conditionally suitable for development, under medium threat of sinkholes due to previous shallow mining exploitation, 7 – transformed area, conditionally suitable for development, under high threat of sinkholes due to previous shallow mining exploitation, 8 – land conditionally suitable for development, characterized by gas hazard due to a tectonic fault, 9 – area conditionally suitable for development, under high threat of sinkholes due to a tectonic fault, 10 – area conditionally suitable for development, under medium threat of sinkholes due to a mine shaft, 11 – area conditionally suitable for development, under high threat of sinkholes due to a mine shaft, 12 – land conditionally suitable for development, threatened by flooding, 13 – land unsuitable for development, threatened by flooding.

Conclusion

- 1) The key research finding addressed by this paper is recognition of site-specific REMs and HHFs of MSA surfaces (the main elements of the REM method) as the so far hitherto missing dedicated tools for hydrology, hydrogeology, civil engineering and spatial planning policy.
- 2) To eliminate and/or reduce perpetual water pumping and flood-related geohazards and risks, environmentally sustainable spatial planning policy in mining and post-mining areas

should include management of the HH and the associated flood-related geohazards and risks through the use of these decision support tools.

- 3) The maps resulting from the REM method, named as spatial hydromorphological maps of MSAs, should become a main element of municipal physical environment plans. Their content (REMs and HHFs) gives policy makers and mining entities the ability to a priori assess the necessity and desirability of any hydrotechnical and mitigation works taking into account subsidence, flood-related geohazards and risks and the requirements of land use revisions in mining and post-mining areas.

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