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GIS-Based Identification of Hazardous Industrial Facilities as Potential Sources of Flood-Induced Water Contamination in the Drohobych District of Ukraine

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Abstract. Oil refining, oil and gas extraction, mining, chemical production, and waste disposal have left petroleum sludge, mineralized brines, and unlined waste bodies in the Drohobych District of Ukraine, where floodwater can carry them into receiving rivers. None of the 7 watercourses in the district that are at potentially significant flood risk have published flood hazard maps. This study identifies and ranks the industrial facilities that are potential sources of flood-induced water contamination. An inventory of 142 point features (59 industrial and municipal facilities and 83 burial sites) was compiled from state register and topographic sources, located on satellite imagery and screened for release potential. A network derived from a 90 m digital elevation model was validated against official watercourse data and combined with ring buffers. A total of 6 industrial and municipal facilities, 4 of them oil and gas, lie within 100 m of a derived channel. Their number stays between 5 and 7 when the channel threshold is changed by a factor of 4 or the 30 m Copernicus GLO-30 model is used. The upper sub-catchment contains 26 of the 57 industrial and municipal facilities within the delineated catchments but covers only 17.6 % of the area. Oil and gas facilities occur there 3 times as often as expected for the area, and waste disposal sites 4.7 times as often. Priority attention is recommended for 9 objects. The results give a reproducible basis for engineering protection and for selecting facilities for national flood risk maps.

Keywords: civil protection, emergency, environmental safety, geoinformation analysis, sustainable cities.

1 Introduction

Floods act on industrial territories in a way that differs greatly from their action on residential or agricultural land. Beyond the direct destruction of structures, floodwater stirs up contaminated sediment, erodes contaminated soils, alters the geochemical conditions that keep pollutants in a fixed form, and breaches the containment of storage units. A recent synthesis of the mechanisms involved shows that metals and persistent organic pollutants migrate mainly with the sediment phase, while more soluble compounds travel in the dissolved phase. A single flood event therefore redistributes a contaminant load accumulated over decades [1]. An industrial site that poses an acceptable and locally contained risk under normal conditions thus becomes a distributed source of contamination for the entire downstream reach.

Accidents of this kind are recognized internationally as natech, denoting technological accidents triggered by natural hazards. An analysis of 272 documented flood-triggered events showed that the release of hazardous substances, rather than fire or explosion, is the dominant consequence, and that storage tanks and pipework are the units most frequently damaged [2].

Subsequent statistical work confirmed that such events form a systematic rather than an exceptional class of industrial accident [3].

Therefore, the exposure of industrial facilities to flooding should be assessed explicitly and separately from the exposure of the population and the building stock.

The regulatory framework for flood risk management in Ukraine derives from Directive 2007/60/EC on the assessment and management of flood risks [4], implemented through the Water Code of Ukraine [5] and subordinate legislation governing flood risk management plans [6]. Under the plan approved for the Dniester River basin district, 103 areas of potentially significant flood risk with a combined length of 4303 km have been designated. Of these, 7 are watercourses of the Drohobych District, namely the Bystrytsia over 81 km, the Kolodnytsia over 45 km, the Tysmenytsia over 42 km, the Trudnytsia over 33 km, the Bar over 32 km, the Solonytsia over 21 km and the Skhidnytsia over 12 km [7]. The same plan assigns to the State Emergency Service of Ukraine the development and refinement of 1236 flood hazard and flood risk maps for the district by November 2028. The atlases of large-scale flood hazard maps published to date cover the Opir, the Bystrytsia-Solotvynska, the Bystrytsia-Nadvirnianska, the Bystrytsia of the Ivano-Frankivsk region, the Kuchurhan and the Dniester delta, and none of these sections lies within the Drohobych District [8]. The Bystrytsia in the published atlases is not the Bystrytsia-Pidbuzka of the study area.

Directive 2012/18/EU on the control of major-accident hazards requires natural hazards to be taken into account as potential triggers of major accidents [9]. The national methodology for developing flood hazard and flood risk maps correspondingly requires that flood risk maps depict facilities that can cause accidental pollution in the event of inundation [10]. The selection criterion applied in that methodology, however, is the activity's environmental impact assessment category rather than the threshold quantities of dangerous substances set out in Annex I to Directive 2012/18/EU. Tailings storage facilities at abandoned mining enterprises and legacy oil sludge impoundments are not classified as planned activities and therefore fall outside the mandatory inventory, even though they contain large quantities of hazardous material.

A toolkit algorithm for identifying hazardous areas during flooding, based on watershed modeling within a geographic information system, was proposed in earlier work by the present authors [11]. That algorithm delivers a qualitative inventory of potentially affected sites at the level of administrative units. It does not quantify the proximity of individual facilities to the watercourses; it does not characterize the hazardous substances accumulated at those facilities, and it does not rank them by the magnitude of the release that inundation would cause. The present study addresses these 3 limitations.

The objective of this study is to identify and rank the industrial facilities that are potential sources of water contamination during river flooding in the Drohobych District.

The study applies a geoinformation analysis of the proximity between a purpose-built inventory of 142 point features and the hydrographic network derived from a digital elevation model. On this basis, it establishes the order of priority for engineering protection measures.

2 Literature Review

The methodological basis for the quantitative treatment of flood-triggered industrial releases has been developed over the past 15 years. The risk management research on natech events associated with hydrometeorological hazards has been surveyed systematically [12]. The coupling of hazard characterization with equipment-specific vulnerability remains the principal open problem in the field, since the vulnerability models available in the literature are limited to atmospheric storage tanks and pressurized vessels. Vulnerability models for the flood loading of atmospheric storage tanks relate the probability of loss of containment to flow depth and velocity, as well as to vessel geometry and filling level [13]. These models have been embedded in a comprehensive quantitative procedure for assessing risk from natech scenarios caused by floods [14]. A mapping framework that automates the assessment and cartographic presentation of natech risk has also been operationalized [15]. The common prerequisite of all these approaches is a hydraulic model that supplies inundation depths and velocities, which is precisely the input unavailable for territories where flood hazard maps have not yet been produced.

For the categories of facilities present in the study area, the environmental consequences of inundation have been documented individually. A comprehensive review of tailings storage facilities records 257 failures since 1915 with a combined release of about $250 \cdot 10^6$ m^3 of tailings. It attributes them to earthquakes, overtopping, weak foundations, and liquefaction, among other mechanisms, and finds that the severity and volume of failures have increased since the year 2000 [16]. A global-scale impact analysis of mine tailings dam failures over the period 1915–2020 confirms that such collapses are a systemic rather than an isolated phenomenon [17]. Physical and numerical modeling of a tailings dam failure, specifically under flooding conditions, reproduces the breach geometry and the post-failure spreading of the released material, and shows that the flood and the breach reinforce one another [18]. The environmental consequences of flooding of closed mine workings, including the rise of mineralized water and associated surface deformation, have been analyzed by combining satellite interferometry with geospatial analysis [19]. For potash deposits in particular, isotope investigations in the area of the Dombrovsky quarry of the Kalush-Holyn deposit in Ukraine established a hydraulic connection between potash tailings and the neighboring surface waters. This is directly relevant to the Precarpathian potash province to which the study area belongs [20].

For municipal solid waste landfills, a systematic review of leachate impacts on surface water and groundwater documents accelerated contaminant migration during flooding of the waste body [21]. A Ukrainian study developed an approach to sizing the sanitary protection zone of a municipal landfill based on measured environmental hazards rather than a fixed legal distance [22].

The flood vulnerability of landfills has been assessed by coupling hydrological and hydraulic modeling with climate-adjusted precipitation, which shows that landfills sited in floodplains retain residual release potential long after waste acceptance ends [23]. For petroleum infrastructure, the characterization of ground oily sludge shows oil content at levels an order of magnitude above regulatory limits, along with barium, zinc, chromium, arsenic, nickel, mercury, and carcinogenic aromatic compounds. This defines the contaminant spectrum that would be released by inundation of a sludge impoundment [24]. Long-term monitoring conducted between 2007 and 2016 in the central part of the Boryslav-Pokuttia oil and gas bearing area showed that the mean concentration of petroleum products in the humus-eluviated horizon declined by a factor of 2.7 within 18 months after drilling stopped and by more than a factor of 4 within 30 months. The decline in the underlying eluvial-humus horizon was slower, because contaminants continued to migrate downward from the horizons above. The highest concentrations were recorded in the transsuperaqual landscape positions, that is, in the low-lying ground beyond the drilling pads themselves [25]. Attenuation at the surface therefore proceeds faster than the removal of the contaminant from the soil profile as a whole, so that a residual pool remains in the low-lying ground that floodwater occupies first.

The state of the Precarpathian hydrosphere within the study area has been investigated using geophysical methods for civil protection purposes [26]. A retrospective analysis of flood frequency ranked the territorial communities of the Lviv region and identified the Boryslav community as having the highest documented flood frequency in the Drohobych District [27]. The repeating pattern of catastrophic floods in western Ukraine has been examined separately, and recurrence intervals for destructive events of approximately 6, 12, and 19 years have been proposed [28].

This body of work leaves 2 gaps. First, the quantitative natech methodologies require hydraulic inputs that do not exist for territories without flood hazard maps, and no intermediate procedure has been proposed for the screening stage that necessarily precedes them. Second, the environmental characterization of the individual facility categories has been carried out in isolation, without an integrated spatial inventory that places facilities across all categories within a common frame of reference relative to the receiving watercourses. The present study addresses the screening stage for territories without flood hazard maps. It constructs such an inventory and ranks its elements based on proximity to the hydrographic network and the quantity and nature of the hazardous material held.

3 Research Methodology

3.1 Study area

The Drohobych District of the Lviv region occupies 1493.4 km^2 in the central part of the Carpathian Foredeep, on the boundary between the East European Platform and the Carpathian geosynclinal zone. The relief is a rolling plain sloping towards the Dniester, with a marked increase in valley cutting towards the mountain front. The landscape is formed by a multilevel system of river terraces developed during the Pleistocene through successive valley cutting. This structure is confirmed by the geomorphological reconstruction of the Bystrytsia-Pidbuzka valley, which belongs to the hydrographic network of the study area [29]. The widest and lowest-lying terraces align with the floodplains and host the most intensive economic development.

The district extends roughly between 49.03° N and 49.55° N and between 23.10° E and 23.81° E and consists of 5 territorial communities, namely Drohobych, Boryslav, Truskavets, Skhidnytsia, and Medenychi. The district's position in Ukraine, the administrative boundaries of the communities, the principal settlements, and the coordinate grid in the WGS 84 geographic system are shown in Figure 1.

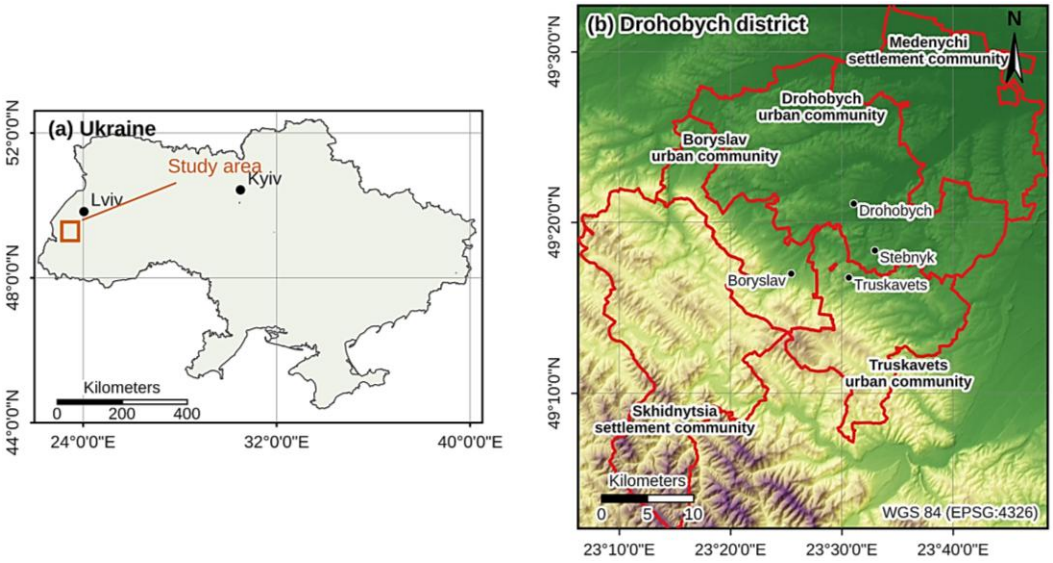


Figure 1 – Location of the Drohobych District in Ukraine (a) and its communities on the relief (b)

The climate is moderately continental. Annual precipitation is of the order of 750 mm on the foothill plain and rises above 800 mm in the mountainous southern part of the district under the barrier effect of the Carpathians. The hydrographic network is dense and belongs to the Black Sea basin, the principal watercourses being the Tysmenytsia, the Bystrytsia, the Stryi and the Svicha. Under Ukraine's approved hydrographic and water management zoning, the territory belongs to the upper Dniester sub-basin [30]. The combination of foothill relief, high precipitation, and a dense channel network produces rapid runoff concentration and frequent inundation of the low terraces. The district has undergone more than 6 centuries of varied industrial development, resulting in the concentration of oil refining, oil and gas extraction, mining, chemical production, and municipal waste disposal within a limited area.

3.2 Workflow of the study

The workflow consists of 4 blocks (Figure 2).

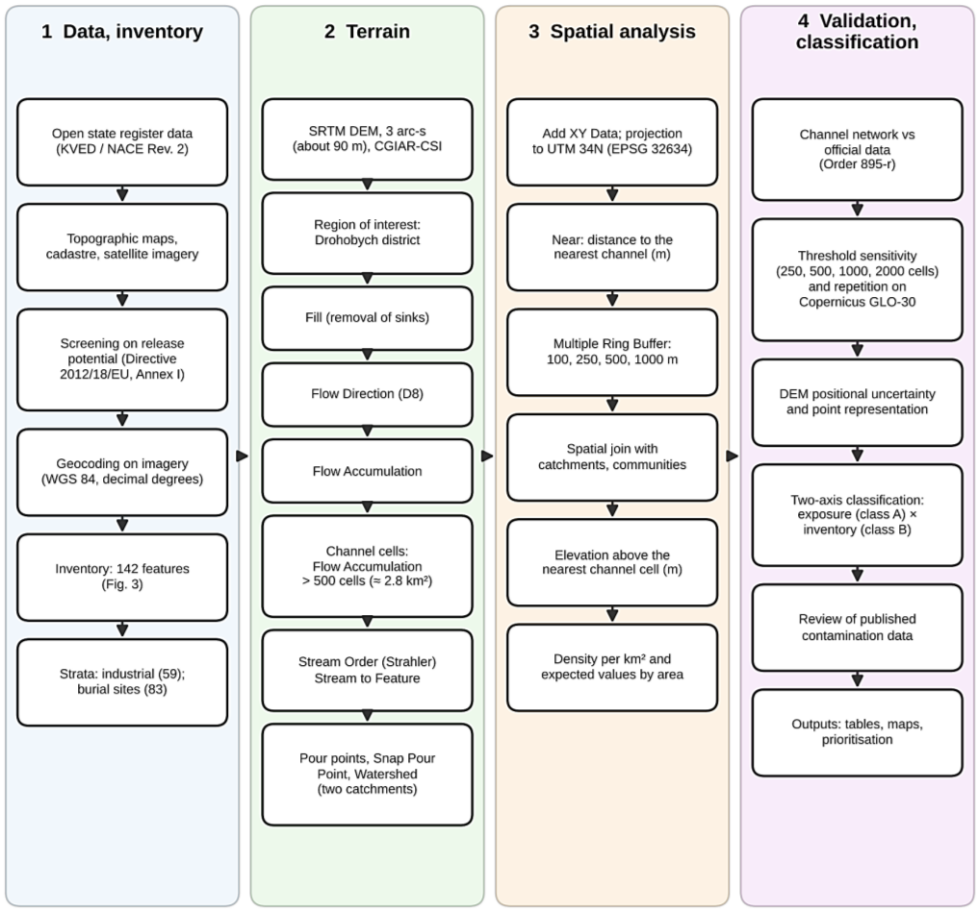


Figure 2 – Flowchart of the methodology of the study

The first block covers the compilation, the geocoding, and the screening of the inventory of pollution sources. The second block derives the hydrographic network and the catchments from the digital elevation model. The third block combines the two through analyses of proximity, buffer, containment, and elevation. The fourth block checks the derived network against the official data, tests the sensitivity of the results to the channel threshold, evaluates the effect of position error in the point representation, and classifies the facilities.

3.3 Compilation of the inventory of pollution sources

Facilities were classified by the type of economic activity and by the class of the object. The classification framework is set out in Annex I to Directive 2012/18/EU. It defines the categories of substances whose release is relevant to the contamination of surface water, namely petroleum products, substances hazardous to the aquatic environment in categories E1 and E2, liquid chlorine and anhydrous ammonia. An activity or an object class was retained where its normal operation implies the handling, the processing or the long-term accumulation of a substance belonging to one of those categories. The criterion was applied uniformly to every element of the inventory, so that the composition of the inventory is reproducible from the activity codes and the object classes reported below without recourse to any further information. The inventory was compiled through 2 independent data streams. The first is the state register of economic entities, filtered on activity codes. Its elements

carry an activity code and were assigned to a thematic layer by the code group given below.

The second covers objects that are not registered as economic entities and therefore cannot be retrieved by such a query, although their inundation releases contaminants of comparable environmental significance. Its elements were assigned to a thematic layer based on the object's class. The complete selection procedure, with the number of records at every step, is presented in Figure 3.

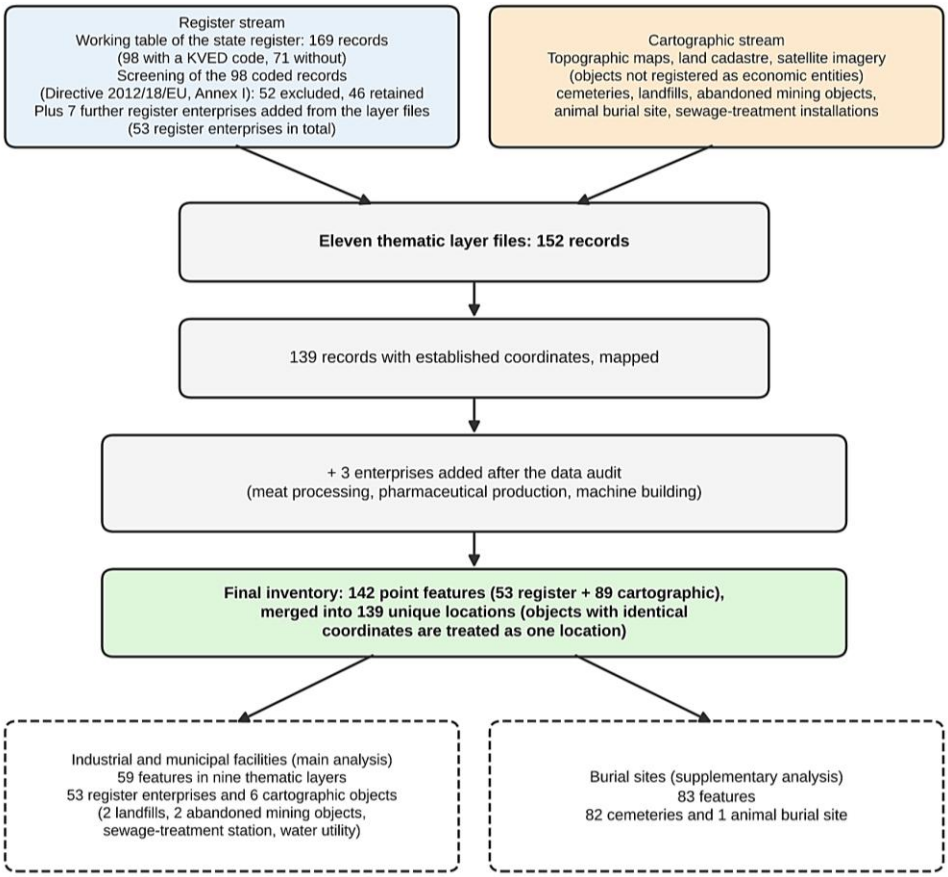


Figure 3 – Selection of pollution sources for the inventory with the number of records at each step

The first data stream drew on open state register data aggregated through the Opendatabot platform, from which the extract was taken in May and June 2026. The working extract consists of 169 records, of which 98 carry an assigned activity code. Activities are coded according to the national classifier of economic activities of Ukraine, denoted KVED, which is the national implementation of the European statistical classification NACE Rev. 2. The 2nd classifications are identical down to the 4-digit class, so that every code reported here is directly interpretable as its NACE Rev. 2 counterpart without conversion.

Codes were retained where the associated activity implies the storage or processing of substances that can release contaminants into a water body upon inundation. The retained codes, their NACE Rev. 2 designations, and the release mechanism for each group are listed in Table 1.

Placing the objects on the map followed. In addition to the type of economic activity, the geographic coordinates of each facility were the defining parameter. The registered legal address of an enterprise does not always coincide with its physical location, and the registered address was accordingly not accepted as a location. Every facility was located visually on satellite imagery from digital mapping services, and the coordinates were read at the facility's position on the imagery. Coordinates were recorded in decimal degrees in the WGS 84 geographic coordinate system with 5 to 8 decimal places. Each facility is represented by 1 point on its territory, and for extended objects, such as waste bodies and tailings storage facilities, the point is placed at the object's center. All distances reported below are measured from that point.

An object of area A is equivalent to a circle of the following radius $r = \sqrt{A/\pi}$. For the landfills of A = 3.0 ha and A = 3.48 ha considered below, this radius is about r = 100 m, and it does not change the distance class of either of them. The extended objects are ranked in this study by the amount of material they hold, not by the point distance alone.

Screening on contaminant-release potential was then applied. The question posed of every record was whether the site holds or processes a quantity of a substance capable of contaminating a river reach under inundation. In total, 52 records were removed. They comprised 45 holdings of crop and livestock farming (code 01), 1 logging company (code 02.20), 2 freshwater aquaculture

units (code 03.22), 2 manufacturers of wood products (code 16.29) and 2 road freight operators (code 49.41).

The release potential of these activities is negligible at the scale of a river reach, so that their retention would have diluted the inventory without adding contamination sources. Where the registered code differed from an enterprise's actual activity, the retention decision was based on the registered code.

Table 1 – Activity codes retained in the inventory and their release mechanisms under inundation

Code(s)	Designation under NACE Rev. 2	Release mechanism under inundation
06.10, 06.20	Extraction of crude petroleum and of natural gas	Displacement of hydrocarbons through legacy wells under elevated groundwater pressure and washout of sludge impoundments
09.10	Support activities for petroleum and natural gas extraction	Washout of stores of drilling fluids, reagents and recovered oil
08.12	Operation of gravel and sand pits and mining of clays and kaolin	Capture of the excavation by the flood wave and mobilization of suspended sediment into the channel
08.91	Mining of chemical and fertilizer minerals	Erosion of tailings embankments, entry of highly mineralized brines into the channel network and activation of karst collapse
19.20	Manufacture of refined petroleum products	Loss of containment of storage tanks and washout of oil sludge impoundments
20.11, 20.30, 20.59	Manufacture of industrial gases, of paints and varnishes and of other chemical products	Entry of insoluble toxicants into the water, washout of heavy metals contained in pigments and leaching of volatile organic compounds
21.20	Manufacture of pharmaceutical preparations	Release of active pharmaceutical ingredients and of solvent residues into the receiving water
22.21	Manufacture of plastic plates, sheets, tubes and profiles	Leaching of phthalates and of lead- and cadmium-based stabilizers from polymer products
25.21, 25.62, 25.91, 28.11	Manufacture of fabricated metal products and of machinery and equipment	Inundation of electroplating shops, washout of cutting fluids and galvanic sludge and surge release of chromium, zinc and nickel
10.11	Processing and preserving of meat	Entry of organic effluent with a high biochemical oxygen demand and of pathogenic microorganisms
36.00	Water collection, treatment and supply	Contamination of the intake and of the treatment line and loss of the potable supply of the settlement
37.00	Sewerage	Reverse discharge of untreated municipal wastewater into the channel network
38.11, 38.21, 38.32	Waste collection, treatment and disposal and recovery of sorted materials	Total washout of leachate from the waste body

The distance of a facility from a watercourse is not a criterion for inclusion in the inventory. Were it used as one, the inventory would contain only facilities situated close to a channel, and the finding that the facilities lie close to water would follow from the selection rule rather than from the territory itself. Facilities remote from the channel network are therefore retained in the inventory and appear in the corresponding distance band of the results.

The second data stream drew on topographic maps, the land cadastre, and satellite imagery, yielding 89 mapped features. Cemeteries and animal burial sites are not registered as economic entities and, consequently, cannot be retrieved from the register under any activity code. They were included because their inundation releases products of organic decomposition, pathogenic microorganisms and, in the case of animal burial sites, biological material of the highest hazard class. Cemeteries are the largest group in the inventory, comprising 82 of 142 features (57.7 %), and their release mechanism differs from that of industrial facilities. The results are therefore reported for the whole inventory and, separately, for the 59 industrial and municipal facilities that remain when the 83 burial sites are set aside. In this way, the effect of the cemeteries on every conclusion can be judged. The same data stream supplied the municipal solid waste landfills, the abandoned mining sites of the Boryslav ozokerite deposit and the Stebnyk mine No. 2. It also supplied the sewage treatment and water intake installations that operate without a separate legal identity.

The final inventory consists of 142 point features distributed across 11 thematic layers: cemeteries; oil and gas; chemicals and fertilizers; waste disposal sites; water supply and sewerage; extractive industry, including abandoned workings; meat processing; metallurgy; plastics and packaging; salt and minerals; and animal burial sites. The thematic layer files contained 152 records, of which 139 had established coordinates and were mapped, and 3 enterprises were added after a data audit, giving 142 point features (Figure 3). Of these, 53 come from the register stream and 89 from the cartographic stream.

2 objects occupy each of 3 locations with identical coordinates. Separating objects that occupy the same location adds no spatial information, so such objects were

treated as a single location, reducing the 142 point features to 139 unique locations. Of the 142 features, 59 are industrial and municipal facilities, namely 53 enterprises in the register stream and 6 objects in the cartographic stream (2 landfills, 2 abandoned mining sites, 1 sewage treatment station, and 1 water utility). The other 83 are burial sites, namely 82 cemeteries and 1 animal burial site.

The division of the unified dataset into separate files by thematic category was necessary to ensure correct symbology configuration during mapping and to import the spatial data into ArcGIS.

3.4 Terrain processing and derivation of the hydrographic network

Elevation data were processed in 6 consecutive stages, summarised in Figure 2.

The input data and the geoprocessing parameters are summarised in Table 2.

Table 2 – Input data and geoprocessing parameters

Parameter	Value(s)
Digital elevation model	Hole-filled SRTM*, CGIAR-CSI, 3 arc-seconds (about 90 m at the equator), heights relative to the EGM96 geoid; comparison model Copernicus GLO-30, 1 arc-second, EGM2008 [31]
Software	ArcGIS Desktop with Spatial Analyst (primary analysis)
Registry source and extraction date	State register of economic entities via Opendatabot, May and June 2026
Retained classification codes	06.10, 06.20, 08.12, 08.91, 09.10, 10.11, 19.20, 20.11, 20.30, 20.59, 21.20, 22.21, 25.21, 25.62, 25.91, 28.11, 36.00, 37.00, 38.11, 38.21, 38.32
Channel network extraction	Stream Order, Strahler method, 5 ranks
Channel threshold	Flow accumulation > 500 cells, about 2.8 km^2; 4490 cells (2.8 km^2) for Copernicus GLO-30
Cell size of the model	60.5 m (east–west), 92.7 m (north–south)
Pour points; snap distance	2; 0.01 decimal degrees
Input coordinate system	WGS 84, EPSG 4326
Analysis coordinate system	WGS 84 UTM 34N, EPSG 32634
Buffer distances	50, 100, 250, 500, 1000 m
Facilities in final inventory	142 point features, 139 unique locations
Locational reference	Centroid of the identified installation; center of the object for extended objects

* Shuttle Radar Topography Mission.

Open elevation data from Earth remote sensing and vector layers of Ukraine's administrative divisions served as the initial input.

The elevation input is the hole-filled SRTM digital elevation model distributed by the CGIAR Consortium for Spatial Information. Its grid spacing is 3 arc-seconds, which corresponds to about 90 m at the equator; its horizontal datum is WGS 84 and its heights are referenced to the EGM96 geoid. The tile set covering the territory of Ukraine was used. The administrative division of Ukraine was taken from the vector layer of oblast and district boundaries. The primary geoprocessing was performed in ArcGIS Desktop with the Spatial Analyst extension. The results were compared with those obtained from the Copernicus GLO-30 digital surface model with a grid spacing of 1 arc-second, corresponding to about 20–31 m at the study area's latitude. This model is referenced to the EGM2008 geoid, with absolute vertical accuracy better than 4 m and absolute horizontal accuracy better than 6 m at the 90 % level [31, 32].

The resolution of about 90 m was adopted for the primary analysis for 3 reasons. The SRTM model has uniform quality and is openly available across the whole district and the surrounding area needed to delineate the catchments. The analysis requires channel positions at the district and catchment scales, covering 127.6 and 724.6 km^2, respectively. A cell of about 60 m in the east–west direction and 93 m in the north–south direction at the study area's latitude is sufficient to delineate the drainage pattern. The study is a screening stage for territories without flood hazard maps, and its results are stated in distance classes of 100 m and wider. The published accuracy assessment of SRTM for Eurasia reports an absolute geolocation error of 8.8 m, an absolute height error of 6.2 m, and a relative height error of 8.7 m at the 90 %. The effect of resolution on the results was assessed by randomly displacing the facilities and by repeating the analysis using the Copernicus GLO-30 model with a cell size of about 30 m, as described below.

The district boundary was selected from the administrative division layer and exported as a separate vector file to define the region of interest. The workspace, the scratch workspace, and the processing extent were set to that region. Closed depressions were removed with the Fill tool of the Spatial Analyst hydrology toolset, which ensures a single clear flow direction for every raster cell. Flow direction was then computed with the 8-direction algorithm [33, 34], and flow accumulation was computed as the number of upslope cells draining into each cell.

Channel cells were extracted from the flow accumulation raster as the cells draining more than 500 cells, which corresponds to a contributing area of about 2.8 km2 at the cell size of 60.5–92.7 m (Figure 4).

This threshold reproduces the principal watercourses of the flood risk management plan, and its influence on the results was tested for thresholds from 250 to 2000 cells.

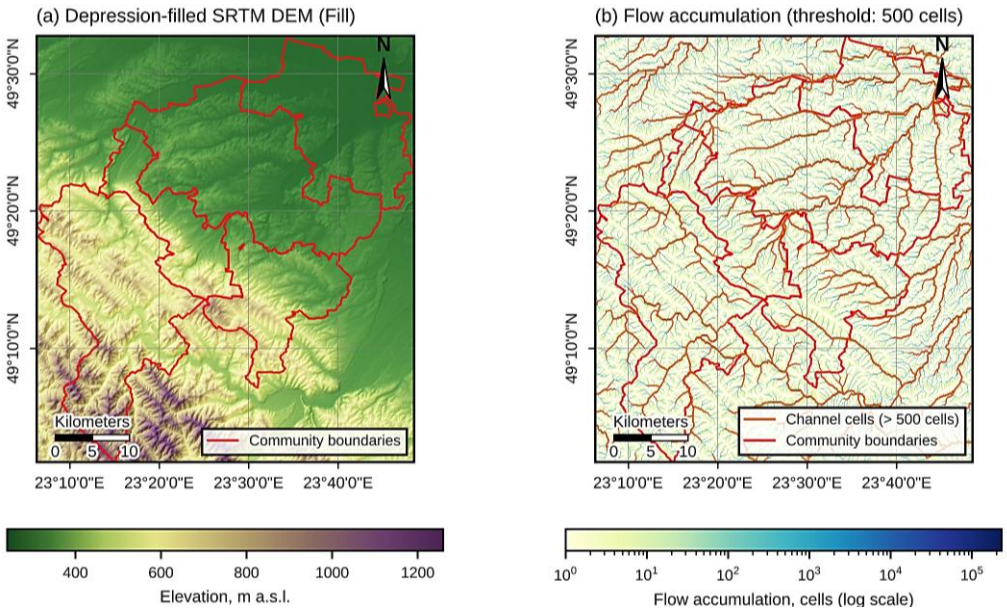


Figure 4 – Depression-filled SRTM model (a) and flow accumulation above the 500-cell threshold (b)

The resulting network was ranked using the Strahler stream order tool, which returned 5 ranks for the territory; the ranked raster was then converted into a vector layer with the Stream to Feature tool. A hillshade raster was generated from the filled elevation model to support the visual interpretation of the network.

Catchment boundaries were delineated from the flow direction and flow accumulation rasters. A separate point layer was created in the coordinate system of the processed rasters, and 2 pour points were digitized on it, positioned at the confluences of the highest-order channel segments downstream of the district's principal settlements.

The pour points were relocated to the cells with the maximum flow accumulation using the Snap Pour Point tool. The snap distance was 0.01 decimal degrees, which corresponds to about 1.1 km in latitude and 0.7 km in longitude at the study area's latitude. The catchment polygons were then generated with the Watershed tool. For the computation of areas, the layers were projected from geographic coordinates into the WGS 84 UTM Zone 34N projection, EPSG 32634. The district lies within UTM zone 34N, whose central meridian is 21 degrees east, and areas were obtained with the Calculate Geometry function.

3.5 Validation of the derived network and sensitivity analysis

The derived network was compared with 2 reference sources. The first is the official description of the 7 watercourses in the flood risk management plan, which provides the coordinates of the sources and mouths, as well as the lengths of each watercourse [7]. The source and the mouth were snapped to the nearest node of the derived network, the shortest path along the network between them was computed, and its length was compared with the official length. The accuracy of the derived lengths was assessed against this official reference. The second reference is the small-scale hydrographic layer of the project database, which served as a supplementary check of the position of the network. The distance between the densified lines of the 2 networks was computed at 50 m intervals in both directions.

Medians and percentiles are used throughout to describe distances. The median is the middle value, so that half of the distances are smaller and half are larger. It is used instead of the mean because a few very large distances do not distort it. The 90 % value is the threshold below which 90 % of distances fall, indicating how large the distance is in the less favorable cases. The median absolute difference is the median of the absolute values of the differences between 2 sets of distances.

The sensitivity of the results to the channel threshold was tested at thresholds of 250, 500, 1000, and 2000 cells, corresponding to contributing areas of 1.4, 2.8, 5.6, and 11.2 km^2. For each threshold, the Euclidean distance from every facility to the nearest channel cell was computed on the raster, and the number of facilities within 100 m was counted. The raster distance obtained at the adopted threshold was then compared with the vector Near distance. The analysis was repeated using the Copernicus GLO-30 model, which was processed with depression filling, the priority-flood algorithm, 8-direction flow routing, and flow accumulation. The channel threshold of 4490 cells corresponds to the same contributing area of 2.8 km^2. The same distance, height, displacement, and watercourse length tests were applied.

3.6 Proximity and buffer analysis

The tabulated inventory was imported with the Add XY Data function, which converts the recorded latitude and longitude of each facility into a point feature. The proximity analysis consisted of 2 operations performed on the resulting point layer in the projected coordinate system EPSG 32634. The Near tool of the Proximity toolset was applied to the point layer, using the derived channel

network as the near feature, which appends the Euclidean distance in meters to the nearest watercourse for every facility. The Multiple Ring Buffer tool was then applied to the channel network with buffer distances of 50, 100, 250, 500, and 1000 m. The buffer polygons were combined with the point layer via a spatial join, yielding the number of facilities in each thematic category within each distance band. A second spatial join assigned each facility to its catchment polygon and the territorial community in which it is located. Facility density was computed as the number of facilities divided by the catchment area.

Distance to the nearest watercourse is used in this study as an indicator of the degree to which a facility is subject to inundation. It orders the facilities by their proximity to the channel network, which is what the available data for the whole district allow. To take account of the terrain and of the elevation of the site, the elevation of every facility above the nearest channel cell of the filled model was calculated in the manner of the height above the nearest drainage [35]. The vertical accuracy of SRTM over Eurasia is of the order of 6 m at the 90 % level [32], and this elevation is therefore used to separate the facilities lying on the valley floor from those lying well above it. The scope of this approach and its extension to hydraulic modeling are described in the Discussion section.

3.7 Reference hydrological data

Reference water levels of defined exceedance probability were taken from the flood risk management plan approved for the Dniester River basin district [7]. For the gauging station on the Tysmenytsia at Drohobych, which records both water level and discharge, the plan specifies the levels corresponding to exceedance probabilities of 0.2, 1, and 10 %, together with the historical maximum. The documented record of flood events in the district over 1880–2024, and the ranking of the territorial communities by flood frequency derived from it, were taken from the published retrospective analysis [27].

4 Results

4.1 Derived hydrographic network and its reliability

The processing of the filled model and the flow accumulation raster is shown in Figure 4.

Flow accumulation spans 5 orders of magnitude, and a threshold of 500 cells separates channel cells from slope cells.

The stream ordering returned 5 Strahler ranks, and the derived network is shown below together with the 7 watercourses of the flood risk management plan, which are labeled with the names used in the order of the Cabinet of Ministers of Ukraine approving the flood risk management plans [7].

Accordingly, of the 7 watercourses, 5 are reproduced by the derived network (Table 3).

Table 3 – Derived network compared with the watercourses of the flood risk plan*

Watercourse	Official length, km	Derived path, km	Ratio of lengths	Source offset, m	Mouth offset, m
Bystrytsia	81	75.5	0.93	1020	560
Tysmenytsia	42	48.6	1.16	30	1180
Bar	32	26.4	0.83	2220	440
Solonytsia	21	16.3	0.78	60	70
Skhidnytsia	12	9.6	0.80	1440	0

* The offsets are the distances from the official source and mouth to the nearest channel of the derived network, rounded to 10 m. The larger offsets at the sources result from the 500-cell channel threshold, as explained in the text.

The length of the derived path ranges from 78 to 116 % of the official length, and the official sources and mouths lie at distances up to 2.2 km from the nearest channel of the derived network. The largest offsets occur primarily at the sources and are a consequence of the channel threshold rather than positional error. Only cells that drain more than 500 cells, about 2.8 km^2 of catchment, are classed as channel, so that headwaters and small streams that drain smaller areas are not resolved, and the derived channel begins downstream of the official source.

For the same reason, the derived path is shorter than the official length for 4 of the 5 watercourses (ratios of 0.78–0.93), whereas on the Tysmenytsia it is longer (1.16). The mouth of the Kolodnytsia lies outside the extent of the model, and the channel of the Trudnytsia is not resolved as an independent line by either of the 2 elevation models. These 2 watercourses are therefore shown in Figure 5 by their official sources and mouths and are not included in the length comparison. In the Copernicus GLO-30 model, the same 5 watercourses are reproduced, with derived lengths ranging from 85–121 % of the official lengths.

Against the small-scale hydrographic layer of the project database, the median distance from the reference lines to the derived channels is 165 m, the mean is 320 m, and the 90th percentile is 876 m. Of 15,004 reference points, 33 and 57 % lie within 100 and 200 m of a derived channel. The median distance from the derived channels of rank 3 and above to the reference is 188 m. The horizontal agreement between the 2 networks is therefore on the order of 100–200 m, and the findings are reported for distance classes of 100 m or wider.

The effect of the position error of the facilities on the proximity result was quantified by displacing every industrial and municipal facility at random 300 times with a normally distributed horizontal error of radial root mean square 60, 90 and 120 m. These values bracket the model's

cell size, which is about 60 by 93 m. For each run, the facilities that fell within 100 m of a channel cell in the raster were counted. The mean number of facilities within 100 m is 5.1, 5.2, and 5.5 for the 3 error levels, with 90 % of the runs between 3 and 7 (between 3 and 8 at 120 m). For comparison, 5 facilities lie within 100 m at the nominal positions on the raster and 6 by the vector Near distance.

For each facility, the result is expressed as the share of the 300 runs in which it lies within 100 m (radial error 90 m). For 5 of the 6 facilities within 100 m, this share is 70 % or more, and for the meat processing enterprise, it is 38 %. The number of facilities in the first distance class is therefore of the order of 5 and lies between 3 and 8 in 90 % of the runs. The same test on the Copernicus GLO-30 model gives means of 6.1, 6.2 and 6.4 facilities within 100 m. In 90 % of the runs, the number lies between 4 and 8 at 60 m, between 4 and 9 at 90 m, and between 3 and 9 at 120 m.

The raster distance obtained at the adopted threshold of 500 cells is consistent with the vector Near distance, with a correlation coefficient of 0.947, a median absolute difference of 17.6 m, and a 90th percentile of 40.4 m. Between the thresholds of 250 and 1000 cells, the number of industrial and municipal facilities within 100 m of a channel remains at 5, while the number of all features within 100 m falls from 11 to 7 (Table 4).

Table 4 – Sensitivity of the proximity results to the channel threshold and to the elevation model

Threshold, cells	Contributing area, km^2	Median distance of the 142 features, m	Features within 100 m	Industrial and municipal facilities within 100 m
250	1.4	373	11	5
500 (adopted)	2.8	413	10	5
1000	5.6	478	7	5
2000	11.2	672	4	2
4490 (Copernicus GLO-30)	2.8	360	15	7

Only at 2000 cells, where the number of channel cells falls to 53 % of that at 500 cells, does the number of industrial and municipal facilities fall to 2. The facilities nearest to a channel are therefore consistently identified within the threshold range of 250 to 1000 cells.

On the Copernicus GLO-30 model, at the same contributing area of 2.8 km^2, 7 industrial and municipal facilities lie within 100 m. These are the 6 class A facilities and 1 additional oil and gas enterprise at 95 m (Table 4). The distances obtained on the 2 models correlate with a coefficient of 0.954 and differ by a median of 37 m.

4.2 Composition and spatial distribution of the inventory

Processing of the digital elevation model produced a continuous hydrographic network for the district's territory, along with the boundaries of the contributing catchments (Figure 5).

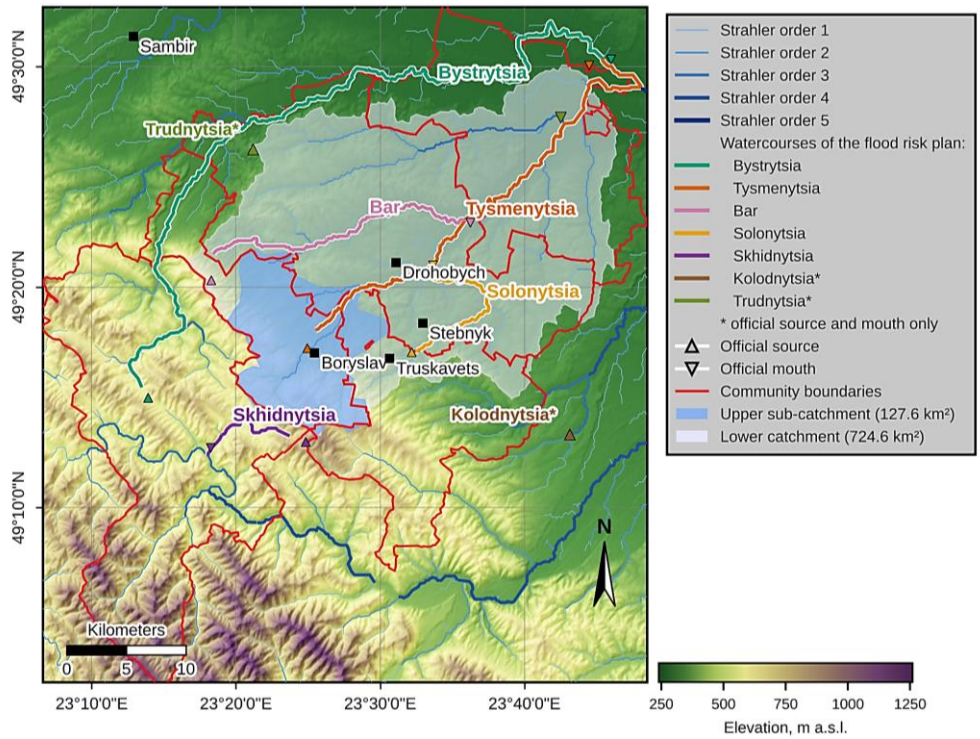


Figure 5 – Network derived from the elevation model and watercourses of the flood risk plan (adapted from [7])

The automated delineation refines at the local scale the macro-regional boundaries established by the official water management zoning [30, 36]. The map presented in Figure 6 shows the boundaries of the 5 territorial communities of the district, namely Drohobych, Boryslav, Truskavets, Skhidnytsia and Medenychi, the delineated catchments, and the distribution of the inventoried facilities across the 11 thematic categories.

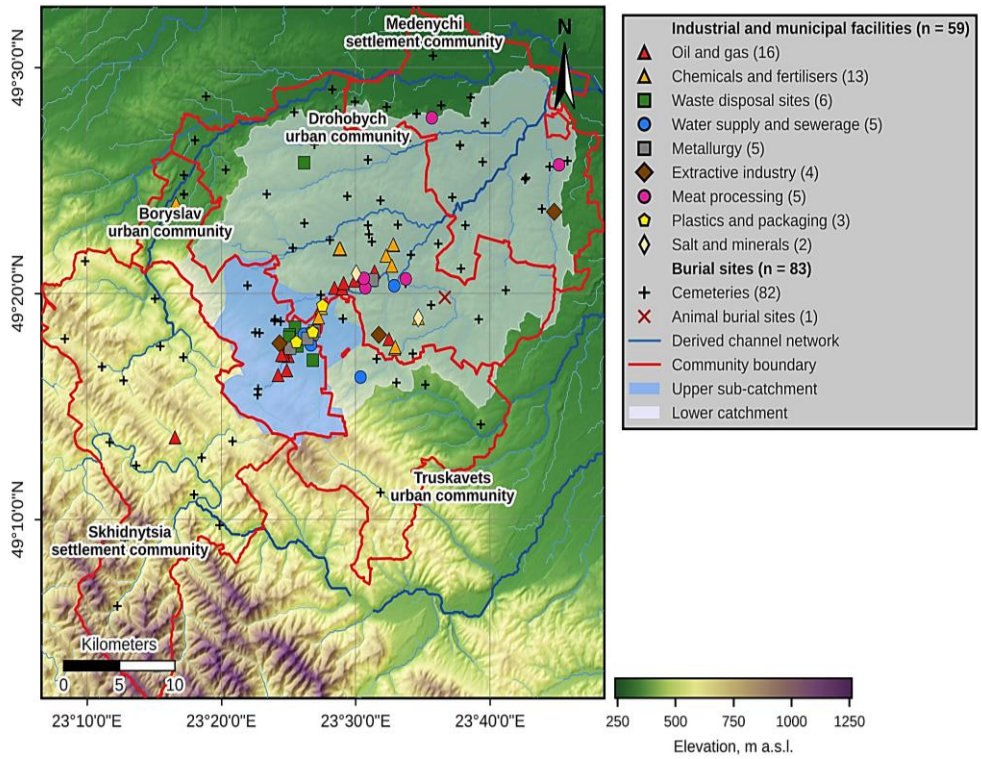


Figure 6 – Inventoried pollution sources in relation to the derived network and the delineated catchments

The delineation produced a lower catchment and, within it, an upper sub-catchment, which is the ordinary hierarchical structure of a drainage basin. Table 5 accordingly reports 3 positions that do not overlap: the upper sub-catchment, the remainder of the lower catchment, and the territory outside both.

Table 5 – Inventory by category and by position relative to the delineated catchments

Category	Upper sub-catchment	Lower catchment, remainder	Outside the delineated catchments	Total	Share, %	Within 100 m
Cemeteries	11	37	34	82	57.7	6
Oil and gas	8	7	1	16	11.3	4
Chemicals and fertilizers	2	10	1	13	9.2	1
Waste disposal sites	5	1	0	6	4.2	0
Water supply and sewerage	3	2	0	5	3.5	0
Metallurgy	4	1	0	5	3.5	0
Extractive industry	1	3	0	4	2.8	0
Meat processing	0	5	0	5	3.5	1
Plastics and packaging	3	0	0	3	2.1	0
Salt and minerals	0	2	0	2	1.4	0
Animal burial sites	0	1	0	1	0.7	0
Total	37	69	36	142	100	12

The delineation was performed at the level of the principal receiving reaches, not at the level of every tributary, thereby defining the spatial unit of the analysis. Of the 142 point features of the inventory, 106 lie within the delineated catchments and 36 lie outside them. Within the catchments, the distribution is uneven. The upper sub-catchment contains 37 features on a markedly smaller area, including 8 of the 16 oil and gas facilities, which is the largest share of the inventory's oil and gas facilities.

When the 83 burial sites are set aside, the 59 industrial and municipal facilities are distributed as follows. Of these, 57 lie within the delineated catchments and 2 outside them, and the upper sub-catchment holds 26 of them against 31 in the remainder of the lower catchment. Of the 59, 6 lie within 100 m of a derived channel: 4 in the oil and gas category, 1 in the chemicals category, and 1 in the meat processing category. Their distribution by distance to the derived channels is shown in Figure 7 and given in Table 6.

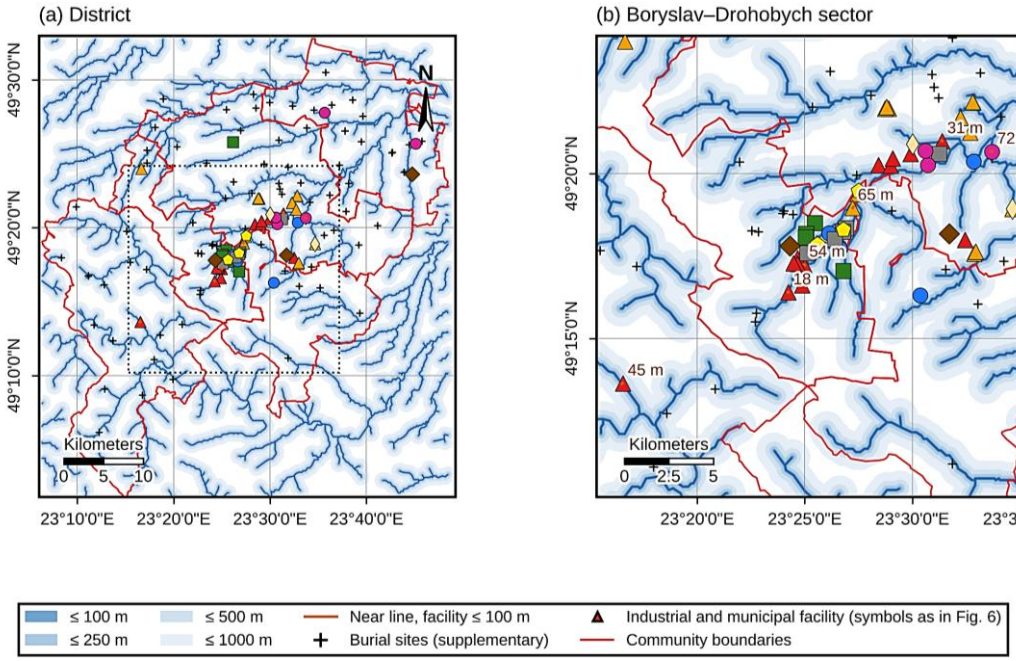


Figure 7 – Distance classes around derived channels in the district (a) and in the Boryslav–Drohobych sector (b)

Table 6 – Distribution of facilities by distance to the nearest watercourse, m

Category	0–50	50–100	100–250	250–500	500–1000	> 1000
Oil and gas	3	1	0	7	5	0
Salt and minerals	0	0	1	0	1	0
Extractive industry	0	0	0	2	2	0
Waste disposal sites	0	0	2	0	3	1
Chemicals and fertilizers	0	1	1	5	4	2
Other categories	2	5	21	31	27	15
Total	5	7	25	45	42	18

The 83 burial sites are distributed close to, but not proportional to, area, since 11 of the 49 burial sites within the catchments lie in the upper sub-catchment, against an expected 8.6.

Figure 5 also shows the hydrographic network derived from the elevation model over the shaded relief. The Strahler order is a rank given to every channel segment. A segment without tributaries has rank 1, and the rank rises by 1 where 2 segments of the same rank join, so that rank 5 marks the principal receiving channels. The 7 watercourses of the flood risk management plan are drawn in color, with upward triangles at the official sources and downward triangles at the official mouths. The Kolodnytsia and the Trudnytsia, marked with an asterisk, are shown only by their official source and mouth, because the derived network does not reproduce them over their full length. The red lines are the boundaries of the territorial communities, and the shaded areas are the upper sub-catchment (127.6 km^2) and the lower catchment (724.6 km^2). Coordinates are given in WGS 84.

Figure 6 shows where the inventoried facilities lie in relation to the derived network and the catchments. Thematic categories mark industrial and municipal facilities; burial sites are marked separately, and the red lines are the boundaries of the 5 territorial communities. The facilities are concentrated in the upper sub-catchment and along the channels between Boryslav and Drohobych, and this is quantified in Table 5.

Figure 7 shows the distance classes of up to 100, 250, 500, and 1000 m around the derived channels for the whole district (Figure 7a) and for the Boryslav–Drohobych sector outlined in Figures 7a and 7b. The orange lines in Figure 7b connect the industrial and municipal facilities within 100 m to the nearest channel, and the labels give their Near distances. The burial sites are shown as a supplementary layer.

The composition of the inventory by thematic category is given in Table 5, and its distribution by distance to the nearest watercourse is given in Table 6.

The upper sub-catchment contains 37 of the 106 features within the delineated catchments, including 8 of the 16 oil and gas facilities, 5 of the 6 waste disposal sites, and 4 of the 5 metallurgical enterprises (Table 5).

Table 6 gives the distribution of the features by distance to the nearest derived channel.

Under the Water Code of Ukraine, the coastal protection strip of a small river is 25 m wide, and the construction of buildings and structures in it is prohibited, with limited exceptions [5]. The position of a channel in the model is uncertain by about 1 cell, that is 60 to 93 m, and the result is stated for the class of up to 100 m.

All distances in the Results are Near distances measured to the vector channel lines; raster distances are used only in the sensitivity analysis. Of the 142 features of the inventory, 2 lie within 25 m of a watercourse, 5 within 50 m, and 12 within 100 m. The nearest object in the inventory, a cemetery, stands 4.8 m from a channel. Among the industrial facilities, the nearest is the enterprise Novi Tekhnolohii of the oil and gas category at 18.1 m, followed by the gas distribution unit of Lvivgaz at 31.4 m and the company Oranta at 45.3 m. Of the 5 features within 50 m, 3 belong to the oil and gas category and are closest to the district's channel network.

Among the 59 industrial and municipal facilities taken separately, 6 lie within 100 m, 9 between 100 and 250 m, 24 between 250 and 500 m, 17 between 500 and 1000 m, and 3 beyond 1000 m.

A total of 9 objects were identified for priority attention on the criteria stated below, and their parameters are summarized in Table 7.

Table 7 – Facilities identified for priority attention

Facility	Category	Distance, m	Height above channel, m	Share within 100 m	Class	Basis of the hazard
Boryslavnaftohaz oil and gas extraction department, Boryslav field	Oil and gas	54	2	0.85	A, B	Open sludge impoundments and several thousand legacy wells within the field [37]
Novi Tekhnolohii	Oil and gas	18	3	0.70	A	Release mechanism of the category (Table 1); quantity kept in place not documented
Lvivgaz gas distribution unit	Oil and gas	31	0	0.92	A	Release mechanism of the category (Table 1); quantity kept in place not documented
Oranta	Oil and gas	45	0	0.82	A	Release mechanism of the category (Table 1); quantity kept in place not documented
DEZO	Chemicals and fertilizers	65	2	0.72	A	Release mechanism of the category (Table 1); quantity kept in place not documented
Ranevytski Kovbasy	Meat processing	72	0	0.38	A	Release mechanism of the category (Table 1); quantity kept in place not documented
Stebnyk tailings pond	Salt and minerals	512	16	0.00	B	$2.9 \cdot 10^6$ m^3 of brine and $1.6 \cdot 10^6$ m^3 of solid phase in section 2 [38]
Boryslav municipal solid waste landfill	Waste disposal sites	730	26	0.00	B	Operating landfill, area 3 ha, serving the whole district [36]
Drohobych landfill near Bronytsia	Waste disposal sites	1424	34	0.00	B	Closed to acceptance in 2018, area 3.48 ha, waste body kept in place [36]

The table gives for every facility the distance to the nearest derived channel, the height above the nearest channel cell, the share of 300 random displacements (radial error 90 m) that keep the facility within 100 m, the priority class (A – distance up to 100 m; B – documented body of waste kept in place) and the basis of the hazard. For extended objects, the point is placed at the object's center.

The facilities were ranked by 2 criteria, which keeps the criteria transparent and reproducible and preserves the case of a remote but massive waste body that a weighted index would conceal. The first criterion is exposure, expressed by a distance of up to 100 m from a derived channel (class A). The second criterion is a documented body of waste or hazardous material that is kept in place (class B), and it applies regardless of distance.

For a mass kept in place, the release is governed by the failure or washout of the body, not by the proximity of the channel alone.

Facilities of both classes have the highest priority, and a facility that is remote from the watercourses and does not contain a body of waste has no priority. The exposure criterion is quantified by distance, height above the nearest channel cell, and the share of random displacements of the facility that keep it within 100 m (Table 7). The radial error of these displacements is 90 m. The second criterion is quantified by the mass retained in place wherever the source documents it. Documented attributes thus define each class and can be reproduced from the open data.

Class A includes 6 facilities. These are the enterprise Novi Tekhnolohii, the gas distribution unit of Lvivgaz, the company Oranta, the Boryslavnaftohaz extraction department in the oil and gas category, the enterprise “DEZO” in the chemicals category, and the Ranevytski Kovbasy enterprise in the meat processing category. All 6 lie 0–3 m above the nearest channel cell, that is, on the valley floor, and each of them remains within 100 m in 38–92 % of the random displacements.

Class B includes 4 facilities. Of these, 3 (namely the tailings storage facility and the 2 landfills) lie 510–1420 m from the nearest derived channel and 16–34 m above the nearest channel cell, so that no distance criterion would select them, and 1, the oil and gas infrastructure of the Boryslav field, satisfies both conditions. For the 2 landfills, with areas of 3.0 and 3.48 ha documented [36], the equivalent radius of about 100 m places the nearest edge at distances of about 630–830 m and 1320–1530 m from the channel. This does not change the class.

The tailings storage facility of the Stebnyk enterprise occupies land between the left tributaries of a stream that flows into the Solonytsia, a right tributary of the Tysmenytsia [38]. Thefacility’s embankment is 2061 m long and up to 21.5 m high. About $13.0 \cdot 10^6$ m^3 of liquid and solid phases have accumulated in its 2 sections, $8.2 \cdot 10^6$ m^3 in section 1 and $4.5 \cdot 10^6$ m^3 in section 2.

Section 2 consists of $2.9 \cdot 10^6$ m^3 of brine and $1.6 \cdot 10^6$ m^3 of solid phase [38]. The point of the facility is placed at the center of the pond, whereas the inventory point of the Stebnyk enterprise lies 721 m from the nearest channel. The pond lies in the remainder of the lower catchment, 512 m from the nearest channel of the derived network and 16 m above it, and the facility is classed by the mass of waste kept in place and not by the distance.

The facility is associated with 2 release mechanisms. The first is the direct discharge of mineralized brine following a hydrodynamic breach of the embankment, for which the historical precedent of the 1983 failure, which released about $4.5 \cdot 10^6$ m^3 of highly mineralized brine into the basin of the Dniester [38], and the resulting large-scale salt pollution of rivers and soils is established. The second is the activation of karst dissolution and the formation of sinkholes above the underground workings as floodwater enters the mining cavities. The increased seismicity recorded in the area of Mine No. 2 of the Stebnyk deposit following the artificial collapse in 2017 confirms that the workings are unstable regardless of hydrological conditions [39].

The oil and gas extraction infrastructure of the Boryslav field consists of the Drohobych oil refinery and the operations of the Boryslavnaftohaz oil and gas extraction department. It also includes a legacy of several thousand old wells, sludge ponds, and artificial impoundments filled with petroleum waste [37]. Measured contamination indicators for the district’s 2 waste disposal facilities are presented in Table 8.

Table 8 – Contamination indicators at 2 landfills and MPC* in soil (adapted from [36, 40])

Facility	Indicator	Value	Unit	MPC
Boryslav landfill	Lead (Pb) in surface substrate	0.05–0.12	mg/kg	6.0
Boryslav landfill	Cadmium (Cd) in surface substrate	0.002–0.003		0.74
Boryslav landfill	Chromium (Cr) in surface substrate	0.838–1.855		6.0
Boryslav landfill	Chemical oxygen demand of meltwater at the base	9.8–12.4	mg/dm^3	n/a**
Drohobych landfill near Bronytsia	Lead (Pb) in surface substrate	3.56–4.06	mg/kg	6.0
Drohobych landfill near Bronytsia	Cadmium (Cd) in surface substrate	0.021–0.033		0.74
Drohobych landfill near Bronytsia	Iron (Fe) in surface substrate	70.00–81.01		3500
Drohobych landfill near Bronytsia	Zinc (Zn) in surface substrate	2.84–3.67		23.2
Drohobych landfill near Bronytsia	Dry residue of meltwater at the base	23.8–125.6	mg/dm^3	n/a

* Maximum permissible concentration; ** not applicable.

They characterize the contamination of the surface substrate and snowmelt water at the foot of the waste bodies and document the presence of contaminants in these bodies.

The metals in the surface substrate were determined by inductively coupled plasma mass spectrometry in 24 samples taken on 10 September 2021 at depths of 0–10 and 0–20 cm [40]. All the measured values are below the maximum permissible concentrations in soil cited by the authors of that source and given in Table 8. These are 6 mg/kg for Pb and Cr, 0.74 mg/kg for Cd, 23.2 mg/kg for Zn, and 3500 mg/kg for Fe. The meltwater indicators are derived from snow samples collected in February 2021 at the foot of each waste body.

The sampling was carried out by the author of source [36]. At the foot of each landfill, 4 samples were taken from all sides of the horizon, that is, 1 on each of the 4 sides of the waste body, each of 1 dm3 of meltwater after

filtration. The quoted values are the lowest and the highest of the surface interpolated from those 4 points [36]. The environmental quality standards for surface water bodies [41] cannot be applied directly to the substrate or to the meltwater at the foot of a waste body, and no comparison with them is therefore made.

The lead content of the surface substrate at the closed Drohobych landfill near Bronytsia exceeds that at the operating Boryslav landfill by a factor of between 30 and 80. The Cd content exceeds it by a factor of between 7 and 16. Both results are consistent with toxic elements remaining in the waste body after waste acceptance ceases [40]. The Boryslav landfill is at present the only operating municipal solid waste landfill in the district, with the Drohobych landfill near Bronytsia having ceased accepting waste in 2018 [36]. Despite covering only 3 ha, the Boryslav facility receives municipal solid waste from Drohobych, Boryslav, and Truskavets, as well as from the settlements of Skhidnytsia and Medenychi. The load from human activity that it carries is therefore out of proportion to its nominal dimensions [36].

Table 9 gives the levels approved in Annex 1 to the flood risk management plan for the Dniester River basin district [7], expressed as absolute marks in meters of the Baltic height system.

Table 9 – Reference water levels of defined exceedance probability (adapted from [7])

Watercourse	Gauging station	0.2 %	1 %	10 %	Historical maximum
Tysmenytsia	Drohobych	275.57	275.40	274.46	275.28 m, 27 July 1997
Bystrytsia	Ozymyna	282.31	281.80	280.74	281.82 m, 25 July 2008

The exceedance probability is the chance that the water level at the gauge reaches or exceeds a given mark in any one year. A probability of 1 % corresponds to a level reached or exceeded once in 100 years on average, and a probability of 10 % to a level reached or exceeded once in 10 years on average. It describes the river level, not the probability that a given site is flooded.

At the Drohobych gauge on the Tysmenytsia, the 10 % level is 274.46 m and the 1 % level is 275.40 m, so the rarer flood is 0.94 m higher than the more frequent one. A rise of about 1 m is comparable to the heights of 0–3 m above the nearest channel cell found for the facilities of class A (Table 7). The marks correspond to the river level at the gauge, and their transfer to the inundated area of a particular site is handled by the hydraulic modeling that follows this screening.

5 Discussion

5.1 Sources of contamination and the documented flood record

The concentration of industrial and municipal facilities in the upper sub-catchment corresponds to the part of the district where floods are most frequently documented. The retrospective catalog for 1880–2024 contains 18 significant events, 9 of which occurred in the Boryslav community in 1997, 2008, 2017, 2019, 2020, and 2023, compared with 3.6 expected under an even distribution of events among the 5 communities [27]. The expected value is only a rough benchmark, because it ignores the area and the river network of each community. Of these 6 years, 4 fall between 2017 and 2024, and the documentation density increases towards the present, so that the record shows that the hazard is current but not that it is growing. The highest level at the Drohobych gauge, 275.28 m in July 1997, was 0.12 m below the level of 1 percent exceedance probability [7].

The excess is a property of the industrial and municipal facilities and not of the cemeteries. Of the 57 industrial and municipal facilities within the catchments, 26 lie in the upper sub-catchment, compared with 10 expected, and 11 of the 49 burial sites, compared with 8.6 expected. The excess is most pronounced for the 2 categories that hold the largest quantities of material that can be released, namely petroleum products and unlined waste bodies. Oil and gas facilities occur 3 times more often, and waste disposal sites 4.7 times more often, than would be expected for the sub-catchment area.

Smaller categories, such as metallurgy, plastics and packaging, and water supply and sewerage, are also concentrated in the upper sub-catchment, but they contain only 3 to 5 facilities each. The binomial tests yield *p*-values of 0.002 and 0.0009 and describe only the departure from a uniform distribution, because the facilities are spatially clustered and the assumption of independence is not met. The co-location of the sources and recurrent floods in the Boryslav community is the main finding, and the p-values are approximate.

5.2 Interpretation of the contamination data

The legal basis for assessing the indicators in Table 8 against the criteria for good ecological and chemical status is the national order that approves the environmental water quality standards for surface water bodies and implements Directive 2000/60/EC [41]. The metals in the surface substrate of both landfills lie below the maximum permissible concentrations cited by the authors of the source, so that Table 8 does not by itself indicate a failure to achieve good chemical status. Its function is to document the presence of contaminants in the waste bodies and the contrast between the closed and the operating landfill. Whether these contaminants reach water bodies during a flood depends on the cover’s erodibility and the hydraulic loading, and should be established through modeling or sampling during the flood.

The accelerated migration of leachate during the inundation of municipal solid waste landfills is an established pattern [21], and the remaining release potential of facilities closed to waste acceptance has been

shown to persist for decades [23]. Modeling of tailings dam failure under flooding indicates that the flood and the breach reinforce each other, so that the 2 release mechanisms identified for the Stebnyk facility should not be treated as independent [18]. These studies support the class B criterion, under which a body of waste kept in place has priority regardless of its distance from the channel, although they do not quantify the release in the district.

5.3 Practical implications

The priority is physical isolation of the accumulated waste bodies identified in Table 7. For the tailings storage facility, this includes reinforcement and monitoring of the protective embankments, upland channels that capture and divert surface runoff, and grouting of the underground workings where sinkholes have been recorded. For the oil sludge impoundments, this consists of bank stabilization along the neighboring reaches and reclamation of the open sludge surfaces with impermeable screens. For the landfills, this consists of a bottom sealing layer and a leachate collection system at the operating facility, and the completion of reclamation of the closed one. The second priority concerns the remaining facilities within 100 m of a channel and is differentiated by terrain. It consists of channel clearance and protective embankments in foothill areas, and the modernization of the stormwater network in densely urbanized areas.

5.4 Limitations and further work

The method ranks the facilities by their proximity to the derived channels and their height above them, and first identifies those that merit attention. Its scope is that of a screening stage for territories without flood hazard maps. The positions of the channels are resolved to about 1 cell in the elevation model, that is, 60 to 93 m, and the distances are therefore interpreted in classes of 100 m or wider. The reported quantities of accumulated waste are drawn from published sources of varying dates; the extended objects are represented by points at their centers; and the comparison with the flood record covers 5 territorial communities and serves as a rough benchmark. The inundation depths and velocities that the vulnerability models of flood loading [13, 14] require are supplied by hydraulic modeling, and the threshold quantities of Annex I to Directive 2012/18/EU that are needed for the magnitude of an individual release are held in the state register of high-hazard objects, which is not in the public domain. The next stage of the work is therefore to replace the proximity measure with inundation boundaries of defined exceedance probability, which would permit the use of established equipment vulnerability models [13, 14] and a quantitative estimate of release probability. Openly available flood hazard maps covering the river basins entering the Black Sea at a resolution of 100 m and for return periods between 10 and 500 years [42] can serve as a first approximation of these boundaries for the larger rivers, since the dataset includes rivers with upstream areas above 500 km^2.

6 Conclusions

An inventory of 142 point features of potential sources of flood-induced water contamination was compiled for the Drohobych District. It consists of 59 industrial and municipal facilities and 83 burial sites and was combined with a hydrographic network derived from a digital elevation model. The network reproduces 5 watercourses in the flood risk management plan, and the derived lengths are 78–116 % of the official lengths. A total of 6 industrial and municipal facilities, 4 of which are in the oil and gas category, lie within 100 m of a derived channel, and the number remains between 5 and 7 when the channel threshold is varied by a factor of 4 across both elevation models.

The upper sub-catchment contains 26 of the 57 industrial and municipal facilities within the delineated catchments, covering 17.6 % of the area. Oil and gas facilities occur 3 times more often and waste disposal sites 4.7 times more often than would be expected for the area, which is consistent with the highest documented flood frequency in the Boryslav community. Priority attention is proposed for 9 objects: 6 selected within 100 m of a channel and 4 associated with a documented body of waste kept in place, with 1 shared between the groups. Of the 4 objects selected by a documented body of waste, only 3 (namely the tailings storage facility of the Stebnyk enterprise and the Boryslav and Bronytsia landfills) lie 510–1420 m from the nearest derived channel and 16–34 m above it. The contaminants documented in these bodies, namely mineralized brine, petroleum products, and landfill leachate, are a potential load on the receiving watercourses of the Dniester basin.

The inventory and classification by 2 criteria provide a reproducible basis for prioritizing protection measures and selecting facilities for the national flood risk maps. For this selection, a criterion based on the quantity of hazardous material kept on site would also cover abandoned tailings storage facilities and legacy sludge impoundments, which are not classified as planned activities and therefore do not fall under the present criterion based on the environmental impact assessment category. The next stage of the work is to replace the proximity measure with inundation boundaries for a specified exceedance probability and to quantify the release using hydraulic modeling.

Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval

This study did not involve human participants.

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