Remote monitoring of minewater rebound and environmental risk using satellite radar interferometry

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Abstract

The cessation of dewatering following coalfield abandonment results in the rise of minewater, which can create significant changes in the local and regional hydrogeological regime. Monitoring such change is challenging but essential to avoiding detrimental consequences such as groundwater contamination and surface flooding. Inverse modelling methods using satellite radar interferometry (InSAR) have proven capable for retrospectively mapping minewater level changes, however, there is a need for the capability to remotely monitor changes as they occur. In this study, ground deformation measurements obtained from InSAR are used to develop a method to remotely monitor the spatio-temporal rise of minewater, which could be implemented in near real-time. The approach is demonstrated over the Horlivka mining agglomeration, Ukraine, where there is no other feasible approach possible due to a lack of safe ground access. The results were blindly validated against *in-situ* measurements before being used to forecast the time until minewater will reach the natural water table and Earth's surface. The findings reveal that, as a result of military conflict in Donbas, an environmental catastrophe could occur where potentially radioactive minewater is forecast to reach the natural water table between May and August of 2024.

Keywords

Coal mining; Minewater rebound; Hydrogeology; Modelling; Surface deformation; InSAR

1. Introduction

In deep mines that operate below the groundwater table, water is often pumped to the surface to facilitate safe mining, disrupting the natural hydrogeological conditions. When a mine is closed, it is common practice for pumping regimes to partially remain in place to prevent toxic minewater, or acid minewater drainage, from rising rapidly. Such pumping is implemented to avoid groundwater contamination, gas emissions, surface flooding and pollution, soil settlement and subsidence of the surface (Younger, 2016). Obtaining sufficient knowledge of the spatio-temporal rise of minewater is highly desirable to avoid the aforementioned detrimental environmental and socio-economic consequences following the cessation of dewatering. Mine plans and minewater level measurements provide important information with regards to the direction and structural control of groundwater flow. However, information regarding inter-seam connections within collieries, as well as connections between adjacent collieries from mine plans, are often inaccurate or incomplete. In addition, many mine shafts are backfilled after colliery closure and so *in-situ* minewater level measurements often are spatially sparse and drilling new monitoring boreholes is expensive. As a result, only limited information is available to form the basis of remediation strategies in typically vast and complicated mine systems, which have often been extensively worked for decades (Younger & Adams, 1999).

A host of modelling methods have been developed in the past decades to quantify and predict the hydrogeological changes that occur following coalfield closure. Ongoing developments of computer hard/software have increased computational capacity. This has facilitated the use of numerical methods to simulate the flow of groundwater through aquifers which have been applied to model the flooding of recently abandoned mines (e.g. Yu *et al.*, 2007; Surinaidu *et al.*, 2014). Bespoke simulation packages have subsequently been developed specifically for investigating the flooding of coalfields, including physical-based, spatially distributed models (e.g. Adams & Younger, 1997; Hamm *et al.*, 2008) and simplified semi-distributed models such as Groundwater Rebound in Abandoned Mineworkings (GRAM) (Sherwood & Younger, 1997; Younger & Adams, 1999). GRAM, for example, has been shown to produce useful and realistic results for predicting the time until the hydrogeological conditions return to the pre-mining state. As a different approach, Younger (2016) proposed an alternative to computer-based simulations by using rudimentary calculations based on information such as voidage, water inflow rates and topography.

Changes in groundwater levels can cause the Earth's surface to rise and fall, which can be measured remotely using satellite radar interferometry (InSAR) (Hoffmann *et al.*, 2001). InSAR is an Earth observation technique which is capable of measuring millimetric rates of ground deformation from the differences in phase between radar images. Such data provide the means to calibrate groundwater models, delineate lithological boundaries, map aquifer storage variations and assist aquifer characterization (e.g. Boni *et al.*, 2016; Castellazzi *et al.*, 2016; Béjar-Pizarro *et al.*, 2017). InSAR has become a standard technique for surface motion measurement (Crosetto *et al.*, 2020) and, advantageously, can be utilized to generate historical, present and future ground deformation measurements in inaccessible areas around the world. This capability has been greatly enhanced since 2014 by the free, open-access and global data supplied by the Sentinel-1 mission (Torres *et al.*, 2012). Furthermore, novel processing methods such as the APSIS (Advanced Pixel System using Intermittent SBAS) (Sowter *et al.*, 2013; Sowter *et al.*, 2016) InSAR method are able to significantly extend the coverage of conventional techniques – such as persistent scatterers interferometry (PSI) and the small baseline subset (SBAS) method – to provide a near 100% coverage of measurements over urban and rural areas alike. This is vital for InSAR inversion approaches, since the response of the subsurface to pressure changes associated with variations in groundwater can be highly spatially variable due to differences in the compressibility, thickness and confinement of the strata (Castellazzi *et al.*, 2018).

With the increased availability of InSAR data, numerical methods have more recently been developed and applied to determine the surface deformation associated with minewater rebound (e.g. Todd *et al.*, 2019; Dudek *et al.*, 2020; Zhao & Konietzky, 2020). In this regard, numerical approaches have proven to be valuable for effectively simulating minewater rise in complex geologies and mining conditions. Moreover, they also have the potential to provide more comprehensive information than just surface displacements, such as strain, stress and fracture patterns (Zhao & Konietzky, 2021). However, numerical approaches require detailed mining information, are typically difficult and time-consuming to set-up, and are often too complex to implement at the coalfield scale. Alternatively, analytical approaches are much easier to set-up, can be implemented over vast areas and use relatively simple calculations, hence, crucially, they are well suited to solve inverse problems (i.e. inference of minewater levels from surface deformation data). Temporal correlations between the rise of minewater and InSAR measurements have been recognized (e.g. Samsonov *et al.*, 2013; Gee *et al.*, 2017; Malinowska *et al.*, 2020) and such measurements have been used in inversion approaches to retrospectively map minewater changes in recently abandoned coalfields (e.g. Cuenca *et al.*, 2013; Gee *et al.*, 2020). However, there is still a lack of approaches for monitoring changes in minewater levels across entire coalfields as they occur.

Monitoring such change is challenging yet essential to avoiding the potential detrimental environmental impacts of minewater rebound. This is because access to detailed and up-to-date information could be used to help identify when and where appropriate mitigation measures need to be put in place. Accordingly, the aim of this study is to present a method for near real-time remote monitoring of minewater levels across an entire abandoned coalfield, for the purpose of determining the potential environmental risk. Pertinently, this is demonstrated over the Horlivka mining agglomeration, Donbas, Ukraine, where there is no other feasible monitoring approach due to a lack of safe ground access and intermittent *in-situ* measurements owing to the military conflict between Ukraine and Russia. The specific objectives are to:

(i) generate and calibrate a model to establish the relationship between the change in minewater levels and surface deformation;

(ii) remotely monitor the change in minewater levels using InSAR and blindly validate against the available *in-situ* measurements;

(iii) forecast the time it will take for minewater to reach the natural water table and Earth's surface;

(iv) discuss the environmental implications of abrupt mine closure in Donbas.

The remainder of the manuscript is structured as follows. The study site and materials are introduced in section two providing the geological and hydrogeological context for the study. Objectives i-iii provide the structural sub-headings for the methodology and results and discussion in sections three and four, respectively. A discussion is provided in section five to addresses objective four before a conclusion in section six.

2. Study site & materials

2.1 Land cover

The study site is approximately 40 x 50 km and is located in the north-east of the Donetsk oblast, Ukraine (Fig. 1). Artificial surfaces make up 19% of the area which predominantly correspond to the cities of Toretsk, Horlivka and Yenakiieve which orientate from WNW-ESE. The remainder of the land cover is rural, dominated by agricultural land (59%) as well grasslands (16%), forest (4%) and wetlands (<1%) (Chen *et al.*, 2015). Water bodies comprise the remaining two percent.

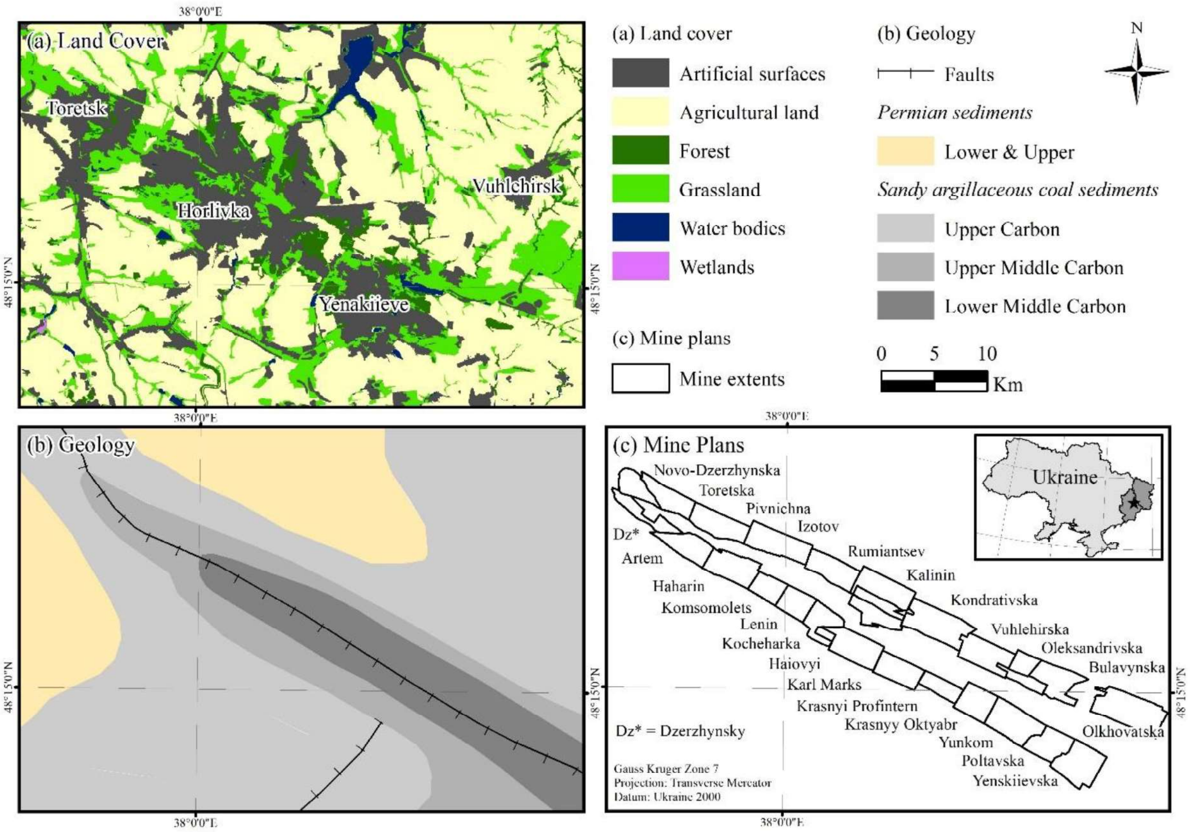

Figure 1. Horlivka mining agglomeration: (a) Land cover (Chen *et al.*, 2015); (b) geology; (c) mine plans.

2.2 Geology

The Horlivka mining agglomeration is situated within the Donets Basin (colloquially referred to as Donbas), which is one of the world's major Late Palaeozoic coalfields with proven reserves of ~60 Gt (Alsaab *et al.*, 2009). The Donets Basin forms the south-eastern part of the Dniepr-Donets Basin, which is a Late Devonian rift structure on the southern part of the Eastern European craton (Stovba & Stephenson, 1991). The Donets Basin fill comprises Devonian pre- and syn-rift rocks and a complete Carboniferous-Palaeogene post-rift sequence several thousands of metres thick (Sachsenhofer *et al.*, 2002). A major part of the basin, the Donbas Foldbelt, has been inverted and is characterized by a series of WNW–ESE-trending folds and faults. The most dominant of these structures is the Gorlovka (Horlivka) Anticline, which is a near-symmetrical structure with steeply dipping limbs of 60-80°, bordered by the Main (north) and South synclines and North and South Anticlines (Sachsenhofer *et al.*, 2002).

There are more than 300 coal layers contained to within a depth of 1800 m of the Carboniferous fill of the Donets Basin, of which approximately 130 are considered to be workable coal seams due to their thickness (i.e. >0.45 m) and depth constraints (Alsaab *et al.*, 2009). Coal mines in the region have operated at depths of 220–1380 m, with an average depth of 620 m (Privalov *et al.*, 2003). Coals within the Donets Basin have high ash yields (12–18%), high sulphur contents (2.5–3.5%) and are rich in hazardous trace elements such as Hg, As, Cd, Pb and Zn, with particularly high concentrations of Hg found along the Gorlovka anticline (Sachsenhofer *et al.*, 2012), where the Horlivka mining agglomeration is located. In this study, the Horlivka mines are grouped into the northern and southern agglomeration according to their location on the northern and southern limbs of the Gorlovka anticline, respectively (Fig. 1). A measurement of the (initial) porosity is required for the establishment of the minewater model and, in the absence of laboratory samples, a measurement of 0.15 was defined in accordance with Donabedov (1940).

2.3 Hydrogeology

The eastern Ukrainian oblasts of Donetsk and Luhansk have been subject to conflict between the Ukraine military and Russian-backed separatists since 2014. The ecology in eastern Ukraine was in a fragile state prior to the hostilities and is worsening over time as the quality of water and soils are being degraded by the mass and abrupt closure of over 30 deep coal mines in the region. Many of pumping systems have been switched off, damaged or subject to power cuts and, consequently, the rise of minewater risks contamination of the region's soils, groundwater and surface waters (Hook & Marcantonio, 2022). The uppermost geological zone of the agglomeration is subject to high levels of chemical contamination and over 4000 ecologically hazardous facilities have been identified, including metallurgical and chemical enterprises, sludge depositories and waste ponds, which include the Horlivka Chemical Plant, Mykytivskyi mercury mine and the Yunkom coal mine (Ministry of Ecology and Natural Resources of Ukraine, 2019; Yermakov *et al.,* 2019). Many mines have been operating for 50-70 years and there is a significant quantity of steeply dipping coal seams (over 55°). Due to mining operations, anthropogenic cracking has increased permeability and developed new routes for the accelerated migration of contaminants and interconnection between ground and surface waters. This has reduced the protective ability of the uppermost zone of the geological system. At present, practically all of the mines within the Horlivka urban mining agglomeration, on the northern and southern flanks of the anticline, are hydraulically interconnected at depths that range from 230–1080 m, creating a unitary system with high anthropic groundwater vulnerability (Chumachenko & Yakovliev, 2017).

Minewater depth measurements were supplied by State Ecological Academy of Postgraduate Education and Management, Ukraine. The measurements were obtained manually from the mine shafts because the monitoring network is no longer operational. The levels, acquired at monthly intervals, were made available to the modelers for 19 mines in the Horlivka mining agglomeration and cover nearly a two-year period from 1st November 2017 to 1st September 2019. Once the modelling had been conducted, the depths in the February 2022 were supplied for validation. There were less validation measurements available, ten, owing to the lack of safe ground access.

2.4 Earth observation data

Two hundred and seventy-eight Sentinel-1 Level-1 Interferometric Wide (IW) Single Look Complex C-Band radar images covering the period 5th March 2015 to 20th February 2022 were available over the Horlivka mining agglomeration. The images were acquired on a descending orbit from track 94 and have a medium revisit time of 6 days. The incidence angle at Horlivka is ~ 37° and the IW products have a pixel spacing of 2.3 m in slant range and 13.9 m in azimuth, corresponding to a spatial resolution 5 m in ground range and 20 m in azimuth at scene centre (Torres *et al.*, 2012). There is insufficient data covering a similar time epoch from an ascending track making a stereo analysis unfeasible.

3. Monitoring methodology

3.1. Generation & calibration of minewater model

3.1.1. Forward minewater model

An analytical model was established to ascertain the relationship between the change in minewater levels and surface deformation (and vice-versa). Using basic correlations that universally determine a value of groundwater rise per unit of surface deformation lead to erroneous interpretations because minewater rising closer to the surface has a stronger effect on surface deformation than rising minewater at depth. Similarly, minewater rise in an unconfined aquifer results in more surface deformation than a rise within coal measures that are confined by overlying strata (Gee *et al.,* 2020). The forward model is based upon the principle of effective stress (Terzaghi, 1925; Poland, 1984) and calculates the increase or decrease in the thickness of the strata (i.e. heave or subsidence) for a given change in minewater levels, in accordance with Gee *et al.* (2020). The model is treated as a homogeneous matrix, where the initial bed thickness (b_0) (m) was calculated as the depth from the surface to the minewater level at the start of the modelling epoch, for each individual mine. The strata is subject to a level of geostatic pressure (p) (kPa), which increases as more material is overlain over time. Geostatic pressure is resisted by the intergranular (effective) stress (p_{s0}) of the rock matrix and the fluid pressure of pore water (p_{w0}) (Poland, 1984) such that:

$$p = p_{s0} + p_{w0} \quad \text{(Eqn. 1)}$$

Equilibrium must be maintained in Eqn. 1, thus, an increase in minewater increases the pore fluid pressure and decreases the effective stress on the strata. This causes an expansion of the strata until equilibrium is again reached. The geostatic pressure (p) was calculated from the initial bed thickness (b_0) using 10 kPa/m to calculate the stress transfer from fluid to rock matrix per unit change in minewater levels (Poland, 1984) as:

$$p = 10.b_0 \quad \text{(Eqn. 2)}$$

The entire coalfield is exposed (i.e. there is no overlying strata) and therefore it is treated as an unconfined aquifer where geostatic pressure is attributed as 65% effective stress and 35% pore fluid pressure. Following the change in minewater levels (Δh), the new pore fluid pressure (p_w) is calculated as:

$$p_w = p_{w0} + 10.\Delta h \quad \text{(Eqn. 3)}$$

and by maintaining the equilibrium in Eqn. 1, the new effective stress (p_s) is:

$$p_s = p - p_w \quad \text{(Eqn. 4)}$$

Hence, the change in effective stress (Δp_s) can be expressed as a function of the initial geostatic pressure (Eqn. 1) and change in minewater where:

$$\Delta p_s = p_s - p_{s0}$$

$$= p - p_w - p_{s0}$$

$$= p - p_{w0} - 10.\Delta h - p_{s0} \quad \text{(Eqn. 5)}$$

The initial void ratio (e_0) is calculated from the initial porosity (n_0) by:

$$e_0 = \frac{n_0}{1 - n_0} \quad \text{(Eqn. 6)}$$

and after a change in effective stress a new void ratio (e) is calculated as:

$$e = e_0 - c_c . log\left(\frac{p_s}{p_{s0}}\right) \quad \text{(Eqn. 7)}$$

expressed as a function of the initial void ratio (e_0), the compression index (c_c) and the initial (p_{s0}) and new effective stress (p_s). The compression index is a dimensionless parameter that determines the compressibility of the stratigraphic bed and considers the elastic properties of the unit. For each mine, the InSAR data were used to determine the compression index and calibrate the model, as outlined in sub-section 3.1.2.

The coefficient of volume compressibility (m_v) relates the coefficient of compressibility (a_v) and the initial void ratio (e_0) as:

$$m_v = \frac{a_v}{1 + e_0} \quad \text{(Eqn. 8)}$$

where,

$$a_v = \frac{\Delta e}{\Delta p_s} \quad \text{(Eqn. 9)}$$

and Δe is the difference in void ratio.

The change in bed thickness (Δb) is caused by the change in effective stress (Δp_s), and is calculated as a function of the coefficient of volume compressibility (m_v) and the initial thickness of the unit (b_0) by:

$$\Delta b = \Delta p_s . m_v . b_0 \quad \text{(Eqn. 10)}$$

3.1.2. Model calibration & inversion

Surface deformation measurements are required to calibrate the model and provide measurements for inversion. The Sentinel-1 data were processed using the APSIS InSAR method (Sowter *et al.,* 2013; Sowter *et al.,* 2016). The APSIS algorithm was used due to the dominance of rural land cover, since it has been shown to be capable of returning a set of dense measurements over almost every land cover type over wide areas (e.g. Sowter *et al.,* 2018; Gee *et al.,* 2019). This is vital given that 91% of land cover is rural within Donetsk and Luhansk (Chen *et al.*, 2015). Importantly, unlike conventional InSAR techniques, APSIS can provide such coverage without the installation of ground infrastructure or recourse to ground survey, both of which are currently unfeasible in Donbas due to the inaccessibility of the region during the conflict.

Once the image stack was co-registered, 3243 small-baseline interferograms were generated between pairs with a maximum temporal baseline of 365 days and a maximum perpendicular baseline of 30 m. Topographic phase was simulated and removed using a 90 m digital elevation model from the TanDEM-X mission (German Aerospace Center, 2018), and interferograms were multi-looked by a factor of 7 in range and 2 in azimuth. Unwrapping was performed using a modified version of the SNAPHU algorithm. The average rate of motion and time-series were calculated for pixels at a resolution of 20 m using linear and non-linear models of deformation, respectively. The measurements were projected from the satellite line-of-sight into the vertical by means of dividing by the cosine of the incidence angle.

Finally, to reduce the effect of noise in the model the time-series were spatially averaged over a 1 km window.

The model was calibrated over the period for which *in-situ* minewater level measurements were available (1st November 2017–1st September 2019). The difference in the relative heights of the time-series over this period was calculated, with the time-series being linearly interpolated to the latter date given that no image and, hence, no time-series measurement was available for this date. The compression indices that minimized the root-mean-square-error between the forward model at the mine shaft location and 99th percentile of the InSAR time-series difference within the mine extent were calculated for each mine. Once suitably calibrated, the forward model was implemented across the coalfield. Finally, the InSAR time-series difference was utilized as the measure of the change in bed thickness (Δb), which was inverted to quantitatively map the change in minewater levels (Δh) across the coal district over the calibration period (2017–2019), as given by:

$$\Delta h = \frac{1}{10}\left(p - p_{so} - p_{wo} - \left(\frac{\Delta b}{m_v . b_0}\right)\right) \qquad \text{(Eqn. 11)}$$

3.2. Remote monitoring of minewater rise

The recovery of minewater is not a linear process as the rate of rebound decreases exponentially over time, as minewater approaches the surface (Younger & Adams, 1999). The relationship between the compression indices and groundwater depths for each of the mines over the calibration epoch were analyzed to determine the reduction of inflow with depth. As minewater gets closer to the surface the compression index decreases; a logarithmic fit between the compression index and minewater depth was established producing a coefficient of determination (R^2) of 0.77. To estimate the minewater rise for the remaining portion of the time-series, the model was run iteratively. The time-series were offset to the end of the calibration period (1st September 2019) and the first relative height change of the remaining portion of time-series was inverted to retrieve the change in minewater levels (Δh) (Eqn. 11). This results in a new minewater depth, and a new compression index was retrieved utilizing the function between the compression index and minewater depth. The forward model was re-generated to determine the change in bed thickness (Δb) using the newly inverted change in minewater depth and new compression index (Eqns. 1–10). This was repeated for the remainder of the time-series. The iterative model was developed and implemented blind of the *in-situ* minewater measurements over the period 2019–2022.

3.3. Forecasts of minewater rise

A linear trendline, with ± one standard deviation of the linear regression, was fitted to the inverted minewater depths and used to forecast the time interval until the minewater will reach the water table and Earth's surface. In Donbas, the natural water tables lies between 20–70 m below the surface so a conservative value of 70 m was utilized (State Ecological Academy of Postgraduate Education and Management of the Ministry of Ecology and Natural Resources of Ukraine, 2018). Linear projections are often used by managing authorities as they provide an estimate towards the worst case. This is preferable to an exponential fit which might erroneously indicate an area is not at risk.

4. Results and discussion

4.1. Generation & calibration of minewater model

The forward model estimates the surface deformation caused by the change in minewater levels as measured within the mine shafts and good agreement between InSAR and modelled heave is found (i.e. heave occurs over mines where minewater is rebounding) (Fig. 2a,b). This confirms that heave observed at the surface above the mines is due to minewater rebound. The coal measures rock are subject to a level of geostatic pressure which is resisted by the rock matrix and the pore space within the rock. As the mines flood, the pore fluid pressure increases causing expansion of the strata which manifests as heave at the surface (Bekendam & Pöttgens, 1995; Poland, 1984). The forward model represents a simplification of the rebound occurring as a single measurement from within the mine shaft is used for the entire mine extents and the boundaries of which may not be wholly accurate. The InSAR measurements capture the variability in minewater rise which, when inverted, provides a detailed characterization of the rise in minewater. The inverted InSAR measurements assume that heave occurs solely as a result of rising minewater, which may not always be the only cause of the observed ground motions. However, it is a reasonable assumption given that the spatially correlated heave is delimitated by the structural geology and has been validated by the forward model. The inverted measurements demonstrate good agreement with the *in-situ* minewater measurements over the calibration period (November 2017–September 2019) (Fig. 2c,d). The inverted measurements account for the depth of minewater and, for example, correctly determine that minewater rose over twice as fast at Yunkom (612 m) than at Lenin (291 m) despite surface heave measuring four times less at Yunkom, ~15 mm compared to ~60 mm at Lenin.

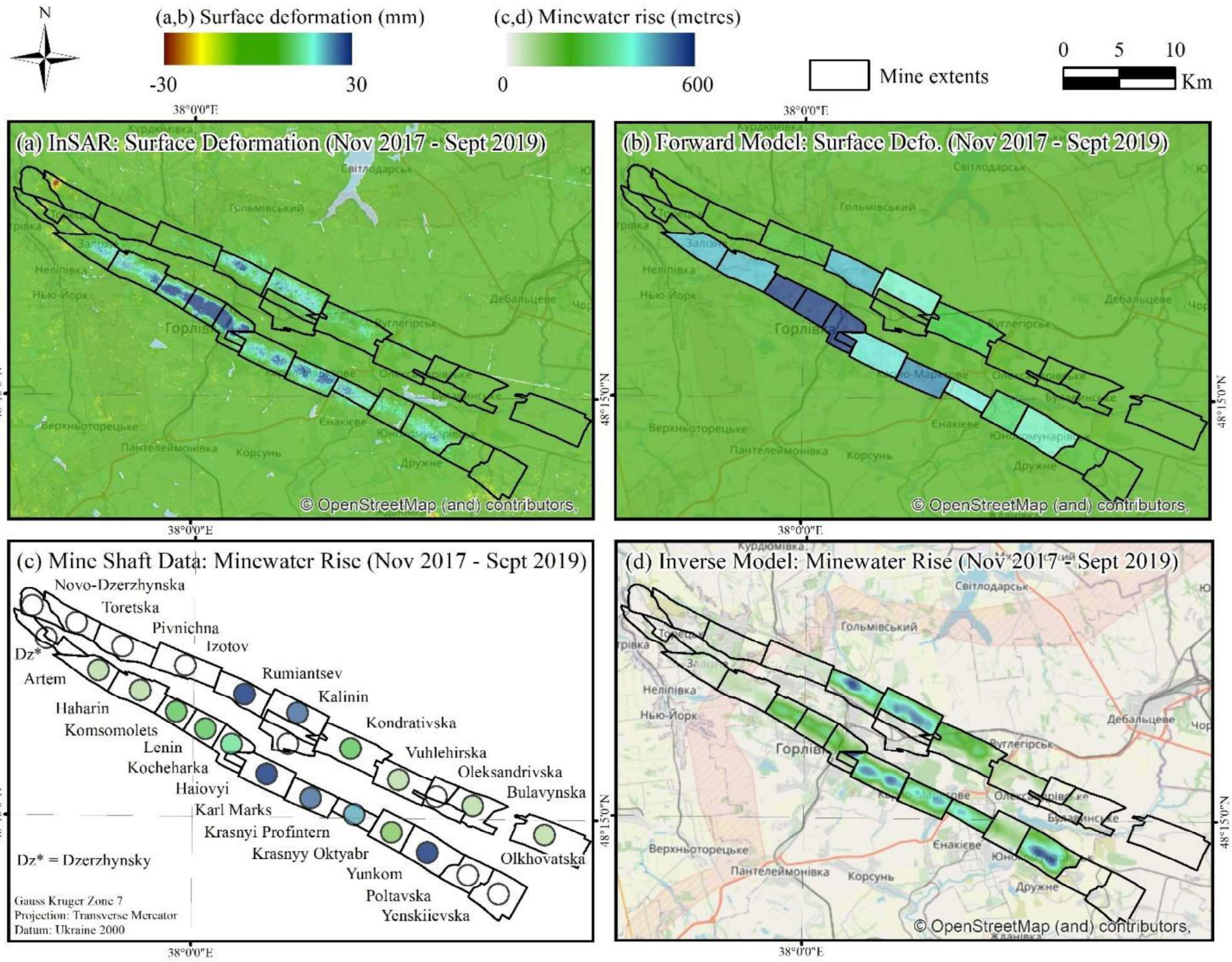

Figure 2. Surface deformation and minewater rise over the initial calibration period (1st of November 2017-1st September 2019) at the Horlivka mining agglomeration: (a) InSAR surface height change; (b) surface height change estimated by the calibrated forward model; (c) changes in minewater levels as measured within the mine shafts; (d) change in groundwater levels as derived from the inverse model.

4.2. Remote monitoring of minewater rise

The cross-sections through the northern and southern group of mines show the depth of minewater above mean sea level (a.m.s.l) as measured from *in-situ* data in November 2017 and September 2019, and the modelled levels in February 2022 (Fig. 3). The total change in minewater levels over September 2019 – February 2022 is shown in Fig. 4 and Fig. S1, which demonstrate good agreement with the *in-situ* data, where available. Making a direct quantitative comparison between the two datasets is challenging since the shaft measurements are of a single point, whereas the modelled data provides measurements over the entire mine complex. The effects of rebound can often be highly spatially variable, even within a single mine, and the most prominent areas of rebound can occur away from the shaft. For instance, a mine might have a small concentric area of rebound (e.g. Haiovyi) or a broader area covering the entire mine extents (e.g. Kalinin). Consequently, determining an evaluation metric, such as the mean within 500 m of the shaft or the median of all pixels within the mine extents, to compare against the *in-situ* data that appropriately reflects the models capability is challenging because the most appropriate and representative metric can change from mine to mine. One of the benefits of using this satellite based method is that measurements are provided across the entire mine extents and not just of a single point. Furthermore, it does not require detailed mine plans, hydraulic connections or fault information to achieve this. Advantageously, the presence of such features can be detected by the model. For example, if a connection to a neighbouring mine is reached uplift and the modelled minewater levels will begin to plateau. As minewater decants into the neighbouring mine, heave will likely start to be detected by the InSAR data and, therefore, rising minewater levels will be observed by the model.

Rebound is greater over the period from 2017–2019 than over 2019–2022, which is because the recovery of minewater is not a linear process, whereby the rate of rebound exponentially slows as the minewater approaches the surface. This occurs because the groundwater head difference between the recovering mined areas and the surround strata reduces with recovery and, hence, so does the rate of inflow into the recovering areas. Additionally collapsed shallow workings act to increase effective permeability closer to the surface and as minewater reaches shallower depths it interacts with the broader hydrogeological cycle (i.e. inflows and outflows into the river network) (Younger & Adams, 1999).

Within the string of mines in the north, pumping continues in Novo-Dzerzhynska and Toretska, while no data is available for the Pivnichna mine. Pumping ceased within Rumiantsev and Kalinin in 2017, which has resulted in minewater rising from depths of -600 m – -700 m a.m.s.l to -100 m, which is characterized in the inverted minewater rates over the calibration period (Fig. 1d). The cessation of pumping in these two mines has likely caused levels in the adjacent Kondrativska mine to rise (where pumping ceased in 2013), given that known connections are present between the mines at these depths (Ministry of Ecology and Natural Resources of Ukraine, 2019). Further east, with the exception of Vuhlehirska where pumping ceased in 2018, the Oleksandrivska, Bulavynska and Olkhovatska mines ceased pumping in 2014 and as a result minewater depths are closer to the surface than the mines further west. No data is available in the Oleksandrivska mine, however, given that the adjoining Vuhlehirska and Bulavynska mines have near identical minewater levels in 2017, 2019 and 2022 and that a connection between all three mines exists at -260m a.m.s.l. (Ministry of Ecology & Natural Resources of Ukraine, 2019), it could be inferred that levels here are similar.

The characteristics of rebound within the southern agglomeration of mines can approximately be characterized into three areas. Pumping ceased prior to 2015 in the west (consisting of the Artem, Haharin, Komsomolets, Lenin and Kocheharka mines), and by 2019 levels are approximately between ~ ±50 m a.m.s.l. Whilst minewater continues to rise at Artem and Haharin in 2022, the Komsomolets and Lenin minewater levels have plateaued and/or fallen. At this depth minewater can be prone to seasonal chances (Fig 3; 5a). In the central area, consisting of Haiovyi, Karl Marks, Krasnyi Profintern, Krasnyy Oktyabr and Yunkom, pumping ceased later (in 2017 or 2018) and, consequently, minewater instantly rose rapidly – over 600 m over two years in the case of Yunkom. Since 2019, rates of rebound have slowed as the minewater levels approach the surface but are still rising in 2022. The Poltavska and Yenakiievska mines are furthest east and are isolated from those to the west (Ministry of Ecology & Natural Resources of Ukraine, 2019). Here, pumping ceased in 2014 and levels have remained relatively stable since 2017. A connection exists between Yunkom and Poltavska at ~ 70 m a.m.s.l. and the inverted levels within Yunkom in February 2022 predict that minewater is close to reaching this connection, hence, facilitating the mixing of minewaters between these groups of mines.

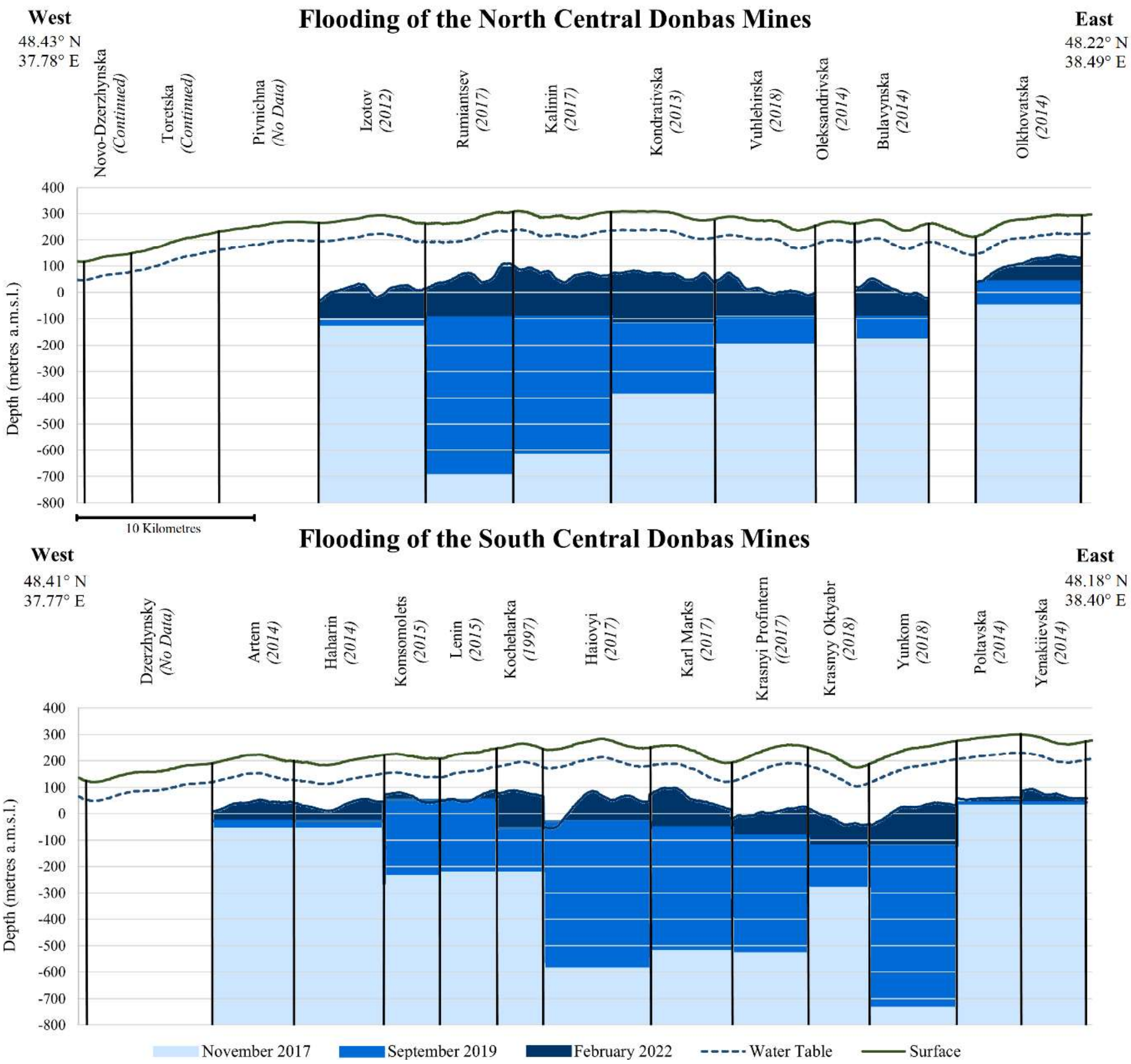

Figure 3. Minewater depths in 2017 (mine shaft measurements), 2019 (mine shaft measurements) and 2022 (inverted InSAR depths) for the northern and southern groups of the Horlivka mining agglomeration. The two transects where the inverted InSAR depths have been extracted are marked on Figure 4a. The horizontal black lines demark the mine boundaries. The date that pumping ceased is detailed below the mine labels (Ministry of Ecology & Natural Resources of Ukraine, 2019).

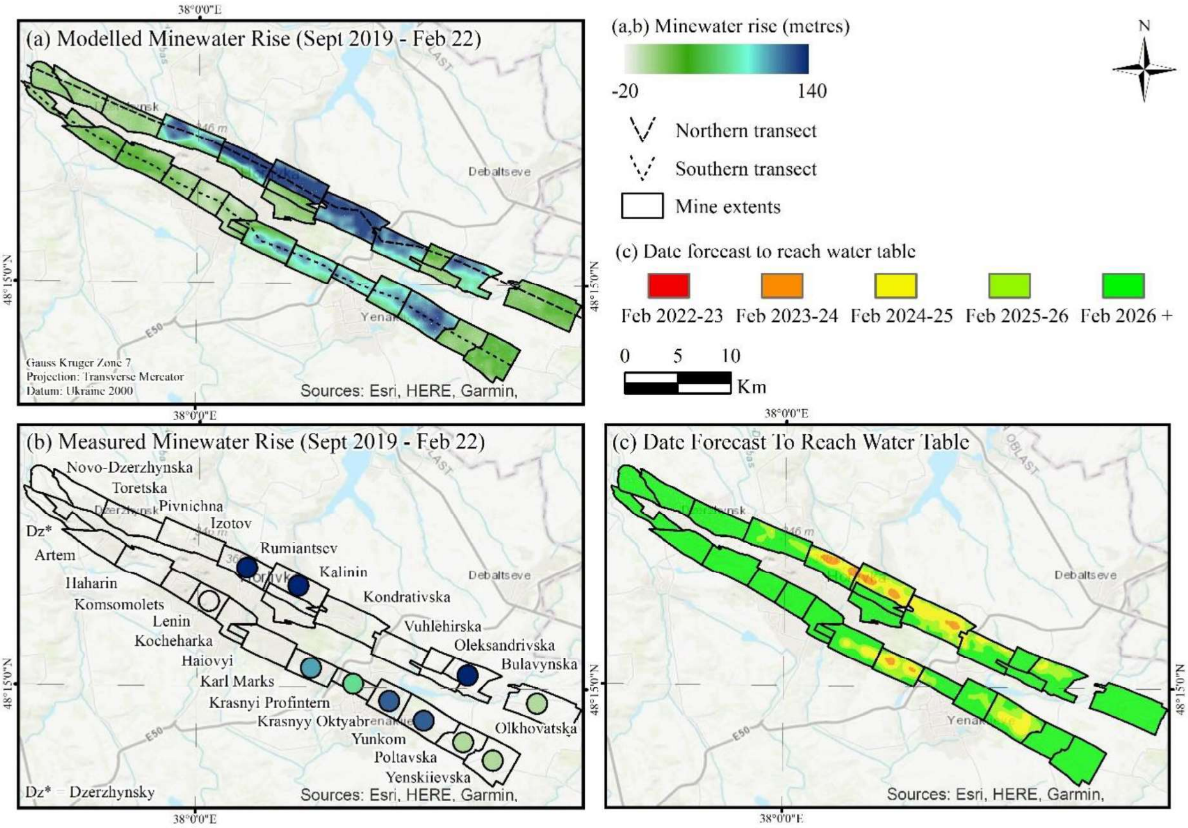

Figure 4. Minewater rise and forecasts: (a) Modelled change in minewater depth (September 2019 – February 2022); (b) actual change in minewater depth as measured in the mine shafts (September 2019 – February 2022); (c) estimated time until minewater will reach the water table.

4.3. Forecasts of minewater rise

The projected time at which minewater will take to reach the water table is shown in Fig 4c and selected time-series are shown in Fig. 5. The projections are indicative of the area's most at risk and assume that the minewater regime of the remotely monitored period continues (2019-22) which might not be the case. For instance, rates could increase if pumping is reduced or if a seam interval of relatively low yield rapidly floods. Alternatively, rates could decrease if an extensively worked seam of relatively high specific yield floods or if a connection to a neighbouring mine is reached. Nevertheless, it is indicative of when and where minewater discharges will occur based upon the latest measurements, which could be regularly updated in the implementation of a monitoring scheme. Within the coalfield, the Rumiantsev mine is forecast to reach groundwaters first, in Spring 2023, albeit towards the end of the time-series there is some evidence that the rate of rebound is reducing and levels appear that they could stabilize in the future. In the neighbouring mines of Kalinin, Kondrativska and Vuhlehirska, the minewater is predicted to reach the water table in the second half of 2023 and early 2024. In the west of the southern agglomeration (Artem to Kocheharka), rates have slowed significantly or are declining as in the case of Lenin, for example. In the east within Yunkom, minewater is predicted to reach groundwaters by the middle of 2024 and there is no evidence that the rate of rebound is decreasing as of February 2022.

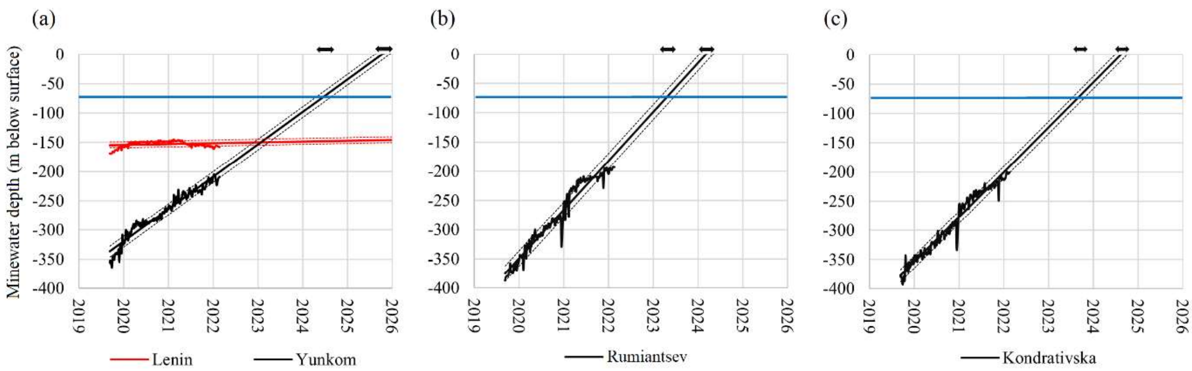

Figure 5. Time-series of minewater rise and forward forecast: (a) Lenin and Yunkom (forecast to reach the water table between 3rd May 2024 & 31st August 2024 and the surface between 8th July 2025 & 6th December 2025); (b) Rumiantsev (forecast to reach the water table between 22nd March 2023 & 12th June 2023 and the surface between 23rd January 2024 & 14th May 2024); (c) Kondrativska (forecast to reach the water table between 25th June 2023 & 1st November 2023 and the surface between 22nd June 2024 & 29th September 2024). The dashed lines show ± one standard deviation of the linear regression and the blue horizontal lines 70 m below the surface demarks the water table.

5. Environmental implications for Donbas

It is only relatively recently that attention has been brought to the environmental consequences of military conflicts (Ulytsky *et al.*, 2018). Donbas hosts one of the world's largest coal-mining technogenic geosystems with a high density of potentially hazardous facilities (Yermakov *et al.*, 2019). The neglect of pumping by the occupying administrations poses a serious risk of uncontrolled flooding and the leakage of toxic and/or radioactive substances (Yakovliev & Chumachenko, 2017; Yakovliev *et al.,* 2020). Access to the Donbas mines by scientists and Ukrainian authorities has become more and more limited and there is now insufficient and incomplete information about the state of the geological environment and mining space in a majority of mines or hydraulically connected groups of mines (Yakovliev & Chumachenko, 2017; Ulytsky *et al.*, 2018; Sadavenko *et al.*, 2020). The Ministry of Ecology and Natural Resources of Ukraine (2019) concluded it was essential that the monitoring network of boreholes be upgraded and modernized to provide complete and up-to-date data on the status of the groundwater, the geodynamic status of the rock mass and the chemical and ecological status of the surrounding environment. However, on 24th February 2022 Russia launched a full-scale invasion of Ukraine and this is likely to make the remediation of rising minewater in Donbas even less of a priority and therefore highly challenging.

The remotely identified changes in minewater levels and the forecasts of rebound are notable. Chumachenko & Yakovliev (2017) concluded that, should the mines in the Horlivka agglomeration become partially or fully flooded without engineered safeguards to isolate and protect the waterproofing of waste-storage facilities, the arrival of contaminated materials into the mines, aquifers and surface waters will likely prove disastrous. Whilst the exact outcomes are hard to predict, consequences are likely to include: surface deformations which might result in damage to the foundations of ecologically hazardous facilities such as toxic waste ponds and oil pipelines; a risk of atmospheric contamination from mine workings and other facilities with highly toxic unstable compounds in liquid or gaseous forms; long term migration of anthropic contaminants into ground and surface waters that are used for domestic water supply; and entry of toxic compounds into the food chain due to the flooding of agricultural areas (Chumachenko & Yakovliev, 2017; Ulytsky *et al.,* 2018). There is already evidence of surface waters becoming polluted with minewater in the surrounds of Horlivka and Yenakiieve (Eastern Option, 2020).

It is not fully understood what levels of pumping and management are undertaken in mines outside of Ukrainian control. Within the Horlivka mining agglomeration, according to unofficial information, the occupying authorities may still pump at so-call buffer mines, suggested to be Kalin, Lenin, Karl Marks, Yenakievksa and Olhovatska. However, the projected time until minewater reaches the natural water table within the Yunkom mine, mid 2024, is alarming. In 1979, an industrial underground nuclear explosion was undertaken within the mine to assess its effectiveness for reducing the occurrence of sudden gas and coal outbursts (Sadavenko *et al.*, 2020). The radioactive remnants of explosion chamber, the Klivazh facility, remain at approximately 900 m below the surface and Yakovliev *et al.* (2020) note that insufficient technological and physical remediation measures have been implemented in concurrence with the abandonment of the mines of the central mining district. The uncontrolled flooding of the Klivazh facility, which was designed to remain dry, could cause anthropogenic radionuclides to contaminate groundwater and the wider geological environment and lead to human exposure to radiation. A looming environmental catastrophe could be virtually impossible to control, driven by the amplifying power of winds, water flows, and the interconnectedness of mines (Yakovliev & Chumachenko, 2017). The active migration of contaminants in the direction of the drainage basin of the Siverskyi Donets, as well as rivers flowing into the Sea of Azov (e.g. the Krynka and Mius), highlight that this is of international significance (Chumachenko & Yakovliev, 2017) (Fig. 6).

Surface deformation data over the Donetsk and Luhansk oblasts reveal that other areas of Donbas are undergoing rebound, such as the Pervomaysk mining district in Luhansk (Ulytsky *et al.,* 2018; Ministry of Ecology and Natural Resources of Ukraine, 2019) (Fig. 6). Heave is also identified in the surrounds of the city of Donetsk, over areas known to be mined, and is identified nearby to concentric and often high-rate areas of subsidence. Similar deformations are detected elsewhere across the oblasts, particularly notable in central Donetsk and southern Luhansk. Implementing such a modelling approach as applied to Horlivka would likely provide beneficial information to the Ukrainian authorities as well as to environmental, diplomacy and intergovernmental organizations. The data highlights the 'hidden' environmental degradation that is occurring and such information could help to avoid a potential ecological disaster. A monitoring service could be implemented in near real-time with the aid of the Sentinel-1 mission. This could provide updates as frequently as every six days and could also be of use to assist in remediation efforts once the conflict is resolved.

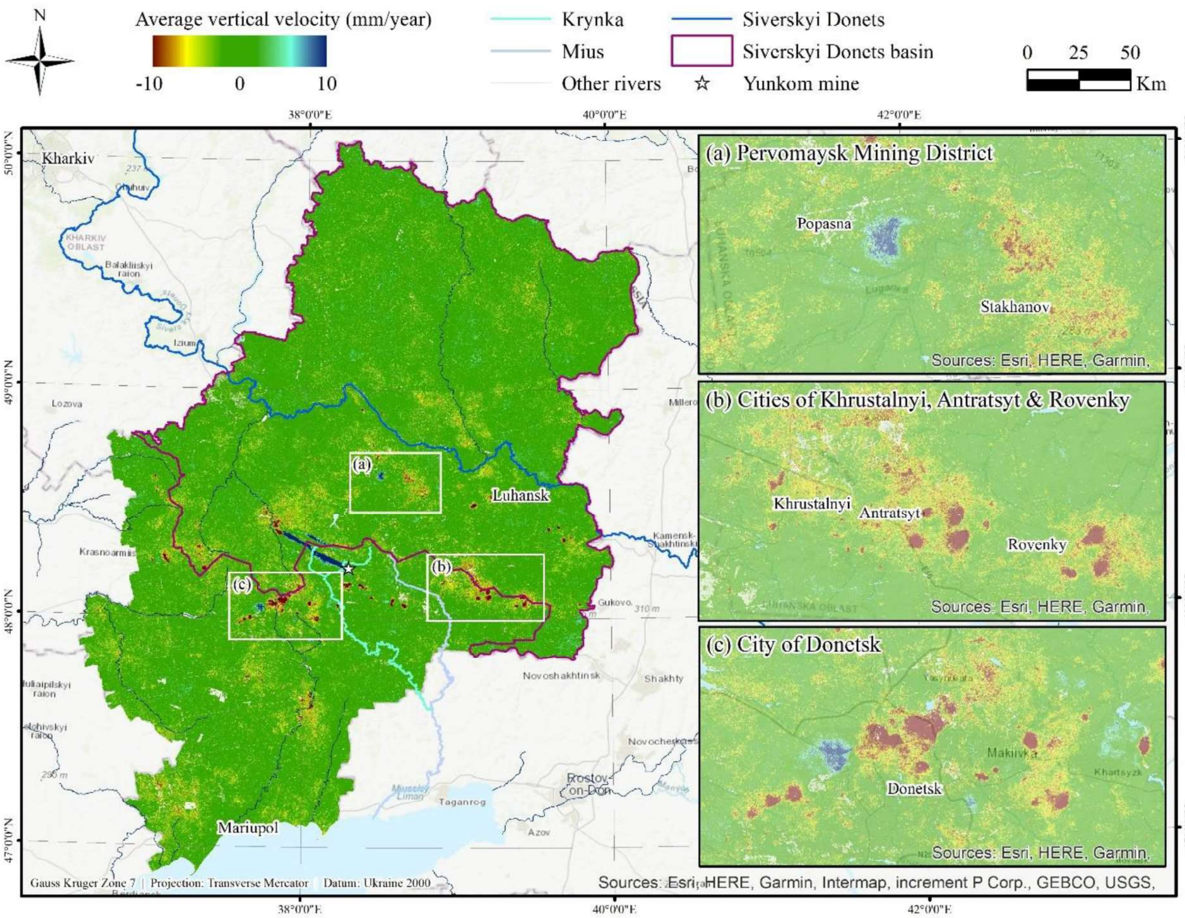

Figure 6. Surface deformation over the Donetsk and Luhansk oblasts with rivers (Polczynski, 2018) and the Siverskyi Donets drainage basin (Ministry of Ecology and Natural Resources of Ukraine, 2019) (within Donetsk and Luhansk only) overlaid. The river Krynka includes the tributaries of the Korsunka and Bulavina.

6. Conclusion

Identifying the rise of minewater in recently abandoned coalfields is challenging because ground measurements are often spatio-temporally sparse or not available at all. Obtaining adequate information on when and where minewater might surface are vital to avoid detrimental consequences following coalfield abandonment. The method presented in this study, based upon satellite radar interferometry, provides a remote, non-invasive solution to spatio-temporally monitor and forecast the rise of minewater which could be implemented in near-real time. The application to Horlivka identified that potentially radioactive minewater within the Yunkom mine could reach the level of the natural water table by the middle of 2024. This approach is highly advantageous in isolated or inaccessible areas, such as Donbas, where there is an urgent need to assess the hydrodynamic state of the mines due to the possibility of the spread radioactive contaminants, but no possibility of carrying out a comprehensive *in-situ* analysis.

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Author Contributions

A.A., D.G., Z.W., and A.S. contributed to the InSAR processing. D.G. devised the modelling framework and performed the groundwater analysis. All of the authors participated in the data interpretation. D.G. led the writing of the manuscript where all of the authors contributed and participated in manuscript editing and final approval.

Declaration of Competing Interest

The authors declare no conflicts of interest.

Data Availability

Data is available from the corresponding author on reasonable request.