Application of HySpex hyperspectral images for verification of a two-dimensional hydrodynamic model

Anita Sabat-Tomala, Anna Maria Jarocińska, Bogdan Zagajewski, Artur Stanisław Magnuszewski, Łukasz Maciej Sławik, Adrian Ochyra, Edwin Raczk and Jerzy Ryszard Lechnio

ABSTRACT
This research focuses on the use of HySpex hyperspectral images for verification of two-dimensional hydrodynamic modelling of open-channel flow over loose bed (CCHE2D) and assessment of water quality in the Zegrze Reservoir. The CCHE2D hydrodynamic model results show the distribution of hydraulic parameters of water flow and the sediment concentrations in the reservoir. HySpex images were used to obtain remote sensing indices of water quality. The images were compared to the hydrodynamic model results and field measurements. The analysis of hydrodynamic model results and hyperspectral image indices show the spatial distribution of the water’s physico-chemical properties in the reservoir, and poor mixing of the Bug River and the Narew River at their confluence. This study shows that there is synergy potential in using hydrodynamic modelling results and remote sensing indices of water quality for analysis of the reservoir’s water quality.

Introduction
Hydrological studies of artificial reservoirs face the problems of their large spatial dimensions and the complex dynamics of water bodies. Hydrodynamic models are helpful in such a task, as they make it possible to visualise basic hydraulic properties. Computational fluid dynamics (CFD) methods are capable of describing water velocities in river channels, both two dimensionally and three dimensionally. The problem of describing the process of sediment transport in a riverine environment is altogether more complex, with the difficulty stemming both from limitations on the measurement of concentrations of suspended sediments and bed load and from the need for empirical description of the river channel processes.

To study the dynamics of water in the Zegrze Reservoir, we use a two-dimensional hydrodynamic and sediment transport model for unsteady, open-channel flows over loose bed (CCHE2D), which was developed at the National Center for Computational Hydroscience and Engineering of the University of Mississippi, Mississippi, USA (Altinakar, Czernuszenko, Rowiński, & Wang, 2005). The model uses vertically averaged Navier–Stokes equations (Pedlosky, 2014) whose solutions provide information on the average flow velocity in the water column and across the water’s surface, and also on parameters describing sediment transport. The model’s equations were solved employing a modified finite-element method, using a control-cell technique (Altinakar et al., 2005; Strang & Fix, 1973). The calculations were carried out at the nodes of a curvilinear grid of irregular quadrangles. The model developed by Wu, Wang and Jia (2000) describes sedimentation processes using equations for suspended-load and bed-load transport.

Bed-load transport rate:

$$\frac{q_{bk}}{p_{bk}\sqrt{(y_s/y-1)d_k}} = 0.0053 \left(\frac{\tau}{\omega_{cri.k}} - 1\right)^{2.2}$$

(1)

Suspended-load transport rate:

$$\frac{q_{sk}}{p_{bk}\sqrt{(y_s/y-1)d_k}} = 0.000262 \left[\left(\frac{\tau}{\omega_{cri.k}} - 1\right)^{1.74}\right]$$

(2)

In the above two equations, $q_{bk}$, $q_{sk}$ denote bed-load and suspended-load transport rates, respectively, of sediment size class $k$ (m$^2$s$^{-1}$); $d_k$ denotes representative diameter of size class $k$ of the sediment mixture; $p_{bk}$ denotes fraction of sediment size class $k$ in the bed material; $g$ denotes gravitational acceleration; $y_s$
\(y\) denote specific weights of sediment and water, respectively; \(\tau\) denotes shear stress on the wetted perimeter of the cross section including bed and banks; \(\tau'_{b}\) denotes bed shear stress corresponding to grain roughness; \(\tau_{cr,k}\) denotes critical shear stress for the incipient motion of sediment size \(k\) on the bed; \(\omega_{k}\) denotes settling velocity; \(U\) denotes depth-averaged flow velocity.

In this approach, sediment transport rate is related to the rate of energy available in the stream and to the resistance to sediment suspension.

Hyperspectral images make it possible to perform multiple studies, commonly are calculated indices used to analyse the state of objects, for example vegetation (Jarocińska et al., 2016; Kycko et al., 2017). Hyperspectral indices are a mathematical combination of two or more reflectance values recorded on the image. Water quality indices are created based on the spectral properties of waters and are used to determine the distribution of selected substances in water. The studies are also conducted for the waters of an entire body of water within a short time, which allows for analysis of the spatial dynamics of changes in the physico-chemical properties of the waters (Koponen, 2006; Östlund, Flinka, Strömbeck, Pierson, & Lindella, 2001). The method is based on analyses of specific ranges of the electromagnetic spectrum, which correspond to the absorption of radiation by suspended load, microphytes and macrophytes.

The transparency of water is heavily influenced by suspended matter – mineral and organic particles. They cause an increase in the reflection of radiation in the 500–700 nm range (Ritchie, Schiebe, & McHenry, 1976). Analysis of the content of suspended matter has been carried out in, inter alia, the Erken lake in Sweden (Östlund et al., 2001). Suspended matter content taken from in situ studies was correlated with reflectance (\(\rho\)) values from a compact airborne spectrographic imager (CASI) sensor. Total Suspended Solids (TSS) in the water was determined using the equations:

\[
\text{TSS} = 0.46 + 2.41^* \rho_{555.9-564.8 \text{ nm}} \quad (3)
\]

\[
\text{TSS} = 1.92 + 4.49^* \rho_{614.5-625.2 \text{ nm}}. \quad (4)
\]

A spectral band of 555.9–564.8 nm resulted in coefficient of determination \(R^2\) which is equal to 0.79 as a measure of correlation, and 614.5–625.2 nm gave \(R^2 = 0.82\). The number of samples (\(N\)) was equal to 22.

For studying the contents of suspended solids in lakes in Finland, the 705–714 nm range was used. The best results were obtained in May of 1997, when the coefficient of determination was \(R^2 = 0.91\) (sample size \(N = 19\)), while in August of the same year it was \(R^2 = 0.85\) (\(N = 74\), Kallio et al., 2001).

Water quality can be related to coloured dissolved organic matter (CDOM) originating from phytoplankton and surface runoff. An increase of content is identifiable in the blue range (Fan, 2014) and in the 571–670 nm range (Menken, Brezonik, & Bauer, 2005). The quotient of 430 nm and 620 nm bands (Dekker, 1993) was also used.

Water transparency, measured with a Secchi disk (a black-and-white disc lowered on a measuring tape), decreases with an increase in suspended matter concentration. For remote sensing estimation of water transparency, the following light radiations were used: blue (~490 nm), green (~520 nm) and red (~670–750 nm) (Osińska-Skotak, 2010). From CASI and HyMap scanners, the \(\rho_{400/750}\) nm ratio correlates closely \((R^2 = 0.85, N = 30)\) with Secchi Disk Depth (SDD) measured in situ (Thiemann & Kaufmann, 2002).

One key research problem is the eutrophication of lakes resulting from the enrichment of their water with nutrients such as phosphorus and nitrogen (Lampert & Sommer, 1996). Phosphorus concentrations are indirectly estimated by using reflectance in red light \((\rho_{706/676} \text{ nm}, R^2 = 0.96)\), Dekker, 1993).

The process of eutrophication leads in turn to phytoplankton growth, detected by chlorophyll \(a\) concentrations. This pigment causes an increase in spectral reflectance in the green and near infra-red (NIR) ranges, and absorbs blue (~430 nm) and red light (~665 nm, Hejmanowska et al., 2006).

Kallio, Koponen and Pulliainen (2003) analysing the state of the waters of the Lohjanjärvi lake from AISA images used the following formula:

\[
\text{Chl} a = 108.5 \times (L_{705}/L_{662})-68.7 \quad (5)
\]

where \(L\) denotes radiance and obtained a high correlation coefficient with field measurements of chlorophyll \(a\) \((R^2 = 0.98, N = 12)\).

The same spectral ranges were used to estimate chlorophyll \(a\) content in the Hiiðenvesi lake, with the following formula:

\[
\text{Chl} a = 112.1 \times (L_{705}/L_{662})-77.1 \quad (6)
\]

where \(L\) denotes radiance, which also turned out to correlate strongly with in situ measurements \((R^2 = 0.96, N = 15)\), Kallio et al., 2003).

Studies of the Hafifa Bay lake conducted in June of 1995 showed that the reflectance for the water with a chlorophyll concentration of up to 20 mg/m\(^3\) falls in the 400–550 nm range, while for waters with a higher content of the pigment, it increases significantly in this range. The spectral reflectance curves also show a peak in the range of 680–710 nm, associated with the fluorescent properties of chlorophyll (Gitelson, Yacobi, Karnieli, & Kress, 1996).
Using a compact high-resolution imaging spectrometer (CHRIS) scanner on the European Space Agency (ESA) PROBA satellite, an analysis of water quality was carried out in the Masurian lakes and the Vistula Lagoon in Poland (Osińska-Skotak, 2010). The CHRIS scanner has a “water” mode (18 spectral channels in the range of 405–1035 nm, spatial resolution of 18 m), which is useful for investigations of surface water properties. Much better spatial resolution of images compared to other scanners (e.g. MERIS – 300 m, MODIS/TERRA – 250 m) enables analysis of lakes and other inland waters. The spectral reflectance values and field measurements (northwestern Poland) carried out in the period 2004–2008 had high correlation coefficients for the following: SDD ($R^2 = 0.90–0.96$ for the range 622–706 nm), Total Suspended Solids (TSS) ($R^2 = 0.82–0.87$ for the range 650–706 nm), Chlorophyll a (Chl a) ($R^2 = 0.71–0.72$ for the range 718–725 nm) and Total Phosphorus (TP) ($R^2 = 0.96$ for the wavelength 872 nm).

This paper presents a combination of three study methods: hydrodynamic modelling, hyperspectral remote sensing and traditional field measurements. The CCHE2D hydrodynamic model provided information on water flow dynamics and sediment transport. Parameters were generated describing the intensity and extent of bed-load transport rate, suspended sediments concentration, the Froude number (the ratio of flow inertia to gravity) and flow velocity. The hyperspectral images after geometric and atmospheric corrections were used to calculate indices of water quality presenting the spatial distribution of selected parameters, namely: TSS, CDOM, SDD, TP, Chl a, Turbidity (Turb) and Photochemical Reflectance Index (PRI). Field measurements provided supplementary information on water temperature, electrical conductivity and dissolved oxygen.

The objectives of this study are to assess the mutual relationship between hydrodynamic modelling and remote sensing indices of water quality, and analysis of the reservoir’s water quality. This is a significant problem, which should be solved in accordance with the requirements of the Water Framework Directive (2000/60/WE of 23 October 2000), which requires an analysis of water quality based on assessment of biological, chemical and physical indicators, since these determine the suitability of water to consumer, economic and industrial needs. In the long list of water quality parameters, there are suspended matter content, CDOM, phosphorus, phytoplankton and water colour and transparency (Frensenius, Quentin, & Schneider, 1988; Nollet and De Gelder, 2000).

**Study area**

The study was conducted on the Zegrze Reservoir (Figure 1), an artificial lake located 30 km to the north of Warsaw (Poland). It was built in the years 1957–1963 below the confluence of the Bug and Narew rivers. The highest water head near the Dębe dam is 7.10 m, while the average head is about 6.8 m. The backwater of the Zegrze Reservoir extends along the Narew to the vicinity of Pultusk at 63.3 km, and along the Bug to the town of Popowo at 17.0 km. The lake has a volume of $94.3 \times 10^3$ m$^3$, a surface area of 30.3 km$^2$, a length of 40 km, an average depth of 3.0 m and a shore length of over 100 km (Dojlido & Gromiec, 2003).

The catchment enclosed by the dam at Dębe has an area of 69,700 km$^2$. In the years 1951–2010, the average annual flow of the Bug was MQ = 162 m$^3$ s$^{-1}$ at Wyszków and of the Narew was MQ = 139 m$^3$ s$^{-1}$ at Zambski Kościelne. The other watercourses supplying the reservoir are the Rządza, the Prut and the Żerański Canal. The Dębe dam continuously stores water with the head at an elevation between 79.10 m and 78.60 m a.s.l. Under normal conditions of use, fluctuations in water level in the reservoir are small, of the order of 0.5 m.

The Bug River has a transboundary catchment located on the territory of Ukraine, Belarus and Poland. The Bug River catchment area is dominated by agriculture, but in Ukraine there are also sources of industrial and domestic effluents. The Narew River has a catchment with a large share of forest and meadows, and has better water quality than the Bug River (Dojlido, Taboryska, & Dmitruk, 2006). The denudation rate of the Bug River catchment measured at the Wyszków gauge in the period of 1951–1990 is 3.2 t km$^{-2}$ while for the Narew River at the Ostrołęka gauge it is 1.4 t km$^{-2}$ (Brański & Banasik, 1996). The intensity of sedimentation in the reservoir is not great, with the silting in the years 1963–1992 amounting to approximately 119,000 m$^3$ year$^{-1}$ (Dojlido & Gromiec, 2003). The accumulation of

![Figure 1. Location of the Zegrze Reservoir in Poland on the fifth band of Landsat 8 OLI – 29 October 2017 (source: https://earthexplorer.usgs.gov/).](image-url)
sediment at the mouth of the Bug is particularly intense, due to the river’s greater transport of suspended load and bed load (Magnuszewski, 2014).

**Methods**

The method is based on two elements. The first is modelling of the water and sediment fluxes in the reservoir, while the second is the development of remote sensing indices corresponding to the quality of the water and their correlation with the results of the hydrodynamic modelling and field measurements. The most important stages of work were as follows:

1. A digital terrain model (DTM) of the Zegrze Reservoir is developed based on bathymetric measurements. Contour lines were drawn manually and then a DTM of 10-m resolution was calculated by interpolation between the contour lines.
2. A numerical mesh containing \( i = 435 \) by \( j = 899 \) nodes was generated for the CCHE2D model on the basis of the DTM of the reservoir bed. The discharge of the Bug River and the Narew River on the day when the hyperspectral image was registered was assigned as the upper boundary condition.
3. Results of the model simulation as vector data layers were generated describing the spatial distribution of the bed-load transport rate, suspended sediment concentration, Froude number, total shear stress on the bed and flow velocity.
4. Based on the results of the CCHE2D hydrodynamic model, 39 monitoring points were selected for field verification works. Field measurements were performed on the water temperature, electrical conductivity, dissolved oxygen, and land-based ASD FieldSpec spectrometric measurements for atmospheric corrections.
5. Parallel with field measurements, aerial hyperspectral imaging of the Zegrze Reservoir was carried out using a HySpex scanners. Pre-processing of hyperspectral image consisted of geometric and atmospheric correction (using ASD FieldSpec4 spectrometric measurements) and masking.
6. Calculations of remote sensing water indices were: SDD, TSS, TP, Chl \( a \), CDOM, Turbidity.
7. Correlation of the value of remote sensing indices with the layers generated by the CCHE2D model, and with field measurements of water quality. The spectral properties were correlated with the layers generated by the CCHE2D model, and with field measurements.

This general study methodology is presented in Figure 2 and described in detail in the following sub-sections.

**Hydrodynamic modelling**

The topography of the bed of the Zegrze Reservoir was determined using detailed bathymetric measurements with GPS location, conducted by the company MGGP in 2004 for the Regional Water Management Authority in Warsaw. Additional bathymetric measurements were taken by sonar with a GPS receiver at the mouths of the Bug and the Rządza in 2015. Based on over 460,000 points of the echo-sounding measurements of the reservoir, a contour lines were drawn manually with the spacing of 1 m. Drawing of contour lines was assisted by the scans of old topographic maps showing the relief of the terrain before inundation by the reservoir. DTM in the format of a 10-m resolution raster grid was obtained by linear interpolation between the contour lines and single values representing bottom of isolated depressions or elevations.

Based on the 10-m DTM raster of the reservoir bed, a numerical mesh was created for the CCHE2D model, with separate resolutions for the main reservoir and its tributaries. The numerical mesh consisted of \( i = 435, j = 899 \) lines spaced every 10 × 10 m in the channels of the Rządza and Bug, and up to every 70 × 20 m in the main reservoir basin. At the part of main pool of the reservoir coarse computing grid with the spacing lower than the DTM resolution was applied due to calculation time limits. Finer computing mesh was used for mouths of the rivers where pattern of flow is more complicated.

Steady flow conditions were assumed: simulation time was 8,000,000 s, time step 60 s. A single value of \( n = 0.025 \) for the Manning coefficient of roughness was used for the entire body of water, and wind action was not taken into account in the simulation. The flows of the Bug (\( Q = 45.9 \text{ m}^3\text{s}^{-1} \)) and the Narew (\( Q = 41.0 \text{ m}^3\text{s}^{-1} \)) were
assumed for the upper boundary conditions, while for the lower boundary conditions the normal water head level of 79.02 m a.s.l. at the Dębe dam was adopted. These boundary condition values are appropriate to the conditions on the day for which the hyperspectral image was registered (2 October 2015). The inflows of the Narew and the Bug represent the low conditions, while the damming level corresponds to the normal water head level of the reservoir.

The model assumes a lack of clear boundary between suspended load and bed load, as is appropriate for an unsteady transport process in turbulent water flow. The diameter of individual fractions and their participation as a percentage of total transport were used as input data (Table 1). After Skibiński, Ciepielowski, Dąbkowski, Mordziński and Winiarczyk (1967), it was assumed that in the analysed lower courses of the rivers the share of suspended load was 70% of total load, while bed load comprised 30%.

The results of the CCHE2D hydrodynamic model describing the sedimentation conditions in the Zegrze Reservoir (i.e. intensity and extent of bed-load transport, amount of suspended load, Froude number, total shear stress on the bed and flow velocity) were prepared for analysis. The output data of the CCHE2D model in tabular format were converted to point maps according to the coordinate system adopted for the hyperspectral images (PUWG-92). Water quality parameters from remote sensing indices are represented by 391,065 points.

### Obtaining and processing of field data

Field measurements of the Zegrze Reservoir water quality were carried out at the end of September and beginning of October, 2015. Based on the results of the CCHE2D hydrodynamic model, 39 measurement points were determined, with a distribution which would ensure that cross sections and the longitudinal profile from the dam to the confluence of the Bug and the Narew would reflect the variability of the lake’s water quality properties.

During in situ studies, basic water quality parameters were measured, i.e. electrical conductivity (27 September 2015, $N = 39$), water temperature and dissolved oxygen (3 October 2015, $N = 41$) (Figure 3). Water samples for estimation of suspended mineral and organic matter content were taken using a PIHM (Polish Hydro-Meteorological Institute) bottle sampler; locations of measurement points were determined by a Leica GPS receiver.

During field measurements, the spectral properties of spectrally stable objects (water, concrete, asphalt and sand) were recorded using the ASD FieldSpec 3 spectrometer (ASD Inc., Longmont, CO, USA).

### Obtaining and processing of hyperspectral data

Hyperspectral data were obtained by the company MGGP Aero Sp. z o.o. on 2 October 2015.

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**Table 1.** Parameters of $d_{50}$ diameter suspended-load and bed-load grains, concentrations of suspensions ($C_s$) and bed-load transport rate ($q_r$), assumed as boundary conditions in the CCHE2D model.

| Profile                  | Suspended load | Bed load | $C_s$ (kg/m$^3$) | $q_r$ (kg/s m) |
|--------------------------|----------------|----------|------------------|----------------|
| Bug/Wyszków              | 0.000002       | 0.000368 | 0.016            | 0.032          |
| Narew/Zambski Kościelne  | 0.012          | 0.012    | 0.012            | 0.012          |
| Rządza/Rynia             |                |          |                  |                |
Overflights were made over the Zegrze Reservoir, with HySpex scanners (VNIR-1800 and SWIR-384) installed in a Cessna 402B aeroplane. For each line, the images from the two scanners were combined. Next, mosaic was done using 10 scanning lines of width 3600 m. The result was an image composed of 451 bands of spectral resolution of 416.2–2510.3 nm and spatial resolution of about 2 m (Figure 4).

Hyperspectral images were radiometrically and geometrically corrected based on the DTM (ATCOR 4 atmospheric correction using a MODTRAN5 model and a bidirectional reflectance distribution function was done), and the Savitzky–Golay filter was applied. Verification of the atmospheric correction was conducted basing on the field-acquired ASD FieldSpec spectral characteristics.

Next, a mask covering all elements of ground cover other than surface water was developed for the hyperspectral image, in order to isolate the signal originating from the waters of the reservoir. For this purpose, values from band 137 (wavelength: 850.8 nm) and reflectance in the range of 0 to 240 were set to show up in the image. In the pre-processing of the hyperspectral data ATCOR software was used, but in the further processing and building of the mask ENVI 5.1 software was used.

**Calculation of remote-sensed indices of water conditions**

The obtained HySpex hyperspectral image served to determine the distribution of the selected physicochemical parameters of the water with a spatial resolution of 2 m. On the masked image, the basic hyperspectral indices for water quality analysis were calculated (SDD, TSS, Turbidity, CDOM, TP, Chl a, PRI). This allowed us to determine the relative content of the above parameters in the Zegrze Reservoir waters. Table 2 presents the details of each index.

**Determining the relationship between parameters**

In order to establish the relationship between the water quality indices and the field measurements, the statistical correlation method was applied. The locations of field measurements (temperature, electrical conductivity and dissolved oxygen) were identified using a Leica GPS receiver. From the calculated images of water quality indices, values for pixels located up to 3 m from the measuring points were selected, thus reducing the possibility of errors stemming from the inaccuracy of GPS measurements or the mixing of water by boat. The values in the buffers were averaged and then correlated with the values of the water parameters. The normality of the data distribution was checked using the Shapiro–Wilk test. The distribution did not approximate to normal; therefore, to determine the relationship between the variables, a Spearman rank correlation was used. The sample size for the area of the Zegrze Reservoir was \(N = 39\).

![Figure 4. Hyperspectral HySpex image used in the analysis of water quality of the Zegrze Reservoir (RGB 640, 550, 471 nm) overlapped on the fifth band of Landsat 8 (source: earthexplorer.usgs.gov).](image-url)
The same method was used to analyse the relationship between values of the hyperspectral indices and the results of the hydrodynamic modelling (suspended sediment concentration, bed-load transport rate, Froude number, total shear stress on the bed and flow velocity). From among 390,000 points on the computing mesh of the CCHE2D hydrodynamic model, 600 were randomly selected, and their values were then correlated with the corresponding index values from the HySpex image.

Results

Hydrodynamic modelling results

The hydrodynamic modelling results show that the axis of the reservoir is the former bed of the Narew, together with its flood plains (Figure 5).

Starting from the Dębe dam, the greatest depths of the reservoir are arranged along the former bed of the Narew, which runs parallel to the right, upland bank. Within the most southerly part of the reservoir basin, a large, deep pool (between Zegrze and Nieporęt) and a small one (in the vicinity of Białobrzegi) have formed. In the central part of the reservoir, localised hollows in the bed have occurred as the result of commercial gravel excavation.

The obtained image of the distribution of hydraulic parameters within the modelled reservoir allows the riverine and lacustrine sections to be distinguished in the basin (Figure 6).

Up to its mouth into the reservoir, the Bug has the typical traits of a river, i.e. a flow velocity of 0.4–0.6 ms\(^{-1}\), while conditions typical of a lake prevail in the main pool, where flow velocities are below 0.03 ms\(^{-1}\). This division of the body of water is confirmed by the CCHE2D model, which depicts the distribution of suspended load in the reservoir; the main stream of sediment is transported by the Bug and then travels together with the water from the Narew to the main pool, where it is diluted.

Hyperspectral image analysis results

Images of the water quality parameters are presented in (Figure 7, along with a detailed analysis. (Figure 7(a–g)) Based on the TSS index (Figure 7(a)) and spectral curves for water (Figure 8), it can be stated that the greatest quantity of suspended matter is brought by the water flowing into the reservoir from the Bug (TSS index values above 60). This is due to the higher denudation rate and flux of municipal and industrial pollution. For the transport of the sediments, the high velocity of the Bug River is also important. The Bug enters the Zegrze Reservoir at a speed of 0.08–0.3 m s\(^{-1}\). Meanwhile, the Narew has a longer zone of backcurve and velocities below 0.06 m s\(^{-1}\), similar to the southern part of the lake. Differences between the rivers are also visible in the depths of the water. The Bug River has a depth of less than 2 m and is shallower than the Narew (depth of 2–8 m).

Flowing southwards, the waters of both rivers mix and, after losing velocity, deposit their suspended mineral load on the bed. This results in a lower mineral suspended load content in the surface waters of the southern part of Zegrze Reservoir (TSS index values around 30). The lowest concentration of mineral suspended load (TSS index values below 10) occurs in the eastern part of the reservoir, between the bridge in the town of Zegrze and the dam at Dębe.

Suspended load levels are related to water transparency. The SDD index on the Zegrze Reservoir has relative values from −1 to 3 (Figure 7(b)). The low
Figure 7. (a–g) The spatial distribution of water quality indices: TSS (a), SDD (b), CDOM (c), TP (d), Chl a (e), PRI (f), Turbidity (g) in the Zegrze Reservoir.
water transparency results from the high concentration of suspended sediments originating from the Bug (SDD index values below 0). The waters flowing into the reservoir from the Narew have a lower mineral suspended matter content and so greater transparency (SDD index values above 0.1). The southern waters of the reservoir have the greatest transparency, as a result of matter having fallen out of suspension to the lake bed in a process of sedimentation.

Based on the values of the CDOM index (range from 0 to 3), it can be stated that the waters of the Bug and the Narew have relatively low organic matter contents (Figure 7(c)) compared to the content of mineral matter (Figure 7(a)). There is also a low dissolved organic matter concentration around the port and the bridge at Zegrze (CDOM index values below 1.4), where the waters are partially isolated from the rest of the reservoir. In the north, waters rich in organic matter enter the Żegrzyński reservoir from the pumping station in Arciechów (CDOM index values around 1.9). Due to southerly winds, these waters are carried northwards. The next concentration of organic matter is found around Euzebia Island at the mouth of the Rządza, where the water loses velocity, creating an arrangement conducive to the closed circulation of water. There is also a high concentration of organic matter in the western part of the large deep pool and in the eastern part of the Narew, in the vicinity of the Dębe dam (CDOM index values around 2).

The waters flowing into Zegrze Reservoir from the Bug and the Narew are very varied in their phosphorus content, as seen in the TP index (Figure 7(d)). The highest concentration of this element is to be found in the water from the Bug (TP index values above 1.5). The high concentration of phosphorus in the Bug River results from the surface runoff of fertilisers from cultivated fields, the inflow of salt water from mines and the discharge of sewage. In contrast, the water of the Narew River has a lower content of phosphorus (TP index values around 1.1), and this can be explained by the higher share of forest in the land cover and the smaller number of point sources producing untreated sewage. This state of affairs, which arises from catchment management methods, is confirmed by national water quality monitoring results (Dojlido & Gromiec, 2003). The phosphorus load is transported to the south of the lake, where it is diluted. In the main deep pool between the Żerański Canal and the Narew, phytoplankton grows rapidly. In this process, phytoplankton uses phosphorus, so in the southern part of the lake the concentration of this element is the lowest (TP index values below 1).

In order to detect plant pigments (chlorophyll $a$, carotenoids) in the waters of Zegrze Reservoir, the Chl $a$ index (range from $-50$ to 25) and the PRI (range from $-0.3$ to 0.3) were used (Figure 7(e,f)). The highest concentration of plant pigments is found in the waters of the Narew and the southern part of the reservoir (Chl $a > 15$), where phytoplankton takes the most advantage to grow and develop (water stagnation, sufficient light due to high transparency of water, etc.). Meanwhile, conditions limiting the development of flora, i.e. high water velocity and low water transparency due to high sediment transport, are noticed at the mouth of the Bug (Chl $a < 2$).

The presence of phytoplankton is usually associated with turbidity in a lake. Turbidity is mainly due to phytoplankton blooms and decay processes, and occurs in places where the water velocity is low. With an increase in plant pigments in the water, turbidity also increases. The highest values for the Turbidity index (above 20) are found in the southern part of the Zegrze Reservoir, where there is fast-growing phytoplankton (Figure 7(g)). The water in the Narew is also fairly turbid, because the river has a low velocity and there is no strong turbulence, so there are good conditions for phytoplankton growth. However, the lowest turbidity (index values below 0) was observed at the mouth of the Bug, where the presence of phytoplankton is limited by the high flow rate and high concentration of TSS.

**Verification of the hydrodynamic model using remote-sensed indices of water condition and the results of field measurements**

The final stage of the study was to establish the relationship between the values of indices calculated for the HySpex image and the results of the field measurements and the hydrodynamic model.

Field studies of water quality encompassed the following parameters: electrical conductivity, dissolved oxygen and temperature. The distributions of the above data did not approach a normal distribution, so it was decided to calculate the Spearman rank
correlation coefficient. The level of significance was 0.05.

Measurements of electrical conductivity carried out at 39 points on 27 September 2015, that is to say, before the image was acquired, turned out to correlate reasonably with the values of remote sensing indices (Table 3).

Electrical conductivity is the water’s ability to allow the flow of electricity and is associated with the level of dissolved matter in the water, as is confirmed by their strong correlations with indices of turbidity, visibility and chlorophyll $a$. Oxygen and temperature measurements were carried out on 3rd October at the same points as those for electrical conductivity. The relationship between the indices and dissolved oxygen was closer than with temperature, which may indicate the decidedly higher diurnal variability of water temperature than of dissolved oxygen quantity. The highest positive correlation ($R_s = 0.62$) was noticed for dissolved oxygen and phosphorus, which reflects the fact that waters high in phosphorus come from the Bug, which is well aerated as a result of its high flow velocity.

Oxygen permeates into the water at the interface of the air from the surface of the water, and therefore flowing water absorbs more oxygen than standing water. Meanwhile, in waters high in chlorophyll $a$ and other plant pigments, oxygen content is low. This can be explained by the fact that the highest concentration of chlorophyll $a$ occurs in the lacustrine section of the reservoir, where mixing of the water is limited, which promotes sedimentation and can lead to water stagnation and the development of processes of decay. Therefore, despite the high concentrations of phytoplankton at the water’s surface, reduction processes predominate in the overall oxygen balance.

The correlation of the hydrodynamic model (total shear stress on the bed, extent of bed load, Froude number, concentration of suspensions, velocity) with the remote sensing indices also had quite a high coefficient (about $R_s = 0.5$, Table 4). Such a correlation for sample numbers of $N = 600$ indicates a strong relationship between the parameters.

The highest negative correlation values were for matches of the Froude number with Secchi disk indices and chlorophyll $a$. This means that as the flow velocity of the water decreases, the water becomes more transparent and phytoplankton content increases. Phytoplankton develops most quickly in stagnant waters with a plentiful supply of light. Suspensions calculated from the HySpex image and the hydrodynamic model correlate highly ($R_s = 0.52$), confirming the accuracy of the analysis conducted. Low correlation coefficients were obtained for the CDOM index.

**Discussion of results**

The methodology for processing remote sensing data for water quality information was based on principles similar to those of other researchers (Chen et al., 2004; Fan, 2014; Koponen et al., 2004; Olmanson, Brezonik, & Bauer, 2013; Thiemann & Kaufmann, 2002). The range of values of remote sensing water status indices presented in numerous publications was, despite the use of different algorithms and sensors, similar to those obtained in the Zegrze Reservoir watershed studies (Fan, 2014; Thiemann & Kaufmann, 2002). Used hydrodynamic model was confirmed by the HySpex image; similar accuracies were achieved from Landsat 7 satellite images in the study on surface water temperature of Rotorua lakes and Lake Taupo, North Island, New Zealand (Allan, Hamilton, Trolle, Muraoka, & McBride, 2016). Also radar image Envisat/ASAR was used to verify the results of wind drag action flooding of the Doñana Wetlands in Spain simulated by a 2D hydrodynamic model (Ramos-Fuertes, Marti-Cardona, Bladé, & Dolz, 2014). First attempt to verify CCHE2D model results of the suspended sediment concentration using an AISA hyperspectral image has been investigated on the Zegrze Reservoir in Poland (Magnuszewski, Sabat, Jarocińska, & Sławik, 2018).

The spatial distributions of the remote sensing indices for organic matter content and vegetation pigments developed in this study have the same tendency as the results of hydrological analyses conducted on the Zegrze Reservoir by the Institute of Meteorology and Water Management in the years 1994–2003 (Dojlido et al., 2006). The differences in physico-chemical parameters between the waters of the Narew and those of the Bug are confirmed in publications describing these rivers (Bok, 1994; Lubelska Fundacja Ochrony Środowiska

### Table 3. Spearman rank order correlations for the values of the HySpex image indices and field measurements.

| Conductivity | Dissolved oxygen | Temperature |
|--------------|------------------|-------------|
| 27 September 2015 | 03 October 2015 |            |
| TSS          | −0.52            | 0.36        | −0.38       |
| SDD          | 0.52             | −0.54       | 0.46        |
| Turbidity    | 0.54             | −0.61       | 0.46        |
| TP           | −0.43            | 0.62        | −0.39       |
| DOM          | 0.18             | −0.22       | 0.13        |
| Chl $a$      | 0.43             | −0.63       | 0.38        |
| PRI          | 0.46             | −0.60       | 0.32        |

### Table 4. Spearman rank order correlations for the values of the HySpex image indices and the results of hydrodynamic modelling.

| Total shear load | Bed load | Froude number | Suspended solids | Velocity |
|------------------|----------|---------------|------------------|----------|
| TSS              | 0.47     | 0.38          | 0.51             | 0.52     | 0.43     |
| SDD              | −0.57    | −0.41         | −0.60            | −0.56    | −0.52    |
| Turbidity        | −0.55    | −0.43         | −0.59            | −0.46    | −0.50    |
| TP               | 0.55     | 0.42          | 0.58             | 0.56     | 0.51     |
| DOM              | −0.08    | −0.31         | −0.12            | −0.09    | −0.06    |
| Chl $a$          | −0.55    | −0.42         | −0.58            | −0.57    | −0.51    |
| PRI              | −0.54    | −0.29         | −0.58            | −0.56    | −0.50    |
Naturalnego w Lublinie, 1997). The Secchi disk index distribution obtained from the HySpex image concurs with hydrodynamic model results presented in other works (Magnuszewski, 2014; Slapinska, Berezowski, & Chormański, 2014). Moreover, in past years, very similar water quality studies have been conducted on the Zegrze Reservoir using an AISA scanner (Sabat et al., 2016). The analyses of the HySpex image are a continuation of – and complement to – these studies.

The correlations between field measurements (in situ water parameter measurements) and hyperspectral index values obtained from these studies are somewhat lower than the determination coefficients obtained by other researchers (Table 5). This was due to the low number of field measurements and the fact that some relationships were being sought between different parameters for which the matched measurements in reality related to different water properties. Obviously, however, traditional and remote measurements of the same index yield a better result ($R^2 = 0.93 –$ Kallio et al., 2001; $R^2 = 0.96 –$ Dekker, 1993).

### Summary and conclusions

The objective of the research was to examine the relationship between the results of the implemented methods, to evaluate the usefulness of hyperspectral images in verifying hydrodynamic modelling and to analyse the water quality of the reservoir. An aerial measurement campaign and terrestrial measurement of water quality were conducted. Remote sensing water quality indices were calculated on the basis of HySpex images. Hydrodynamic modelling provided information on the water body dynamics described by the spatial distribution of the hydraulic parameters. The division of the water body into two parts (riverine and lacustrine) visible on the map of water velocity distributions obtained from the hydrodynamic model is also visible in the images of indices and clarifies the spatial variability of water quality parameters across the area. The strength of the correlation between water velocity and remote sensing indices values was approximately $R = |0.5|$ for SDD, TP, Chl a, PRI and Turbidity.

One benefit of the use of the HySpex scanner in analysing the reservoir water quality was the ability to get a synoptic view of the whole reservoir, and also the high repeatability of observations, which allows for monitoring of seasonal variations in water quality. The imaging’s spatial resolution, at almost 2 m, was sufficient to conduct a very detailed analysis. One limitation on the use of this kind of imaging is the need to obtain images in optimal weather conditions.

Verification of the CCHE2D hydrodynamic model by remote analysis and the accuracy of remote sensing indices were checked using field measurements of water quality. Spearman rank correlations between the index values from the HySpex image and the water chemistry measurements showed that field measurements of conductivity and dissolved oxygen correlated strongly with the majority of remote sensing indices. Moreover, the strongest relationship was between dissolved oxygen and Chl a ($R = -0.63$). Correlations between indices and the CCHE2D hydrodynamic model results show a strong relationship between hydraulic parameters and water quality.

Research showed that the low water velocity of the Narew, which results from the long backcurve extending to the town of Pultusk, causes a decrease in the suspended load and chemical content transported to the Zegrze Reservoir (the correlation coefficient between velocity and TSS was $R = 0.43$). The waters of the Narew are transparent and stable, which facilitates the development of phytoplankton. Meanwhile, the Bug has a greater flow velocity and carries a high amount of suspended mineral sediments and chemical pollutants, limiting the development of phytoplankton in its waters. The waters of the Narew and the Bug intermix as they flow towards the main reservoir pool. In the southern part of the Zegrze Reservoir and near the Dębe dam, the water velocity decreases, which, together with the high phosphorus load brought by the Bug River, creates conditions conducive to the growth of phytoplankton.

The implementation of HySpex images made it possible to verify the result of the hydrodynamic

### Table 5. Summary of the correlation results of water quality indices with field measurements.

| Remote sensing index/ in situ parameter | Instrument | Algorithm | $N$ | $R^2$ | Area | Source |
|-----------------------------------------|------------|-----------|-----|-------|------|--------|
| SDD/water transparency                  | CASI/HyMap |           | 30  | 0.85  | Germany | Thiemann & Kaufmann, 2002 |
| SDD/conductivity                        | HySpex     |           | 39  | 0.52  | Poland | Sabat et al., 2016 |
| TSS/suspended matter                    | MODIS      |           | 31  | 0.9   | USA    | Hu et al., 2004 |
| Turbidity/water turbidity               | MERIS      | R(645) – R(859) | 47  | 0.81  | Finland | Hamra et al., 2001 |
| Turbidity/conductivity                  | HySpex     |           | 105 | 0.93  | Finland | Kallio et al., 2001 |
| Chl a/chlorophyll                       | MERIS      | R(620)/R(705) | 12  | 0.76  | Italy   | Strömbeck et al, 2004 |
| TP/dissolved oxygen                     | CAESAR     |           | 19  | 0.96  | Netherlands | Dekker, 1993 |
| TP/dissolved oxygen                     | HySpex     |           | 39  | 0.62  | Poland | Sabat et al., 2016 |
modelling with regard to evaluating the accuracy of the mapped distributions of sediment concentrations, while the hydrodynamic model results were also helpful in interpreting the hyperspectral data. Combining these methods made it possible to understand the influence of hydraulic parameters on the water quality in the reservoir and to show the locations of concentrations of various substances such as suspended sediments or chlorophyll in the Zegrze Reservoir.

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ORCID

Anita Sabat-Tomala http://orcid.org/0000-0001-8954-5047
Anna Maria Jarocińska http://orcid.org/0000-0003-3610-4656
Bogdan Zagajewski http://orcid.org/0000-0001-7882-5318
Artur Stanisław Magnuszewski http://orcid.org/0000-0001-8697-3492
Adrian Ochytra http://orcid.org/0000-0003-4799-8093
Edwin Raczkow http://orcid.org/0000-0003-4843-9955
Jerzy Ryszard Lechnio http://orcid.org/0000-0002-9856-348X

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