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HYDROLOGICZNE UWARUNKOWANIA ROZWOJU ROŚLINNOŚCI NA OBSZARACH ODKRYWKOWEJ EKSPLOATACJI ZŁÓŻ SUROWCÓW MINERALNYCH

Rozprawa doktorska

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Chciałabym podziękować tym wszystkim, bez pomocy i wsparcia których
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Promotorowi, Profesorowi Uniwersytetu Śląskiego, dr hab. Tadeuszowi Molendzie,
Promotorowi, Profesorowi Uniwersytetu Bielsko-Bialskiego dr hab. Damianowi Chmurze,
Profesorowi dr hab. Oimahmadowi Rahmonovowi
za objęcie opieką naukową i pomoc
w przygotowaniu poniższej dysertacji doktorskiej
Oraz
Wszystkim, z którymi miałam przyjemność współpracować
i którzy pomogli mi w trakcie powstawania rozprawy.

Dziękuję.

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Lista artykułów i rozdziału w monografii stanowiących rozprawę doktorską

1. Natural and Anthropogenic Conditions of the Chemical Composition of Pit Lake Waters (Based on Example Pit Lakes from Central Europe) / **Tadeusz Molenda, Joanna Kidawa**.// Mine Water Environ., 2020, Vol. 39, iss. 3, pp. 473-480, ISSN: 10259112, DOI: 10.1007/s10230-020-00660-3
2. Hydrogeochemical conditions of the development of anthropogenic carbonate swamps: a case study of an abandoned Polish sandpit / **Agnieszka Błońska, Joanna Kidawa, Tadeusz Molenda, Damian Chmura.**// Pol. J. Environ. Stud., 2020, no. 1, pp. 561-569, ISSN: 12301485, DOI: 10.15244/pjoes/103444
3. The Hydrological-Hydrochemical Factors that Control the Invasion of the Black Locust (*Robinia pseudoacacia* L.) in Succession in Areas with Opencast Mines / **Joanna Kidawa, Damian Chmura, Tadeusz Molenda**.// Plants, 2021, no 10 (1), pp. 1-16, ISSN: 22237747, DOI: 10.3390/plants10010040
4. Hydrological and hydrochemical condiotions of the reclamation of anthropogenic water bodies and wetlands in opencast mines / **Joanna Kidawa, Damian Chmura, Tadeusz Molenda.//** In: A. Dyczko, A.M. Jagodziński, G. Woźniak G. (eds). The Green Scenarios: Mining industry responding to environmental challenges of the Anthropocene Epoch, CRC Press, Taylor & Francis Group, 2022, London, UK, pp. 23-36

Abstract

The exploitation of mineral deposits leads to changes in the natural environment of mining areas. These changes are most often identified with the transformation of relief and water relations. Particularly profound changes in the environment are caused by opencast mining, during which vegetation, soil, relief and water relations are disturbed. Despite previous research, few studies include a comprehensive description of post-mining areas. The issue of how these facilities operate is still little understood. The current knowledge on the processes (interactions) between water, ground and vegetation conditions in post-mining habitats should be considered negligible. Therefore, the main objective of the research was to clarify the mechanisms and processes that lead to the development and functioning of anthropogenic post-mining environments. In the case of some mines that have been rehabilitated, plant species unsuitable for the habitat type have been introduced, often resulting in their fallout and spontaneous colonisation processes. Studies on selected opencast mines indicate that the direction of spontaneous colonisation by vegetation is determined not only by the type of substrate and relief but also by the hydrological and hydrochemical conditions of the workings. Therefore, choosing an appropriate reclamation direction after the cessation of mining should be preceded by a detailed analysis of hydrological relations, geotechnical properties of the substrate, landforms and the nature of vegetation spontaneously colonising the mines. Addressing this research problem was a task that required extensive hydrological, hydrochemical, soil science and botanical studies, the results of which are presented in the publications constituting the basis of this doctoral dissertation. These publications showed significant relationships between vegetation and abiotic conditions of the habitat. The results obtained in the course of the research, reflected in the submitted doctoral dissertation, contribute to the knowledge about the relationship between hydrological and hydrochemical factors and colonisation by plants.

Streszczenie

Eksploatacja złóż surowców mineralnych prowadzi do zmian środowiska przyrodniczego obszarów górniczych. Zmiany te najczęściej utożsamiane są z przekształceniem rzeźby i stosunków wodnych. Szczególnie głębokie zmiany w środowisku powoduje eksploatacja odkrywkowa, podczas której zniszczeniu ulega roślinność, gleba, ukształtowanie rzeźby terenu oraz zaburzone zostają stosunki wodne. Pomimo prowadzonych wcześniej badań nieliczne są opracowania, które w sposób kompleksowy opisują obszary poeksploatacyjne. Problematyka funkcjonowania tych obszarów jest nadal mało poznana. Dotychczasowy stan wiedzy na temat procesów (interakcji) pomiędzy warunkami wodnymi, glebowymi a szatą roślinną, które występują w siedliskach poeksploatacyjnych należy uznać za znikomy. Dlatego też głównym celem badań było wyjaśnienie mechanizmów i procesów, które prowadzą do rozwoju i funkcjonowania antropogenicznych środowisk poeksploatacyjnych.

W przypadku niektórych kopalń, które zostały poddane rekultywacji wprowadzono gatunki roślin nieodpowiednie do danego typu siedliska, co często kończyło się ich wypadnięciem, a procesy kolonizacji przebiegały na drodze spontanicznych procesów. Badania wybranych kopalń odkrywkowych wskazują, że kierunek spontanicznej kolonizacji przez rośliny zdeterminowany jest nie tylko rodzajem podłoża, rzeźbą terenu lecz także stosunkami hydrologiczno – hydrochemicznymi wyrobiska. Dlatego też wybór właściwego kierunku rekultywacji po zaprzestaniu eksploatacji poprzedzony powinien zostać szczegółową analizą stosunków hydrologicznych, właściwości geotechnicznych podłoża, ukształtowaniem terenu oraz charakteru roślinności spontanicznie kolonizującej kopalnie. Podjęcie tego problemu badawczego było zadaniem wymagającym przeprowadzenia szeroko zakrojonych badań hydrologicznych, hydrochemicznych, gleboznawczych oraz botanicznych. Wyniki tego typu kompleksowych badań przedstawiono w publikacjach, które stanowią podstawę przedstawionej dysertacji doktorskiej. W publikacjach tych wykazano bardzo istotne zależności pomiędzy roślinnością a warunkami abiotycznymi siedliska.

1. Wstęp

Eksploatacja złóż surowców mineralnych prowadzi do zmian środowiska przyrodniczego obszarów górniczych. Zmiany te najczęściej utożsamiane są z przekształceniem rzeźby i stosunków wodnych (Dulias, 2016; Jaguś, Rzętała, 2012). Szczególnie głębokie zmiany w środowisku powoduje eksploatacja odkrywkowa, podczas której zniszczeniu ulega pokrywa glebowa i roślinna, rzeźba terenu oraz zaburzone zostają stosunki wodne. Zmiana stosunków wodnych może być zarówno następstwem celowych, zamierzonych działań człowieka (np. budowa studni odwadniających, przełożenia cieków), jak również następować niezamierzenie jako pośredni skutek eksploatacji. Do zmian tego typu możemy zaliczyć zanik cieków w strefie oddziaływania wyrobiska. W przeszłości po zakończeniu eksploatacji większość kopalń odkrywkowych nie była rekultywowana i pozostawiona naturalnym procesom geomorfologiczno – biologicznym (Molenda, 2005). W przypadku obszarów po eksploatacji odkrywkowej nowy, mineralny typ podłoża ogranicza możliwość kolonizacji tych obiektów przez roślinność. Jedynie nasiona wyspecjalizowanych gatunków roślin są w stanie się osiedlić i wykiełkować na tego typu podłożach. Rośliny te nazywamy pionierskimi, a sam proces ich wkraczania nosi nazwę kolonizacji. Kolonizacja danego obszaru przez rośliny jest związana z różnymi czynnikami, m. in. zależy od puli gatunków, a także od czynników abiotycznych, takich jak: warunki klimatyczne, a także lokalne warunki siedliskowe (światło, skład granulometryczny, odczyn, żyzność gleby, wilgotność itp.; Zobel, 1997; Poschlod i in., 2005). Każdy gatunek posiada zestaw cech, które umożliwiają wykorzystanie dostępnych zasobów i pozwalają w danych warunkach siedliska na funkcjonowanie tego gatunku (Bazzaz, 1996). Z biegiem czasu rośliny pionierskie zmieniają czynniki edaficzne i biotyczne umożliwiając kolonizację siedliska przez nowe gatunki roślin (Borgegard, 1990). W wyniku zachodzących przemian zwanych sukcesją może dojść do sytuacji wytworzenia na tego typu obszarach bardzo ciekawych biocenoz z wieloma gatunkami roślin w tym często chronionych. Różnorodność biologiczna nowo powstałych siedlisk może w niektórych przypadkach przewyższać bioróżnorodność siedliska, które występowało uprzednio przed okresem eksploatacji (Tokarska-Guzik i in., 2001). Utworzone biocenozy można zaklasyfikować jako nowe ekosystemy („*novel ecosystems*"). Nowe ekosystemy mają skład gatunkowy i względną obfitość gatunków, niespotykaną wcześniej. Kluczowymi ich cechami są: (1) nowość: nowe kombinacje gatunków/organizmów, które powodują zmiany w funkcjonowaniu ekosystemu; oraz (2) czynnik ludzki: ekosystemy, które są wynikiem świadomego lub nieumyślnego działania człowieka, ale nie zależą od ciągłej interwencji człowieka w celu ich utrzymania (Hobbs i in., 2006). Wg Ostręgi (2004) za Chodakiem (2013) można wyróżnić 7 kierunków rekultywacji: kulturowy, przyrodniczy, leśny, wodny, gospodarczy, rekreacyjny i rolniczy. Techniki rekultywacji często wiążą się z nasadzeniami gatunków roślin zarówno rodzimych jak i obcych. W przypadku niektórych kopalń, których tereny zostały poddane rekultywacji wprowadzono gatunki roślin nieodpowiednie do danego typu siedliska, co często kończyło się ich wyginięciem, a procesy kolonizacji przebiegały na drodze spontanicznych procesów (Krzaklewski, 1988; Rostański, 2003; Tokarska-Guzik, 2003).

Badania wybranych kopalń odkrywkowych wskazują, że kierunek spontanicznej kolonizacji przez rośliny zdeterminowany jest nie tylko rodzajem podłoża, rzeźbą terenu lecz także stosunkami hydrologiczno – hydrochemicznymi wyrobiska. Dlatego też wybór właściwego kierunku rekultywacji po zaprzestaniu eksploatacji poprzedzony powinien zostać szczegółową analizą stosunków hydrologicznych, właściwości geotechnicznych podłoża, ukształtowaniem terenu oraz charakteru roślinności spontanicznie kolonizującej wyrobisko. Aby poznać uwarunkowania (głównie abiotyczne) kształtowania procesów przyrodniczych na obszarach górnictwa odkrywkowego przeprowadzono kompleksowe badania hydrologiczne, hydrochemiczne, gleboznawcze i botaniczne.

2. Cele i hipotezy

Antropogeniczne środowiska poeksploatacyjne były już przedmiotem badań. Jednak dotychczas badania te skupiały się najczęściej na jednym aspekcie. Najliczniejsze są prace typowo botaniczne, gdzie podkreślano głównie znaczenie tego typu obiektów dla zachowania różnorodności biologicznej, wskazując na występowanie cennych przyrodniczo gatunków roślin, w szczególności gatunków charakterystycznych dla niskich torfowisk węglanowych rzędu *Caricetalia davallianae* (Czylok, 2004; Bzdon, Ciosek, 2006; Chmura, Molenda, 2007, 2008; Czylok i in., 2008; Bzdon, 2009; Czylok, Szymczyk, 2009; Kompała-Bąba, Bąba, 2009, 2013; Szymczyk, Rahmonov, 2010; Řehounková, Prach, 2006; Řehounková, Prach, 2008; Šebelíková i in. 2016). Procesy kolonizacji gleb mineralnych badane były również na innych obiektach, w których naturalna szata roślinna i pokrywa glebowa została zniszczona pod wpływem oddziaływania czynników antropogenicznych (Cabała, Rahmonov, 2004; Rahmonov, 2007; Rahmonov, Piątek, 2007; Rahmonov, 2009; Rahmonov, Szymczyk, 2010). Inne prace dotyczyły problematyki hydrologicznej (limnologicznej; Rzętała, 2008).

Większość z prac dotyczyła również najczęściej jednego obiektu nie próbując wskazać prawidłowości w funkcjonowaniu obiektów poeksploatacyjnych. Pomimo prowadzonych wcześniej badań nieliczne są opracowania, które w sposób kompleksowy opisują obszary poeksploatacyjne. Problematyka funkcjonowania tych obiektów jest nadal mało poznana. Dotychczasowy stan wiedzy na temat relacji (interakcji) pomiędzy warunkami wodnymi, glebowymi a roślinnością, które występują w siedliskach poeksploatacyjnych należy uznać za niewystarczający. Literatura dotycząca tego typu problematyki liczy zaledwie kilkanaście pozycji. Należy również nadmienić, że nie obejmuje ona wszystkich typów środowisk poeksploatacyjnych. **Dlatego też głównym celem badań było wyjaśnienie mechanizmów i procesów, które prowadzą do rozwoju i funkcjonowania antropogenicznych środowisk poeksploatacyjnych.** Ważnym, niewystarczająco poznanym problemem nadal pozostają badania nad oddziaływaniem specyficznych czynników chemicznych i fizycznych na procesy sukcesji. Dotyczy to w szczególności rozpoznania składu chemicznego wód zbiorników poeksploatacyjnych, który może być kształtowany zarówno przez naturalne jak i antropogeniczne czynniki. Poruszona w rozprawie problematyka jest nowatorska, gdyż podjęto się rozwiązania bardzo ważnego, jednak słabo poznanego problemu. Takie badania są rzadkością, a w Polsce jest potrzeba zwiększenia wiedzy z zakresu funkcjonowania obszarów poeksploatacyjnych. Podjęcie tego problemu badawczego było zadaniem wymagającym przeprowadzenia szeroko zakrojonych badań hydrologicznych, hydrochemicznych, gleboznawczych oraz botanicznych.

W celu realizacji powyższego zadania do badań wytypowano obszary eksploatacji odkrywkowej. Były to zarówno stare nieczynne wyrobiska poeksploatacyjne różnych surowców mineralnych, jak również zwałowiska skał nadkładu lub osadów popłuczkowych.

Identyfikacja różnych obszarów poeksploatacyjnych była przyczynkiem do poszukiwania odpowiedzi na następujące pytania badawcze:

- Czy poszczególne środowiska poeksploatacyjne wykazują zróżnicowane właściwości hydrochemiczne?,

- Czy poszczególne środowiska poeksploatacyjne wykazują zróżnicowane właściwości hydrologiczne?,

- Czy zróżnicowanie właściwości hydrograficzno – hydrochemiczno – glebowych środowisk poeksploatacyjnych wpływa na kierunek ich kolonizacji.

Aby odpowiedzieć na postawione pytania badawcze przeprowadzono badania w obrębie zróżnicowanych środowisk poeksploatacyjnych położonych zarówno na terenie południowej Polski, jak i północnych Czech.

Wyniki badań opublikowano w trzech artykułach naukowych w czasopismach znajdujących się w bazie Web of Science, Scopus, Journal Citation Reports oraz rozdział w monografii w wydawnictwie Taylor & Francis. Są to:

1. Molenda T, Kidawa J., 2020: *Natural and Anthropogenic Conditions of the Chemical Composition of Pit Lake Waters (Based on Example Pit Lakes from Central Europe).* Mine Water Environ., 2020, Vol. 39, iss. 3, pp. 473-480, ISSN: 10259112
2. Błońska A, Kidawa J, Molenda J, Chmura D., 2020: *Hydrogeochemical conditions of the development of anthropogenic carbonate swamps: a case study of an abandoned Polish sandpit.* Pol. J. Environ. Stud., 2020, no. 1, pp. 561-569, ISSN: 12301485
3. Kidawa J, Chmura D, Molenda T., 2021: *The Hydrological-Hydrochemical Factors that Control the Invasion of the Black Locust (Robinia pseudoacacia L.) in Succession in Areas with Opencast Mines*. Plants, 2021, no 10 (1), pp. 1-16, ISSN: 22237747
4. Kidawa J, Chmura D, Molenda T., *Hydrological and hydrochemical conditions of the reclamation of anthropogenic water bodies and wetlands in opencast mines*, A. Dyczko, A.M. Jagodziński, G. Woźniak G. (eds). The Green Scenarios: Mining industry responding to environmental challenges of the Anthropocene Epoch, CRC Press, Taylor & Francis Group, 2022, London, UK, pp. 23-36

Prace te stanowią podstawę prezentowanej dysertacji doktorskiej. Wkład Autorki rozprawy w poszczególne publikacje jest szczegółowo przedstawiony i potwierdzony załączonymi oświadczeniami współautorów.

3. Materiał i metody badań

3.1. Obiekty badawcze

Badania realizowane były na obszarach nieczynnych lub funkcjonujących kopalń odkrywkowych. Badane obiekty położone były zarówno na terenie południowej Polski, jak i północnych Czech (Rys. 1). Obecnie prawie wszystkie nieczynne wyrobiska kopalń odkrywkowych zostały zatopione i funkcjonują jako zbiorniki lub mokradła poeksploatacyjne. Należy podkreślić, że obszary starych kopalń cechują się dużym zróżnicowaniem warunków morfologicznych i hydrologicznych. W obrębie kopalń odkrywkowych występują nie tylko formy wklęsłe (wyrobiska), ale zlokalizowane są tam również składowiska skał nadkładu oraz osadniki szlamów popłuczkowych. Stwarza to bardzo dużą mozaikę siedlisk o zróżnicowanych właściwościach hydrologiczno – hydrochemiczno – glebowych.

Rys. 1. Regiony, w obrębie których położone są obiekty badań

3.2. Zbiór danych

Postawione cele badawcze wymagały przeprowadzenia szeroko zakrojonych badań hydrologicznych, hydrochemicznych, gleboznawczych oraz botanicznych.

3.2.1. Metody badań hydrologicznych i hydrochemicznych

Kartowanie hydrograficzne pozwalające na ocenę stosunków wodnych które występują w obrębie kopalń odkrywkowych lub wyrobisk poeksploatacyjnych przeprowadzono zgodnie z wytycznymi podanymi przez Gutry – Korycką i Werner – Wieckowską (1996). Przeprowadzono również analizę archiwalnych materiałów kartograficznych, która pozwoliła uchwycić zmiany jakie następowały w następstwie eksploatacji odkrywkowej. Podczas analiz kartograficznych i hydrologicznych wykorzystano oprogramowanie ArcGIS firmy ESRI wraz z rozszerzeniami w Arc Map 10.6.

W terenie wykonano pomiary podstawowych parametrów fizykochemicznych wody (temperatury, odczynu, przewodności elektrolitycznej, potencjału Redox) za pomocą sondy wieloparametrowej EDS 6600 firmy YSI produkcji USA lub miernika wieloparametrowego Hanna HI98194. Przed każdymi badaniami sonda była kalibrowana za pomocą roztworów wzorcowych. W trakcie badań terenowych pobierano również próbki wody do analiz chemicznych.

Próbki wody do analiz laboratoryjnych pobierane były do butelek polietylenowych o pojemności 0,5 L. Wody warstwy powierzchniowej pobierane były za pomocą wysięgnika teleskopowego. Transport prób wody do laboratorium odbywał się w warunkach chłodniczych w temperaturach 5 ± 2ºC. Przed analizami próby były filtrowane na sączku 0,45 µm (Millipore). Analizy laboratoryjne objęły oznaczenie głównych kationów i anionów w wodzie: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+}, Br, F, HCO_3^{-}, SO_4^{2-}, Cl^{-}, NO_3^{-}, PO_4^{2-}. Analizy te przeprowadzone zostały na chromatografie jonowym Metrohm 850 Professional IC, a wodorowęglany oznaczono metodą miareczkową ze wskaźnikiem b-r (blue-red). Typ hydrochemiczny wód ustalono w oparciu o klasyfikacje Szczukariewa – Prikłońskiego (Macioszczyk, 1987).

3.2.2. Metody badań gruntów i osadów

Jakościowe analizy składu chemicznego ewaporatów stwierdzonych w obiekcie „Szczakowa" oraz odpadów przemysłowych, które miały wpływ na jakość wód zbiorników poeksploatacyjnych oznaczone zostały za pomocą:

- fazowych badań rentgenowskich (dyfraktrometr rentgenowski Philips PW 3710 z monochromatorem grafitowym),

- badań submikroskopowych (mikroskop skaningowy Philips XL 30 z przystawką analityczną EDS, EDAX typu Sapphire).

W poletkach badawczych pobierano próbę mieszaną gleby i oznaczono następujące właściwości fizykochemiczne:

- pH – metoda potencjometryczna w 1mol KCl i H_2O;
- azot ogólny (NT) – metodą Kjeldahla;
- fosfor przyswajalny (P) – metodą Egnera-Riehma;
- węglan wapnia ($CaCO_3$) - metodą Scheiblera
- węgiel organiczny – metodą Tiurina.

Ponadto oznaczono uziarnienie badanych prób za pomocą metody areometrycznej Prószyńskiego oraz metody sitowej. Badania te przeprowadzono zgodnie z normami obowiązującymi w Polsce. Wilgotność gruntu (mocy ssącej wody glebowej) mierzono bezpośrednio w terenie za pomocą tensjometru Stelzner.

3.2.3. Metody badań botanicznych

Przy oznaczeniach gatunków roślin korzystano m.in. z kluczy do oznaczania roślin „Klucz do oznaczania roślin naczyniowych Polski niżowej" (Rutkowski 2017), „Rośliny zielne i krzewinki Polski" (Urbisz, Urbisz 2004), atlasu Exkursionsflora von Deutschland (Rothmaler 1994) i wielu innych.

Na terenie piaskowni w Szczakowej przeprowadzono inwentaryzację florystyczną roślin naczyniowych. Dane florystyczne przeanalizowano pod kątem ekologicznym wymagań gatunków przy użyciu wartości wskaźników Ellenberga (Ellenberg, Leuschner 2010), które w skali od 1-9 a dla wilgotności w skali 1-12 prezentują optima występowania gatunków w tym dla światła (L), wilgotności (F), odczynu gleby/podłoża (R) i azotu (trofii, N). Nie użyto jedynie wskaźnika kontynentalności (K), ponieważ na małym terenie użycie tego wskaźnika nie ma uzasadnienia. Wyliczono zarówno średnie arytmetyczne wskaźników Ellenberga, jak również pokazano rozkład gatunków prezentujących określone wartości wskaźników.

W obliczeniach pominięto gatunki, które miały przydzieloną wartość „X", ponieważ nie mają żadnej wartości diagnostycznej. Klasyfikacji syntaksonomicznej gatunków tj. przynależności do zbiorowisk roślinnych dokonano w oparciu o „Przewodnik do oznaczania zbiorowisk roślinnych" (Matuszkiewicz 2011). Określono gatunki chronione prawnie (Rozporządzenie...) oraz gatunki zagrożone wg „Czerwonej Księgi" (Kaźmierczakowa i in. 2016).

W obrębie poletek badawczych na terenie kopalni „Wójcice" dokonano spisu florystycznego (roślin naczyniowych i mszaków) oraz wyceniono wizualnie pokrycie stwierdzonych roślin w % (1,2,5,10,20....100), przy wspomaganiu aplikacji Canopy Cover Free 5/12 1.03) na mobilne urządzenia z systemem android, a pod okapem drzew użyto aplikacji GLAMA do oceny zwarcia drzewostanu (Tichý, 2015).

3.3 Analiza danych

Aby zbadać podobieństwa i różnice we właściwościach fizykochemicznych wód zbiorników poeksploatacyjnych zastosowano analizę wielowymiarową w postaci analizy skupień. Jako miarę podobieństwa użyto odległości euklidesowej i metody grupowania Warda.

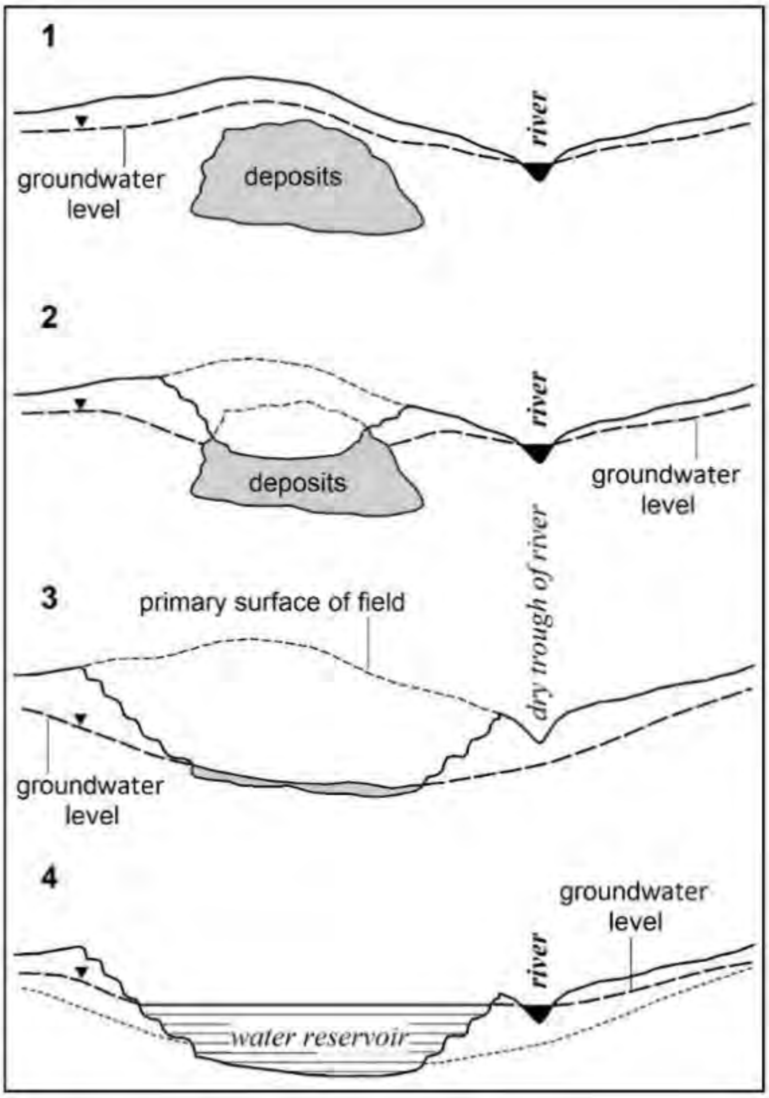
Dla sprawdzenia istotności różnic pomiędzy stężeniami analizowanych jonów zastosowano nieparametryczny odpowiednik analizy wariancji test Kruskala-Wallisa, a do porównań wielokrotnych test Conovera, gdy wynik testu Kruskala-Wallisa okazał się istotny statystycznie (Artykuł 1 i 2). Wszystkie dane zaprezentowano przy pomocy wykresów pudełkowych z wąsami (*box-and-whiskers plots*). W przypadku porównań istotności różnic w medianach odpowiednich zmiennych np. fizycznych czy chemicznych parametrów wody między danymi obiektami różnice te zaznaczono przy pomocy odpowiednich małych liter (a, b, c) umieszczonych na górze rysunku. Różne litery oznaczają, że wartości różnią się istotnie przy $p<0,05$.

W oparciu o zebrane dane roślinności wyliczono wskaźniki różnorodności biotycznej: liczbę gatunków (S), wskaźnik różnorodności Shannona-Wienera (H') i równomierności gatunkowej (E), a także sumę pokrycia gatunków (COVER). Następnie przeprowadzoną niemetryczne wielowymiarowe skalowanie (*Non-metric multidimensional Scalling NMDS*) celem zbadania kierunków zmienności analizowanej roślinności. Na potrzeby NMDS dane gatunkowe zlogarytmowano. W celu oceny różnic w składzie gatunkowym między roślinnością 4 poligonów badawczych przeprowadzono analizę centroidów reprezentujących roślinność danego poligonu za pomocą pasywnego dopasowania wektorowego (*vector fitting*). Istotność różnic zbadano przy pomocy testu permutacyjnego Monte Carlo (999 iteracji). Tego samego testu (999 permutacji) użyto do dopasowania pasywnego wskaźników różnorodności biotycznej (S, H, E) na przestrzeń ordynacyjną NMDS, aby sprawdzić czy one tłumaczą zmienność w danych gatunkowych. Pasywne dopasowanie wektorowe było jedyną dopuszczalną techniką statystyczną ponieważ wskaźniki różnorodności biotycznej nie są niezależnymi danymi i zostały obliczone na podstawie danych gatunkowych. Aby zbadać wpływ niezależnych czynników siedliskowych pH, zawartości azotu ogólnego, fosforu, frakcji spławialnych podłoża (<0,05 mm) zastosowano bezpośrednia analizę gradientową jaką jest kanoniczna analiza korespondencji (*Canonical Correspondence Analysis CCA*). Wyliczono wskaźnik VIF (*variance inflation factor*) aby wyeliminować potencjalne skorelowane zmienne. Żaden ze wskaźników nie osiągnął wartości powyżej 10. Porównań w wartościach wskaźników różnorodności biologicznej, wskaźnikach Ellenberga oraz w czynnikach siedliskowych między poligonami badawczymi dokonano za pomocą testu Fishera-Pitmana, nieparametrycznego odpowiednika analizy wariancji ANOVA. Przed zastosowaniem testów statystycznych sprawdzających hipotezy badawcze sprawdzono założenia dla testów parametrycznych czyli zgodność z rozkładem normalnym (wynik testu Shapiro-Wilka $p >0,05$) lub z homogeniczność wariancji (wynik testu Levene'a p >0,05). Ponieważ hipotezy o zgodności z rozkładem normalnym i jednorodności wariancji zostały odrzucone zastosowano testy nieparametryczne.

4. Wyniki pracy

4.1. Artykuł nr 1 Molenda T, Kidawa J., 2020: *Natural and Anthropogenic Conditions of the Chemical Composition of Pit Lake Waters (Based on Example Pit Lakes from Central Europe)*. Mine Water Environ., 2020, Vol. 39, iss. 3, pp. 473-480, ISSN: 10259112

W tej publikacji przedstawiono problem zróżnicowania hydrochemicznego środowisk poeksploatacyjnych. Jednym z głównych następstw eksploatacji odkrywkowej jest powstanie zbiorników wyrobiskowych. Ich utworzenie następuje po zatopieniu wyrobiska po odkrywkowej eksploatacji złóż surowców mineralnych (Rys. 2).



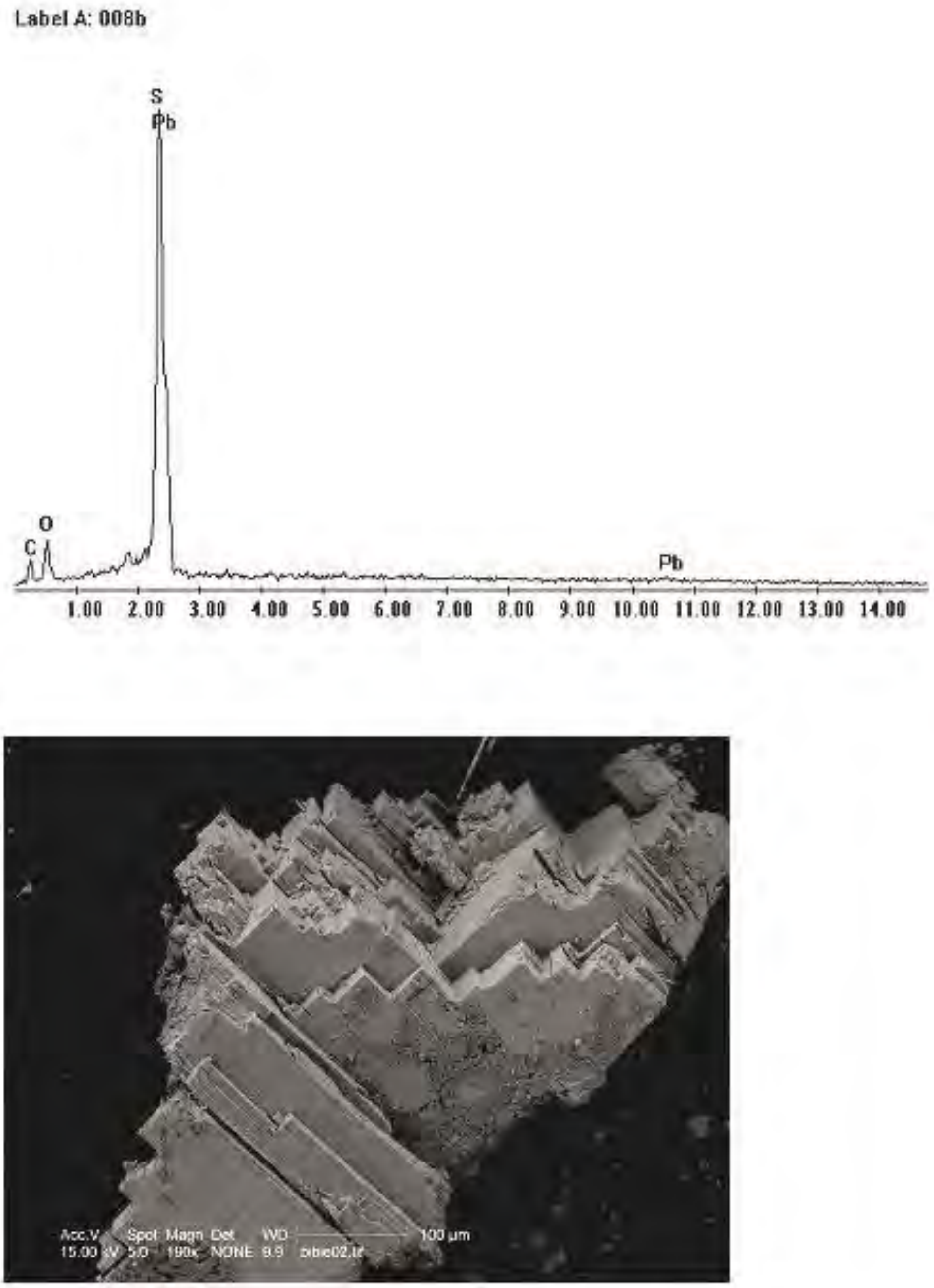
Rys. 2. Etapy formowania się zbiornika poeksploatacyjnego (wg Molenda, 2011)

1– okres przed eksploatacją, 2 i 3 – w trakcie eksploatacji, 4 – okres po zakończeniu eksploatacji

Chociaż zbiorniki te nie mają naturalnej genezy, to jednak od momentu powstania (zatopienia wyrobiska) zaczynają podlegać takim samym procesom przyrodniczym jak naturalne jeziora. W ich wyniku kształtuje się m.in. skład chemiczny wód. Badania właściwości chemicznych wód zbiorników antropogenicznych prowadzone były na licznych obiektach (Rzętała, 2008, Rzętała, 2012). Dotyczyły one jednak w większości przypadków pojedynczych obiektów, natomiast analizy hydrochemiczne ograniczyły się do kilku wybranych jonów. Bardziej kompleksową charakterystykę ze względu na typ hydrochemiczny retencjonowanych wód przeprowadzono dla naturalnych jezior (Hutchinson, 1975; Rahaingomanana, 1998).

Celem artykułu było wykazanie, jak właściwości zlewni zbiornika (naturalne i antropogeniczne) wpływają na skład chemiczny wód zbiorników poeksploatacyjnych. Przedstawiono również klasyfikację zbiorników poeksploatacyjnych ze względu na typ hydrochemiczny retencjonowanych wód. Do badań wybrano 30 zbiorników poeksploatacyjnych położonych na terenie Europy środkowej (w granicach Rzeczpospolitej Polskiej i Republiki Czeskiej). Zbiorniki te różniły się rodzajem eksploatowanego surowca mineralnego, bowiem były to zarówno surowce energetyczne, budowlane jak i metaliczne.

Przeprowadzone badania wskazują, że skład chemiczny wód zbiorników poeksploatacyjnych zdeterminowany jest w głównej mierze rodzajem skał, które były eksploatowane w danym wyrobisku. Wpływ ten jest szczególnie zauważalny w przypadku wyrobisk po eksploatacji skał krasowiejących (gipsów, siarki, dolomitów oraz wapieni). Zbiorniki w wyrobiskach po eksploatacji gipsów i siarki charakteryzuje dwujonowy siarczanowo – wapniowy typ wód (SO_4^{2-} - Ca^{2+}), a dolomitów wodorowęglanowo - magnezowy (HCO_3^- - Mg^{2+}). Również domieszka minerałów siarczkowych w eksploatowanych skałach nie pozostaje bez wpływu na typ hydrochemiczny (dotyczy to głównie węgla brunatnego). Oprócz czynników naturalnych (geogenicznych) istotny wpływ na skład chemiczny wód ma dopływ odcieków ze składowisk odpadów przemysłowych oraz zrzut wód kopalnianych. Przykładem składowiska który ma wpływ na jakość wód limnicznych jest obiekt Bibiela, na którym zdeponowane są głównie siarczki cynku (ZnS), ołowiu (PbS) oraz żelaza (FeS) - Rys. 3.



Rys. 3. Widmo pierwiastkowe i zdjęcie cząsteczki o składzie PbS z hałdy Bibiela, pow. 190x. (wg Molenda, 2011)

W wielu przypadkach dopływ odcieków lub zrzut wód kopalnianych prowadzi do całkowitej transformacji naturalnego (wynikającego z uwarunkowań geogenicznych) składu chemicznego wód. Przykładem są zbiorniki do których odprowadzane są silnie zasolone wody z kopalń węgla kamiennego. Wody te cechuje duże zasolenie >3 g/L oraz dominacja jonów chlorkowych i sodowych. Odprowadzanie tych wód do zbiorników spowodowało całkowitą transformację naturalnego typu hydrochemicznego. Retencjonują one wody o typie chlorkowo – sodowym *(Cl^{-} - Na^{+})*. W warunkach naturalnych tego typu wody występują w jeziorach stref okołozwrotnikowych.

4.2. Artykuł nr 2 Błońska A, Kidawa J, Molenda J, Chmura D., 2020: *Hydrogeochemical conditions of the development of anthropogenic carbonate swamps: a case study of an abandoned Polish sandpit.* Pol. J. Environ. Stud., 2020, no. 1, pp. 561-569, ISSN: 12301485

Przeprowadzone badania wykazały jak istotnym czynnikiem wpływającym na kierunek kolonizacji przez rośliny naczyniowe są warunki hydrochemiczne występujące w obrębie wyrobisk poeksploatacyjnych. Obiektem badań było mokradło położone w obrębie starego wyrobiska po eksploatacji piasku w miejscowości Jaworzno – Szczakowa na Wyżynie Śląskiej (południowa Polska). Wykazano, że wyrobisko które po zakończeniu eksploatacji piasku nie było rekultywowane podlegało spontanicznym procesom sukcesji, w następstwie których doszło do rozwoju mokradła. Znaczącą rolę w zasilaniu mokradła odgrywa infiltracja wód z rzeki Białej Przemszy. Wody Białej Przemszy wykazują wysoki stopień zanieczyszczenia, gdyż są odbiornikiem wód kopalnianych z kopalni rud cynkowo – ołowiowych położonych na Wyżynie Olkuskiej. Wody te oprócz wysokiego stężenia metali ciężkich cechuje również duża twardość. Wody o dużym stężeniu jonów wapnia i magnezu sprzyjają wkraczaniu i rozwojowi gatunków wapniolubnych. Stąd też 16 % flory badanego mokradła stanowią gatunki kalcyfilne. Niektóre z tych gatunków są rzadkie (lipiennik Losella, kruszczyk błotny) i zagrożone wyginięciem. Szczególnie cennym gatunkiem jest *Liparis loeselii* gatunek o znaczeniu priorytetowym w Unii Europejskiej, którego liczebność na badanym mokradle wynosi kilkaset osobników. W obrębie innych części piaskowni (o miękkich wodach) nie stwierdzono występowania gatunków kalcyfilnych.

W przedstawionych artykułach *"Natural and Anthropogenic Conditions of the Chemical Composition of Pit Lake Waters (Based on Example Pit Lakes from Central Europe)"* oraz *„Hydrogeochemical conditions of the development of anthropogenic carbonate swamps: a case study of an abandoned Polish sandpit"* przedstawiono zróżnicowanie hydrochemiczne obszarów poeksploatacyjnych oraz jego wpływ na kierunek kolonizacji przez roślinność. Najlepszym przykładem wpływu jakości wody na roślinność jest acidotroficzny zbiornik położony w Bibieli, którego wody cechuje bardzo duża mineralizacja oraz silnie kwaśny odczyn wód. Doprowadziło to całkowitej eliminacji roślinności wodnej ze zbiornika (Rys. 4).

Rys. 4. Ekstremalnie acidotroficzny zbiornik – (pH<3) całkowity brak roślinności litoralnej (Fot. T. Molenda)

4.3. Artykuł nr 3 Kidawa J, Chmura D, Molenda T., 2021: *The Hydrological-Hydrochemical Factors that Control the Invasion of the Black Locust (Robinia pseudoacacia L.) in Succession in Areas with Opencast Mines*. Plants, 2021, no 10 (1), pp. 1-16, ISSN: 22237747

Najbardziej kompleksowa charakterystyka interakcji zachodzących pomiędzy wodą, podłożem i roślinnością przedstawiona została w tym artykule.

Badania prowadzono na terenie zakładu górniczego „Wójcice", gdzie prowadzona jest eksploatacja kruszyw mineralnych metodą podwodną, w strefie zbiornika zaporowego „Jezioro Nyskie". Urobek poddawany jest płukaniu i przesiewaniu (sortowaniu) w celu usunięcia najdrobniejszych frakcji (głównie piaszczystych i ilastych). Woda do procesów płukania pobierana jest z Jeziora Nyskiego, jednak jej obieg odbywa się w cyklu zamkniętym. Po przejściu przez osadnik jest ponownie wykorzystana w procesach sortowania materiału. Z jeziora woda pobierana jest tylko do uzupełnienia strat technologicznych. Pozyskiwanym do sprzedaży kruszywem są żwiry. W efekcie oddzielone podziarno, w postaci silnie uwodnionej pulpy, hydraulicznie transportuje się do stawu osadowego, gdzie poddawane jest sedymentacji i odwodnieniu (Rys. 5).

Rys. 5. Staw osadowy, na pierwszym planie koryto powstałe w następstwie przepływu pulpy (Fot. J. Kidawa)

Pulpa stanowi produkt uboczny dla kopalni, który ze względu na swoje specyficzne właściwości nie jest wykorzystywany do sprzedaży. W obrębie osadnika w pierwszej jego części dochodzi do sedymentacji najgrubszych frakcji (piaszczystych z niewielką domieszką żwirów), a w dalszej jego części (głównie w strefie wodnej osadnika) dochodzi do sedymentacji frakcji drobnoziarnistych – pyłowych i iłowych. Zdeponowane w osadniku osady cechuje charakterystyczne laminowanie będące następstwem cyklicznych zalewów pulpy. Obszar osadnika stanowi bardzo dobry przykład, jak zróżnicowanie warunków wilgotnościowych i gruntowych wpływa na kierunek kolonizacji. Warunki hydrochemiczne w analizowanym przypadku nie są kluczowe, gdyż w obrębie całego osadnika wody cechuje ten sam typ hydrochemiczny, a różnice w stężeniu poszczególnych jonów w różnych częściach osadnika są statystycznie nieistotne.

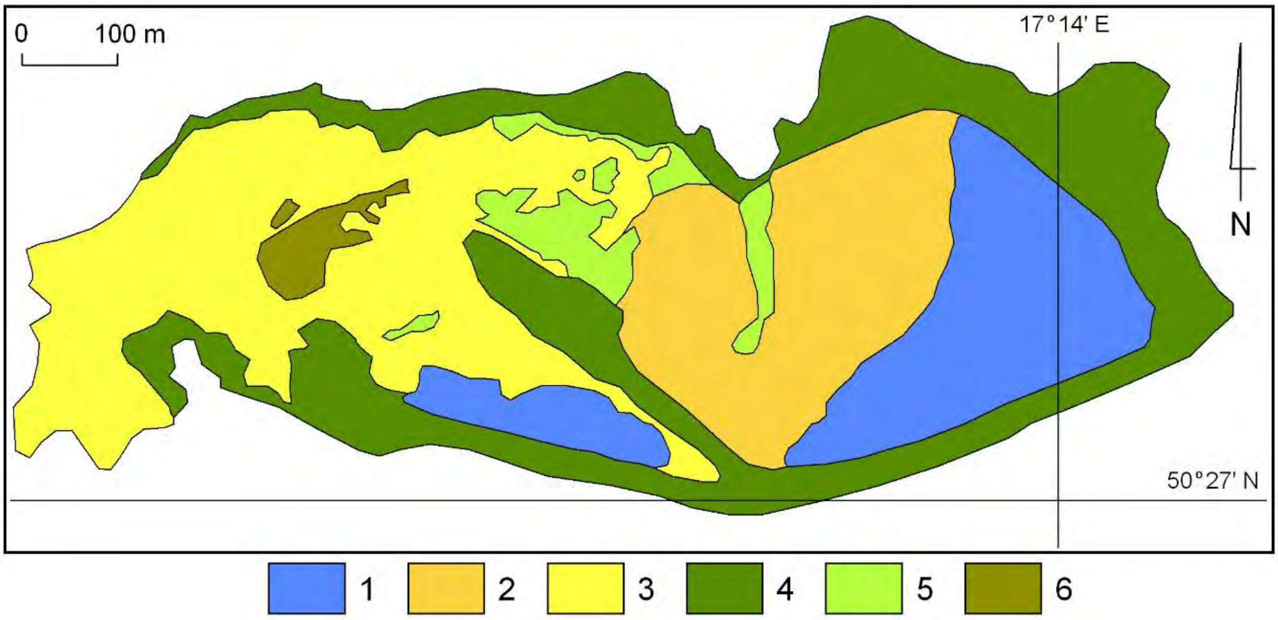
Rozwój roślinności na terenie kopalni "Wójcice" ma charakter sukcesji pierwotnej, ponieważ zaczyna się na odsłoniętym podłożu bez pokrywy glebowej i roślinnej. Można wyróżnić kilka kierunków sukcesji roślinności, jak i stadiów zachodzących na terenie kopalni. Kierunek sukcesji zależy przede wszystkim od wilgotności i typu materiału podłoża (Rys. 6).

Rys. 6. Zbiorowisko robinii akacjowej (w głębi zdjęcia) na mocno przesuszonych i luźnych piaskach (Fot. J. Kidawa)

Na wilgotność gruntu dominujący wpływ ma zawartość części spławialnych w analizowanych próbach. Im większa (%) zawartość frakcji drobnoziarnistych, tym podłoże wykazywało większą wilgotność (w tych samych warunkach pogodowych). Dlatego nie dziwi, że na gruncie ilastym rozwinęła się głównie roślinność szuwarowa (szuwary trzcinowe i mozgowe). Na przeciwległym biegunie są miejsca piaszczyste, które są porośnięte roślinami typowymi dla muraw napiaskowych z klasy *Koelerio glaucae Corynephoretea canescentis* z dużym udziałem szczotlichy siwej *Corynephorus canescens* (Rys. 7).

Rys. 7. Kolonizacje luźnych piasków przez Szczotlichę siwą (Fot. J. Kidawa)

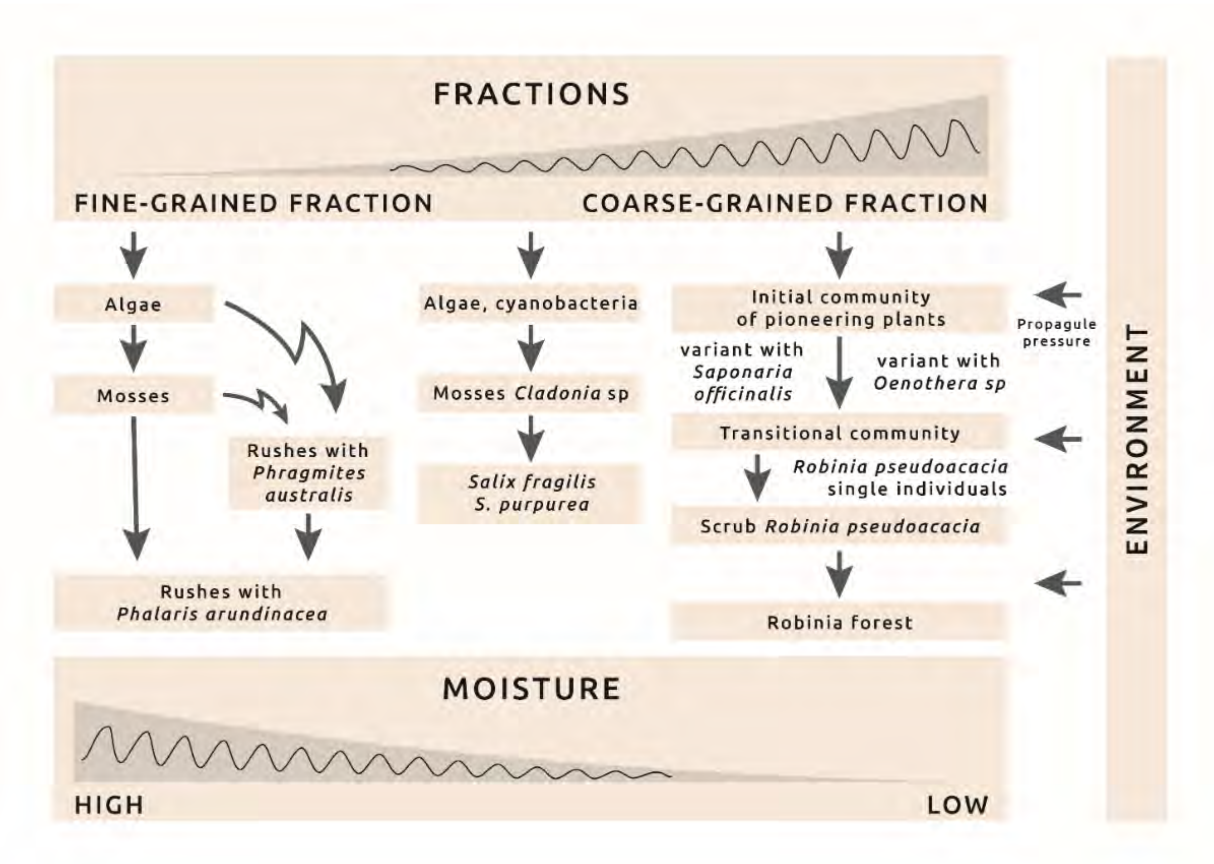
Najlepiej rozwijają się one na pryzmach piasku dobrze nasłonecznionych, gdzie gleba ma małą wilgotność oraz wyższą temperaturę. Dlatego też na obszarze kopalni obserwujemy bardzo dużą mozaikę siedlisk, a co z tego wynika duże zróżnicowanie zbiorowisk roślinnych (Rys. 8).



Rys. 8. Zróżnicowanie siedlisk i roślinności na terenie kopalni „Wójcice" (Kidawa i in., 2021)

1 – wody, 2 – mokradła na materiale ilastym porośnięte głownie szuwarami trzcinowymi, 3 – otwarte tereny piaszczyste, 4 – lasy, 5 – zarośla wierzbowe, 6 – zbiorowisko z robinią akacjową na piaskach

Warunki abiotyczne, które występują w obrębie osadnika całkowicie determinują kierunek kolonizacji tego obiektu przez roślinność. Schematycznie przedstawiono to na rysunku 9. Przebiegają one w trzech kierunkach. Jeden kierunek sukcesji zaczyna się na siedliskach silnie uwodnionych, który prowadzi do powstania szuwarów. Drugi kierunek rozpoczyna się na siedlisku mniej wilgotnym i skutkuje powstaniem zarośli wierzbowych. Natomiast trzeci kierunek sukcesji i typ roślinności rozwija się na suchych, lotnych piaskach tworząc inicjalne zbiorowiska roślin pionierskich. Cały ten proces jest częściowo zaburzany poprzez masowe występowanie w otoczeniu robinii akacjowej *Robinia pseudoacacia*, inwazyjnego obcego gatunku w naszej florze, drzewa pochodzącego z Ameryki Północnej (Rahmonov, 2009). Jednakże udział robinii wynika przede wszystkim z presji propagul, czyli jednego z podstawowych mechanizmów inwazji obcych gatunków, a w mniejszym stopniu z uwarunkowań hydrologiczno-gruntowych.



Rys. 9. Model sukcesji: kierunki i fazy rozwoju roślinności w sąsiedztwie kopalni "Wójcice" (Kidawa i in., 2021)

4.4. Rozdział w monografii Kidawa J, Chmura D, Molenda T., 2022: *Hydrological and Hydrochemical Conditions for the Reclamation of Anthropogenic Water Bodies and Wetlands in Opencast Mines.* In: A. Dyczko, A.M. Jagodziński, G. Woźniak G. (eds). The Green Scenarios: Mining industry responding to environmental challenges of the Anthropocene Epoch, CRC Press, Taylor & Francis Group, London, UK, pp. 23-36

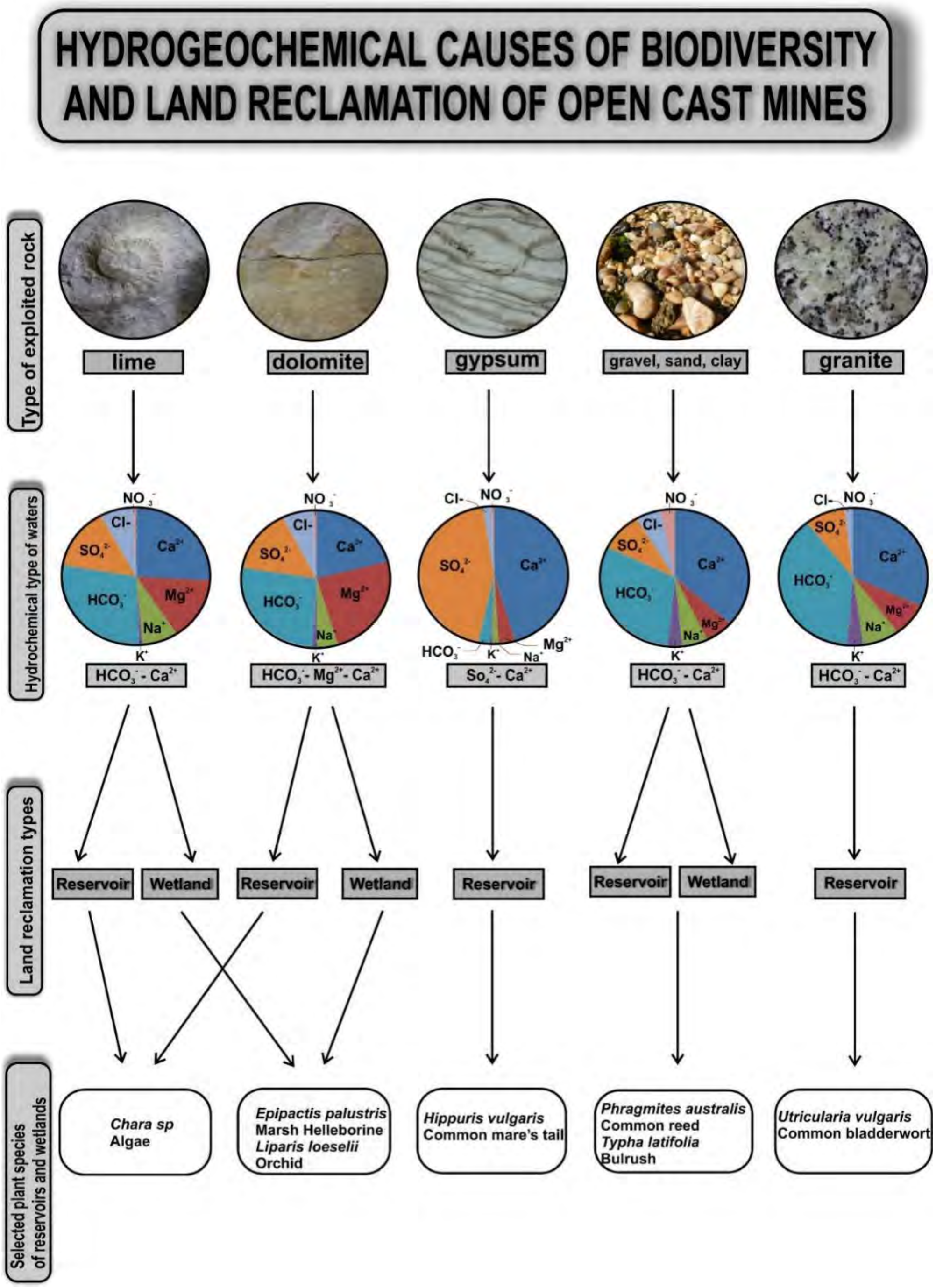
Praca przedstawia wyniki badań prowadzonych w trzech różnych typach kopalni odkrywkowych „Górażdże" (kamieniołom wapienia), „Nowogród Bobrzański" (kopalnia piasku) i „Wójcice" (żwirownia). Badania objęły studia hydrologiczno-hydrochemiczne oraz florystyczne. Zaproponowano kierunki rekultywacji w zależności od typu podłoża, chemizmu wód oraz stopnia zaawansowania roślinności powstałej w wyniku sukcesji naturalnej.

Na podstawie badań w tych trzech różnych obiektach oraz przeglądu literatury można stwierdzić, że nie ma jednej optymalnej metody wspomagania rekultywacji obszarów poeksploatacyjnych ze względu na duże zróżnicowanie warunków hydrologicznych i hydrochemicznych. Należy ocenić czy spontaniczne procesy sukcesji są wystarczające czy należy je wspomóc. Uzyskane wyniki wykazały, że o kierunku samoistnej sukcesji roślinności w kopalniach odkrywkowych decydują dwa czynniki: rodzaj eksploatowanej skały oraz warunki hydrologiczne. W zbiornikach po eksploatacji wapienia i dolomitu najcenniejsze rośliny, jakie mogą się pojawić ramienice to *Chara* sp (Owsianny, Gąbka 2007). Fitocenozy z udziałem tych roślin są typem roślinności należącym do Dyrektywy Siedliskowej NATURA 2000 (kod 3140), natomiast w siedliskach podmokłych torfowiska ze storczykami i innymi rzadkimi roślinami rozwijają się samoistnie lub mogą być ukształtowane. W zbiornikach po eksploatacji gipsu mogą pojawić się gatunki rzadkie zamieszczone w „Czerwonej Księdze", które w tego typu zbiornikach znajdują optymalne warunki dla bytowania jak np. przęstka pospolita (*Hippuris vulgaris)*. Roślina ta wykazuje dużą tolerancję na wysokie stężenie jonów wapnia i siarczanów, typowe dla tego typu wód (Gałczyńska 2006). Potwierdziły to również badania eksperymentalne z przeszczepami tego gatunku (Gałczyńska i in. 2010). W zależności od warunków lokalnych rekultywacja powinna koncentrować się na utrzymaniu roślinności wodnej i / lub mokradeł lub może być prowadzona w celu wspierania naturalnego potencjału tych terenów w zakresie rozwoju i utrzymania roślinności wodnej i / lub bioróżnorodności ekosystemu mokradeł.

5. Podsumowanie i wnioski

Wyniki uzyskane w toku badań, które znalazły odbicie w niniejszej dysertacji doktorskiej wnoszą wkład do wiedzy na temat relacji między czynnikami hydrologiczno-hydrochemicznymi a kolonizacją przez rośliny. Prowadzone przez Autorkę badania potwierdzają wpływ chemizmu wody na kolonizację roślinności w innych zbiornikach antropogenicznych. Badania te prowadzone były na zbiornikach po eksploatacji skał surowców chemicznych takich jak: siarka, gips oraz wapień i dolomit. Wody tych zbiorników cechuje dwujonowy siarczanowo - wapniowy (SO_4^{2-} - Ca^{2+}) lub wodorowęglanowo - wapniowy (HCO_3^- - Ca^{2+}) typ wód i mineralizacja w większości przypadków powyżej 1g/L. Są to więc zbiorniki o bardzo dużej twardości wody > 20 ^{o}d. Takie warunki abiotyczne są korzystne dla ramienic (Chara), które wbudowują w swoje tkanki węglan wapnia $CaCO_3$. Dlatego też w zbiornikach tych obserwowano „podwodne łąki" ramienicowe (Rys. 10). Ramienice stwierdzono również w obrębie rowów odwadniających mokradło „Szczakowa". Retencjonowana w rowach woda jest twarda (>20 ^{o}d) i reprezentuje ten sam siarczanowo – wapniowy lub okresowo wodorowęglanowo – wapniowy typ wód jak wody zbiorników na obszarach po eksploatacji siarki. Należy nadmienić, iż wszystkie gatunki ramienic podlegają ochronie prawnej, a antropogeniczne zbiorniki wodne i rowy są ich siedliskiem zastępczym kiedy naturalne (ze względu na eutrofizację wód) ulegają zanikowi. Stwierdzenie występowania ramienic w wodach o dużej twardości i tym samym typie hydrochemicznym podkreśla prawidłowości oraz kluczową rolę czynnika hydrochemicznego w kierunku procesu kolonizacji akwatycznych środowisk poeksploatacyjnych przez rośliny (Rys. 11).

Rys. 10. „Podwodne łąki” ramienicowe – zbiornik poeksploatacyjny Novy Rozdol (Ukraina, fot. J. Kidawa)



Rys. 11. Hydrogechemiczne uwarunkowania kolonizacji obszarów poeksploatacyjnych (Kidawa i in., 2022)

Dzięki obszernemu zakresowi badań od studiów hydrologiczno-hydrochemicznych, glebowych oraz botanicznych można próbować ekstrapolować na inne układy geograficzne i ekologiczne pochodzenia antropogenicznego. Badania pozwoliły zarówno na lepsze zrozumienie zależności abiotyczno-biotycznych na terenach poeksploatacyjnych, jak i mogą być podstawą do przeprowadzenia przemyślanych i zakończonych sukcesem rekultywacji na terenach kopalni odkrywkowych.

Jako rezultat przeprowadzonych badań stwierdzono m.in., że:

- skład fizykochemiczny wód zbiorników poeksploatacyjnych zdeterminowany jest rodzajem eksploatowanego surowca,

- zbiorniki powstałe w wyrobiskach skał krzemianowych (granity, piaski) cechuje niska mineralizacja wód oraz małe stężenie głównych kationów i anionów,

- zbiorniki powstałe w wyrobiskach skał krasowiejących (wapienie, dolomity, gipsy) cechuje wysoka mineralizacja wód oraz duże stężenie głównych kationów i anionów,

- w przypadku eksploatacji specyficznych złóż surowców mineralnych (np. metalicznych, organicznych) mogą wykształcić się zbiorniki dysharmoniczne,

- paradoksalnie w niektórych przypadkach zanieczyszczone wody mogą przyczynić się do powstania cennych i rzadkich siedlisk kolonizowanych chronione gatunki roślin,

- nawet w obrębie jednego obiektu poeksploatacyjnego możemy stwierdzić bardzo dużą mozaikę siedlisk – od skrajnie suchych do podmokłych. Kolonizowane są one przez gatunki roślin o określonych preferencjach co do wilgotności podłoża,

- podłoże w rozumieniu skały macierzystej determinuje hydrochemiczny typ wód a tym samym kierunek sukcesji roślinności a wiedza ta powinna mieć zastosowanie w wyborze kierunku rekultywacji terenów poeksploatacyjnych;

- zależności między wodą a siedliskiem i typem sukcesji roślin są bardzo trwałe i przewidywalne, mogą być jedynie zakłócone przez presję gatunków inwazyjnych.

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TECHNICAL ARTICLE

Natural and Anthropogenic Conditions of the Chemical Composition of Pit Lake Waters (Based on Example Pit Lakes from Central Europe)

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Abstract
The article presents a classification of hydrochemical types of waters in pit lakes. Although natural factors significantly influence the chemical composition of water, the differences between hydrochemical types are also determined by anthropogenic factors. The chemical composition of the water in pit lakes is primarily determined by the kind of rocks mined during the excavation, while secondary anthropogenic impacts can modify the chemical composition of the water. A multidimensional clustering analysis of the water was performed, which allowed three main types of hydrochemical reservoirs to be delimited for the pit lakes assessed in this study: a bicarbonate–magnesium–calcium water type (HCO_3–Mg–Ca), a bicarbonate–calcium water type (HCO_3–Ca), and a sulphate–calcium water type (SO_4–Ca).

Keywords Mining water · Hydrochemical type of water · Water pollution · Industrial waste · Mineral resources

Introduction

Anthropogenic water bodies are a new element in the natural environment (Jankowski 1995). These water bodies are divided into various types, depending on the origin of the basin and include pit lakes that have formed due to the flooding of excavations that were once used for the opencast exploitation of mineral resources (Fig. 1). Although these pit lakes do not have a natural origin, they are subject to the same processes as natural lakes. These effects include the chemical composition of the water. Studies on the chemical properties of the water in pit lakes have included numerous objects (Castendyk et al. 2015a, b; Eary 1999; Jones et al. 2003; Rzętała 2008; Schultze et al. 2013). However, they have primarily concerned individual water bodies. Hydrochemical analyses have also been limited to a few selected ions (Boehrer et al. 2017; Malata et al. 2018; Molenda 2014, 2015, 2018; Sánchez-España et al. 2014; Schultze et al. 2017a, b). Studies of their more general characteristics that were based on the hydrochemical type of the retained waters have been carried out for natural lakes (Hammer 1986; Hutchinson 1975; Rahaingomanana 1998).

This article demonstrates how the properties of the catchment (natural and anthropogenic) affect the chemical composition of the water in post-exploitation pit lakes. A classification of the pit lakes investigated in this study is also presented relative to the hydrochemical water type.

Study Sites

Thirty pit lakes in the Republic of Poland and the Czech Republic were selected for this research. The detailed locations of the pit lakes are presented in Table 1 and Fig. 2. The pit lakes differed regarding the type of minerals that had been extracted, which ranged from energy resources to construction (Table 1). The stages of pit lakes that were formed are presented Fig. 1. All of the tested pit lakes are endorheic. They are supplied only by groundwater inflow, rainfall, and surface runoff from their direct catchments. The surface area of the tested pit lakes is diverse and ranges from 3000 m^2 to several ha.

Research Methods

Water samples were collected in spring and autumn in 0.5 L polyethylene bottles and then transported to the laboratory at

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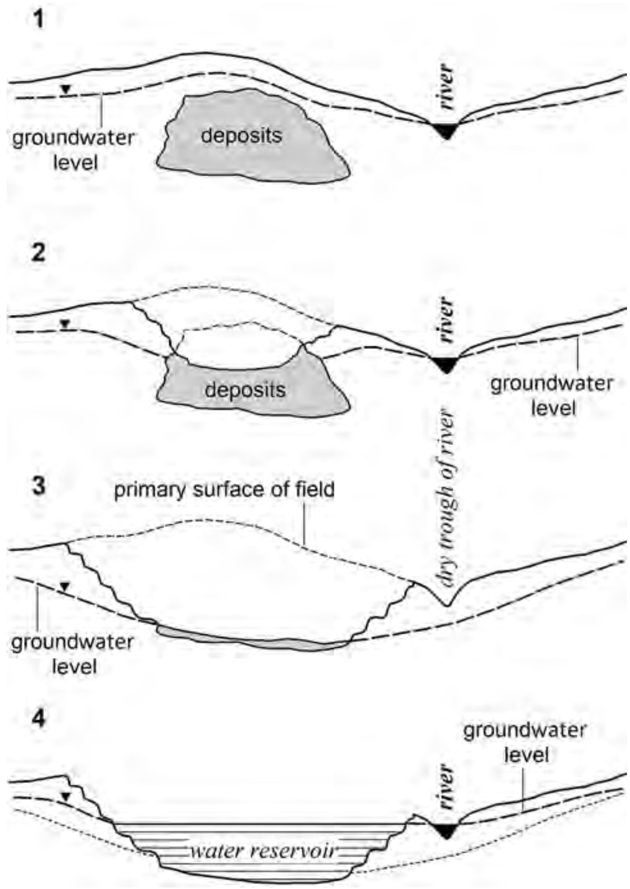

Fig. 1 Stages of excavation reservoir forming according to Molenda and Chmura (2011)

+4 °C for analysis. The aim of this sampling was to obtain homogeneous samples of the mixed water of each pit lake (Schultze et al. 2017a, b). These pit lakes are located in mid latitudes, which have four seasons (Tables 1, 2, and 3). In both spring and autumn, the water temperature in the tested pit lakes falls below 4 °C and the water circulates completely (Imberger and Patterson 1990). During this period, there were no differences in the concentrations of individual ions in the water column of these pit lakes (Malata et al. 2018; Molenda and Chmura 2011). Therefore, a surface water sample is representative of the entire water body. Six samples were taken from each pit lake from 2015 to 2017 (three in spring and three in autumn; n = 6).

Before analysis, the samples were filtered (0.45 µm Millipore). The major cations and anions in the water: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, Cl^{-} were determined using a Metrohm 850 Professional IC ion chromatograph (anion column A Suup 7-250/4.0, eluent 3.6 mM Na_2CO_3 and a cation column C4-150/4, eluent 0.7 mM dipicolinic acid and 1.7 HNO_3).

Classification of the hydrochemical type of the water retained in the pit lake was based on the Altowski-Szwiec classification (Pazdro and Kozerski 1990). This method determines the hydrochemical type by the ions whose content in the water is greater than 20 ± 3% equivalents (meq), provided that the sum of anions and cations equals 100%. The name of the water type begins with the ion whose content is the highest in the water, regardless of whether it is a cation or an anion. If the name of three- or four-ion water starts with an anion, then the following elements of the name are other anions followed by cations in the same order. In natural conditions, the six most critical ions of over 20% meq are Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}. For this reason, these ions were selected for analysis. Potassium (K^{+}) was also included.

In addition to the chemical analyses of water, an analysis of the mineral composition of the industrial waste that had been deposited in the shore zone of some of the pit lakes was also carried out. The mineral composition of the industrial waste was determined using: a phase X-ray diffractometer (XRD) Philips PW 3710 with a graphite monochromator, and sub-microscopic tests (scanning microscope Philips XL 30, analytical EDS, EDAX, sapphire type).

To examine the similarities and differences between the individual pit lakes, a multivariate analysis andcluster analysis was used in which the Euclidean distance was used as a measure of similarity and the Ward method of grouping was adopted. The average concentration (meg/L) of the basic ions in the water of the tested pit lakes was assumed to be its features. The statistical analysis was performed using R (R Development Core Team 2009) software.

Results and Discussion

The multidimensional clustering analysis delimited three main groups of pit lakes that differed in the chemical composition of their waters (Fig. 3). The most specific group included pit lakes 1 and 2, which were of a chloride–sodium (Cl^{-}–Na^{+}) water type. These pit lakes are located in the post-exploitation excavations of construction resources, i.e. sands and tills. Usually one would expect these waters to represent a bicarbonate–calcium type (HCO_3^{-}–Ca^{2+}), like the waters of the other pit lakes located in this type of excavation (24–27, Table 1). Studies by other authors have also documented a bicarbonate–calcium type (HCO_3^{-}–Ca^{2+}) type of the water in pit lakes located in disused sand and till pits (Molenda 2007). This Cl–Na^{+} type of water is due to an anthropogenic factor: strongly saline waters from hard coal mines had been discharged into the pit lakes. These waters had a high salinity > 3 g/L and chloride and sodium ions were dominant. The discharge of these waters into the pit lakes completely transformed the natural hydrochemical type of the water. In the case of pit lake 2, it also resulted

Table 1 General characteristics of reservoirs

Location	Extracted material	Ca^{2+} [meq/L]	Mg^{2+} [meq/L]	Na^{+} [meq/L]	K^{+} [meq/L]	Cl^{-} [meq/L]	SO_4^{2-} [meq/L]	HCO_3^{-} [meq/L]	Hydrochemical type
N: 50°15′40″ E: 19°7′30″	Sand	18	16.8	98	1.1	147	8.5	5.2	Cl–Na
N: 50°14′24″ E: 18°59′34″	Clay	9.7	6.2	57	0.8	75	6.9	1.8	Cl–Na
N: 50°4′36″ E: 18°24′36″	Gypsum	26.8	0.4	0.9	0.4	1.4	22	4.7	SO_4–Ca
N: 49°95′51″ E: 17°89′45″	Gypsum	27.4	2.9	1.1	0.22	1.8	21.7	2.2	SO_4–Ca
N: 50°27′37″ E: 20°35′28″	Gypsum	33	3.3	1	0.26	1.3	32	1.9	SO_4–Ca
N: 50°27′19″ E: 20°35′9″	Gypsum	32	3.3	0.9	0.26	2.1	32.5	2.2	SO_4–Ca
N: 50°17′8″ E: 19°16′39″	Sand	2	0.8	0.08	0.08	0.16	2.4	0	SO_4–Ca[a]
N: 50°30′48″ E: 18°59′21″	Dolomite	2.6	1.3	0.05	0.06	0.07	3.7	0	SO_4–Ca[a]
N: 50°27′21″ E: 19°24′46″	Lignite	2.7	0.6	0.1	0.08	0.2	3.7	0	SO_4–Ca
N: 50°27′5″ E: 19°23′19″	Lignite	2.7	0.67	0.1	0.12	0.15	3.4	0.0	SO_4–Ca
N: 50°56′3″ E: 20°40′51″	Quartzite	4.6	0.95	0.17	0.08	0.15	13.7	0.00	SO_4–Ca
N: 49°43′50″ E: 18°44′10″	Limestone	4.2	0.2	0.05	0.06	0.09	0.96	3.5	Ca $(HCO_3)_2$
N: 50°13′42″ E: 19°18′40″	Dolomite	3	3.48	0.57	0.12	0.84	1.93	3.58	HCO_3–Mg–Ca
N: 50°13′30″ E: 19°19′1″	Dolomite	3.34	3.5	0.64	0.14	0.97	2.14	3.82	HCO_3–Mg–Ca
N: 50°9′51″ E: 19°27′48″	Limestone	4.1	1.9	1	0.1	0.9	1.85	3.6	Ca $(HCO_3)_2$
N: 50°17′51″ E: 17°8′1″	Granite	0.56	0.16	0.31	0.04	0.17	0.17	1	HCO_3–Ca
N: 50°17′23″ E: 17°7′18″	Granite	1	0.2	0.16	0.12	0.065	0.067	1.36	HCO_3–Ca
N: 50°21′30″ E: 17°10′55″	Granite	1.43	0.25	0.41	0.1	0.16	0.017	1.82	HCO_3–Ca
N: 50°21′35″ E: 17°11′28″	Kaolin	0.3	0.11	0.03	0.1	0.07	0.13	0.41	HCO_3–Ca

Table 1 (continued)

Location	Extracted material	Ca^{2+} [meq/L]	Mg^{2+} [meq/L]	Na^{+} [meq/L]	K^{+} [meq/L]	Cl^{-} [meq/L]	SO_4^{2-} [meq/L]	HCO_3^{-} [meq/L]	Hydrochemical type
N: 50°18′11″ E: 17°6′18″	Granite	1.7	0.26	0.29	0.07	0.175	0.26	1.66	HCO_3–Ca
N: 50°19′57″ E: 17°5′1″	Granite	1.85	0.6	0.18	0.2	0.26	0.27	2.15	HCO_3–Ca
N: 50°18′2″ E: 17°6′45″	Granite	1.05	0.18	2.5	2.88	1.9	0.08	4.95	HCO_3–K–Na[a]
N: 50°14′25″ E: 19°1′16″	Clay	2.8	2.1	0.6	0.2	0.2	1.1	2.7	Ca $(HCO_3)_2$
N: 50°39′32″ E: 18°17′59″	Gravel	0.6	0.1	0.07	0.02	0.04	0.15	0.45	HCO_3–Ca
N: 50°39′28″ E: 18°17′53″	Gravel	0.6	0.1	0.09	0.05	0.09	0.15	0.5	HCO_3–Ca
N: 50°15′55″ E: 19°7′7″	Sand	2.4	2.1	1.08	0.16	2.5	0.43	2.85	HCO_3–Ca
N: 50°00′6″ E: 19°12′4″	Gravel	1.49	0.46	0.51	0.08	0.42	0.62	1.5	HCO_3–Ca
N: 50°00′35″ E: 19°26′55″	Gravel	2.3	0.63	0.43	0.05	0.45	1.7	1.3	Ca–SO_4–HCO_3
N: 50°00′47″ E: 19°27′12″	Gravel	2	0.65	0.43	0.05	0.53	1.3	1.3	Ca–HCO_3–SO_4
N: 50°39′30″ E: 18°17′55″	Gravel	0.6	0.1	0.09	0.05	0.09	0.15	0.5	HCO_3–Ca

[a]Reservoirs with industrial waste deposition in the coastal zone

Fig. 2 Location of the study area

in the permanent stratification of the water—meromixing (Molenda 2014).

Pit lakes 3–6 contained double-ionic sulphate–calcium water (SO_4^{2-}–Ca^{2+}, Table 1). These pit lakes are located in post-exploitation gypsum excavations. Gypsum is susceptible to dissolution, which produces calcium Ca^{2+} and sulphate SO_4^{2-} ions in such large quantities that they determined the chemical composition of the water. Therefore, in the case of these pit lakes, the chemical composition of the water was conditioned by a geological factor.

The same sulphate–calcium (SO_4^{2-}–Ca^{2+}) type of water was also found in pit lakes 7–11. A characteristic feature of these pit lakes, however, was the complete lack of a bicarbonate ion (HCO_3^{-}, Table 1). In the case of pit lakes 9, 10, and 11, the lack of a bicarbonate ion was conditioned by the mineral composition of the rocks that had been exploited in the excavation. In the case of pit lakes 9 and 10, the extracted material was lignite, while quartzite sandstones were extracted at the site of pit lake 11. These rocks contain

Table 2 Climatic characteristics of the study area representative for reservoirs located in Poland

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Mean air temperature (°C)	−3.3	−2.1	1.9	7.6	13.0	16.5	18.0	17.3	13.6	8.1	3.4	−0.6	7.8
Mean precipitation (mm)	49	46	41	37	40	49	85	89	105	88	53	50	731
Mean speed of wind (m/s)	3.0	2.5	3.0	4.0	3.5	3.5	3.0	2.5	3.0	4.0	4.0	3.0	3.25

Table 3 Climatic characteristics of the study area representative for reservoirs located in the Czech Republic

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Mean air temperature (°C)	0.1	−5.5	5.6	10.1	15.6	17.9	20.6	19.7	14.9	9.2	6.5	−1.0	9.4
Mean precipitation (mm)	25.3	31.8	45.2	50.5	76.1	102.8	114.2	82.3	69.7	38.6	42.2	33.6	712.3
Mean speed of wind (m/s)	2.4	2.3	2.4	2.6	2.4	2.1	2.1	2.1	2.4	2.2	2.3	2.3	2.3

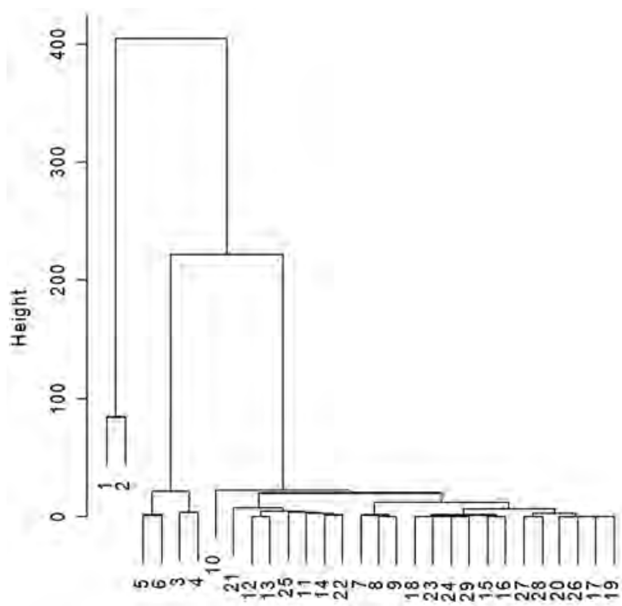

Fig. 3 The multidimensional clustering of reservoirs due the chemical composition of their waters

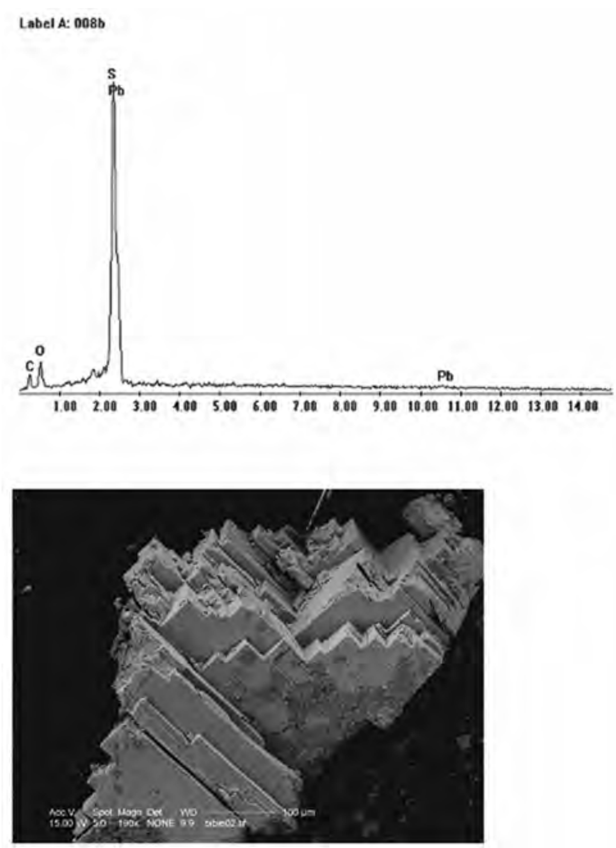

Fig. 4 The elemental spectrum and a photo of the PbS molecule from the heap of Bibiela, magn. 190×

iron sulphides in their composition, mainly pyrite (FeS_2) (Matl 1991; Migaszewski and Gałuszka 2007). The weathering of these minerals leads to the acidification of the pit lake waters (pH < 4.0), and the disappearance of bicarbonate ions. This effect of the weathering of sulphide minerals has also been documented at other excavations of lignite (Schultze et al. 2010; Solski and Jędrczak 1990) and polymetallic ores (Sánchez-España et al. 2013; Shevenell et al. 1999).

Pit lake 8 also had no bicarbonate ions (Table 1). The basin of this pit lake was developed in dolomite rocks. Therefore, it should have been a bicarbonate–magnesium–calcium water type (HCO_3^-–Mg^{2+}–Ca^{2+}) like the other pit lakes located in disused dolomite pits (Table 1). However, it is a sulphate–calcium–magnesium (SO_4^{2-}–Ca^{2+}–Mg^{2+}) water type, due to the inflow of acidic leachate from an industrial waste landfill located in the direct catchment of the pit lake. The waste in this landfill contains significant amounts of metal sulphides, mainly pyrite (FeS_2) and galena (PbS) (Fig. 4). Because of the weathering process of these minerals, acidic leaks with pH < 2 reach the pit lake (Fig. 5), which leads to the transformation of the ionic composition

Fig. 5 Acidic leachate (pH < 2, the average: EC—5.9 mS/cm, SO_4^{2-}—4800 mg/dm)

of the waters. The formation of acid leachates was also found in other landfills containing metal sulphides (Lin 1997). A similar situation occurred in the case of pit lake 7. Its basin is a disused sandpit, and thus we dealt with an unusual type of water for this type of sediment (SO_4^{2-}–Ca^{2+}). In addition, in this case, the source of the water acidification was an inflow of leachate from a hard coal mining landfill. These wastes contained pyrite and hydrogen jarosite—the source of acidic substances (Table 4).

A distinctive chemical composition was also found in the pit lakes that formed in dolomite excavations 13 and 14. The water of these pit lakes is of a tri-ionic bicarbonate–magnesium–calcium type (HCO_3^-–$Mg^{2+}Ca^{2+}$). Periodically, they can turn into bicarbonate–magnesium water (HCO_3^-–Mg^{2+}). However, the meq/L concentration of the magnesium is always higher than that of the calcium, due to the nature of the dolomites.

A characteristic, double-ion calcium–bicarbonate ($Ca(HCO_3)_2$) type of water was recorded in the pit lakes located at limestone excavations 12 and 15. This is a typical hydrochemical composition of waters in limestone areas (Miche et al. 2018).

The pit lakes located in granite and granodiorite quarries (16–22) were the double-ion bicarbonate–calcium (HCO_3^-–Ca^{2+}) water type. Only one of the lakes (22) differed; it was a bicarbonate–potassium–sodium (HCO_3^-–K^+–Na^+) type, due to the deposition of industrial waste in the coastal zone of the pit lake. The mineral composition of the waste deposited in the landfill is shown in Table 5. The waste leaching processes in the landfill transformed the ionic composition of the pit lake water. The impact of industrial waste landfills on the ionic composition of water was also found in the "Górka" pit lakes, located in Trzebinia (Czop et al. 2011).

The bicarbonate–calcium hydrochemical type of water is also characteristic of the other pit lakes located in former gravel excavations. It is the most commonly occurring type of water, and has been recorded in many pit lakes (Meybeck and Helmer 1989; Meybeck 2005; Wetzel 2000).

Summary and Conclusions

The chemical composition of the water of pit lakes depends on several factors, the most important of which is geogenic, i.e. the type of rocks in which the pit lake basin is located. This is particularly noticeable in excavations developed by the mining of karst rock (gypsums, dolomites, and limestones). The dissolution of these rocks completely determines the hydrochemical type of water retained in the lake. An admixture of sulphide minerals in the disturbed strata rocks also affected the hydrochemical type of mine waters. This applies mainly to the lignite excavations in this study, which often contained a significant admixture of pyrite (FeS_2).

In the case of pit lakes embedded in poorly soluble rocks (granite, granodiorite), the water has a very low ion concentration. Its chemical composition is primarily determined by rainwater and is of a bicarbonate–calcium type, which is the most common one in nature. The low mineralisation of both surface and underground water is characteristic of areas

Table 4 Composition [%] of mining waste

Phase	[%]
Calcite	89.1
Dolomite	9.5
Gypsum	1.1
Quartz	0.1
Magnesite	0.2

Table 5 Composition [%] of waste

Phase	[%]
Minerals clay	37.5
Quartz	27.5
Feldspar soda and potassium	12
Hydronium jarosite	5
Potassium halite	2
Pyrite	1
Amorphous substance (carbonate)	15

that are built of crystalline rocks. In addition to the natural (geogenic) factors, the inflow of leachates from industrial waste dumps can have a significant impact on the chemical composition of waters. Very often, old excavations become places to dispose of various types of waste (Czop et al. 2011). The significant impact of industrial waste landfills was demonstrated by pit lake 22, in which an atypical three-ionic (HCO_3^-–K^+–Na^+) type of water was found.

The chemical composition of water (resulting from geogenic conditions) can also be completely transformed by the discharge of mine waters from deep mines. Pit lakes 1 and 2, into which brine from coal mines was discharged, are good examples.

The concentrations of ions in the water of central Europe's pit lakes situated in the excavations of the same rock types may show slight differences, which are determined by the amount of rainwater inflow. However, they always represent the same hydrochemical type, unless influenced by secondary anthropogenic factors.

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plants

Article

The Hydrological-Hydrochemical Factors that Control the Invasion of the Black Locust (*Robinia pseudoacacia* L.) in Succession in Areas with Opencast Mines

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Abstract: Studies on opencast mines have indicated that the spontaneous colonization of excavations and sedimentation tanks by vegetation is determined not only by the substratum and the land relief, but also by the hydrological and hydrochemical relations in the exploitation hollow. Sometimes, biological invasions can also disturb the natural revegetation. *Robinia pseudoacacia* L. black locust is an invasive alien species that frequently colonizes sandy habitats. Thirty study plots were randomly established on four types of sites: (1) sandy sediments, extremely dry places located mainly on heaps of post-washer slime; (2) sandy sediments, dry areas that are periodically flooded and have pulp; (3) clay sediments, damp areas that are periodically submerged, and (4) the control, a forest with *R. pseudoacacia* in its neighborhood. A total of 94 species of vascular plants and seven species of mosses were found. The vegetation at the sites differs and the role of the black locust increases along the dryness gradient and developmental phase of vegetation. Older phases of succession resemble a forest in the surrounding area. It is a *R. pseudoacacia* species-poor monodominant stand that has been forming for around 30 years. A lack of trees and dense grasses favor the successful invasion of the black locust on man-made sandy habitats.

Keywords: sand-gravel mine; primary succession; biological invasion; propagule pressure

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1. Introduction

Botanical studies that were conducted on opencast mines including sand mines revealed that spontaneous revegetation and forestry reclamation yielded congruent results: the species richness and the length of time required to achieve the stage of forest vegetation is similar. In addition, vegetation in abandoned sand mines can be more diverse in terms of species diversity [1]. On the other hand, local factors such as the bedrock [2–6] and hydrological conditions [7–9] can control the processes of spontaneous colonization. Depending on the geological substrate (e.g., gypsum, granite), the species composition of the flora is the result of the habitat requirements of the species that are colonizing excavations [10–12]. In sand pits where sand heaps and excavations, hydrological-hydrochemical conditions can differ. Xerothermic sand grasslands and the vegetation of therophyte swards tend to develop in dry places, i.e., on the top or slopes of heaps [13,14]. Usually, annual and stress tolerators prefer such extreme habitats [15], while reed beds and tall-sedge vegetation grow on the wetter sites that are situated at the bottom of excavations [16,17]. A similar phenomenon occurs in gravel opencast mines where sand is not the mineral being exploited, but is regarded waste that can be disposed of which form sand heaps. The aforementioned processes of natural revegetation can be disturbed by the appearance of invasive alien species. Usually, invasive species as well as ruderal plants can only occur during the younger successional stages and then disappear after a few years. However, under favorable conditions, some species such as *Robinia pseudoacacia* L. can develop and change the direction of succession and finally form a monodominant stand [18].

In this study we selected a site that is characterized by a wide diversity of morphological conditions (excavations, landfills, settling tanks) as well as water relations and hydrochemical characteristics. It is the opencast mine "Wójcice" where gravel and sand, which form bedrock of this area, are exploited. This mine, which is situated in southern Poland, has arable fields (corn plantations) and a forest in which *R. pseudoacacia* grows in close proximity. The territory of the mine has not yet been subjected to land reclamation because it is still active. Due to the legally sanctioned necessity to reclaiming degraded land in the future, the area of mine will be reclaimed. Three forms of management are being employed—forest reclamation, aquatic reclamation, and mining waste disposal [19]. Based on the conditions in the mine, it can be assumed that aquatic reclamation will probably be selected.

The aforementioned species, Black locust *Robinia pseudoacacia* L., is a legume tree that is native to North America and has been present in Europe since the beginning of 17th century and in Poland as a naturalized tree since mid-19th century. The species is considered to be invasive at least in nine European countries including, among others, Austria, Czechia, France, Germany, the Netherlands, Poland, and Switzerland [20–22]. It was deliberately introduced into Poland as an ornamental tree by gardeners, as a timber tree by foresters and as a way to improve the quality of the soil, namely, to enrich it with nitrogen. Currently, it is a species that is widespread in the country except for north-eastern part where it occurs less abundantly [23,24]. It frequently colonizes xerothermic meadow communities, dry forests, agricultural land, roadsides, as well as urban and industrial areas [20]. As a result of nitrogen fixation via symbiosis with the *Frankia* spp. and *Rhizobium* spp. bacteria in stands that are occupied by the Black locust the amount of nitrogen in the humus profile can be more than three-fold higher than it was originally [20,25,26]. Thus, it can change the properties of an ecosystem, which can lead to the displacement of oligotrophic and acidophilic species and the appearance of nitrophilic species [27,28]. It can also have an impact on the light conditions. In the stands in which this species dominates, the decrease in the size of the crowns is smaller and the cover of leaves is shorter than that of other deciduous trees [29]. This change in conditions promotes light-demanding species including herbaceous plants, especially grasses and geophytes, at the expense of the survival of the seedlings of shade-loving species, thereby strengthening and consolidating the effect of the conversion of a forest stand. Apart from plants, the species also has a negative influence on animals, e.g., birds. It was reported that it causes a decrease in the diversity of specialists to the benefit of the generalists [29]. *R. pseudoacacia* has invaded dry areas near disused gravel-sand mines. It is troublesome plant that can change the direction of spontaneous succession on these sites. Two final stages of vegetation development are also likely to form: shrubby grasslands or *Robinia* groves [18]. Taking into account that the species can also be encountered in alluvial habitats, we wondered whether it could thrive equally in both the dry and wet habitats that occur at the studied mine. Therefore, we studied the hydrological and hydrochemical properties of the water that could affect vegetation and observed the species composition of the vegetation along the environmental gradients in the vicinity of the mine.

The main objective of the research was to in order determine whether the natural succession at this mine is under pressure from *R. pseudoacacia*. The specific goals were to answer the following questions: How do the water affect the vegetation and *R. pseudoacacia* in the vicinity of the mine? Are there any differences in the contribution of *R. pseudoacacia* on the sites that differ in the amount of moisture and land relief? What is the approximate age at which the species forms a monodominant stand? What are the other environmental factors that control the development of the vegetation in the vicinity of the mine?

2. Results

2.1. General Hydrochemical Characteristics of the Water

The ionic composition of the water is dominated by bicarbonate anions (about 27%, 2.55 mval/L) and calcium cations (29%, 2.7 mval/L) (Figure 1). The water of the sedimentation tank is characterized by an average value of electrolytic conductivity of 360 µS/cm and neutral (pH~7) pH. A characteristic feature of the water is the trace amounts of biogenic substances—nitrogen and phosphorus. The average concentration of nitrates (NO_3^-) was only 1.5 mg/L and the concentration of phosphates (PO_4^{2-}) was below the limit to be quantified.

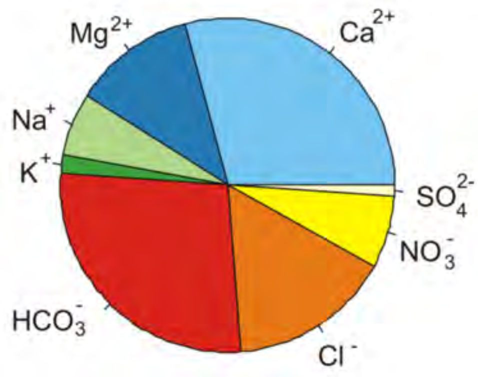

Figure 1. The chemical composition of the water in sedimentation tank is of the bicarbonate-calcium type.

2.2. Characteristics of the Vegetation and Substratum on the Study Sites

On the study sites, a total of 101 taxa were found, including 94 vascular plant species, 7 moss species and lichens (*Cladonia* sp) (Supplementary Materials Table S1). Additionally, there was a cover of algae but the species were not identified. On the 30 research plots, from 3 to 20 (on average 8.9 species) were recorded per plot. Species of rush and reed beds (the *Phragmitetea* R. Tx. et Prsg 1942 class), sand swards (the *Koelerio glaucae-Corynephoretea canescentis* Klika in Klika et Novak 1941 class), meadow communities (the *Molinio-Arrhenatheretea* R.Tx. 1937 class) and scrub-forest were also found. On the study sites, which include SH—sand heaps, ST—a sandy bottom of the sedimentation tank, and WT—wetlands, there are several stages and processes that caused succession: colonization by algae and mosses on clay material in the first stage of succession around bird feces (study site WT) (Appendix A, Figures A2 and A3) and colonization by grassland species on the desiccated parts of the settling tank (study site SH), while on the sandy material periodically flooded with pulp, algae and moss grow (study ST). In the second stage of succession, shrubs or biogroups of saplings (willows *Salix purpurea* L., *S. fragilis* L.—study site ST) occur and on study site WT, *S. purpurea* mainly occurs. According to the Indicator Species analysis (ISA), sand heaps are characterized by one indicatory species, *Picris hieracioides* L., whereas the grass *Cynodon dactylon* is the only species that is significantly affiliated to the sandy bottom of sedimentation tanks. The wetlands had five indicatory species and the highest number, nine, was growing in the adjacent forest, which was the control. The species *Oenothera biennis* L. and *Saponaria officinalis* L. had a high IndVal value in the two sandy habitats.

The grass *Calamagrostis epigejos* occurs significantly more often in the sand heaps and in the forest (Table 1). On the other hand, on the study site SH, on which the sand is stabilized by the roots of the grasses *Corynephorus canescens* and *Cynodon dactylon* L. dominated, Black locust (*Robinia pseudoacacia*) also occurs. The final stage of succession is the formation of black locust thickets or a black locust forest (study site SH), willow scrubs (study site ST), and a mosaic of rushes and willow scrubs (study site WT).

Table 1. The estimates of the indicator values of the species in a specific type of vegetation. *—$p < 0.05$; **—$p < 0.01$, ***—$p < 0.001$.

Habitat	IndVal	Habitat	IndVal
Sand heaps (1)		Control (4)	
Picris hieracioides L.	0.603 *	*Rubus sp*	0.683 *
Sandy bottom of the sedimentation tank (2)		*Quercus robur* a L.	0.665 *
Cynodon dactylon L.	0.612 *	*Arrhenatherum elatius* (L.) P.Beauv. ex J.Presl and C.Presl	0.578 *
Wetlands (3)		*Convallaria majalis* L.	0.578 *
Equisetum palustre L.	0.894 ***	*Corylus avellana* b L.	0.578 *
Epilobium cilatum Raf	0.756 **	*Euphorbia cyparissias* L.	0.577 *
Phragmites australis (Cav.) Trin. ex Steud.	0.731 *	*Impatiens parviflora* DC.	0.577 *
Carex nigra (L.) Reichard	0.632 *	*Polygonatum multiflorum* (L.) All.	0.577 *
Lythrum salicaria L.	0.632 *	*Quercus rubra* a L.	0.577 *
1 + 2		1 + 4	
Oenothera biennis L.	0.761 *	*Calamagrostis epigejos* (L.) Roth	0.686 *
Saponaria officinalis L.	0.753 *		

A Nonmetrical Multidimensional Scaling (NMDS) analysis showed a large variation in the species composition of vegetation among the study sites. The vegetation of the study sites differed significantly from each other according to a centroid analysis using passive vector matching ($r^2 = 0.74$, $p = 0.001$). The total cover of plants, species richness, and the value of Shannon-Wiener significantly explained gradient of the vegetational changes from a wetland to forest communities ($p = 0.001$, $p = 0.013$, $p = 0.011$), respectively. The Ellenberg indicator values (EIV) indicators for moisture and nitrogen were also significant ($p = 0.001$, $p = 0.012$), respectively. All of these variables are associated with the first axis of NMDS (Figure 2A).

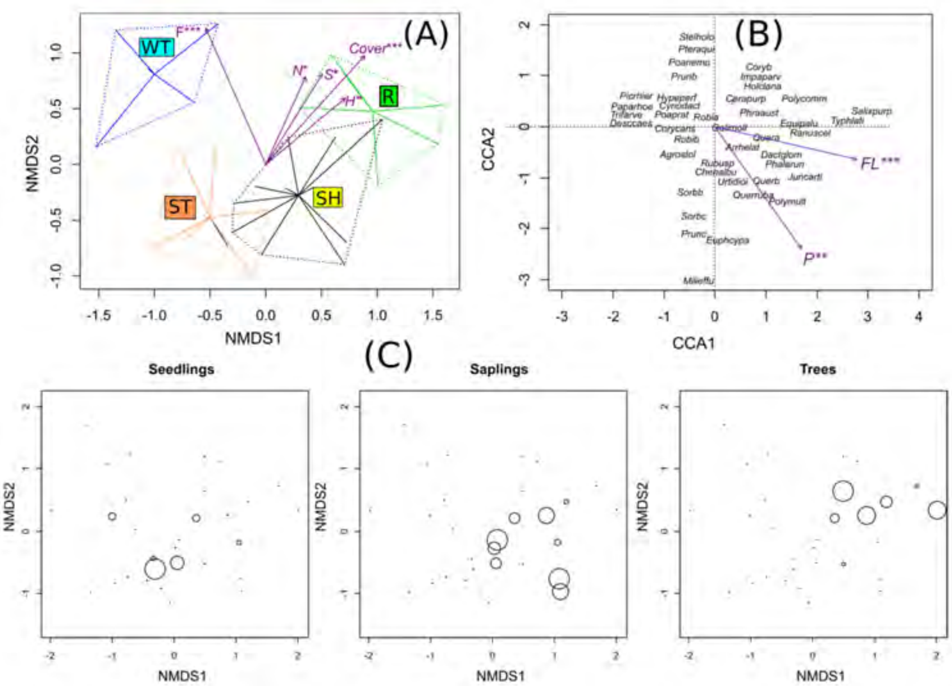

Figure 2. Nonmetrical Multidimensional Scaling (NMDS) and Canonical Correspondence Analysis (CCA). NMDS centroids (**A**), biplot of the study plots and environmental factors according to the CCA ($\gamma1 = 0.5954$ $\gamma2 = 0.5443$ and for which the cumulative explained proportion was 0.3350 and 0.6413 for the two axes, respectively) (**B**) and ordination of the *Robinia pseudoacacia* in relation to the layer and cover (**C**). Explanations: Cover—total cover of plants, S—species richness, H'—Shannon-Wiener index, N—nitrogen, FL—floatable parts fraction, *—$p < 0.05$; **—$p < 0.01$, ***—$p < 0.001$. 1 R—reference site, adjacent forest, SH—sand heaps, ST—sandy bottom of the sedimentation tank, WT—wetlands.

According to the Canonical Correspondence Analysis (CCA), the only significant habitat factors are the content of floatable parts ($p = 0.001$) and the content of phosphorus ($p = 0.001$). Higher values of these factors are associated with the wetland plots on clay material and to some degree with the forest plots (Figure 2B). On these sites, there were differences in the frequency of mature trees and saplings (G = 9.858, $p = 0.01981$, and G = 11.366, $p = 0.009904$), respectively, whereas the differences in the frequency of the seedlings of *R. pseudoacacia* among the habitats were not significant (G = 2.7291, $p = 0.4353$). There were no significant differences in the cover abundance. Only a few individuals of Black locust were found in the WT and the ST habitats (Figure 2C).

There were significant differences in the total plant cover. The highest mean values were found for the study plots in the adjacent forest and the lowest were found on the sandy sediments that are flooded with pulp. The highest value of the Shannon-Wiener index was found for the forests and heaps of sand, and the lowest for the wetlands and the sandy bottom of the sedimentation tank. The highest EIV values for light and temperature were observed for the sandy bottom of the sedimentation tank followed by the sand heaps. The EIV for moisture was highest in the wetlands and they also were the characterized by the highest content of phosphorus and floating parts (Figure 3). Differences in other environmental variables (pH, total nitrogen) were not statistically significant.

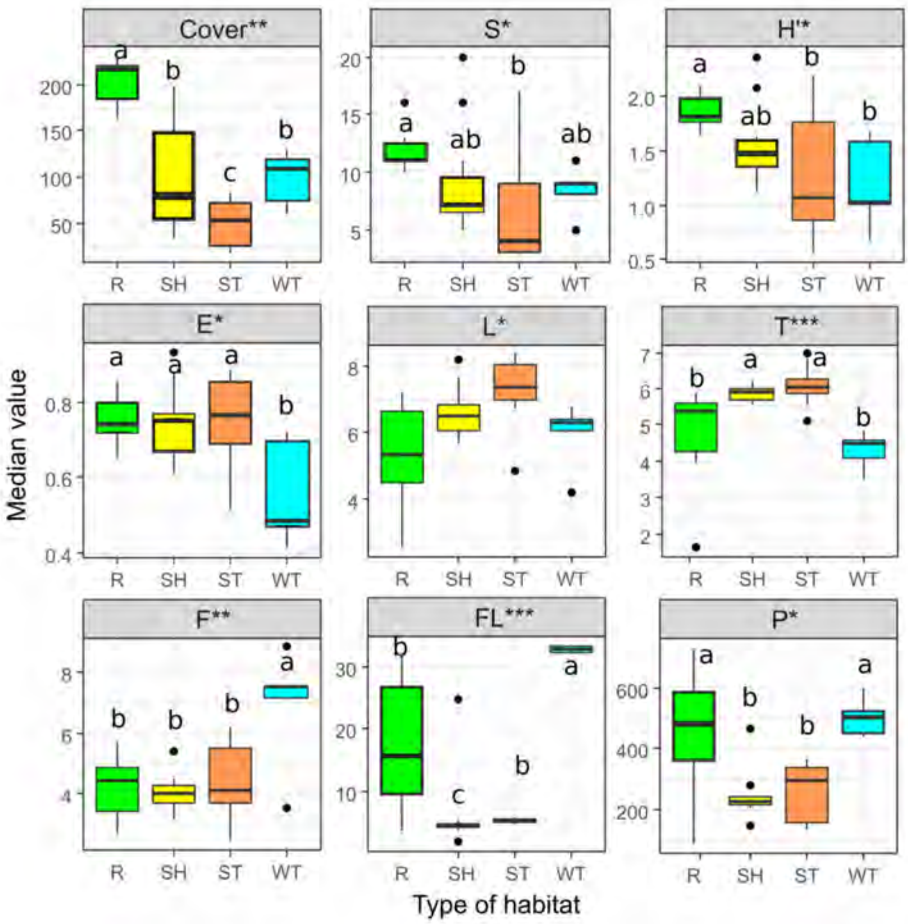

Figure 3. Comparison of the total cover of plants (COVER), species richness (S), Shannon-Wiener index (H′) and evenness index (E); Ellenberg indicators for light (L), temperature (T), and moisture (F); soil characteristics for phosphorus (P), and floatable parts (FL), among study sites. R—reference site, adjacent forest, SH—sand heaps, ST—sandy bottom of sedimentation tank, WT—wetlands. Significance of the differences according to the Fisher-Pitman test *—$p < 0.05$; **—$p < 0.01$, ***—$p < 0.001$. The same lowercase letters indicate no significant difference.

3. Discussion

3.1. Hydrochemical Assesment of Water and Pulp

The detected double-ion domination of bicarbonate ions and calcium is a common hydrochemical type of water that occurs in nature [30]. The values of electrolytic conductivity and pH are comparable to those found in most anthropogenic water bodies [31]. The trace amounts of nutrients in the water are another factor that limits colonization. The lack of nutrients in the water is a consequence of the closed water cycle in the sedimentation tank. The water flows through reeds that are located in the sedimentation tank, which removes nutrients from the water. In this case, the sedimentation tank acts as a "hydrophytic treatment plant". The high efficiency of the settling tank also purified the suspended matter. In the pulp discharge zone, the water turbidity exceeded 100 NTU and in the re-entry zone was about 50 NTU. The periodic flooding with water in the settling tank affects the development of the vegetation on study site WT (wetland) and sporadically on study site ST (sedimentation tanks).

3.2. Type of Succession of the Vegetation in the Vicinity of the Open-cast Mine

The development of vegetation in the vicinity of the "Wójcice" mine has the character of primary succession because it begins on bare ground without a plant cover. Several different directions of the succession and stages of vegetation in the vicinity of the mine can be distinguished (Figure 4). These are facilitation processes that mainly result in the modification of the habitat by pioneer species [32]. The direction of succession primarily depends on the hydration and type of substrate material, which is well illustrated by comparing not only the vegetational gradient (Figure 2A) but also the effect on the species composition and differences in the fraction of floatable parts (Figure 2B). The floatable parts correlated with the first CCA axis. While we did not determine moisture, its indirect proxy is the fraction of floatable parts. The higher the content of the fractionable fraction, the more the substratum absorbs water. Therefore, it is not surprising that mainly rush vegetation develops (reed and canary beds) on the clay material. On the other hand, there are sandy places that are overgrown with plants that are typical for sandy swards of the *Koelerio glaucae-Corynephoretea canescentis* class that have a large contribution of *Corynephorus canescens*. They develop best on sunny slopes where the soil temperature is higher. The high content of sands and gravels means that the substrate dries quickly even after heavy rains [33]. In the area of the sandy sediments that are periodically flooded with pulp, there are places with a large fraction of floating parts, which can be seen as the outlier on Figure 3. At the bottom of the sedimentation tank, which carry a lot of clay materials, periodic rivers occur. The sandy grasslands in the vicinity of the mine are quite species poor. The plots had an average of 9.1 species and the average value of the Shannon-Wiener index was 1.5. In the review paper by Sienkiewicz-Paderewska [34], the examined communities of the *Koelerio glaucae-Corynephoretea canescentis* class were characterized by an average number of species in the phytosociological relevé between 8.0 and 18.6 and the value of the Shannon-Wiener index was 1.5 and 3.5. The observed patches of grasslands in the vicinity of the mine are close to the lower values in that paper. In the patches of the grasslands of the vicinity of the sandy mine, there are several variants of the initial stages with *Corynephorus canescens*, *Saponaria officinalis*, *Oenothera biennis*, and *Senecio viscosus*. There are also intermediate patches that contain a mosaic of the above-mentioned species. The presence of the *Cynodon dactylon* is noteworthy because it is an ephemerophyte, a species that was introduced into Poland in 1825, which probably originated in Africa. Although it is still not naturalized, it has over 30 stands in Poland mainly in sandy areas [35].

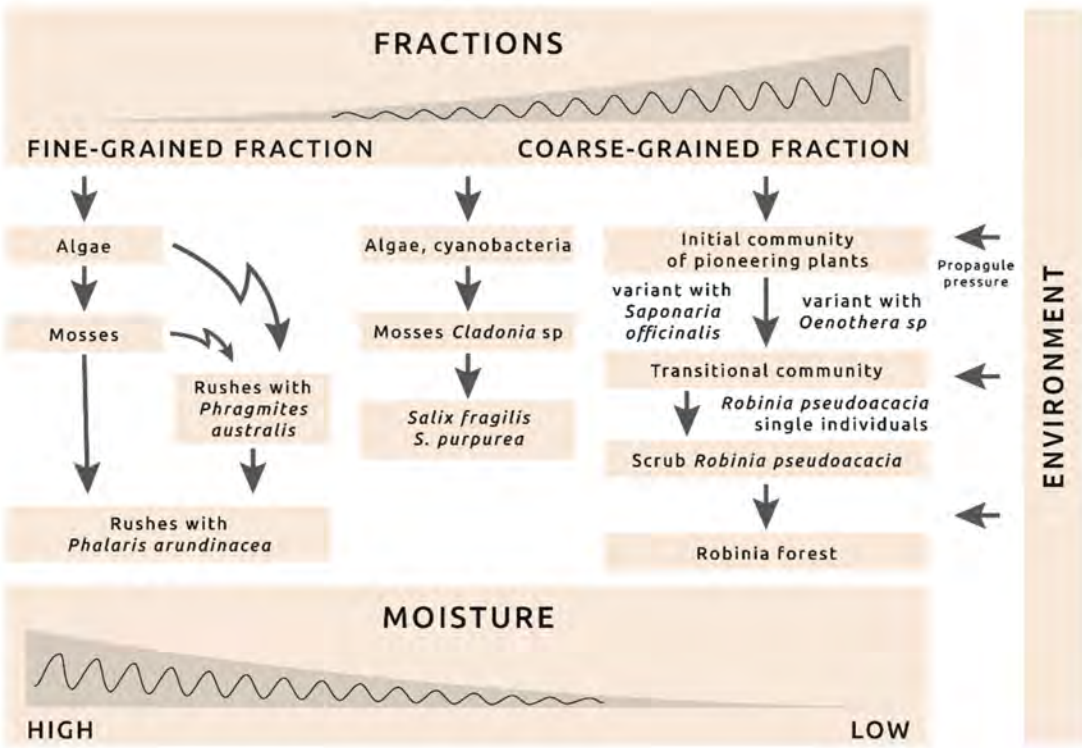

Figure 4. Model of succession: directions and phases of vegetation development in the vicinity of the "Wójcice" mine.

The wetland habitat where study site WT was established differs in both moisture and material—mainly clays. In addition, animal activities play an important role in a succession. It seems that the processes of habitat modification and the facilitation of succession are initiated by bird excrement and algae (enrichment of the habitat in nutrients) and that the ground is stabilized by willow roots and their leaves falling. At the shoreline of the tank, bird tracks (mainly ducks) and their excrement and algae colonies form around them. The impact of bird feces on the circulation of nutrients and the formation of ecosystems has been described in many regions of the world and environments, e.g., in forests [36], in water reservoirs [37], or even in Antarctica around penguin colonies [38]. Bird feces are primarily a source of phosphorus. This is confirmed by our research, where the highest reported values of phosphorus are in the area of wetlands (Figure 3). They are also high in the soil in the forest in the vicinity of the mine. The rush communities that occur in the vicinity of the mine are characterized by a small number of species in the relevé from 5 to 11 with an average of 8.4 and the Shannon-Wiener index is 1.19. This is typical for the rush communities here, which are mainly built by the reed *Phragmites australis* or the reed canary grass *Phalaris arundinacea* [39]. They are mainly monospecific patches with a large total coverage of plants as was the case in this study (Figure 3).

The places that periodically flooded with pulp, which are outside the coastal zone of the water reservoir is where the patches of communities built by willows formed: the crack willow *Salix fragilis*, the purple willow *S. purpurea*, and the almond willow *S. trandria*. They are mainly shrub communities and there are only a few species per plot where an important phenomenon occurs, namely leaf fall. There is an enormous body of literature about the role of leaf decomposition and its impact on the soil properties specifically enriching the soil with nutrients and circulating matter [40]. Compared to the plots on the sand heaps, those with willow are characterized by higher values of nitrogen and phosphorus (Figure 3).

3.3. *Invasion of Robinia Pseudoacacia*

In the later stages of succession in the vicinity of the mine the Black locust *Robinia pseudoacacia* occurs primarily on the sands (study sites 1 and 2) (Figure 2B). In the vicinity of the mine, Black locust individuals in almost all stages of succession occur. Various herbaceous species grow under the canopy of trees, first forming biogroups, then thickets, and finally a compact Black locust forest. The estimated time for this type of forest to develop is about 25 years (based on the observation of the mine personnel). This is a shorter time compared to other results [41] where succession proceeded toward stabilized, (semi-) natural vegetation with an *R. pseudoacacia* contribution within 40 years. The thickets and forest with *R. pseudoacacia* are characterized by a lower species richness (maximum 20 species per plot) and low values of Shannon-Wiener index, which is congruent with the general trend. In other habitats, even those with natural forest conditions, the *Robinia* forest were species poor [42]. In our study, the largest individuals in this phase of the Black locust forest on sandy habitats were about 8 m high and had ca 5 to 13 cm of diameter at breast height (DBH), whereas the largest stems in adjacent forest had a DBH that was no larger than 16 cm. Thus, all of them can be classified as early-successional trees and shrubs of Black locust [43]. The research results show that the older stages of succession, especially on the sand heaps, are similar to the forest in the area in terms of its structure and species composition (Figure 3). Based on the species composition, it can be concluded that the adjacent forest resembles the human-cultivated forest *Chelidonio-Robinietum* Jurko 1963 s.l. [43,44]). Taking into account the relatively small distance from the adjacent forest to the territory of the mine including the sandy habitats, the transport of seeds by the wind could be efficient enough to disperse this plant. It was reported that seeds can be transported by wind on the ground up to 67 m from a single mother plant [43]. The nearby forest with *R. pseudoacacia* is a probable source of the propagules of black locust in the habitats in the vicinity of the sand-gravel mine. The presence of water directly affected the performance of *R. pseudoacacia*. It was not found in the distinguished study plots in the areas that flooded. This contradicts the findings that they can occupy alluvial sites and previously flooded area [20]; however, these authors also state that the species does not occur in wetlands or the parts of alluvial forests that have frequent and long-term waterlogging and in which the soils are compact. In the present study, *R. pseudoacacia* was not found anywhere in the wetlands and in areas that got flooded, there are only a few individuals. The hydrochemical properties of water do not matter at all, especially because they are typical for the majority of surface water in Poland.

A summary of the directions of succession and individual phases of the development of vegetation is presented in the diagram in Figure 4. The processes of colonization and succession in this study resemble the processes that was described in the Błędowska Desert by Rahmonov [45]. Similar to that study, this is a primary succession on sand where algae, mosses, and vascular plants that are typical for dry, xerothermic habitats play an important role. It is also typical that the soil development is slower than the development of the plant cover. It is noteworthy that the changes are progressive in terms of the increase in the number of species and coverage. This pattern is consistent with most similar studies [18,41], but is contrary to the results of Kompała-Bąba and Bąba [46] where the number of species decreased and the role of dominants increased in a sand pit.

4. Materials and Methods

4.1. Description of the Study Area and Study Design

The study area (the Wójcice mine) is the territory of an open cast mine. The mineral aggregate deposits are mined using the underwater method, which is conducted in the dam reservoir zone of the "Nysa Lake". The output is rinsed and screened (sorted) in order to remove the smallest fractions (mainly sand and clay). While the water for rinsing is taken from "Nysa Lake", it is circulated in a closed cycle. After passing through the sedimentation tank, it is used in material sorting processes once again. The lake water is only used to compensate for any technological losses. Of the mineral aggregates that are mined, only the gravel is sold. As a result, the fractions of highly hydrated pulp that are separated are hydraulically transported to the sedimentation tank where it undergoes sedimentation and dehydration (Figure A1A, Appendix A). The pulp is a by-product of the mine, which cannot be sold due to its specific properties. In the sedimentation tank, thickest fractions are separated in the first part of the sedimentation (sands with a small admixture of gravels) after which the fine-grained dust and clay fraction is separated (mainly in the water zone of the settling tank). The sludge that is deposited in the settling tank is characterized by characteristic lamination, which is a consequence of cyclic pulp inflows (Figure A1B). Recently, however, the sandy sediments that is deposited in the settling tank has also been exploited. This is called the exploitation of the anthropogenic deposit, which are primarily heaps of sand that are unstabilized and heavily desiccated (Figure A1C, Appendix A). The analysis of the vegetation mapping, type of substratum, degree of moisture and age of the sedimentation tank enabled four research study sites to be distinguished (Figure 5) and within them 30 study plots (Table 2). These were 1—sand heaps (SH), 2—sandy bottom of sedimentation tank (ST) 3—wetlands (WT), and 4—reference site (R, adjacent forest). The reference site was a forest with a high contribution of *R. pseudoacacia* in its tree layer. Based on the species composition, the forest can be classified as a degenerated oak-hornbeam forest *Tilio-Carpinetum*. Taking into account the internal diversity of the succession stages and the surface area of the distinguished habitats, a total of 30 study plots of 5 m × 5 m were established. During the vegetation season from the end of March to the end of August, soil and botanical studies were carried out and at the site of the discharge of the pulp onto the surface of the settling tank, hydrochemical studies of water were performed.

Figure 5. The spatial distribution of the study plots in the vicinity of the "Wójcice" mine. Explanations: study site SH—zone of sand heaps, extreme dry conditions, advanced succession—11 study plots, site ST—bottom of the sedimentation tank, zone of sand deposits, initial and mid-advanced succession (maybe periodically flooded by pulp)—8 study plots, site WT—zone of clay deposits, moist areas, periodically flooded, various forms of succession—5 study plots and site R—control, situated in the adjacent forest—6 study plots.

4.2. Methods of the Hydrological Studies

The hydrology was mapped according to the guidelines by Gutry-Korycka, Werner-Więckowska [47]. During the research, ten water samples with the pulp that were floating to the surface of the settling tank were collected. The basic physical and chemical properties of water (temperature, pH, oxygen saturation) and redox potential were measured directly in the field using a YSI EDS 6600 multi-parameter probe (US production). Prior to each test, the probe was calibrated using the standard solutions. During the fieldwork, water samples were also collected for the chemical analyses. The samples for the laboratory analyses were placed into 0.5 L polyethylene bottles. The water samples were transported to the laboratory at +4 °C. They were filtered on a 0.45 μm filter (Millipore). Laboratory analyses included determining the main cations and anions in the water: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+}, HCO_3^{-}, SO_4^{2-}, Cl^{-}, NO_3^{-} and PO_4^{2-}. The analyses were performed using a Metrohm 850 Professional IC ion chromatograph. The hydrochemical type of the water was determined based on the classification of Szczukariew-Prikłoński [48].

Table 2. The characteristics of the study sites.

Habitat	Moisture	Grain Fraction	Species
Sand heaps (SH), n = 11	low	coarse	*Saponaria officinalis, Senecio viscosus, Corynephorus canescens, Oenothera sp., R. pseudoacacia*
Sandy bottom of the sedimentation tank (ST), n = 8	high	coarse to fine	*Salix fragilis, S. purpurea, Corynephorus cansecens, Oenothera sp*
Wetlands (WT), n = 5	high	fine	*Phragmites australis, Equisetum palustre,*
Control (R), n = 6	medium	medium	*R. pseudoacacia, Quercus robur, Rubus* sp.

4.3. Methods of the Soil Analyses

Composite soil samples were taken from the study plots and the physical-chemical properties as well as the granulometric composition of soil was determined: pH (in an aqueous solution and in a 1N KCl solution), N_T—total nitrogen according to PN-ISO 11261, P—available phosphorus according to PN-R-04023, and FL—fraction of floatable parts using the Prószyński' aerometric method PN-R-04033 [49].

4.4. Methods of the Botanical Studies

Within the study plots, a floristic inventory was taken (vascular plants and bryophytes) and a modified Braun-Blanquet approach was performed [50]. In total, 30 phytosociological relevés were taken at all of the distinguished study sites. The cover abundance of the recorded plants was visually estimated in % (0.5, 1, 2, 5, 10, 20 ... 100) and the total cover using the Canopy Cover Free 1.03 application for mobile devices with the Android system and canopyscope [51] with our own modifications [52] were used to assess the tree canopy. Based on the occurrence and cover abundance of the species, the Ellenberg indicator values (EIV) were calculated [53]. The cover-weighted EIV were calculated for light (L), temperature (T), moisture (F), and soil reaction (R). The EIV for nitrogen (N) was not considered because the soil samples were analyzed for N_T and the continentality K was not applicable in this study. The nomenclature for the species follows the Euro+MedPlantBase [54], whereas the syntaxonomical nomenclature follows the Guide for Plant Communities in Poland [55].

4.5. Statistical Analysis

The statistical analyses and visualizations were performed in the R software [56]. The Indicator Species Analysis (ISA) using indicator value, i.e., IndVal—the indicator value that indicates the magnitude of species affinity and the p-value of the statistical significance were also calculated (package *indicspecies*). Based on the collected vegetation data, the biodiversity indices were calculated: the number of species (S), the Shannon-Wiener diversity index (H'), and the species evenness (E), as well as the sum of the species cover (COVER). Next, Nonmetric Multidimensional Scaling (NMDS) was conducted to examine the variability direction of the analyzed vegetation. For the NMDS, the data was log-transformed. In order to examine the differences in the species composition of vegetation among the four study sites, the centroids representing the vegetation of a given study site was analyzed using the vector fitting method. The same test (999 permutations) was used to fit the biodiversity indices to the ordination result as passive vectors, which were plotted as an NMDS biplot. In order to investigate the influence of the habitat factors pH, total nitrogen content, phosphorus and percentage fraction of the floating parts of the substratum (fraction < 0.05 mm) on the species composition, a canonical correspondence analysis (CCA) was performed, and the significance of the habitat factors was also assessed using the permutation test (999 iterations). The biodiversity indices and ordination were analyzed using the *vegan* package. In turn, the significance of the differences in the biodiversity indices and habitat factors was analyzed using a non-parametric equivalent of the analysis of variance ANOVA, i.e., Asymptotic K-Sample Fisher-Pitman Permutation Test [57] followed by a post-hoc Conover test. The significance of the differences in the frequency of *R. pseudoacacia* was tested by G-test using the *DescTools* package. The significance was assumed at a level of $p < 0.05$.

5. Conclusions

The various phenomena of the colonization and vegetation succession that occur in the vicinity of the mine were determined by three main factors: the type of substrate, especially the type of the fraction (sands and clays), hydration (overdried areas vs. areas that are flooded with water), and the environment (degenerated oak-hornbeam forest). The development of the plant cover was faster than the soil cover formation, which is shown by the example of succession on sands. On the overdried sites, the older stages of succession resemble the forest with *R. pseudoacacia* in the vicinity of the mine. The occurrence of this species in the study area was possible due to the propagule pressure (fruits, seeds) of *R. pseudoacacia* from the adjacent forest, which was confirmed by other studies. *R. pseudoacacia* is only able to invade dry sites, and on wet sites, its spread and abundance is strongly constrained. On flat sites that are flooded with water, only willow (*Salix* spp) can thrive. Thus, differences in hydrology causes a niche shift of woody species.

Supplementary Materials: The following are available online at https://www.mdpi.com/2223-7747/10/1/40/s1, Table S1: Species data with mean and SD percent cover and type of occupied habitat.

Author Contributions: Conceptualization, D.C., T.M. and J.K.; methodology, D.C., T.M. and J.K.; data collection: J.K., D.C., T.M.; data curation: J.K.; statistical analyses, J.K. and D.C.; writing—original draft preparation, J.K.; writing—review and editing, J.K. and D.C.; visualization, J.K. and D.C.; supervision, D.C. and T.M.; funding acquisition T.M. and D.C. All authors have read and agreed to the published version of the manuscript.

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Appendix A

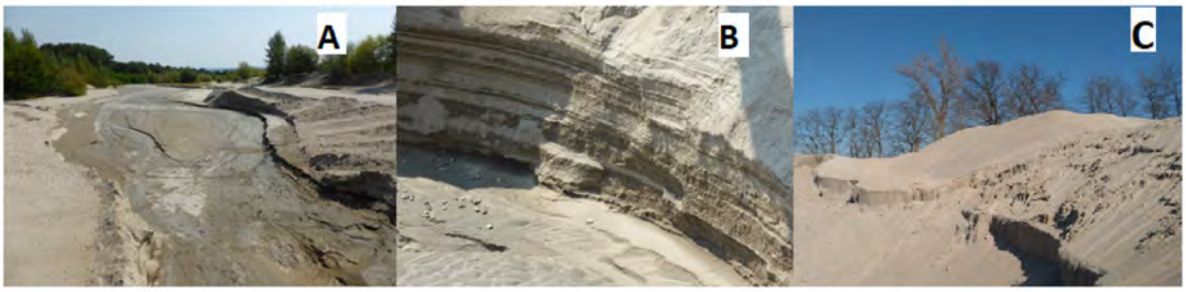

Figure A1. (**A**) Place of the pulp dump into settlement tank which creates the periodic and braided river. (**B**) Characteristic laminated sand sediments deposited on the settling tank. (**C**) Sand heaps (slurry).

Figure A2. Algae colonies around the bird feces on the clay material, first stage of succession and example of habitat modification.

Figure A3. Two extreme habitats: sand heaps and wetlands on the territory of the open cast mine.

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1.3. Hydrological and Hydrochemical Conditions for the Reclamation of Anthropogenic Water Bodies and Wetlands in Opencast Mines

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ABSTRACT: Studies on waters and a botanical survey were carried out in 2014 in the territory and in the vicinity of the three open cast mines: “Górażdże” (a limestone quarry), “Nowogród Bobrzański” (a sand mine) and “Wójcice” (a gravel mine). It was observed that the chemical composition of waters in post-exploited reservoirs and wetlands is determined by the type of rock that is being exploited. The hydrological conditions (the degree of hydration of the excavation, the morphometric parameters of water body, etc.) also contribute to the type of vegetation and the direction of spontaneous succession in post-exploited areas. The proper choice of reclamation should be performed using a modified succession that is adapted to specific hydrological-hydrochemical conditions. In the case of flow-through-containers, it should provide a good quality of water using special technical solutions, i.e. an Olszewski tube. The rehabilitation of slurry clarifiers in which sand is a waste requires a modified succession and the use of stress-tolerating plants that can grow under conditions in which there is a lack of water and low fertility of the substratum such as a forecrop. The vicinity near post-exploited water bodies and excavations on limestone ought to undergo reclamation into wetlands or artificial water bodies due to the flooding of the floor of excavation. This enables the creation of biotopes for fens and aquatic plant communities.

KEYWORDS: Quarry, sand pit, primary succession, spontaneous vegetation, open cast mine

INTRODUCTION

The geological background is the main element influencing the course, pace, dynamics, composition and structural effects of natural processes on sites which have emerged as the by-products of mineral resources exploitation. The habitats established on these sites have varied conditions in terms of moisture. Apart from the terrestrial sites like heaps, there are also wetland and water habitats provided during the processes of post-industrial, post-excavation establishment of sites. In this way the geology determines the hydrological and hydrochemical conditions of anthropogenic water bodies and wetlands in opencast mines.

The studies that were conducted earlier indicated that the direction of natural processes, colonization of post-excavation mineral pits by plant species and vegetation, is mainly determined by the type of rock and mineral resources that were exploited in a particular mine (Kasprowska--Nowak & Beczała 2014; Beczała & Dorda 2015; Molenda *et al.* 2013; Nowak 2005; Nejfeld 2007). Flooded excavations in which the waters are rich in calcium and magnesium ions have the appropriate conditions for forming unique mires with calciphilous plant species. Some of the calciphilous species are protected plant species (König 2017; Stebel & Błońska 2010; Błońska *et al.* 2020).

In sand pits and gravel excavations in which the hydrological-hydrochemical conditions are different or lack of water occurs, other type of vegetation do well (Nowak & Hebda 2006; Woźniak & Sierka 2004; Chmura *et al.* 2013). Temperate sand grasslands and therophyte swards thrive in dry places (Czylok & Szymczyk 2009; Rahmonov & Szymczyk 2010). On wetter sites reed beds and tall-sedge vegetation develop (Chmura & Molenda 2007). The choice of the appropriate type of reclamation should be preceded by a detailed understanding of the hydrological and hydrochemical conditions in an excavation area (Molenda & Kidawa 2020). The kind of soil-substratum in post-exploited areas is also essential. The spontaneous process of succession under natural conditions can proceed very slowly and does not always occur over the entire area of excavation. Therefore, the reclamation of these sites is necessary. The introduction of plant species and the creation of new biotopes must conform to the habitat requirements of these species and the abiotic conditions of a specific site (Řehounková *et al.* 2011). Even when rehabilitation of a given site meets these criteria, it is still possible that the course of succession will be modified compared to succession under natural conditions. We chose three types of open cast mines that differed in a variety of exploited materials. We had water bodies that were created during natural subsidence succession or were formerly existing water reservoirs. The aim was to check whether there were links between abiotic properties of water bodies and characteristics of post-mining vegetation.

OBJECTIVES

The main aim of the research was to answer the following questions:

- What are the hydrographic and hydrochemical relations of excavations in limestone, sand and gravel mines?
- What are the morphometric attributes of the excavations in limestone, sand and gravel mines?
- What is the direction of the natural primary succession on these sites?
- What are the best methods for reclamation of the specific excavations in terms of their hydrological, hydrochemical and vegetation conditions?

STUDY SITES

Three different opencast mines, all of which are located in Poland, were chosen for the purpose of the study: “Górażdże” a limestone quarry; “Wójcice” a gravel mine; “Nowogród Bobrzański” a sand mine (Fig. 1). In the "Górażdże" mine the reservoirs and wetlands that were situated on the floor of the excavation were studied. In the "Nowogród Bobrzański" mine the study focused on the post-exploitation water bodies and their surroundings and in the "Wójcice" mine sedimentation tanks and slurry heaps were the subject of research.

METHODS

The underlying physical and chemical properties of the waters (temperature, pH, electrical conductivity, oxygenation and redox potential) were measured. Measurement in the field was performed by using an EDS 6600 multiparameter probe from the US company YSI. Before the measurements, the probe was calibrated using standard solutions. The water parameters studied were determined in water columns at 0.5 m ("Nowogród Bobrzański"). The profile was located in the deepest parts of the reservoir. In the remaining water bodies ("Górażdże", "Wójcice"), the measurements were conducted in the coastal zone. Additionally, water transparency was determined using a Secchi disk (SD).

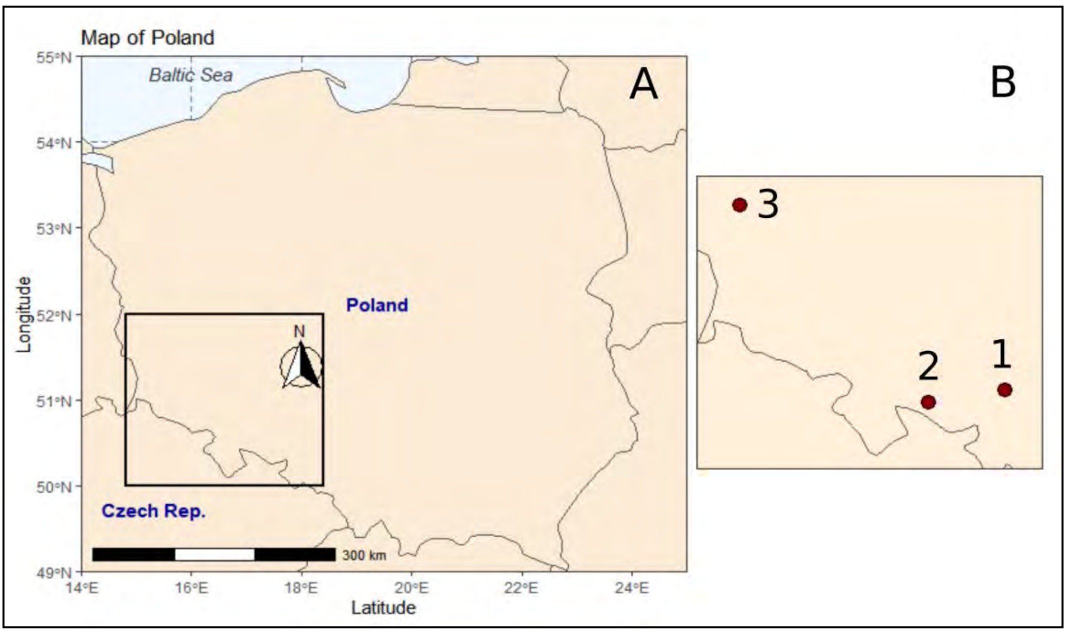

Figure 1. Situation of the studied opencast mines "Górażdże" (1), "Wójcice" (2) and "Nowogród Bobrzański", (3) in the western part (B) of Poland (A)

During field research, water samples were collected in polyethene bottles (0.5 L) for chemical analyses in the laboratory. Samples that were collected represented the surface layer of water (0.5 m). The water surface layer was collected using a telescopic boom. Transport of water samples to the laboratory was conducted at a temperature of +4°C. The samples were filtered using a 0.45 mm filter (Millipore) before analyses. Laboratory analyses included the determination of the major cations and anions in the samples: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+}, HCO_3^{-}, SO_4^{2-}, Cl^{-}, NO_3^{-} and PO_4^{2-}. The analyses were performed using a Metrohm 850 Professional IC ion chromatograph. The hydrochemical type was determined according to the classification by Szczukariew-Prikłoński (Macioszczyk & Dobrzyński 2002).

The botanical survey included mapping of vegetation in the vicinity of the post-exploited reservoirs or sedimentation tanks and slurry heaps, using the Braun-Blanquet approach (Westhoff & Van Der Maarel 1978). The distribution of rare and protected species in relation to the geological characteristics of the mineral excavated within the phytocoenoses was studied. The description of succession was done using the chronosequence method (Johnson & Miyanishi 2008). Information about the hydrochemical and hydrological conditions and vegetation composition was collected. The analyses enabled us to propose reclamation practices for re-establishment of wetland ecosystems for sites on which open-cast mines are operating.

RESULTS and DISCUSSION

Hydrological conditions of excavations

In limestone excavations, the waters are rich in calcic, sulphate and bicarbonate ions (Fig. 2). The ponds that are located in the vicinity of the "Górażdże" mines are examples of these types of water bodies. The post-exploitation reservoirs that formed in mineral aggregate excavations (the "Nowogród Bobrzański" mine and the pool in "Wójcice") are distinct in terms of the physical-chemical properties of waters. Their waters are three or four ionic and more similar to each other, characterized by higher participation of bicarbonate ions magnesium and sodium (Fig. 2).

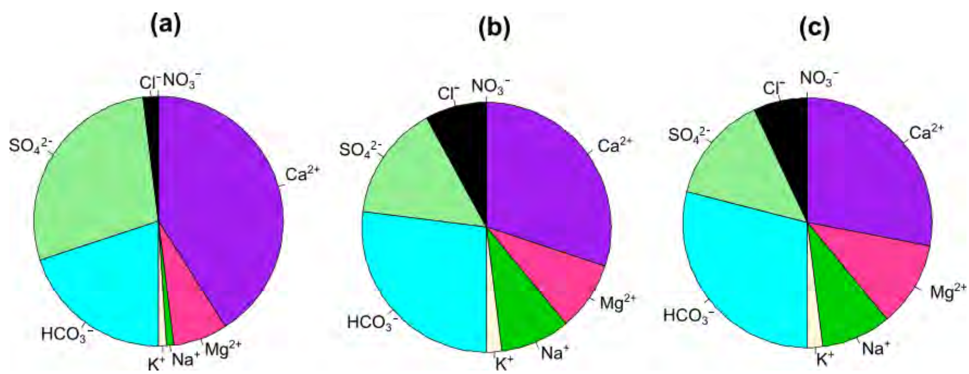

Figure 2. Chemical composition of the waters in the post-exploitation reservoirs
in "Górażdże" (a),"Wójcice" (b), "Nowogród Bobrzański" (c)

In "Górażdże" the water in these reservoirs is representative of a bicarbonate-sulphate-calcic-magnesium type of water (HCO_3^- - SO_4^{2-} - Ca^{2+} - Mg^{2+}). Thus, they are four ionic-type waters, and they differ from the waters that were observed in the sump of the "Górażdże" mine in which the waters are representative of a sulphate-bicarbonate-calcic type of water (SO_4^{2-} - HCO_3^- - Ca^{2+}). Within one excavation (mine) site, profound differences in the hydrochemistry of water were recorded. The mineralization of the water can also be significantly different. There are significant differences in mineralization of the water among the ponds that were situated in the vicinity of the "Górażdże" opencast mine, which results from differentiation in the water supply of these sites. The ponds that were mainly supplied by underground waters were characterized by higher mineralization (> 0.6 g/L). In contrast, the shallow water bodies that have precipitation as the dominant type of water supply were typified by lower mineralization of the waters (< 0.6 g/L). The highest mineralization was found in the underground waters of the sump (> 0.7 g/L). In "Wójcice" and "Nowogród Bobrzański" the waters of these reservoirs were characterized by lower mineralization (0.2 g/L).

Vegetation in the vicinity of reservoirs

The chemistry of water bodies has a major impact on riparian vegetation. In the immediate vicinity of the reservoirs of each of the mines, reed beds of the *Phragmition* alliance, i.e. patches of plant associations: *Phragmitetum australis*, *Typhetum latifoliae*, *Scirpetum lacustris*, *Sparganietum erecti*; however, the surrounding vegetation differed significantly. In the area of the "Górażdże" mine, in spite of cultivation of Scots pine *Pinus sylvestris* and larch *Larix decidua*, species of broadleaved forest prevail on the forest floor (the *Fagetalia* alliance) such as: *Anemone nemorosa*, *Viola reichenbachiana*, and *Primula elatior.* However, the tree stands are dominated by coniferous trees and birch *Betula pendula* due to previously conducted land-reclamation. Moreover, the amount of invasive alien boxelder *Acer negundo* and black alder *Alnus glutinosa* is still increasing (Kacprzak & Bruchal 2011). These forests grew in beech forest habitats. Potential natural vegetation in this area is best illustrated by the vegetation in the "Kamień Śląski" reserve (Spałek 2003) which is located in the surrounding area. Close to the bank zone in an adjacent area of rushes there are patches of initial fens with *Epipactis palustris* and *Centaurium erytharea* of the *Scheuzcherio-Caricetea nigrae* (Fig. 3).

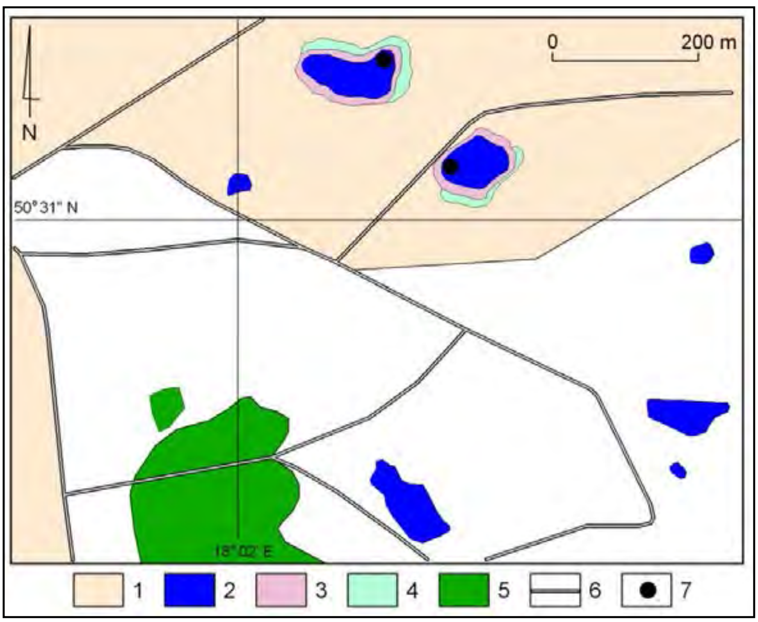

Figure 3. Localization of investigated objects and vegetation in the limestone quarry "Górażdże". Explanations: 1 – woodland/thickets, 2 – reservoirs, 3 – rushes (*Phragmition*), 4 – initial fen communities (the *Scheuzcherio-Caricetea nigrae* class), 5 – forest, 6 – roads, 7 – sampling points

In the "Wójcice" mine area, the vegetation developed on two different sites: at the bottom of the sedimentation tanks and slurry heaps, mainly built by sand. Along the banks of water bodies rushes of the *Phragmition* alliance grew. The only vegetation with high contribution of trees was at the border of the territory of the mine. These are disturbed patches of species-poor oak-hornbeam forest *Tilio-Carpinetum* (Fig. 4). In this forest, apart from *Q. robur*, the codominant tree was *Robinia pseudoacacia* of North American origin. Several species found within the area of the mine originated from this forest. However, a majority of the area of the mine is almost non vegetated or with only initial development of sand grasslands. The most frequent plants on sand heaps were *Saponaria* *officinalis*, *Oenothera* spp., and *Senecio viscosus*. The lack of water and nutrients in the soil substratum seemed to be limiting factors for growth of plants on slurry heaps. In remaining areas on the flat sites *Salix* scrub developed (thickets of *Salix purpurea*, *S. fragilis*).

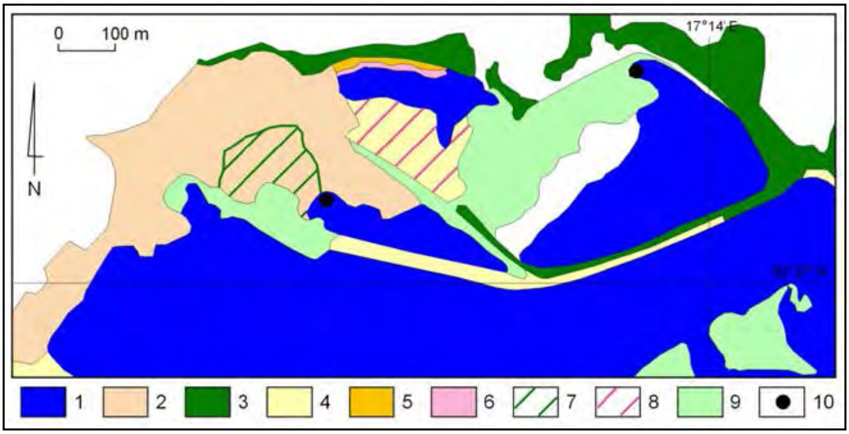

Figure 4. Localization of investigated objects and vegetation in the gravel mine "Wójcice". Explanations: 1 – reservoirs and the slurry clarifiers, 2 – old slurry heaps, 3 – degenerated oak-hornbeam forest, 4 – the contemporary dry slurry clarifier, 5 – meadow, 6 – ecotone, 7 – the area of succession with *Saponaria officinalis*, *Oenothera* spp., 8 – the area of succession with willow (*Salix* spp.), 9 – rushes (the *Phragmition* alliance), 10 – sampling points of water

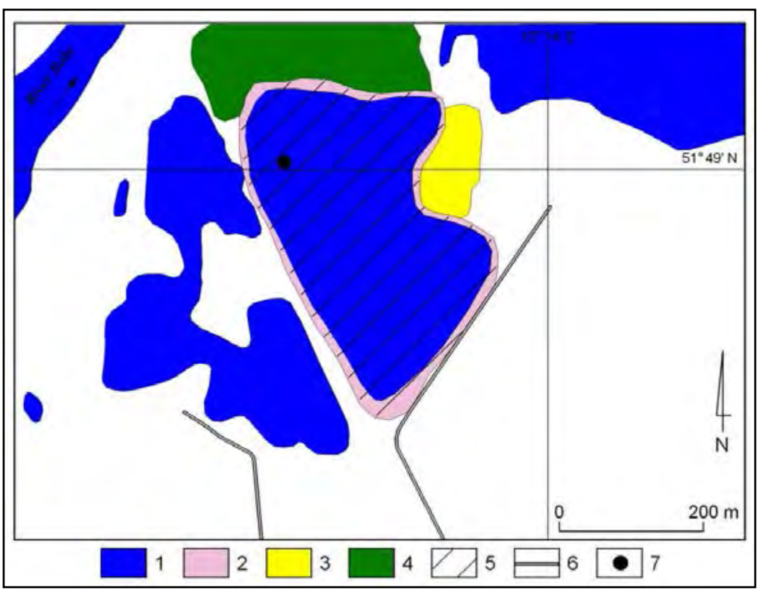

Figure 5. Localization of investigated objects and vegetation in the sand mine "Nowogród Bobrzański". Explanations: 1 – reservoirs, 2 – rushes (*Phragmition*), 3 – sand grasslands and therophyte swards (the *Koelerio-Corynephoretea* class), 4 – floodplain forest (the *Alno-Ulmion* alliance), 5 – reservoir, 6 – roads, 7 – sites of profile studies and sampling points of water

In the area of the “Nowogród Bobrzański” mine, there were patches of temperate sand grasslands and therophyte swards (the *Koelerio-Corynephoretea* class) in the sandy sites close to two main artificial water reservoirs (Fig. 5). In a further zone of the reservoirs there was a degenerated floodplain forest of the *Alno-Ulmion* alliance with abundant populations of the invasive alien species *Impatiens parviflora* and *I. glandulifera*, however, other dominant species included native *Iris pseudacorus*, *Urtica dioica*, and *Chaerophyllum aromatcium*. The causeway was planted with trees, mostly monumental individuals of oaks: red oak *Quercus rubra* of alien origin and native European oak *Q. robur.* In this area more than 120 vascular plant species were found including the Red List species *Potentilla rupestris* (Burda *et al.* 2016).

Management of excavations after the exploitation of limestones and dolomites (a study of “Górażdże” mine)

The most interesting ecosystems are associated with the transitional zones between the land and a water body. There were several occurrences of protected and rare species, including *Epipactis helleborine* and (not previously registered) *Centaurium erythraea*. There were conditions for shaping of wetland ecosystems (Fig. 6). The occurrence of species was closely associated with the hydrogeochemical conditions. The floor of the excavation pit is permanently wet (the water table during the year is no lower than 0.5 m from the surface area). The waters are rich in calcium ions and magnesium and therefore they are preferred by calciphilous plants.

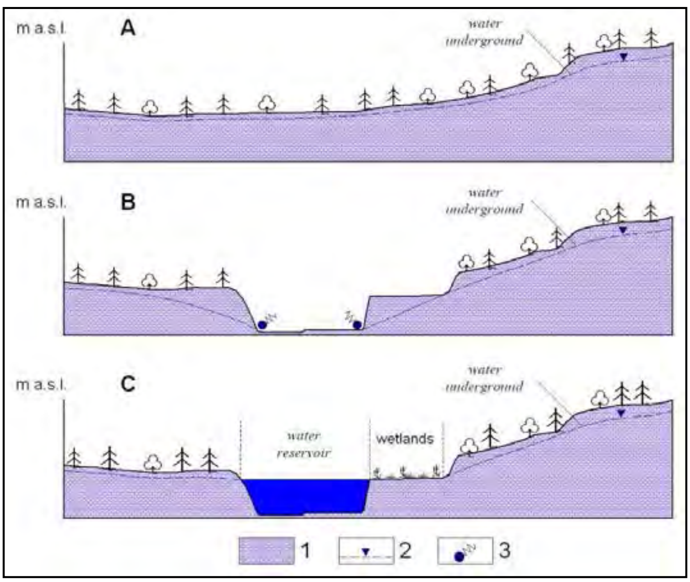

Figure 6. The scheme of water reservoirs forming in excavation of limestones and dolomites. Explanations: A – the state before exploitation, B – the state during exploitation, C – the state after exploitation cessation; 1 – limestones or dolomites, 2 – level of underground waters, 3 – outflows of underground waters

Possible solution – creation of wetland ecosystems

The example of the “Górażdże” mine showed that the reclamation of excavations after the cessation of the exploitation of dolomites and limestones should include the creation of wetland ecosystems.

This is possible in excavation pits in which the floor or the excavation overlap with the underground water table. The deeper parts of excavations after the discontinuation of exploitation that are subjected to flooding should be preserved as water bodies, which can provide habitats for precious rare species such as algae (*Charophyta*). Wetland ecosystems can also be created in sand mines.

RECLAMATION OF SLUDGE (THE CASE OF THE "WÓJCICE" MINE)

The exploitation of gravel deposits creates considerable amounts of wastes. These wastes are the fine-grained mineral fractions (loams, dusts, sands), which are formed during the screening and washing of spoil. The wastes are transported in the form of water pulp into the sedimentation tank. After the sedimentation tank is completely filled, it is desiccated and closed. Such an object was situated in the vicinity of the "Wójcice" mine. Fine-grained material is blown around by winds and contributes to an increase in the dusting area. Land reclamation of this type of site is very difficult. Conditions are unsuitable for vegetation development in old, unexploited sedimentation tanks. These conditions are connected with:

- a lack of organic material and nutrients,
- extremely harsh water conditions (a lack of groundwater).

Colonization by pioneer plants is ongoing in the vicinity of the "Wójcice" mine in spite of harsh conditions for organisms in the sedimentation tank. The succession has proceeded along two pathways and direction was connected with two things – access to water and relief (Fig. 7). In dry biotopes in the initial stage *Saponaria officinalis* and *Oenothera* spp. prevailed. During succession *Robinia pseudoacacia* starts to appear and finally it can form monospecific stands. In wet, temporarily flooded flat terrain, the successional process of vegetation is similar to those described for the "Błędów" desert (Rahmonov 2007), which resulted in willow scrub. In turn, on the slopes of the "dunes", the final stage of the succession is a black locust forest.

Solution to the problem of material blown away by wind

The estimated time for the formation of this forest is about 25 years (based on observations by the mine staff members). Some plants that can tolerate extreme stress conditions, i.e. a lack of water and nutrients, can be used as forecrop species during land reclamation. These include: the common soapwort *Saponaria officinalis* and evening primrose *Oenothera* spp.; the first one is especially easy to cultivate and can be sown in sandy habitats. This plant should be used for the rehabilitation of sand heaps. In flat places, it is recommended that willow shrubs, e.g. *Salix purpurea* be planted. Although the aforementioned plants would appear naturally on the site, this process can be speeded up and extended for the whole area of the excavation using the modified succession land reclamation method. Moreover, sowing potential pioneer plants as *forecrop plants* can prevent the so-called arrested succession in which unexpected conditions delay or even stop ecological processes (Boyes *et al.* 2011).

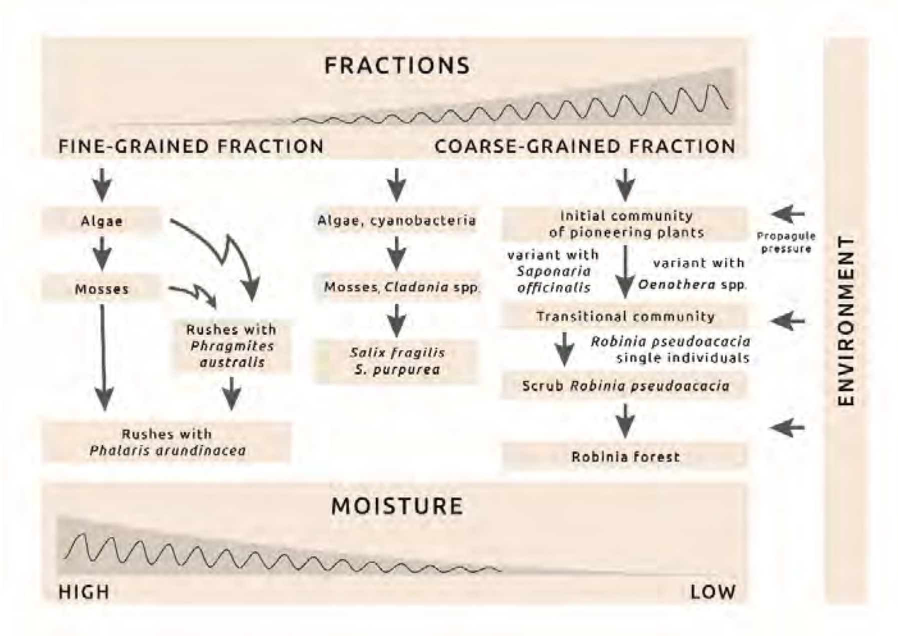

Figure 7. Model of vegetation succession in the "Wójcice" opencast mine and its dependence on moisture of the substratum (according to Kidawa *et al.* 2021)

THE PROBLEM OF WATER EUTROPHICATION OF POST-EXPLOITED RESERVOIRS EXEMPLIFIED BY GRAVEL EXCAVATION – "NOWOGRÓD BOBRZAŃSKI"

The contemporary exploitation of resources uses equipment and ladling methods from significant depths, which often go to depths of 45 meters below the water level (Craig *et al.* 2003). As a consequence, deep post-exploited water bodies are formed after the cessation of exploitation. A few good examples of the morphometric diversity of reservoirs are sites in the vicinity of the "Nowogród Bobrzański" mine. One of two water bodies was created as a result of the use of old methods of exploitation. Its maximum depth was 5.8 m and the bottom was quite diversified. In turn, the second one, which was created using contemporary methods, is different. Its maximum depth was 21.0 m and the morphometry of its bottom was weakly diversified. The underwater slopes of the reservoir were very steep (Molenda 2015).

The morphometric differentiation of post-exploitation water bodies has an impact on the structure of aquatic vegetation. In the case of older water bodies, hydrophytes, aquatic underwater plants such as *Myriophyllum spicatum* and *Ceratophyllum demersum* occurred in many areas of the reservoir and formed underwater meadows. In the case of newer water body, the zone of vegetation that was submerged was limited to the narrow coastal belt while in the case of the quarries of solid rocks (granites, limestones); the depth close to the bank was so deep that it prevented any growth and development of plants rooted on the bottom. Taking into account bathymetric plans (Molenda 2014; 2015) and vegetation structure, it can be concluded that depth is the main factor that determines the development of aquatic plants. In the last phase of any exploitation, it is advisable to form the bottom in such way so as to enable the creation of vegetation zones that are characteristic for natural lakes in a separate section of the reservoir, i.e.:

– a water and marsh zone,
– rushes,
– macrophytes with floating leaves,
– macrophytes with submerged leaves.

Deep post-exploitation reservoirs such as new water bodies were vulnerable to the formation of anaerobic zones in the summer. This especially concerns water bodies that are supplied with poor quality water. The problem of *water eutrophication* arises very quickly in such reservoirs. Eutrophication limits the utilization of these reservoirs for various purposes, mainly recreation. An example of such a site was the newer reservoir in the vicinity of the "Nowogród Bobrzański" mine. The oxygen profile that was depicted indicated that in summer the waters of the hypolimnion were deoxygenated while toxic hydrogen sulfide and ammonia occurred in the demersal zone (Fig. 8).

In the top-most layer (epilimnion), the waters were characterized by a high degree of supersaturation of oxygen (160%), which was the result of the intense processes of photosynthesis, which led to the alkalinisation of the waters. In the summer the water reaction exceeded pH = 9.1, which was a very unfavourable phenomenon because it may have caused a fish kill. Moreover, water transparency as measured using a Secchi disk was low and varied between 1.8 and 1.2 m. Such a low degree of transparency is the result of the intense development of phytoplankton (water bloom). Increasing electrolytic conductivity (EC) was also observed with increasing depth (Fig. 8).

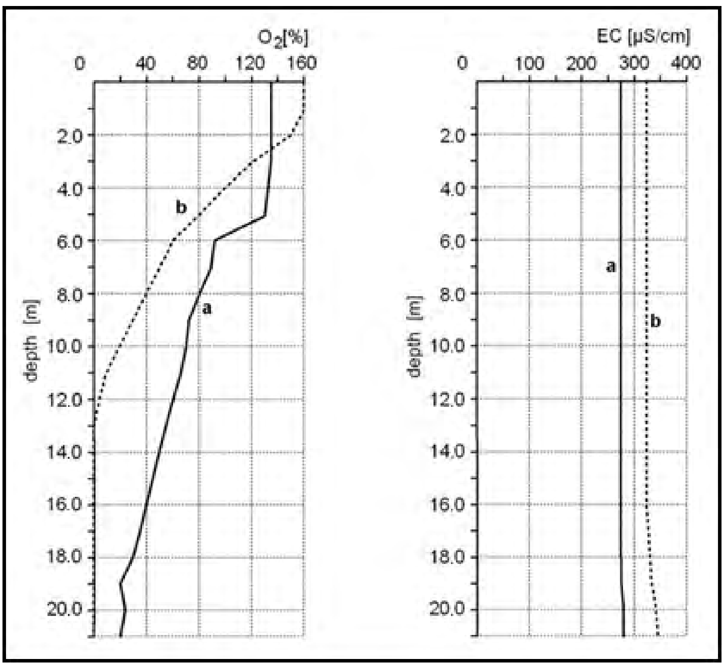

Figure 8. The vertical distribution of electric conductivity (EC) and oxygen saturation in the waters in "Nowogród Bobrzański"; a – spring, b – summer

Methods of water quality improvement in post-exploitation reservoirs

In each reservoir that is a flow-through container, the most rational (and inexpensive) method is the installation of an Olszewski tube (Olszewski 1959; 1961). There are numerous examples demonstrating that this solution enables export of nutrients from the deepest layers and prevents euthrophication (Klapper 2003; Kostecki 2012). Such a solution can only be applied in flow-through containers such as in the newer reservoir in the vicinity of the "Nowogród Bobrzański" mine. This type of tube provides leverage. As a result of the separation of the outflow through the installation of a weir, the hydrostatic pressure increases, which pushes the benthic waters. The deoxygenated waters from the demersal zone are removed, which results in a decrease in the anaerobic zones; thus the water quality improves. A permanent improvement in water quality in a reservoir that has a low capacity can occur in as little as one year after the installation of an Olszewski tube. The Olszewski tube should be a permanent element of the management of flow-through containers and it should be installed immediately after the exploitation has ceased.

FINAL REMARKS

The results obtained in the presented studies of three different objects and review of the literature, lead to the conclusion that there is no one universal method of management of open-cast water bodies. The high differentiation of hydrological and hydrochemical conditions of the water and wetland sites is the reason for the lack of one universal management method. Therefore, the authors propose various directions of reclamation depending on the type of raw material being mined (Fig. 9).

The results demonstrated that the direction of natural succession of vegetation in open-cast mines is ruled by two factors: type of exploited rock and hydrological conditions. They determine the hydrochemistry of waters, which in turn determine the dominant species of aquatic and riparian plants colonising the area and subsequent vegetation development. In limestone and dolomite excavations the most ecologically valuable plants that can appear are species of the genus *Chara* (Owsianny & Gąbka 2007). The plant cover includes species that represent the vegetation type that is protected under the NATURA 2000 Habitat Directive (code 3140). Close to water bodies, in riparian habitats, fens with orchids and other rare plants can occur. In flooded subsidences after gypsum exploitation rare and Red List species, such as common mare's-tail *Hippuris vulgaris* found habitat conditions optimal for growth. This plant has wide-tolerance for calcium ions typical for such type of waters (Gałczyńska 2006) which was proven by transplantation experiments of this species (Gałczyńska & Malas 2010). Depending on local conditions, reclamation can be conducted either for the maintenance of aquatic vegetation and/or wetlands.

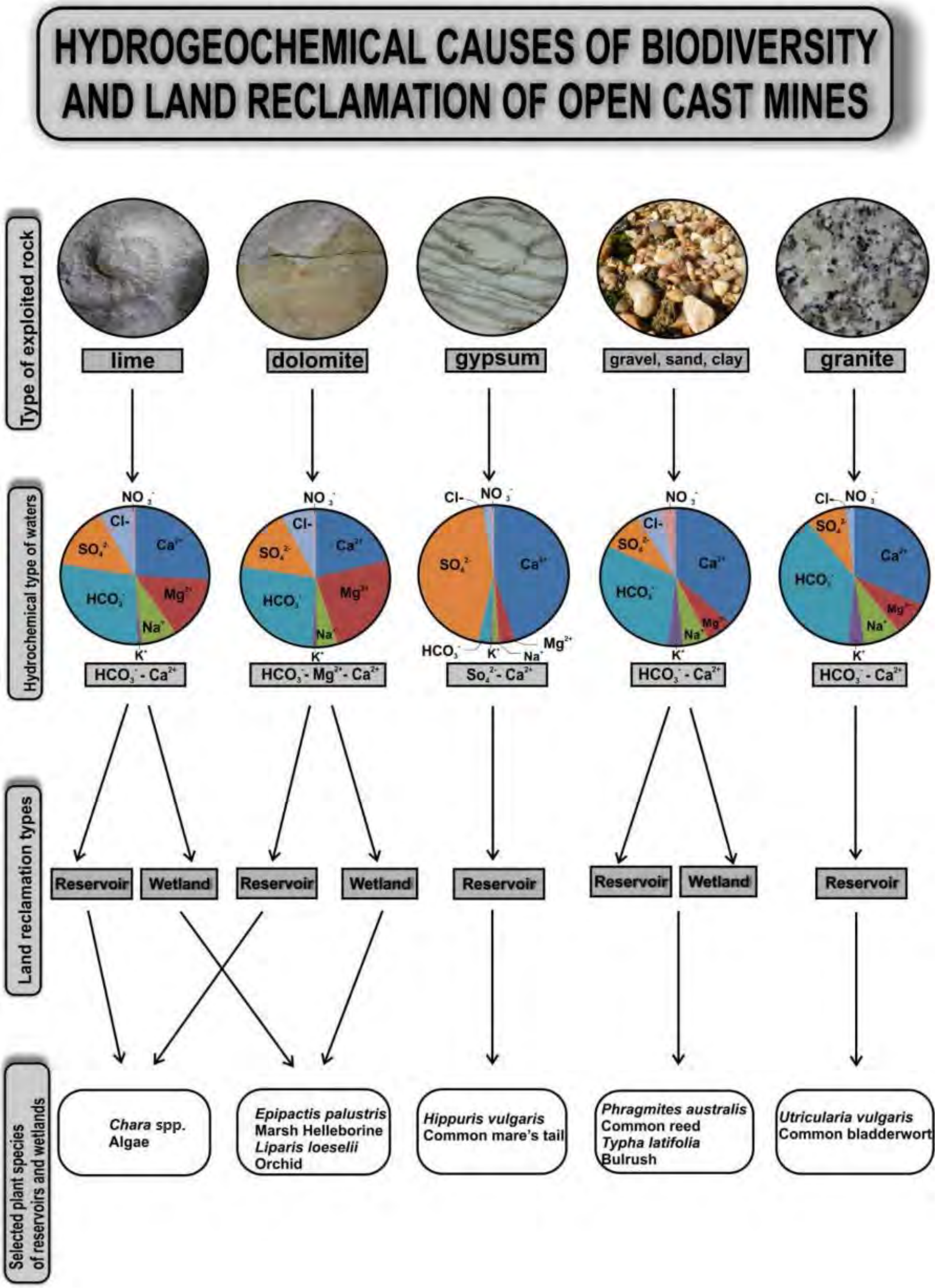

Figure 9. Hydrological-hydrochemical conditions of the reclamation of various opencast mines

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Original Research

Hydrogeochemical Conditions of the Development of Anthropogenic Carbonate Swamps: A Case Study of an Abandoned Polish Sandpit

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Abstract

The hydrogeochemical conditions of the development of a carbonate swamp that had formed in a previous sandpit were studied. The object is located in the town of Jaworzno-Szczakowa in the Silesian Upland of southern Poland. It has been shown that the sandpit, which has not been reclaimed since its operation ceased, underwent spontaneous processes toward the development of calciphilic vegetation. The Biała Przemsza River plays a significant role in supplying the swamp with water. The water of this river is highly contaminated because it receives wastewaters from zinc-lead (Zn-Pb) ore mines. Water that has high concentrations of calcium and magnesium ions favours the occurrence of calciphilic species (e.g., *Liparis loeselii* NATURA 2000 species), which form wetlands of carbonate vegetation that are rare in both Poland and Europe. The population size of this species on the studied swamp is a few hundred specimens. In addition to *Liparis loeselii*, there are other species that are protected or rare and endangered species at the national level and on the "red list" of Poland's plants, hence such swamps could represent an important refuge for biodiversity.

Keywords: human-made wetlands, mining water, opencast, water pollution, vascular flor

Introduction

Non-reclaimed sandpits are spontaneously colonised by plants [1-5]. The colonisation of these areas by plants depends primarily on local habitat factors such as light, the granulometric composition of the soil, pH, soil fertility, moisture, etc. [6-7]. Disused sandpits are mostly spontaneously entered by xerophytic andoligotrophic species, mainly from psammophilous grasslands and ruderal habitats [1-3], thereby creating species-poor phytocoenoses.

Much less frequently, the development of wetlands occurs at the bottom of the excavation at the groundwater outflow [8-10]. Objects of this type were found within a few non-recultivated sand or gravel pits, mainly in

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Poland. At these damp sites at the base of the excavation of sand or gravel pits that have been saturated with groundwater, valuable plant species occur, particularly species that are characteristic of low carbonate bogs. To date, the specialist literature has primarily emphasised the importance of such swamps for the preservation of biological diversity, thus indicating the existence of valuable plant species, particularly those that are characteristic of low carbonate bogs, and in terms of phytosociological units, those of the *Caricetalia davallianae* order [5, 10-15]. However, there is no data on the hydrogeochemical conditions of this type of anthropogenic swamp with bog vegetation, which are valuable from the point of view of nature conservation.

The aim of our study was to demonstrate that water that has been contaminated by the discharge of mine water could be responsible for the development of swamps and thus the direction of vegetation succession in sandpits.

Material and Methods

Description of the Study Area

Our study was conducted in the Szczakowa sandpit, which is located in the Silesian a macro region and that coversan area of ca. 4000 km^2. The mean annual temperature in the Silesian Upland is about 7-8ºC and the annual precipitation in the area ranges from 700 to 800 mm/year and snow retention is approx. 50-70 days. In the Silesian Upland, peat bog ecosystems are very rare, but the occurrence of wetland species of the *Scheuchzerio-Caricetea nigrae* class and combinations of the species that are typical of bogs are observed in the anthropogenic areas. Most of these are disused sandpits, gravel pits, railway areas and the edges of anthropogenic water reservoirs, etc. [15-16].

The swamp that was selected for the study developed at the base of an old sandpit after its operation ceased in the 1970s [personal communication from the employers

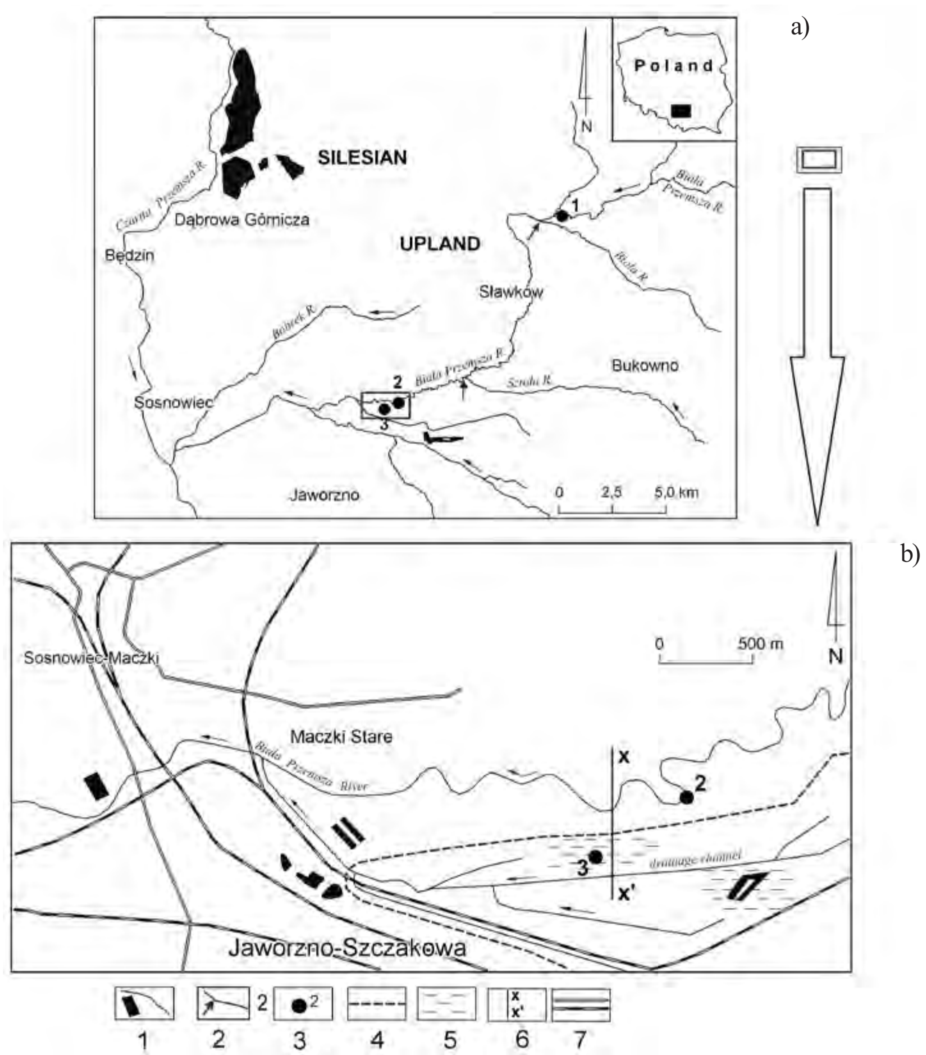

Fig. 1. Location of the study area a) and study design b): 1 – rivers and reservoirs, 2 – mine water discharge into the Biała Przemsza River, 3 – sites of the water sampling for the chemical analyses, 4 – the border of the sand pit excavation, 5 – anthropogenic swamp, 6 – hydrogeological cross-section, 7 – roads and railway lines.

of the Jaworzno Sand Mine]. It is situated in Jaworzno (50°15'11.92''N; 19°18'21.45''E) in the Silesian Upland (Fig. 1) in the valley of the Biała Przemsza River, which is the left tributary of the Vistula River. The area of the wetland that was analysed is ca. 6 ha. This river feeds the swamp that was analysed. The river receives the mining water from the drainage of the zinc and lead ore mines that are located in the upper part of the catchment. In addition, the Biała Przemsza River receives water from the processing of zinc and lead ores and wastewater from the zinc smelter. The peat bog that is fed by the waters of this river is located downstream of the discharge of these pollutants. About 700 million m^3 of sand was excavated for the coal mining (backfilling material). In the initial period of the extraction of the deposit, when the raw materials were located above the groundwater table, the pit was only fed by rainwater and the water from the surface runoff [17]. Once the bottom of the exploitation pit fell below the groundwater table, this water flowed out from the excavation. The dewatering of the excavation occurred either by gravity through a network of ditches and canals or through pumping systems.

After the operation ceased, the pumping was discontinued and water flooded the pit, which in turn led to the creation of an excavation reservoir. When the gravity drainage was in operation, the network of ditches and canals continued to fulfil these functions and the excavation remained dry. In many cases, however, there were cavities within the large pit that were difficult to dewater by gravity. Then the bottom of such hollows was constantly dumped and was even flooded (Fig. 2).

Methods

Hydrological Research

Hydrographic mapping to assess the water conditions in the Szczakowa swamp area was concordant with the guidelines provided by Gutry-Korycka and Werner-Więckowska [18].

The location of the sampling points for the physico-chemical analyses of the water arepresented in Fig. 1. Water samples were collected from both the swamp (sampling point 3) and the Biała Przemsza River (sampling points 1 and 2). The selection of the sampling points on the Biała Przemsza River (1 and 2) was dictated by the need to demonstrate how the mine water discharge affected the quality of the river water. Sampling point 1 is located above the mine water discharge and sampling point 2 below the mine water discharge (Fig. 1).

At every sampling point, a water sample was collected at monthly intervals (from November 2012 through October 2013; n = 12). The field measurements and samplings were performed in the water pools that were stagnating on the swamp surface. No water was squeezed from the organic deposits. River water was collected in the current using a telescopic boom. Water samples were collected in 0.5 l polyethylene bottles. The water samples were transported to the laboratory at a temperature of +4ºC. Before the analyses, the samples were filtered on a 0.45 µm filter (Millipore). Laboratory analyses included determining the major cations and anions, Ca^{2+}, Mg^{2+} and SO_4^{2-}, in the water. These are typical indicators of mine waters [19]. The analyses

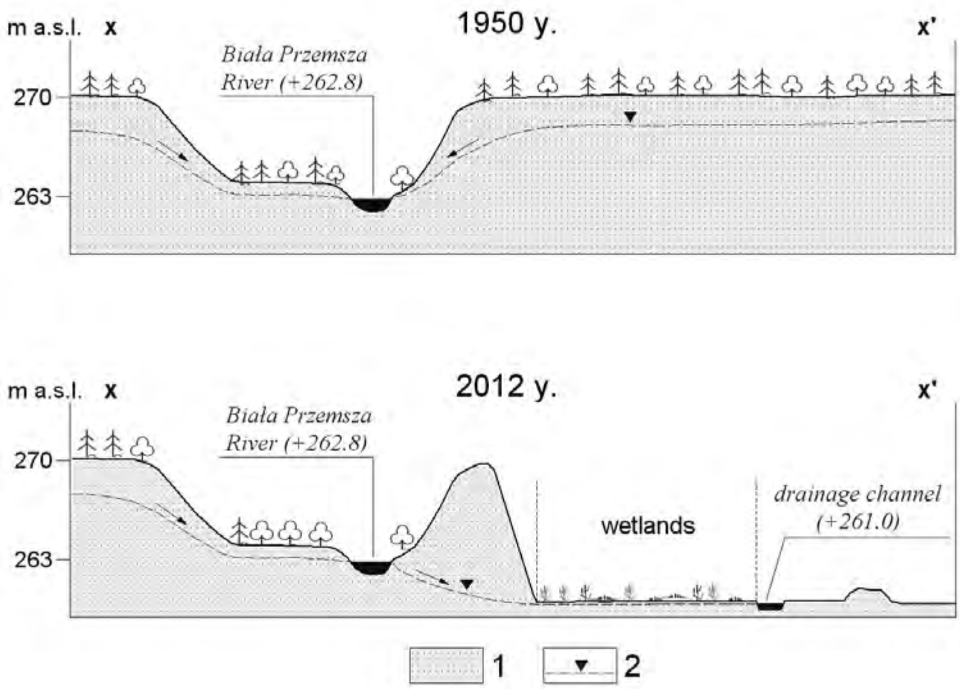

Fig. 2. Hydrogeological cross-section of Szczakowa swamp: 1– sands, 2 – water table.

were performed on a Metrohm 850 Professional IC ion chromatograph. Measurements of pH and electro-conductivity (EC) were performed directly in the field using a professional plus meter by the YSI Company.

Because precipitated evaporites were observed on the swamp surface(supplementary material, Fig. S1), it was decided to determine the type of minerals that were involved. In order to identify the minerals (evaporates) that had precipitated on the surface of the swamp; plants that had encrustings of the minerals were collected. The encrustings were prepared for environmental scanning (SEM) and the test was performed on a Philips XL 30 ESEM / TMP scanning electron microscope with an EDS analysis appliance (EDAX Sapphire type). BSE (back-scattered electron) photographs were taken in the micro areas of the tested preparations. The elemental composition and presumptive identification of minerals was based on ananalys is of the EDS spectra (scanning dispersive electron microscopy).

Floristic Studies

In order to catalogue the spontaneous flora during the growing season (June-August), a full floristic inventory of the vascular plants of the entire swamp was performed in 2013 (Table S1). The collected floristic data were analysed in terms of the ecological requirements using the Ellenbergindicator values for plant species (EIVs, [20]) in order to show the site characteristics for light (L), moisture (F), reaction (R) and nitrogen (fertility, N). Arithmetic means based on the presence/absence of the EIVs and the distribution of the plants that represented specific values of the EIVsare shown. For the calculations, the species waassigned an "X", i.e., without any diagnostic value being excluded from the calculations. In addition, a soil pH-meter was used to determine the soil reaction in the rhizosphere of the majority of the plants, i.e., 3-4 cm in the top layer of the soil and below 10 cm. Ten measurements were performed in randomly selected sites within the swamp. The participation of species of different syntaxonomic groups in the flora of the object with particular emphasis on peat bog species was performed. The syntaxonomic classification of the species was based on the Polish guide to plant determination [21]. To determine the role of the wetlands as biodiversity refuges, plants that are protected in Poland [22] and those that are deemed endangered in the country as well as those that are of European importance were also considered [23]. The nomenclature of the vascular plants was adopted after [24].

Data Analysis

To test the significance of differences between the concentrations of the analysed ions, the nonpar a metric equivalent of ANOVA, the Kruskal-Wallis test was used, while for multiple comparisons we used the Conover test. Statistical analyses were performed using R software (www.r-project.org) and the *stats* and *agricolae* packages.

Results and Discussion

Results

Hydrochemical Conditions of the Szczakowa Swamp Development

The values of all of the tested water parameters were significantly higher at sampling point 2 compared to sampling point 1. The average value of the electrolytic conductivity of the Szczakowa wetland water was the highest, but was only significantly higher than the one at sampling point 1 (Table 1). In turn, in the case of the concentration of the calcium ions and magnesium ions, significantly higher values were recorded in the swamp (sampling point 3), whereas the highest concentration of sulfates was noted at sampling point 2. The higher average concentration of calcium in relation to the water supply was connected with the evaporation processes. When evaporation is complete, the evaporites precipitate. These were identified on the SEM figures (Fig. S1). In the wetland, two zones of mineral formations could be distinguished: an aerated zone and a permanently water-saturated zone (Fig. 4). In the aerated zone, the mineral evaporites such as calcium carbonate ($CaCO_3$) and gypsum ($CaSO_4 * 2H_2O$) were formed. This zone was characterized by an alkaline pH, i.e., 7.5-8.0, which classifies the object as an anthropogenic carbonate wetland. In the water-saturated zone, there were reduced conditions that favoured the formation of pyrites (FeS_2). This was an acidic zone in which pH varied between 4.0 and 5.0.

Flora that were Spontaneously Colonising the Swamp

At the Szczakowa swamp, 91 species of vascular plants were recorded (Table S1). Because the analysed swamp is of an initial character, a small proportion of trees and shrubs was also observed (mainly light-seed species such as *Alnus glutinosa*, *A. incana*, *Betula pubescens*, *Pinus sylvestris*) and thus, there was slight shading. Therefore, species of open habitats were predominant (the average value of the light coefficient based on the Ellenberg indicator value was 7.14) (Fig. 3L). Due to the high degree of the dampness of the substrate, the dominant species represented those of damp and wet habitats and the average moisture ratio (F, EIV for moisture) was 7.4. (Fig. 3F). High concentrations of calcium and magnesium ions in the water that supplied the swamp and that affected the pH were responsible for the presence of alkaliphilic species (Fig. 3R). The average R, EIV for the soil reaction was 6.3 and the calciphytes were dominated

Table 1. Medians ±interquartile range of the physical-chemical parameters of the objects; different letters indicate that the values are significantly different at p <0.05 (Kruskal-Wallis test followed by Conover test as post-hoc).

Sampling points	#1	#2	#3	chi-square	p
Conductivity	b 400±8.5	a 816±36	a 1013±378.3	14.83	<0.001
pH	b 6.6±0.449	a 8.1±0.1	a 7±0.4	12.76	<0.0001
Calcium ions	c 78±1.75	b 111±8.8	a 153.5±27.7	19.91	<0.001
Magnesium ions	c 2.1±2.625	b 32±3.0	a 40.5±6.0	14.44	<0.001
Sulfates	b 43.5±2.7	a 168.7±32.7	a 103.7±143.4	13.38	<0.01

Explanations: Sampling point 1 is located above the mine water discharge, sampling point 2 – below the mine water dischargeand sampling point 3 – at the swamp

by the species that are typical of alkaline bog-springs, namely *Caricion davallianae*. However, there were no species that are associated with acidophilus bogs. Below 10 cm of the top soil layer, the median pH was 4.38 (4.0-5.0) and in the rhizosphere layer it was 7.65 (7.0-8.0) (Fig. 4). The species that have low requirements for the soil trophy (N, EIV for nitrogen is 3.7) were dominant (Fig. 3N). An important role in the floristic composition of Szczakowa swamp was played by meadow species and especially the species of wet meadows of the *Molinietalia* order. The swamp species of the *Scheuchzerio-Cariceteanigrae* class constituted 18% of the flora, of which more than half were species that are typical of the calciphylous bog-springs sedges of the *Caricetalia davallianae* order (Fig. 3). They included *Carexdavalliana*, *C. dioica*, *C. flava*, *Eleocharis quinqueflora*, *Epipactis palustris*, *Eriophorum latifolium*, *Parnassia palustris*, *Tofieldia calyculata* and *Liparis loeselii*. The population of the latter species was estimated to be one hundred individuals on the studied swamp. There were 12 protected species and eight "red list" species, including *L. loeselii* (Table 2). The plant community on the swamp were typical of the alkaline fens of the community of *Caricion davallianae* alliance, according to the NATURA 2000 habitat code 7230.

Discussion of Results

The sand open pit extraction in the study area has led to significant changes in the relief and water conditions. Such changes have been observed in all of the areas in which there was open cast mining of mineral resources [25, 15]. Particularly significant changes in the water conditions occurred within the tested pit. They consisted of the escape (infiltration) of water from the Biała Przemsza River into the workings of the sandpit. The water of the Biała Przemsza River had a high level of contamination, which was a result of the mine water discharge [26]. Increased values of all the tested parameters of water in the Biała Przemsza River downstream of the concentrated water discharge indicated that the mine water carried a load of ions, which also affected the properties of the water that directly supplied the swamp. This mainly referred to the calcium and magnesium ions as well as sulfates. These, in turn, affected the electrolytic conductivity. The concentration of these ions was greater than that commonly found in the surface water and groundwater in the area [27]. The large participation of calcium and magnesium ions in the contaminants resulted from the fact that Zn-Pb ores are found in the dolomite rocks. The higher concentration of calcium ions in the water of the swamp in relation to the water of the Biała Przemsza River, which supplies the swamp, can be explained by the process of water evaporation from the swamp surface.

In the case of Szczakowa swamp, the mean concentration of calcium ions was greater than in the water of the Biała Przemsza River. This phenomenon is explained by the evaporation processes that occurred in the water pools on the surface of the swamp and the increased salinity. In the swamp area, the following evaporites were identified: calcium carbonate ($CaCO_3$) and gypsum ($CaSO_4$ * $2H_2O$). The high concentrations of sulfates in the mine waters were the result of the weathering of sulphide ore minerals [28]. The precipitation of evaporites was also described by [29], who studied other hydrographic objects of an anthropogenic origin.

Water that is rich in calcium and magnesium ions, in this case of an anthropogenic origin, provides favourable conditions for colonisation by calciphilic plants and, over time, vegetation patches that are similar to the floristic composition of alkaline *Caricion davallianae* bog-springs are created. Under natural conditions, this type of vegetation occurs at bog-springs, the water of which infiltrates through limestone and forms a habitat that is rich in minerals, including calcium carbonate [21]. Such vegetation occurs on fens. These are very rare habitats that are the refuge of many rare and endangered plant species, which are often of a narrow ecological scale.

The formation of this type of vegetation in disused and non-reclaimed sandpits is unique. In most cases, the uncovered sands of disused sandpits are colonised by psammophilous grasslands, arid grasslands, ruderal species, trees and shrubs. Wetter areas become over grown with rushes such as the common reed (*Phragmites*

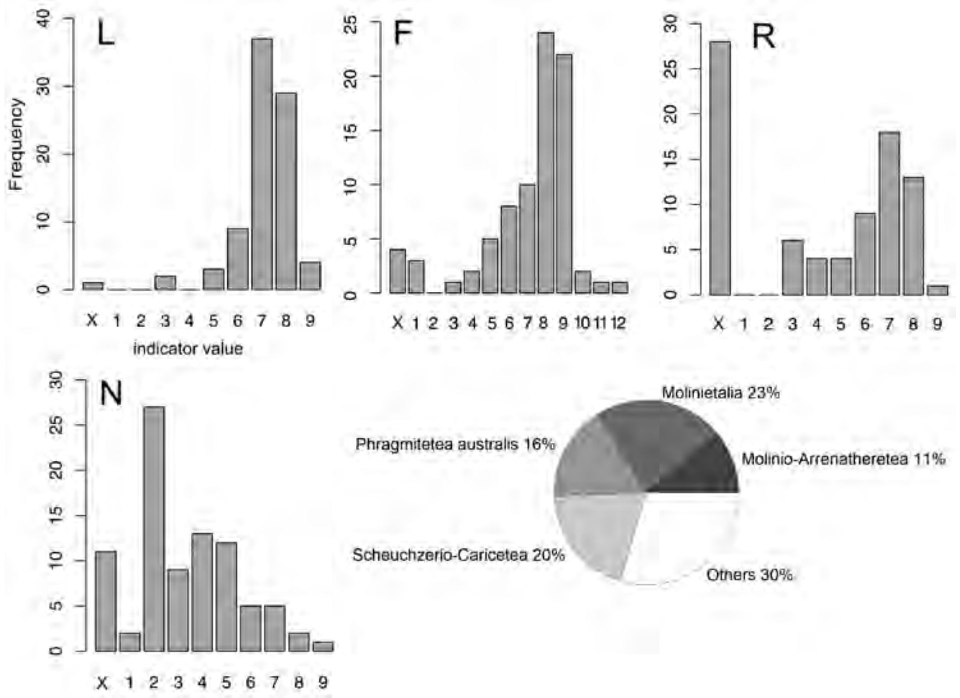

Fig. 3. Distribution of the species that represent specific Ellenberg indicator values (EIVs): L – light, T – temperature, F – moisture, R – soil reaction, N – nitrogen and percent participation of species to syntaxonomic groups. Explanations: 1-12 values of EIVs, x – no specified value.

australis) and broad leaf cattail (*Typhalatifolia*) [1, 2, 30].

Bog-springs with calciphilic species have only been reported in southern [5, 12, 14] and northeastern Poland [13]. Their importance for the conservation of the biodiversity of the region and the country is significant because of the participation of species that are deemed to be endangered in the country as well as the abundance of *Liparis loeselii* – a species that is of European importance [23], especially because the natural swamp communities in the Silesian Upland are very rare and endangered vegetation components. The particular importance of Ca^{2+} and pH is highlighted for the communities of alkaline swamps [31]. Communities that include *Liparis loeselii* and other calciphilic species that have been found by the Rospuda River grow on a substrate where the water has the following parameters: pH – 7.0, conductivity – 466 (max 694), Mg^{+2} – 15.9, Ca^{+2} – 21.7 [32]. In comparison, the concentration of calcium and magnesium ions in the Szczakowa swamp was indeed much higher; nevertheless, they are not toxic to the plant. It is interesting that both magnesium and calcium ions increased in the swamp that was studied because in other anthropogenic habitats (managed forest, agriculture, pastures) there is a negative correlation between the calcium and magnesium ions in soils [33]. The relationship that was observed between the soil pH and moisture and a spectrum of environmental requirements (expressed by Ellenberg indicator values) of the plants colonising the swamp confirms the view that the patterns of species distribution are a response to the habitat conditions/gradients [34]. The strong degree of dampness of the substratum in Szczakowa swamp is an environmental filter that limits the encroachment of ruderal plants both native expansive and invasive alien

Table 2. Protected and threatened vascular plant species of the analysed swamp in Poland.

Species	Protected species in Poland [27]	Threatened species in Poland [28]
Carex davalliana	§§	VU
Carex dioica	§	VU
Dactylorhiza incarnata	§	NT
Dactylorhiza majalis	§	NT
Epipactis palustris	§§	NT
Gentiana pneumonanthe	§§	VU
Gymnadenia conopsea	§§	NT
Liparis loeselii	§§	VU
Malaxis monophyllos	§§	VU
Pedicularis palustris	§	VU
Tofieldia calyculata	§§	NT
Utricularia minor	§§	NT

Categories of protection: §§ – strict protection, § – partial protection, Categories of threat: VU – vulnerable, [NT] – near threat.

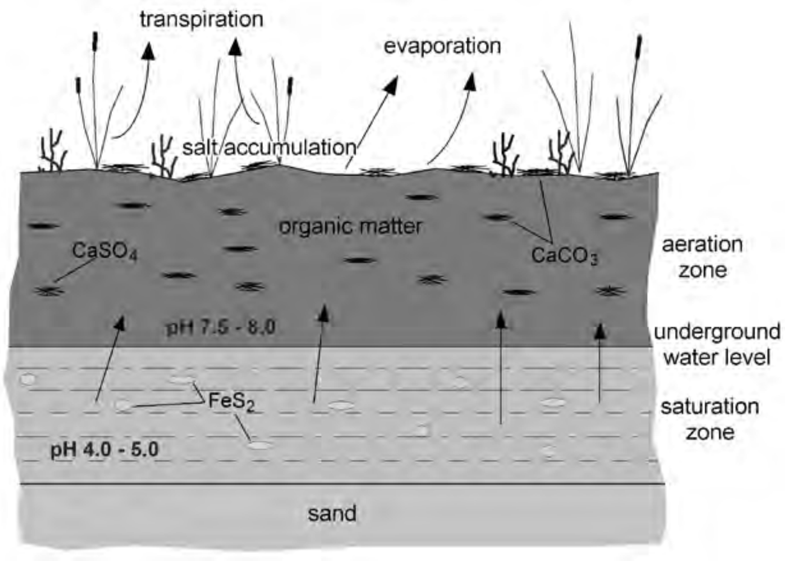

Fig. 4. Process of formation of the evaporites at Szczakowa swamp.

species that threaten the biodiversity of bog-springs, as well as woody plants (shrubs and trees). Thus, if the water conditions are stable, the site will not be overgrown by woody vegetation and will therefore not develop into thickets and forest.

Conclusions

The relatively high moisture of the habitat and the high concentration of calcium and magnesium ions in Szczakowa swamp are the most likely factors that enhance the encroachment of calciphilic species, including protected and rare species. Maintaining the relevant water conditions is essential for the protection of the site. The study demonstrated that, in some cases, human-induced changes result in the formation of habitats that are refuges for plants that are valuable from a nature conservation perspective.

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Conflict of Interest

The authors declare no conflict of interest.

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Table S1. List of vascular plant species found in Szczakowa swamp.

Achillea millefolium	*Juncus tenuis*
Agrostis stolonifera	*Leontodon hispidus*
Alnus glutinosa	*Linum catharticum*
Alnus incana	*Liparis loeselii*
Angelica sylvestris	*Lotus uliginosus*
Betula pendula	*Lycopus europaeus*
Betula pubescens	*Lysimachia thyrsiflora*
Briza media	*Lysimachia vulgaris*
Carex acuta	*Lythrum salicarnia*
Carex davalliana	*Majanthemum bifolium*
Carex dioica	*Malaxis monophyllos*
Carex echinata	*Mantha aquatica*
Carex flacca	*Menthaarvensis*
Carex flava	*Molinia caerulea*
Carex nigra	*Myosotis palustris*
Carex panicea	*Parnassia palustris*
Carex rostrata	*Pedicularis palustris*
Carex vesicaria	*Peucedanum palustre*
Carex viridula	*Phragmites australis*
Cirsium oleraceum	*Picea excelsa*
Cirsium palustre	*Pinus sylvestris*
Cirsiumm rivulare	*Potentilla anserina*
Convallaria majlais	*Potentilla erecta*

Dactylorhiza incarnata	*Prunella vulgaris*
Dactylorhiza majalis	*Ranunculus acris*
Deschampsia caespitosa	*Salix alba*
Eleocharis pauciflora	*Salix pendandra*
Eloecharis uniglumis	*Salix rosmarinifolia*
Epipactis palustris	*Sanguisorba officinalis*
Equisetum fluviatile	*Scirpus sylvaticus*
Equisetum palustre	*Scutellaria gallericulata*
Equisetum variegatum	*Sparganium erectum*
Eriophorum angustifolium	*Succisia pratensis*
Eriophorum latifoium	*Taraxacum officinale*
Euparorium cannabiunum	*Tofieldia calyculata*
Festuca rubra	*Trifoliuim medium*
Filipendula ulmaria	*Triglochin palustre*
Frangula alnus	*Tusillago farfara*
Galium palustre	*Utricularia*
Galium uliginosum	*Valeriana officinalis*
Gentiana pneumonanthe	*Valeriana simplicifolia*
Gymnadenia conopsea	*Vicia cracca*
Hypericum tetrapterum	*Vicia tenuifolia*
Juncus alpino-articulatus	*Schoenoplecutus lacustris*
Juncus atriculatus	*Centhurium erythrea* ssp. *erythrea*
Juncus effusus	

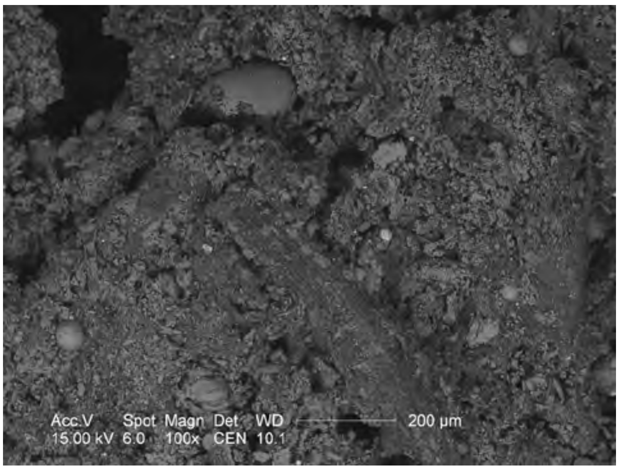

Fig. S1. A SEM photograph of the particles of calcium carbonate $CaCO_3$ (spherical piece in the upper left corner) in the material that was collected from the rhizosphere of *Liparis loeselii* in swamp Szczakowa.

Oświadczenia Autora i Współautorów publikacji wchodzących w skład rozprawy doktorskiej pt.:

HYDROLOGICZNE UWARUNKOWANIA ROZWOJU ROŚLINNOŚCI NA OBSZARACH ODKRYWKOWEJ EKSPLOATACJI ZŁÓŻ SUROWCÓW MINERALNYCH

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OŚWIADCZENIE

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Mój wkład w powstanie tej pracy polegał na kartowaniu hydrograficznym, poborze prób do analiz hydrochemicznych, interpretacji wyników oraz częściowym opracowaniu tekstu.

Natural and Anthropogenic Conditions of the Chemical Composition of Pit Lake Waters (Based on Example Pit Lakes from Central Europe) / Tadeusz Molenda, Joanna Kidawa.// Mine Water Environ., 2020, Vol. 39, (3), pp. 473-480.

Mój wkład w powstanie tej pracy polegał na udziale w wytypowaniu obszaru badań, poborze prób, interpretacji wyników oraz w częściowym przygotowywaniu tekstu.

The Hydrological-Hydrochemical Factors that Control the Invasion of the Black Locust (Robinia pseudoacacia L.) in Succession in Areas with Opencast Mines / Joanna Kidawa, Damian Chmura, Tadeusz Molenda.// Plants, 2021, no 10 (1), pp. 1-16.

Mój wkład w powstanie tej pracy polegał na udziale w poborze prób oraz częściowym opracowywaniem tekstu.

Hydrological and Hydrochemical Conditions for the Reclamation of Anthropogenic Water Bodies and Wetlands in Opencast Mines / Joanna Kidawa, Damian Chmura, Tadeusz Molenda // In: A. Dyczko, A.M. Jagodziński, G. Woźniak G. (eds). The Green Scenarios: Mining industry responding to environmental challenges of the Anthropocene Epoch, CRC Press, Taylor & Francis Group, London, UK, 2022, pp. 23-36

Mój wkład w powstanie tej pracy polegał na udziale w wytypowaniu obiektów badań, kartowaniu hydrograficznym oraz w interpretacji wyników.

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My contribution to this work consisted of hydrographic mapping, collecting samples for hydrochemical analyses, interpretation of the results and partial preparation of the text.

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My contribution to this work consisted of participating in selecting the research area, collecting samples, interpreting the results and partially preparing the text.

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My contribution to this work consisted of participating in sampling and partially preparing the text.

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My contribution to this work consisted of participating in the selection of research objects, hydrographic mapping and the interpretation of the results.

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Mój wkład w powstanie tej pracy polegał na wytypowaniu obszaru badań i kartowaniu roślinności. Mój udział procentowy szacuję na 35%.

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My contribution to this work consisted in selecting the research area and mapping the vegetation. I estimate my percentage at 35%.

Agnieszka Błońska
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Mój wkład w powstanie tej pracy polegał na udziale w interpretacji wyników, udziale w przygotowaniu manuskryptu artykułu i odpowiedzi na recenzję.

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My contribution to this work consisted of participating in the interpretation of the results, participating in the preparation of the article manuscript and responding to the review.

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Hydrological and Hydrochemical Conditions for the Reclamation of Anthropogenic Water Bodies and Wetlands in Opencast Mines / Joanna Kidawa, Damian Chmura, Tadeusz Molenda // In: A. Dyczko, A.M. Jagodziński, G. Woźniak G. (eds). The Green Scenarios: Mining industry responding to environmental challenges of the Anthropocene Epoch, CRC Press, Taylor & Francis Group, London, UK, 2022, pp. 23-36

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My contribution to this work consisted of participating in field analyses, sampling, interpretation of results and partial preparation of the text of the manuscript.

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