Estimation of the qualitative characteristics of post mining lakes in different lignite fields in Greece

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Abstract

This paper summarises available information on water quality associated with post mining lakes of the lignite fields in Greece. In Greece there are three distinctive districts of lignite mining: Ptolemais-Amynteon basin in Northern Greece, Aliveri district in central Greece and Megalopolis in South Greece, Peloponnese. Small lakes have been already formed in some of the remnant voids, while in others the creation of lakes is the main option, after the end of exploitation. Results of various research projects carried out or financed by PPC, concerning the water quality, of the existing and future remnant lakes were used. All remnant lake water is alkaline, due to the alkalinity of geological formations, natural soil and fly ash. The co-dumping of fly ash with mine waste material in the dumping sites improves the absorption of heavy metals and is an unfavourable condition for the dissolution and mobility of heavy metals. Most of them indicate low concentrations or are below detection limits. High values of Mo and Sr are noticed in water of the sumps in Megalopolis and B and Ba in Amynteon, due to their high leaching potential. S content of the lignite is low, usually <1% and even <01%, resulting in relatively low SO_4^{-2} in remnant lakes. Occurrence of carbonate rocks and calcareous sediments in the basement and in the sediments of the fill of the basins plays also an important role. Surface waters from rivers and streams and unaffected ground waters are of good quality, contributing to the acceptable quality of mine water, according to the environmental limits in South field. In Aliveri, mine water is enriched in sodium. The main conclusion of this study is the significant role of the water – rock interaction on the final lake water quality.

Key words: Pit Lake water, geochemical environment, quality, post mining, lignite

1. Introduction

Open lignite mining has become increasingly common over the last few decades due to the improvement in excavation technology techniques where considerable volumes of ore and waste rock are excavated from one or more surface excavations (Castendyk and Eary 2012). After the closure of surface mines, large and deep enough voids are left behind. The creation of remnant lakes is usually an aesthetically acceptable solution for these voids, but with a high possibility of environmental risk. Qualitative characteristics are of great importance both for environmental as well as for industrial purposes.

Pit lakes have unique characteristics such as very small catchment areas, usually great depth, erosion activity on the slopes and unstable geomorphological environment. Water of the remnant lakes is in many cases contaminated with metals, metalloids and trace elements. Its physical and chemical characteristics vary significantly and they rarely approach natural water body chemistry. Geochemical conditions of the remnant lakes is influenced by the evaporation, oxidation and leaching; the variable kinetics of water-rock interactions, the changing influxes and the composition of surface and ground waters.

In Greece there are three distinctive districts of lignite mining: Ptolemais-Amynteon basin in Northern Greece, Aliveri district in central Greece and Megalopolis in South Greece, Peloponnese. Small lakes have already been formed in some of the remnant voids, while in others the creation of lakes is the main option after the end of the exploitation. This paper describes the results of various research projects carried out or financed by PPC, concerning the water quality of existing and future remnant lakes. It also provides a comparative view of the mine water quality of the different lignite fields.

1.1. Geological setting

Amynteon and South lignite field are located in Northern Greece. They belong to Florina – Vegoritis – Ptolemais graben, a large basin filled with Neogene – Quaternary sediments. They consist of rhythmic alternations of lignite beds with lacustrine and fluvial sediments, which overlay both Paleozoic metamorphic rocks and Mesozoic crystalline limestones. Metamorphic rocks, mainly gneiss – schists form the NW boundary of the basin (Dimitrakopoulos 2001).

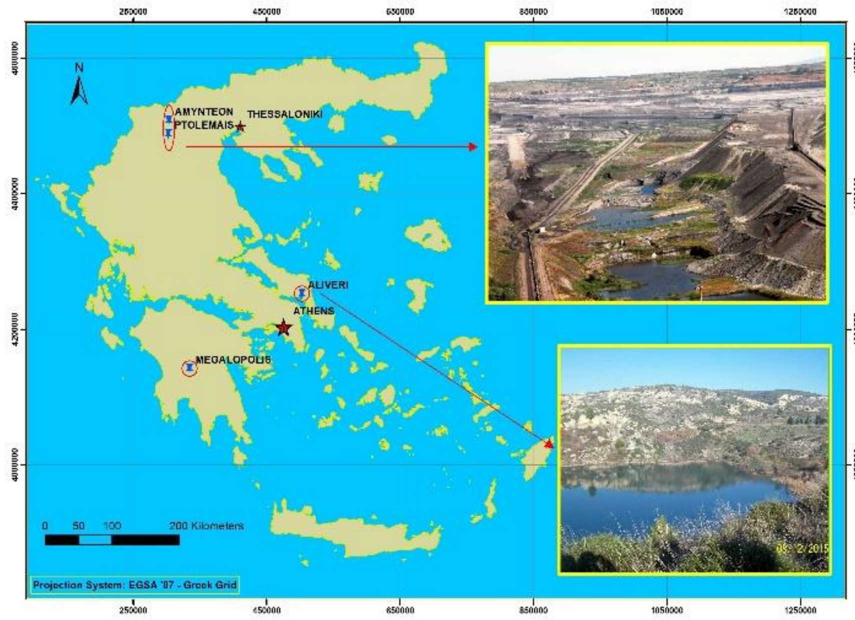

***Figure 1** Map of study mine sites in Greece*

The Neogene-Quaternary sediments of the basin are divided into three lithostratigraphic formations. The lower formation (Upper Miocene to Lower Pliocene) consists mainly of conglomerates, marls, sands and clays. The middle formation (Pliocene) contains the lignite beds. The upper formation (Quaternary) consists of terrestrial and fluvio terrestrial conglomerates, lateral fans and alluvial deposits. The lignite beds alternate with marls, clays and sands (Sachanidis 2001).

In Aliveri area lignite deposits overlie the mio-pliocenic sediments, which consist of marls, conglomerates and breccia (Fig. 2). Above the aforementioned Neogene sediments there are alluvial deposits. In the basement and the surrounding rocks, Jurassic-Cretaceous karstified limestones occur. Surface mining ended in 1990. A wider part of the final void is covered with mine waste dump while a small lake has been created at the lower part. Its dimensions are ~250x250 m, its depth 50 m and its volume 1.000.000 m^3 (Dimitrakopoulos et al, 2009).

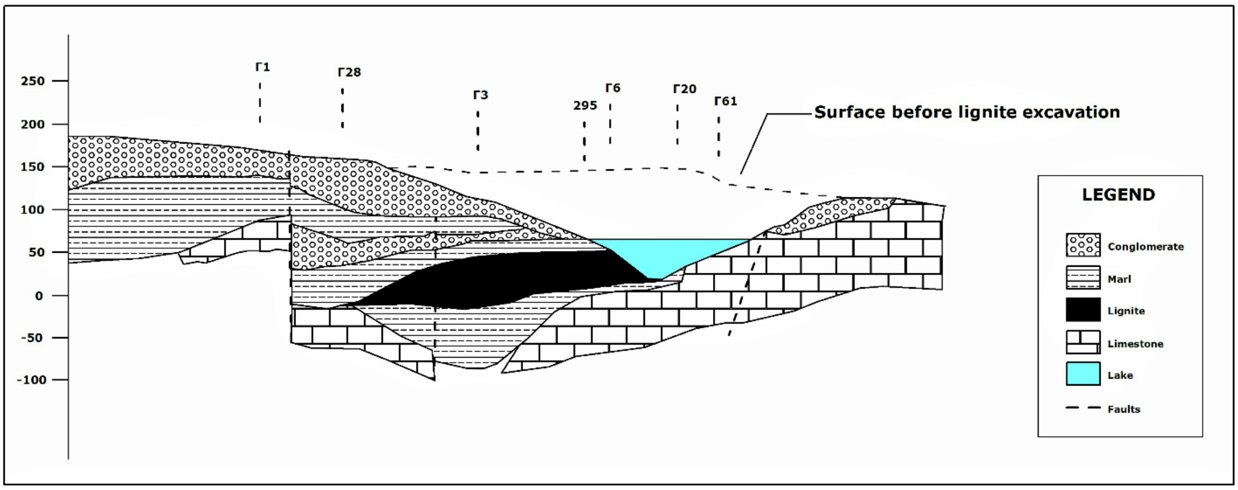

***Figure 2** Geological section of Aliveri area (Minwater 2003)*

In Megalopolis area the overburden consists mainly of marly and clayey material. Basement and surrounding rocks are mainly karstified limestones. Floor of the mine in Kyparissia mine is in contact with the karstic aquifer (sampling from BR), which exists in the limestone, so the pit lake (PK1), which has been created, is hydraulically connected with this aquifer. Dimensions of the lake are (300-500) x1500 m, maximum depth 45 m and its volume is estimated 10.000.000 m^3. Altitude of the lake surface, and consequently its depth and volume, is fluctuating, following roughly the fluctuation of the karstic aquifer. Ponds have been created in the remnant Thoknia mine (Pond I-II), and Choremi mine (P23-P27), which are hydraulically isolated between mine waste dump and impermeable marly formations of the bottom of the mine (fig. 3).

As a conclusion an important aspect of the geology of the Greek lignite mining districts is the occurrence of Mesozoic karstified carbonate rocks in the basement and the surrounding mountains of the mines, and the prevailing of calcareous sediments (marls, marly clays etc) in the filling of the lignite basins.

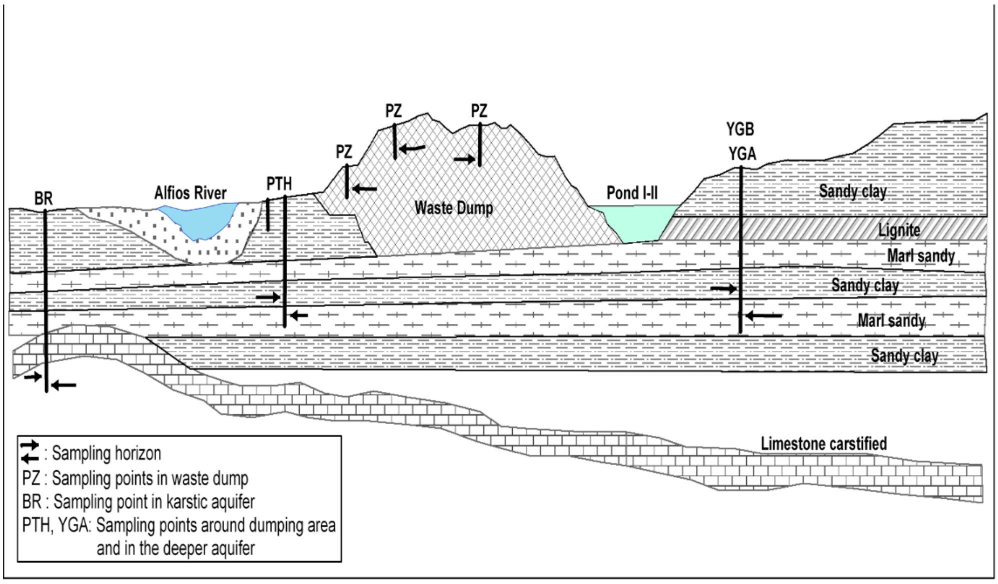

Figure 3 *Pit Lake in Megalopolis lignite site (Pond I-I, Waterchem 2007)*

1.2. Climatic Data

The under investigation areas are situated in a typical Mediterranean climate zone. Time series of more than 30 years of Climatic Data (HNMS[1] and PPC) have been evaluated, since there are meteorological stations around the mines. Rainfall ranges with minimum values in summer and maximum values in winter. Mean annual rainfall is about 900 mm in Megalopolis, 600 mm in Ptolemais-Amynteon basin and 730 mm in Aliveri. Temperatures are mild with relatively high thermal range (~22^0 C). Mean monthly temperature varies between 2,5-24 ^{0}C (average value is 12,9^0C) in Ptolemais basin. In Megalopolis the range of temperature is 5-26,5^0C (av. 15,6^0C) and in Aliveri 9,4-26^0C (av. 17,2^0C).

2. Materials and methods

2.1. Sampling

Samples of mine water (lakes or sumps of the open pits) were collected and analysed, mainly during dry and wet season in 2015. Also samples from natural soil and soil from the dumping areas, where mine waste and fly ash is co-deposited, were analysed. Finally analyses of unaffected ground and surface water from the areas around the open pits were evaluated. The aim was to define the correlation between the geochemical environment of the areas under investigation and the chemistry of mine water of the lakes and sumps.

In Amynteon mine, 13 boreholes were drilled in internal and external waste dumps. Mine waste and fly ash were co-deposited there during the last 10-18 years. Also 4 boreholes were drilled in the natural soil in the perimeter of the mine. Chemical analyses and leaching tests were performed in 48 solid samples taken from these boreholes. Also 6 samples of surface water from the sumps or springs in the dumps were analyzed. D1es, D214b, D4bp, D10kat, D12 are waters flowing along the inside area of the pit, they interact with some of the geological formations or material of the dump and take some chemical load. D3 is the water of the final sump (table 1). Samples from the final sumps at the bottom of the open pits are considered to be representative of the quality of pit lake water.

In South field 4 leaching tests were performed. Two representative samples of the greenish-gray clay and clayey sand series, the overburden geological formation of lignite series, were studied. Water samples were taken from the sumps (E4 and E7), in different periods. Soulou River which is the main drainage body of the area, outflows into Vegoritis Lake at the northern part of the basin. The water that is pumped out for the protection of the mine (from wells or directly from the mining sumps) outflows into Soulou River, so this could be noticed as mine water The water used in the cooling towers of the Power plants of the area is also rejected into Soulou River. 4 samples were taken from it in two different sites, two periods (wet and dry) during 2015.

[1]Hellenic National Meteorological Service

In Aliveri area, 6 water samples were collected from pit lakes in different time periods (2000-2015).

In Megalopolis 16 water samples were collected, mainly during wet and dry season in 2015 Pond I-II are sumps at the bottom of the exhausted Thoknia mine and P23-P27 are sumps in the bottom of Choremi mine. PK1 is the pit lake, which has been formed in Kyparissia mine after the end of the exploitation. A1-A6 are samples from Alfios and E1 from Elissonas River. Also results of previous investigations (Dimitrakopoulou 2010, Waterchem 2007) concerning ground water quality were used. Samples were coming from the karstic aquifer (water wells Br) and from the poor aquitard around Thoknia mine (boreholes PTH, YGA, fig.3)

2.2. Analytical methods

Chemical analyses were performed according to the National German Standard Methods (DEV/DIN). PH, Temp, EC, were measured immediately after sampling with professional plus portable temp/pH/ORP meter. Dissolved ions (K, Na) were measured in a no-acidified sample by flame atomic spectrometry; NH^{+}_{4}, SO^{2-}_{4}, Cl^{-} and NO^{-}_{3} by photo spectroscopy; HCO^{-}_{3} by titrimentry. In the acidified samples Ca, Mg and Fe were measured by atomic absorption, and trace elements (Cu, Zn, Cd, Cr, Pb, Ni, Mn, Co) were determined by inductively coupled plasma mass spectroscopy. The leaching potential of overburden formations in metal elements was determined by performing leaching tests, applying the European Standard Leaching Test EN 12457-2 (CEN, 2002).

3. Results-Discussion

In Amynteon mine, pH values of the solid samples from natural soils and waste dump material (fly ash and waste) range between 6,5-7,4. Concentration of sulphates range 2160-12600 mg/kg. Values of Cd, Hg, Co, Be, Se, Mo are below detection limit. Values of Ni range 18 mg/kg - 295 mg/Kg and 5 samples are over the action values of the new Dutch list (210 mg/kg). According to Petaloti (2003) most of the investigated trace elements in Ptolemais basin have EF (enrichment factor) values less than the unit. This suggests that the origin of these elements is mainly natural (crustal origin). She also mentions that minerals in Western Macedonia consist to a large extent of ophiolites, which are known of their high Cr and Ni content that justifies the relatively high values of Ni.

In the leaching tests of the same solid samples, pH of the leachates ranges 7,8-8,5. Concentrations of Pb, Cd, Cr, Cu, Mo, Ni, Zn, Hg, Se and Sb, are below detection limits. This fact verifies findings of previous investigations (Moutsatsou 2011), that the mixing of fly ash with the waste material in dumping sites improves the absorption of heavy metals. Values of SO_4^{2-} in eluates of natural soil and material of the waste dump range 435-4.000 mg/kg, indicating relatively high leaching potential of the geological formations (Dimitrakopoulos 2016). The fact that the samples of the natural soil show similar behaviors indicates that the low content of SO_4^{2-} is possibly due to the mineralogical composition of the sediments of the basin.

In mine water samples, pH ranges 7,87-8,50 indicating clearly alkaline environment. Content of heavy metals and trace elements are below detection limit with the exception of only Mo (18,65-290 μg/l) and Ba (40-150 μg/l). Sulfate ranges 330-1114 mg/l.

In unaffected groundwater pH ranges 7,23-8,27. At the NW of Amynteon basin, where gneiss-schist bedrock emerges hardness is 337 ppm $CaCO_3$, while in other areas, where carbonate rocks prevail, hardness increases up to 800 ppm $CaCO_3$. Respectively EC ranges from 1043 to the NW -up to 2300 μS/cm to the areas of carbonate influence. Content of heavy metals and trace elements are below detection limit with the exception of Sr (138-938 μg/l), Ba (52-160 μg/l) and B (59-7589 μg/l). Sulfate ranges 20-350 mg/l (Dimitrakopoulos 2016). High Boron content according to Iordanidis (2002) implies a fresh water to middle brackish depositional environment in Amynteon basin.

In Aliveri Pit Lake the mine waters are slightly alkaline, pH values range from 7 - 8. Average values for EC is 1305 μS/cm in the lake and 1780 in the Pond. Dominant water type is Ca-Mg-Na-SO_4. In Pond the chlorides are increased (147-380 mg/l). Sulphates range between 222-1008 mg/lt and higher value is observed in the Pond. There is a tendency of reduction of sulphates in big lake with the time. Trace elements that were measured are below the limits according to Greek legislation. There is no significant change in the water quality of the final lake 17 years after its formation.

In South field the overburden of lignite series consist mainly of illite, vermiculite, chlorite, quartz, feldspars and calcite. Their leachates are alkaline (pH=7,7-8,2). Values of Si, were measured in a range of 4252-10166 ppb. Values for heavy metals are very low in leachates, Cr 0.6-1.5 ppb, Mo 0,7-2 ppb, Rb 0,48-1,29 ppb, Sr 38.4-88.4 ppb and As 2-2,7 ppb (Vasileiou et al. 2015). In Soulou stream, in South field, the average pH value is 8.27, that indicates alkaline waters, the average value of EC was measured at 789 μS/cm. Water type for both samples is Ca-Mg-SO_4-HCO_3. Average concentration of sulphates was 210 mg/lt. All trace elements and heavy metals are below the acceptable limits, considering the environmental legislation.

***Table 1**: Chemical analyses of mine water in different mine sites.*

Site	Mine Water	Water Type	pH	EC µS/cm	SO_4^{2-} mg/L	NO_3^- mg/L	HCO_3^- mg/L	Mg mg/L	Ca mg/L	K mg/L	Na mg/L	Ni µg/L	Cr µg/L	Ba µg/L	Mo µg/l	Mn µg/L
Amynteon	**D1_ ES**	**Mg-Ca-HCO3-SO4**	8,5	1286,0	350,0	2,8	550,0	89,2	109,2	3,9	19,0	n.d.	n.d.	n.d.	290,0	n.d.
	D2_14B	**Mg-Ca-SO4-HCO3**	8,2	1373,0	435,0	0,0	456,0	107,4	110,0	2,8	36,3	n.d.	n.d.	n.d.	270,0	n.d.
	D4_ Bp	**Mg-Ca-SO4-HCO3**	8,5	1043,0	330,0	1,5	391,0	85,8	54,8	3,1	54,7	n.d.	n.d.	150,0	240,0	n.d.
	D10_ KAT	**Mg-SO4-HCO3**	8,1	2300,0	990,0	5,5	760,0	261,4	92,7	3,5	98,5	n.d.	n.d.	110,0	190,0	n.d.
	D12	**Mg-Ca-SO4**	7,9	1597,5	1114,5	27,8	158,0	158,0	136,7	3,7	91,3	20,2	n.d.	131,3	18,7	89,8
	D3_ ANT	**Mg-SO4-HCO3**	8,4	1325,0	445,0	8,3	478,0	128,8	65,7	3,4	62,4	n.d.	n.d.	40,0	210,0	n.d.
	Average mine water		**8,3**	**1487,4**	**610,8**	**7,7**	**465,5**	**138,4**	**94,8**	**3,4**	**60,4**	*****	*****	**107,8**	**203,1**	*****
Megalopolis	**POND1**	**Ca-SO4**	7,9	3180,0	1807,0	13,0	171,0	64,3	402,0	100,0	88,1	<20	<10	81,0	8882,0	435,0
	PONDII	**Ca-SO5**		990,0	402,5	22,5	64,0	15,2	131,0	18,0	26,0	<20	<10	100,0	1015,0	43,5
	EPN4	**Na-SO4**	11,0	630,0	123,0	13,0	0,0	1,5	5,8	3,9	108,0	<20	<10	18,0	547,0	<10
	P23	**Ca-Mg-SO4-NO3**	7,7	2650,0	715,5	525,5	274,0	76,0	314,0	3,5	104,3	11,8	<5	118,5	136,2	261,7
	P24	**Ca-Mg-SO4-NO3**	7,6	2360,0	640,0	449,0	203,0	62,4	281,0	3,0	77,8	11,7	<5,0	155,0	126,0	374,0
	P25	**Ca-Mg-SO4**	7,5	2630,0	1409,0	234,0	137,0	108,0	449,5	2,5	88,1	59,0	<5	75,7	39,2	300,0
	P26	**Ca-Mg-SO4**	7,3	2895,0	1420,5	275,0	218,0	90,5	470,0	2,9	90,7	24,0	<5,0	114,5	89,4	723,0
	P27	**Ca-Mg-SO4-NO3**	7,5	2100,0	693,0	424,0	156,0	65,0	317,0	2,3	52,7	14,3	<5,0	59,8	42,4	255,0
	PK1 (2003)	**Na-Ca**	7,3	3830,0	125,0	30,0	257,1	16,0	360,0	59,0	685,0	12,0	6,0	38,0		150,0
	PK1 (2015)	**Ca-SO4-HCO3**	7,9	1330,0	575,0	11,8	193,0	26,6	258,0	1,6	16,7	11,9	<5,0	61,9	32,3	3,3
	Average mine water		**8,0**	**2259,5**	**791,1**	**199,8**	**167,3**	**52,5**	**298,8**	**19,7**	**133,7**	**20,7**	**6,0**	**82,2**	**1212,2**	**282,8**
	E1	**Ca-Mg-SO4-HCO3**	8,2	575,3	90,7	11,5	223,3	23,1	63,0	2,2	13,2	<20	25,0	32,7	49,0	39,5
	A1-A6	**Ca-SO4-HCO3 (Na)**	7,8	706,2	141,9	10,6	237,8	13,5	100,7	4,2	18,6	<20	<10	57,5	334,0	19,3
Aliveri	**Pond 9/2/00**	**Ca-Na-Mg-SO4-Cl-HCO3**	7,0	1591,0	349,0	0,0	244,0	58,9	181,1	3,1	163,9	<10	94,0	18,0		33,0
	Pond 30/3/01	**Ca-Na-Mg-SO4-Cl**	7,5	1970,0	1008,0	0,0	183,0	77,5	228,0	3,5	210,0	15,0	<10	15,0		<10
	Lake 9/2/00	**Mg-Ca-Na-SO4-HCO3**	7,7	1302,0	222,0	0,0	256,0	90,9	131,4	3,1	95,1	<10	<10	34,0		<10
	Lake 27/11/00	**Mg-Ca-Na-SO4**	8,0	1310,0	665,0	0,0	183,0	86,8	109,0	3,0	105,0	<10	<10	36,0		<10
	Lake 30/3/01	**Mg-Ca-Na-SO4**	7,6	1260,0	530,0	0,0	189,0	97,6	117,0	4,4	101,0	<10	<10	19,0		<10
	Lake 2015	**Mg-Ca-Na-SO4-HCO3**	7,7	1350,0	399,0	0,0	257,0	79,0	102,7	4,1	74,4	11,0	<0,5	33,9	1,0	2,2
	Average mine water		**7,6**	**1463,8**	**528,8**	**0,0**	**218,7**	**81,8**	**144,9**	**3,5**	**124,9**	**13,0**	**94,0**	**26,0**	**1,0**	**17,6**
South Field	**Soulou 1**	**Ca-Mg-Na-SO4-HCO3-Cl**	8,4	774,0	223,0	6,7	137,5	35,0	75,0	2,7	48,4	<10	<5	34,3		30,0
	Soulou2	**Ca-Mg-SO4-HCO3**	8,2	804,0	197,0	12,7	223,0	39,5	96,5	2,9	27,8	<10	<5	41,4		37,0
	E4	**Ca-Mg-SO4-HCO3**	7,6	848,0	166,0	9,9	184,0	30,2	98,0	1,3	10,6	4,6	2,7	48,9	1,4	14,3
	E7	**Ca-Mg-HCO3-SO4**	7,9	792,0	177,0	19,5	243,0	40,1	112,0	1,7	9,3	7,9	5,3	36,2	4,7	8,5
	Average mine water		**8,0**	**804,5**	**190,8**	**12,2**	**196,9**	**36,2**	**95,4**	**2,1**	**24,0**	**6,3**	**4,0**	**40,2**	**3,1**	**22,4**

***Table 2**: Chemical analyses of unaffected groundwater in mine study areas.*

Average	pH	EC µS/cm	TDS mg/l	HCO_3^- mg/l	SO_4^{--} mg/l	NO_3^- mg/l	Ca^{++} mg/l	Mg^{++} mg/l	Na mg/l	K mg/l	Fe µg/l	Mn µg/l	Ni µg/l	Crtot µg/l	Ba µg/l	Sr µg/l	Mo µg/l	B µg/l
Amynteo	7,6	1006,4	647,5	555,6	111,6	1,4	89,5	57,5	73,8	8,3	337,0	203,1	11,0	<5	99,7	427,7	<10	1932,0
South Field	7,8	490,0	306,8	260,0	53,0	16,0	67,1	28,2	12,3	0,9	30,0	281,0	<10	12,9	35,7	199,0	9,5	72,1
Megalopolis-Thoknia	7,7	1533,6	984,3	689,2	276,5	11,6	191,0	30,7	95,5	53,8	271,6	594,2	14,3	21,5	166,5	771,9	109,0	
Megalopolis-Karstic aquifer	7,3	574,0	342,5	134,0	51,5	9,4	92,5	19,5	10,2	1,0	18,0	22,2	11,7	<5	46,1	450,0	100,2	128,4

In the sumps of South field, the water is alkaline and also their water type is Ca-Mg-SO_4-HCO_3. Measured values of pH range 7,5-7,93. Concentrations of sulphates were in a range of 166-200 mg/l. Concerning trace elements and heavy metals, only nickel exceeds the acceptable limits according the Greek legislation (20 ppb).

In Megalopolis area, mine water from sumps and ponds is alkaline (pH=7,70-11,00). Water type of the water of the sumps varies a lot, the main type is Ca-SO_4 with the presence of Na, HCO_3, Mg. Average value of EC is 2260 µS/cm (630-3830 µS/cm). Higher values are observed in smaller ponds or at the beginning of the formation of pit lake in Kyparissia. Increased values of sulphates (640-1420 mg/l) are noticed, the higher of them in smaller sumps PondI, P25, P26, where evaporation is higher and recharge is poor. Higher values of Mo (20-8882 µg/lt), are observed in Pond I-II, where water comes into contact with dumping of fly ash (intervention value of the New Dutch list 300 μg/lt). Mn values vary from <10 to 723 μg/lt. Higher values are recorded in mine waters from the sumps and lower in Kyparissia pit lake. Comparing with the Greek legislation acceptable limit (50 μg/lt), the concentration is considered high.

Alfios River and Elissonas flow between the mines. Their water quality (E1, A1-A6 table 1) is generally good, even though the domestic sewage of Megalopolis town and mine water are rejected in Alfios. Water is alkaline, average pH value is 8. Average values of sulphates is 141,90 mg/l, lower than the acceptable limits (250 mg/l). Average value of Mg in Alfios and in Ellisonas is 18,3 μg/lt, below the acceptable limits (50 μg/lt). Values of Mo are increased in Alfios, (334 μg/lt) comparing to Ellisonas, due to the influence of rejection of mine water and sewage of Megalopolis.

In pit Lake of Kyparissia (PK1), significant changes were recorded during this decade. As it seems from table 1, sodium and EC, were very high in 2003, but in 2015 there are low in normal levels in comparison to natural waters.

Natural waters in Megalopolis, presents similar quality with mine water, the noticeable concentration of them concerning manganese, which is significantly high (Table 2).

Hydrochemical water type of each sample comes from the process of solution kinetics, rock–water interactions, geology and contamination sources. Chemical data of the water samples is also presented by plotting them on a Piper trilinear diagram (Fig. 4). Piper diagram classifies the samples based on the ionic composition of different water samples. This diagram reveals the different types of waters in the four mine sites. In the study sites the type of water that predominates is mainly Ca–Mg–HCO3 type which is mainly due to the geology of the area which comprises limestones. Ca^{+2} is almost the dominant cation for all water samples. According Wilcox diagram, most of samples are classified as C3S1 (High salinity and Low sodium), only one sample from Megalopolis (PK1-2003) is improper even for irrigation uses (C4S3), but the recent one sample, from the same site indicates that this qualitative characteristics were transient.

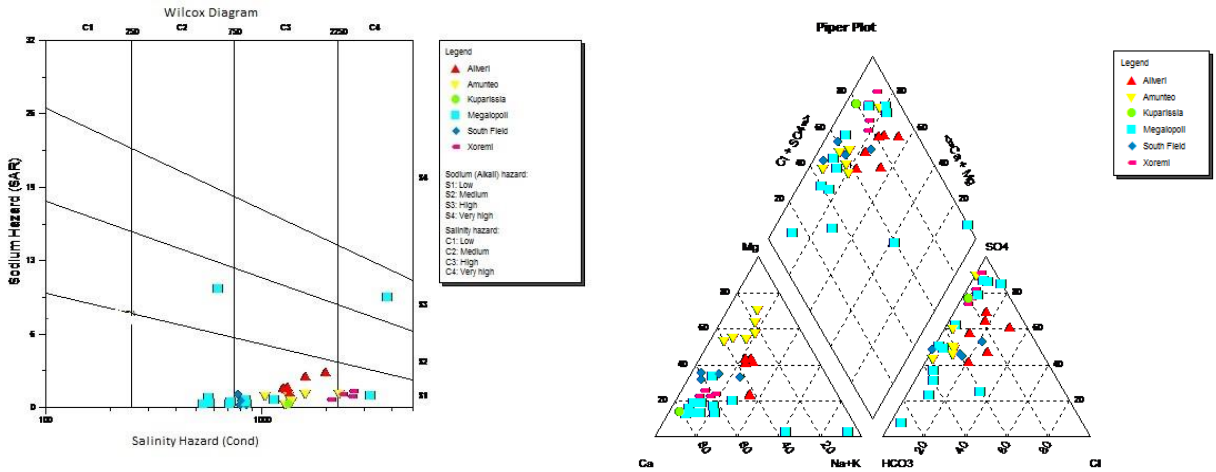

Figure 4 *a) Wilcox diagram and b) Piper diagram in mine waters.*

Ficklin diagram shown in figure 5, illustrates the base metal content of the waters associated to the mine sites in Greece. It is obvious that in Megalopolis, the total dissolved metals/metalloids in water are increased comparing with the other mine sites. Water from pit lakes in Aliveri presents the lower leaching potential. In all mine sites the environments are alkaline, which are not favorable in mobilization of metals (-oids).This is the main reason that most of heavy metals/loids concentrations are undetectable in mine and in natural water. In Megalopolis, molybdenum shows high leaching potential because it is mobile and soluble in alkaline environments. In the other pit mines, it is not observed high leaching of Mo, although there are also alkaline environment, because the geochemical composition of lignite is different from site to site, in Megalopolis the lignite ore is enriched in Mo. All the other heavy metals\oids that are compounded in lignite are immobile in alkaline environment.

The most important parameter that controls pit water quality is pH. This is because the mobility of most metals and metalloids is strongly pH-dependent (Soni 2014). In our study sites, pH values indicate an alkaline environment. Consequently pit lakes water contain low concentrations of heavy metals (e.g., Al, Cd, Cu, Fe, Mn, Ni, Pb, Zn) and/or metalloids (e.g., As, Sb, Se, Te) that can pose a threat to the environment.

Despite the prevalence of acidic pit lakes in central Europe (Schultze et al 2010), pit lakes in Greece are neutral or even slightly to strongly alkaline. If a lake is in contact with a source of carbonate such as limestone or dolomite, a carbonate-cemented sedimentary rock, it may neutralize some or all of the acid produced by oxidation of pyrite and other minerals (Eary 1997). Both alkaline ground water and the very low level of sulphur in and around the lignite seams are probably responsible for the generally good water quality in the lignite pits (Castro 2000). Calcium and magnesium concentrations reflect the ability of buffering any acidity produced by pyrite oxidation (dissolution of carbonates, ion exchange, dissolution of silicates, etc.), the initial composition of overburden and lignite and the source area of the current lake water.

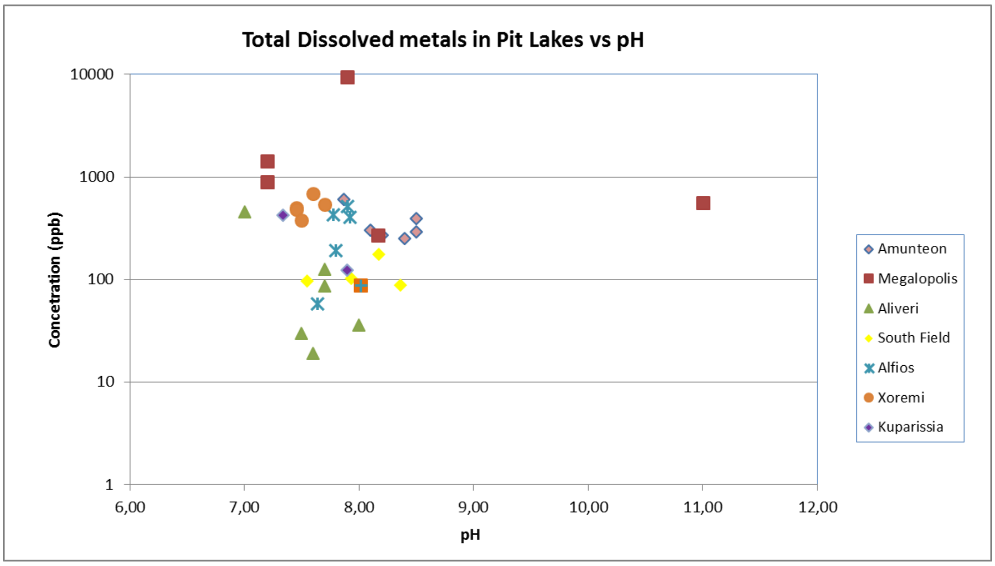

Figure 5 *Ficklin diagram, about the total dissolved metals in mine and natural waters.*

4. Conclusions

Mining pit lakes display a wide diversity in water quality and dependence on the mineral deposits that were extracted. General trends in pit lake chemistry have been reviewed by several researchers (Friese 1998, Eary 1999, Castro 2000, Delgado 2008) and they reflect a wide complexity regarding the chemical analysis.

Post mining lakes in lignite fields in Greece are of good water quality and have acceptable values in most of the elements, as these are described in environmental legislation (EU and Greek law).

Most of Greek lignite pit lakes are surrounded mainly by carbonate formations (limestone, dolomite), ultramafic rocks and neogene-quartenary deposits. This geochemical environment may neutralize some or all of the acid produced by oxidation of pyrite and other minerals. Also the lack of available sulphide minerals and/or large amounts of carbonate in the surrounding rocks of the lignite basins and the sediments of the fill, are probably responsible for the generally good water quality in the lignite pit lakes.

PH values are the most important control factor for the mobilisation of metals/oids and their dissolution in waters. In all mine sites the waters are alkaline. Low values of EC indicate the generally relatively low concentrations of dissolved solids in the pit lake water, which are mainly sulphates, bicarbonate, calcium and magnesium. The highest values of electrical conductivity originate from small lakes or ponds, which are influenced by evaporation, are hydraulically isolated and are not recharged sufficiently by natural ground or surface water.

Low concentrations of heavy metals (i.e. Pb, Cr, Hg, Cd, Cu, Ni, Co, Zn, Mn) were recorded in the mine and in natural waters. The geochemical environment (i.e. high calcite content, high pH values, low Fe, S) also creates favourable conditions for the diminishing of their leaching potential. Mainly the potential contaminants are below mandatory concentrations or exceeding the limits in some sites but as point pollutants. The mixing of fly ash with the waste material in dumping sites improves the absorption of heavy metals (Moutsatsou 2011).

The main conclusion of this study is the significant role of the water – rock interaction that was evaluated in order to assess the water quality of pit lakes at each mine site. All pit lake waters are alkaline, which is an unfavourable condition for the dissolution and mobilisation of heavy metals.

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