SEVENTH FRAMEWORK PROGRAMME
Area 6.4.1.2. Cross-cutting research activities relevant to GEO
ENV.2008.4.1.2.1. Monitoring and observing oxygen depletion throughout the
different Earth system components

**Deliverable D 7.2**
“Report on linking of existing data bases with relevance to
oxygen depletion to HYPOX data base”; month 6
Editor: Henrik Stahl, SAMS
with all partners of WP7

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of coastal and open seas, and land-locked water bodies
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1. Introduction
Deliverable 7.2 belongs to WP 7 – ‘Assessing in situ oxygen depletion in land-locked water bodies’. This report consists of a compilation and review of historical and present data from the respective sites within WP7 that are of relevance to the HYPOX project.

In addition to this report, relevant legacy data from the respective target sites (Swedish and Scottish fjords, Swiss lakes and Greek lagoons) have also been reported and submitted to the HYPOX data base (WP 5) by the different partners within WP 7.

The presented data in this report was selected on the basis of characterization of present status and past conditions in the respective land-locked water bodies with respect to their physical, chemical and biological conditions.

The involved partners in WP 7 have contributed to this report as follows:

- UGOT - has reviewed and compiled existing and historical data from Koljo fjord in Sweden.
- SAMS – has reviewed and compiled existing and historical data from Loch Etive, Scotland
- Eawag - has reviewed and compiled existing and historical data from Lake Lugano and Lake Rotsee in Switzerland.
- UPAT and INGV – have reviewed and compiled existing and historical data from Ionian Sea Lagoons, Greece.

2. Objectives D7.2
The overall objective for this report is to review and compile existing current and historical data from the respective WP7 sites (Swedish fjords, Scottish Sea Lochs, Swiss Lakes and Ionian Lagoons) with respect to hypoxia formation in these land-locked systems. For the respective target areas, this includes:

- Short review of the current knowledge and understanding about the formation of hypoxia.
- Compilation of local/international expertise, relevant for the formation of hypoxia.
- Compilation of available databases relevant to hypoxia.
- Bibliography of relevant publications

All of the above will serve as the basis for defining the most suitable monitoring strategies and in situ observatories at the different target sites (fjords, sea lochs, lagoons and lakes).
3. Swedish fjords

3.1 Oxygen depletion in the Koljo fjord

The Koljo Fjord is situated on the Swedish west coast approximately 100 km north of Gothenburg. Data exist in a database (hosted by the Swedish Meteorological and Hydrological Institute (SMHI) in Gothenburg) on depth distributions in the water column of salinity (S), temperature (T), oxygen, hydrogen sulfide, nutrients, total N, total P, chlorophyll, Secchi depth, pH, alkalinity, etc. at the central deepest (45 m) site. Most of these parameters (and certainly S, T and O$_2$) have been measured on a monthly basis since 1986, on a bimonthly or quarterly basis during 1958-1985, and (at least) annually during 1934-37. There are no measurements for the period 1938-57. The monitoring program in the Koljo Fjord is ongoing and presently run by SMHI.

There are also other data especially on sediments in the Koljö Fjord, e.g. on foraminifera, C and N, water content, etc. The foraminifera and other data have been used for paleo-climatological/paleo-oceanographic studies led by the Earth Science Centre, University of Gothenburg (prof. Kjell Nordberg, kjno@gvc.gu.se). These studies focused on e.g. previous oxygen conditions in the fjord on time-scales of up to hundreds of years.

The Koljo Fjord is a sheltered near-shore fjord. There are very weak tides; max tidal amplitude is 10-15 cm. The fjord is almost permanently anoxic below ca 20 m, and permanently oxic in surface water. The cause of hypoxia-anoxia is man made (discharge of nutrients from farmed land and lack of sufficient sewage treatment), and due to the hydrographical setting of the fjord causing limited exchange of deep water (water below ca 20 m depth). Hence there are both anthropogenic and natural reasons for hypoxia-anoxia. The depth distribution as well as seasonal and decadal (almost three decades, 1980-2008) variability of temperature, salinity and oxygen concentration in the water column of the fjord is shown in Fig. 1 below.

Partner 12 (UGOT) is investigating to what extent the oxygen variations in the Koljo Fjord on time-scales from hours to years can be explained by water exchange with the water outside the fjord. To this end one must know the boundary conditions with respect to vertical stratification (S and T). Therefore partner 12 is carrying out high temporal resolution measurements of the vertical stratification both outside and in the centre of the fjord. An observation system has been set up in the fjord including a long-term mooring for continuous measurements through the water column of horizontal and vertical currents, oxygen, salinity and temperature. Total sediment oxygen consumption will be computed from oxygen gradients in the bottom water and bottom water hydrodynamics, e.g. water velocity. Direct measurements of the total oxygen consumption by the sediment are also being made in-situ during field campaigns using a benthic chamber lander for ground-truthing.
Figure 3.1: Seasonal and interannual (1980-2008) variability of the depth distribution of temperature, salinity and oxygen concentration in the water column of the Koljo fjord. Data from the Swedish Meteorological and Hydrological Institute (SMHI).
3.2. Expertise and databases on the Koljo fjord

UGOT hosts expertise, and a number of data sets/studies, regarding hydrography, oceanography, geology, biogeochemistry and biology of the Koljo Fjord:

- Prof. Kjell Nordberg (kjno@gvc.gu.se), Paleoceanography, Paleobiology and Marine Geology
- Prof. Ingemar Cato (ingemar.cato@sgu.se), Marine Geology and Sediment Chemistry
- Prof. Anders Stigebrandt (anst@gvc.gu.se), Oceanography and Marine System Analysis
- Prof. Per Hall (perhall@chem.gu.se), Biogeochemistry

Also the Swedish Meteorological and Hydrological Institute (SMHI) hosts expertise:

- Dr. Philip Axe, Hydrography

A database on hydrography, nutrients and other chemical parameters is hosted by SMHI in Gothenburg. It is available at [www.smhi.se](http://www.smhi.se). Contact person is Philip Axe (philip.axe@smhi.se).

3.3 Bibliography for the Koljo fjord


Several reports on the hydrography of the Koljo Fjord produced by SMHI.
4. Scottish fjords

4.1 Oxygen depletion in Loch Etive

The main reasons for the duration and magnitude of oxygen depletion in the upper basin in Loch Etive (fig 4.1) are linked to (1) the frequency of bottom water renewal, which was described to take place on average every 16 months in the upper basin (Edwards and Edelsten, 1977), and (2) how rapidly oxygen declines in the bottom water in-between these events. Previous studies have found the bottom water to be moderately hypoxic (20-10% atm sat.) for more than 6 months in a row in the deep basin (Overnell et al 2002).

Figure 4.1: Bathymetric profile of Loch Etive.

Oxygen depletion in the upper basin of Loch Etive (fig 4.2) evolves mainly as a consequence of the prevailing hydrographical conditions (Edwards and Edelsten, 1977; Austin and Inall, 2002). Restricted horizontal and vertical water exchange due to the presence of multiple sills in combination with strong salinity-driven density gradients created by a high river run off results in prolonged isolation of bottom water in the inner basin of Loch Etive. The riverine input of terrigenous material in combination with local primary production (which is small relative to the total OM input) results in a relatively high input of organic matter to the sediments and a high benthic oxygen demand between 11-50 mmol O$_2$ m$^{-2}$ d$^{-1}$ (Ansell 1974; Loh et al, 2002; Overnell et al, 2002 ). This results in hypoxic conditions (as low as ~10% atm sat) and elevated concentration of dissolved Mn$^{2+}$ and Fe$^{2+}$ in the bottom water of the inner basin (Overnell et al 2002).

However, completely anoxic condition has never been recorded so far in the bottom waters of the inner basin in Loch Etive, indicating that renewal events are currently frequent enough for the bottom water not to run out of oxygen completely. Recent paleoclimatic studies (Norgaard-Pedersen et al, 2006) suggest that the strength and
The frequency of renewal events has varied through time in Loch Etive, mainly by changes in relative sea level and freshwater influx to the loch, and that Loch Etive is now going from a more marine to a more terrestrial dominated environment (Murray et al. 2003).

Figure 4.2: Cross section of oxygen concentrations (ml*L$^{-1}$) in Loch Etive in February 2000.

The large catchment area (1400km$^2$) of Loch Etive is spread over a relatively pristine and to a large extent uninhabited part of the Scottish highlands with low agricultural activity. Significant anthropogenic contribution to the prevailing oxygen depletion in the inner basin in Loch Etive is therefore unlikely. However, it should be mentioned that it has been hypothesized that increased anthropogenic deforestation in the catchment area during the late Holocene might have had an effect on the freshwater input and sedimentation in the loch (Norgaard-Pedersen et al., 2006).

Predicted climate changes may very well increase the duration and severity of hypoxia in Loch Etive, a fjord that already is classed as one of the most sensitive Loch’s in Scotland in terms of oxygen depletion (Gillibrand 2005; Gillibrand et al. 2007; Inall et al. 2009). A climate change induced increase in sea surface temperatures and precipitation will enhance water column stratification and possibly reduce the bottom water renewal frequency resulting in enhanced isolation of deep water in Loch Etive. Additional input of terrestrial organic matter due to an increased river runoff as well as higher surface water temperatures will increase the biological oxygen demand and decrease oxygen solubility which could affect the severity of the hypoxic conditions in Loch Etive even further.

As mentioned before, due to relatively low agricultural activity and lack of heavy industry on the Scottish west coast and in the highlands where the Loch Etive catchment area originates from, a significant impact of eutrophication on the oxygen depletion is unlikely. However, it should be mentioned that a few aquaculture farms are located within the loch but these are not predicted to have an eutrophic impact on the loch (T. Nickell pers. com.).
According to literature the soft surface sediments in the outer and inner Loch Etive are dominated by a greeny-black homogenous watery sandy mud occasionally perturbed by methane ebullition (Howe et al, 2002). The inner basin is the main deposition area for terrigenous material carried by rivers Etive, Kinglass and Awe (Howe et al, 2002; Loh et al 2002). Although only semi-quantitatively determined, Loch Etive seem to harbour an abundant benthic fauna but somewhat less diverse compared to other sea lochs nearby, possibly due the high freshwater input (Gage 1972). The same study also showed a higher abundance of deposit feeders in the deep inner basin whereas the outer basin in Loch Etive was dominated by suspension feeders (Gage, 1972). A recent study from Airds Bay in Loch Etive showed very high abundances (>1000 ind m\(^{-2}\)) of the brittlestars *Amphiura filiformis* and *Amphiura chiaeji* (H. Stahl unpublished results).

### 4.2 Expertise and databases on Loch Etive

SAMS hosts/have hosted local and international expertise, and a number of data sets/data bases/studies, regarding Loch Etive hydrography, bathymetry and geology, biogeochemistry and biology:

- **Dr. Mark Inall** (SAMS)/**Dr. Dmitry Aleynik** (SAMS)/**Dr. Phil Gillibrand** (NIVA, Christchurch, New Zealand). *Speciality* - hydrograpy and modelling deep-water renewal periodicity/dynamics, baroclinic tidal regimes and forcing as well as modelling of bottom water oxygen concentrations (Austin and Inall, 2002; Inall et al, 2004; Inall et al, 2005; Stashchuck et al, 2007; Gillibrand et al, 2007).

- **Dr. Julian Overnell** (retired)/**Dr Tim Brand** (SAMS)/**Dr Martyn Harvey** (retired)/**Prof Axel Miller** (SAMS). *Speciality* - biogeochemistry, with emphasis on benthic oxygen, iron- and manganese dynamics as well as organic matter input and composition (Overnell et al 1996; Overnell et al 2002; Overnell 2002, Loh et al, 2002)

- **Dr. Henrik Stahl** (SAMS)/**Prof Ronnie Glud** (University of Southern Denmark, Odense, Denmark). *Speciality* – benthic biogeochemistry, oxygen and nutrient dynamics.

- **Dr. John Howe** (SAMS)/**Dr Tracy Shimmield** (SAMS). *Speciality* - bathymetry, geology and radionuclide chemistry (Howe et al, 2002; Howe et al, 2001; Shimmield, 1993)

- **Prof. Paul Tett** (SAMS). *Speciality* - benthic community structure and plankton dynamics in Loch Etive, ecosystem modelling (Gage, 1972a and b; Gage and Geekie, 1973; Gage and Tett, 1973; Sommerfield and Gage, 2000; Wood et al, 1973; McKee et al, 2002)

- **Mr. Steven Gontarek** (SAMS)/**Mr. Lovro Vlacic** (SAMS). *Speciality* – data-base administrators at SAMS.

List of HYPOX-relevant databases currently held at SAMS and/or Hypox data portal:

- **OARRE** (Tidal Exchange and Energy Propagation in Loch Etive): A physical oceanographic study of the upper basin of Loch Etive, Scotland, by the marine physics groups of the Scottish Association for Marine Science and the
School of Ocean Sciences, University of Wales, Bangor. This study was conducted in June 2001.

- REES (Restricted Exchange Environments Project): From July 1999 March 2001, SAMS undertook regular (approximately monthly) sampling trips in Loch Etive. During each trip, profiles of conductivity-temperature-depth (CTD) were made and water samples collected (oxygen, nutrients and selected metals) at 8 fixed station locations in both basins of the loch and at one site outside the Loch. This data base is also available through the HYPOX data portal.
- Loch Etive bathymetry: Data from a side-scan and bathymetric sonar survey of Loch Etive carried out on the 31 Aug 1999 using an Ultra Electronics Ocean Systems Deepscan system operating at 120 kHz, towed behind the RV Calanus.
- HYPOX observatory: A cabled online observatory was deployed in Nov 2009 in the upper deep basin providing real-time (every 10 min) data for oxygen, current speed/direction, temperature, conductivity and pressure at two depths (15m and 140m below the surface). Data from this mooring can be viewed at http://192.171.158.77/AADI_DisplayProgram/setups/SeaguardRCM/default.aspx
- Local weather data: SAMS weather station has been operating from 1960’s and is still active

4.3 Bibliography for Loch Etive


5. Swiss lakes

5.1 Lake Rotsee

Lake Rotsee is a small mesotrophic prealpine lake near to the city of Lucerne in Switzerland. It is 2.4 km long and 0.4 km wide and situated at an altitude of 436 m. Its mean depth lies at 9 m whereas the maximum depth is 16 m. The lake is wind shielded which allows a relatively stable stratification which begins in June and ends in early winter depending on the prevailing temperatures and winds. Whereas the surface temperatures are triggered by atmospheric temperatures, the hypolimnion has a rather stable temperature of 7 °C. The lake exhibits a strong chemocline during stratification with anoxic waters below this border. During our recent studies from 2004 to 2006 the chemocline was determined to be located between 8 and 11 meters. During the last year in summer the lake has produced so much organic material in the spring bloom due to very warm temperatures already in April. That led later in the year (August) to a strong
oxygen respiration which provoked the build-up of hydrogen sulfide which eventually was smelled by the people living around the lake.

This lake is well suited to be monitored during the summer for oxygen consumption. We had recently a one year long monthly sampling campaign that mainly focused on methane build up that is formed during the break down of organic material due to methanogenesis. For this campaign (February 2007 to January 2008) also oxygen data exists, however, due to the lack of highly sensitive oxygen sensors this data is only valid down to ~1uM. This value is about where Winkler is not valid anymore and no concentrations could be determined below.

![Figure 5.1: Monthly water column profiles of DO in Lake Rotsee between February 2007 - 2008](image)

### 5.2 Lake Lugano

Lake Lugano is a deep subalpine lake located at the border area of Switzerland and Italy (271 m above sea level). It is divided into three sub-basins: the northern and the southern basins separated by an artificial dam, and a smaller basin situated in front of the outlet of the River Tresa. The northern basin has a volume of 4.69 km³ and a maximum depth of 288 m (Barbieri and Polli, 1992). Due to its morphology with steep slopes and its geographic position protected against strong winds the lake is meromictic and hosts permanent anoxic conditions below 100 m depth (Vollenweider, 1964; Barbieri and Polli, 1992). Eutrophication, which started in the second part of the last century, led to significantly increased primary productivity and changes in the planktonic community structure. Highest primary productivity (>400 g C m⁻² yr⁻¹) was reached in the 1980’s with a planktonic community dominated by cyanophyceae and diatoms (LSA, 2003). After the introduction of severe policies limiting the phosphate input into the lake and efficient sewage treatment, in the 1990’s the primary productivity decreased to 300 g C m⁻² yr⁻¹ and nowadays diatoms and cyanophyceae as well as cyclopoida and cladocera predominate and make up about 75% of the total phytoplanktonic and total zooplanktonic biomass, respectively (Barbieri and Simona, 2001). This lake has been stratified year round for at least the last 30 years, however, due to a severe winter with strong wind this lake has mixed down to almost the bottom in 2004. This offers now the opportunity to observe a lake after having taken a deep breath for the first time after a long period of time. We have monthly to biweekly data from the lake for the last 22 years. These measurements include temperature, conductivity, O₂ concentration und saturation, pH, CO₃, alkalinity, N total, nitrate, nitrite, ammonium, hydrogen sulfide, and CH₄.
5.3 Expertise and databases on Swiss lakes

Eawag hosts local and international expertise, and a number of data sets/data bases/studies, regarding Swiss lakes hydrography, bathymetry and geology, biogeochemistry and biology:

- Dr. David Livingstone - David Livingstone is a physical limnologist with over 20 years of experience in the fields of physical oceanography and physical limnology. His main activities centre on lake physics, especially air-water interaction and the climatic control of physical lake processes, and he has published work on a wide range of subjects including rotary spectral analysis, the modelling of lake heat balances, the non-linear influence of wind speed on air-water gas exchange, hypolimnetic oxygen depletion, the effects of climate change on lake temperatures and the evaluation of lake break-up dates as proxy air temperature data. His current research focus is on the effects of climate change on lake systems.

- Prof. Rolf Kipfer - Rolf Kipfer is the Head of the Dept. of Water Resources and Drinking Water at Eawag. He is a geophysist with expertise in the analysis of physical transport and exchange processes in the natural environment and the hydrosphere (e.g. lakes, groundwaters, porous media, gas hydrates, etc.). Fields of research are tracer hydrology, development and application of noble gases and other transient tracer methods as well as isotopic techniques, and the reconstruction of global and environmental change using different natural aquatic archives.

- Dr. Carsten Schubert - Carsten Schubert is a biogeochemist with a strong expertise in stable isotope and organic geochemistry. He applies organic geochemical tools to trace biogeochemical processes and interactions in marine and lacustrine sediments and water bodies.

Eawag has access to oxygen data sets (among other variables) for multiple Swiss lakes (including Lake Rotsee, since 1920; lake Zurich, since 1934; and Lake Lugano, back to 1987). Cantonal offices and other institutions in the vicinity of the respective lakes perform the profile measurements, and therefore have control of the data sets. For this reason, the data sets cannot be uploaded to the HYPOX web portal. Eawag is able to assist any interested parties who seek access to the data sets.

5.4 Bibliography for Swiss lakes


Strasser M., Schindler C., and Anselmetti F. S. (2008) Late pleistocene earthquake-triggered moraine dam failure and outburst of Lake Zurich, Switzerland. Journal of Geophysical Research-Earth Surface 113(F2), -.


6. Greek lagoons

6.1 Aetoliko Lagoon

The Aetoliko lagoon is the north part of the "Messolonghi- Aetoliko Lagoon Complex" located in the western Greece. The extent of the lagoon is $15 \times 10^6$ sq.m. and the maximum depth is 32m. Aetoliko lagoon (Fig 6.1) is connected to the Messolonghi lagoon, where the water depth is approximately 2m by two short, narrow and shallow (~1m deep) channels. To the south the complex is connected to the Gulf of Patras.

The main physical characteristics of the Aetoliko lagoon are the permanent thermocline and halocline and the anoxic conditions in the hypolimnion accompanied with high concentration of $\text{H}_2\text{S}$. Aetoliko lagoon represents one of the most important coastal lagoon systems in the Mediterranean Sea and the largest in Greece, covering approximately 50% of the total Greek lagoon surface. The lagoonal complex is surrounded by evaporation ponds that are used for salt mining purposes. As in the majority of the Mediterranean lagoons, this complex is also exploited as a fishing ground. Traditional fishing activities are common in the lagoon and are very important for the local economy. This wetland is of great ecological importance, rich in biodiversity, belongs to the “Natura 2000” zone (code number GR2310002) and is protected under the Ramsar convention.

![Figure 6.1: General maps showing the location of “Messolonghi- Aetoliko Lagoon Complex” and the Aetoliko lagoon](image)

6.1.1. Bathymetry

Aetoliko lagoon is a deep and almost isolated lagoon (average depth of 12 meters). The deepest areas of the lagoon are situated in the northern part (Fig 6.2). In those areas, the maximum depth is about 32 meters. The shallowest areas are confined to the communication channels with the Messolonghi lagoon at the southern end of the lagoon.
6.1.2. Oceanographic setting

Measurements of temperature and salinity in the water column show the presence of two layers (Fig. 6.3): (i) a surficial layer about 10-15 m thick with a salinity ranging between 16 and 20‰ and (iii) a bottom water layer from 15 to 32 m of rather constant temperature and salinity of about 26 to 28‰. The temperature ranges from 14 to 30°C in the upper layer (epilimnion) of the lagoon and is almost constant (15-16°C) in the hypolimnion over the last fifty (50) years.
6.1.3. Oxygen availability- hypoxia

The two layer water structure appears to control the vertical distribution of the DO in the water column in the lagoon. The DO concentration ranges from 8 to 16 mg/l in the upper layer. The thickness of the well oxygenated upper layer ranges from 14 meters in 1951, to 9-13m during the period 1984-85 and only 5-7 m in 1995-2003 period. From these depths to the bottom (about 32m) the water column is almost anoxic. A recent hydrographic survey showed that the oxygenated upper layer has a thickness of 15-18m due to the widening of the two communication channels between Messolonghi and Aetoliko lagoons (UPAT, unpublished data).

The bottom layer is characterized by high levels of H$_2$S. The hydrogen sulphide concentration was 28.8 mg/l in 1951 and 45 mg/l in 1995. Recent investigation showed maximum H$_2$S concentration up to 55 mg/l (UPAT, unpublished data). The hypoxia/anoxia of the lower layer (5-15 to 32m) of the lagoon is well documented by measurements over the last 60 years. Mass mortality of fishes has been reported over the last 150 years suggesting that the lagoon has been suffered from hypoxia/anoxia in the past. Furthermore, sediment core data from the seafloor of Aetoliko lagoon (UPAT, unpublished data) showed the presence of laminated sediments with black-white colour alterations (varves deposits). This probably suggests annual formation of these deposits and in that case it is an excellent opportunity to study the historical record of the anoxia in the lagoon.

The origin of the H$_2$S, and related O$_2$ depletion, could be related to one or a combination of the following three mechanisms:

(i) Low water circulation between Messolonghi and Aetoliko Lagoons.
(ii) Dissolution of gypsum deposits (outcropping diapirs) at the seafloor of the lagoon at the western margin of the lagoon
(iii) Gas seepages from the lagoon floor

Figure 6.4: Side scan sonar record showing crater-like features (pockmarks?) on the floor of the lagoon. The craters have diameter of nearly 2.0 m and a depth of approximately 1m.

As a result the lagoon is characterized by the permanent anoxic conditions in the deeper water layer (5-15 to 32m) and the formation of hydrogen sulphide. The catastrophic events appeared to correlate with strong southern winds and consequently with stratification destruction. The upward migration of hydrogen sulfide to the surface waters has been caused sudden death of fishes. In the most recent mass mortality of fishes which
occurred in November 1990 it has been estimated that a large part of the fish stock was lost. Hydrobiological studies suggested that the deaths were due to the high concentration of $\text{H}_2\text{S}$ in the hypolimnion. The gas seepages hypothesis is suggested by the presence of crater-like features which were detected during a small scale side scan sonar survey (Fig. 6.4).

6.2 Amvrakikos Gulf

6.2.1. Site description
Amvrakikos Gulf is a shallow (<65m) marine embayment lying on the west coast of Greece and is about 35 km long and 6 to 15km wide (Fig. 6.5). It is separated from the open Ionian Sea by a beach barrier complex and is connected to the open sea through a narrow channel, 600 m wide and less than 8 m deep. Amvrakikos Gulf receives the freshwater inputs of the Arachthos ($2202 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) and Louros ($609\times 10^6 \text{ m}^3 \text{ yr}^{-1}$) rivers at its northern shoreline. Amvrakikos Gulf is characterized by a general two-layer type of stratification in the water column and is considered as the only Mediterranean fjord. It is protected by the Ramsar Convention (1971). The Gulf is an E-W basin occupying the southern part of the Salaora (Arta) graben and was formed in the Middle Quaternary. During the isotope stage MIS3 and MIS2 (Ca 50 to 11 Ka BP), when the sea level was lower than 55 m in relation to its present position, the western part of the gulf emerged whilst the eastern part was occupied by a lake. The marine transgression took place at about 11 ka BP and the Gulf attained its present shape at about 4 ka BP. Therefore, it can be said that the Gulf has a similar evolution to that of the Baltic Sea and the Black Sea.

![Figure 6.5: General maps showing the location of the Amvrakikos Gulf](image)

6.2.2 Bathymetry
The Gulf can be divided morphologically, into two parts: (a) the western part, formed by a number of small basins, with water depths less than 40 m; and (b) the eastern part that is characterised by a basin up to 65 meters deep (Fig. 6.6). The two parts are separated by the Central shoals (30–40 m deep). The northern margin of the gulf consists of the deltaic
deposits of Arachthos and Louros rivers, together with some rock outcrops while the southern, western and eastern margins of the Gulf are largely bounded by bedrock. Therefore, the shallower areas are located within the northern part of the gulf, due to the presence of a wide prodelta platform. The seafloor is covered by very fine-grained sediments (mostly silty clay). The most abundant clay mineral is illite followed by chlrorite/kaolinite and smectite.

6.2.3. Oceanographic setting

The Gulf has a general two-layer (fjord-like) type of stratification in the water column. The Gulf is microtidal, with tidal ranges less than 20 cm and is characterized by a relatively calm wave regime due to the limited wave fetches. Surface water circulation is also weak, presenting a clockwise trend. The water column is highly stratified with a zone of high salinity gradient between 5 and 10 m deep. The surficial water layer in the summer has a salinity ranging from 31 to 33 ppt and a temperature ranging from 23.5 to 27°C. The bottom water layer has salinities of between 37 to 38 ppt and temperatures of between 17.3 and 19.0°C. Measured current speeds in the central part of the Gulf demonstrate mean values ranging from 0.3 up to 0.19 m s\(^{-1}\) (in winter). Fast currents have reported in the Strait of Preveza, ranging from 0.12 to 0.15 m s\(^{-1}\) with some bursts reaching 1 m s\(^{-1}\). The Gulf is characterized by high primary productivity with phytoplankton densities between 7.5 x 10\(^5\) and 2.0x10\(^7\) cells/l and high levels of eutrofication with average yearly concentrations of PO\(_4\)-P, NH\(_4\)-N and NO\(_3\)-N about 0.4, 0.45 and 2.2 µg/l, respectively. Furthermore, Amvrakikos gulf contains 3.8, 1.4 and 3.9 times more PO\(_4\)-P, NH\(_4\)-N and NO\(_3\)-N, respectively than the Ionian and the Aegean Sea.
6.2.3 Oxygen availability- hypoxia

The two layer water structure of the Gulf appears to control the vertical distribution of the DO in the water column (Fig. 6.7). The study of the profiles shows that the surface layer is well oxygenated with a concentration ranging from 7.5 to 9 mg/l. Below the pycnocline, the DO content continuously decreases reaching a concentration of 2 mg/l and zero at a water depth of about 25m below surface and 34 m., respectively. The study of the surficial sediments (black mud 7-10cm in thickness) of the Gulf in conjunction with the sedimentation rates which is about 0.7 cm/yr suggest that the anoxic conditions appeared in the Gulf in the last 10 to 15 years. The excessive use of fertilizers, the increased animal stock, the intensive fish farming and the increased sewage discharge in combination with the strong stratification pattern of the Gulf resulted in the prevalence of hypoxic/anoxic conditions. Additionally, marine geophysical surveys have revealed acoustic characters which are attributed to the presence of fluid (gas) into the surface (0-30m) sediments of the Gulf (Fig 6.8). The escaping fluids may contribute to the establishment of the hypoxic/anoxic conditions.

Figure 6.7: Vertical distribution of physicochemical parameters in the water column of the Amvrakikos Gulf
6.2.4 Coordinates and Depth of experiment site

Proposed site monitoring coordinates: 38° 57’ N, 21° 06’ E. The proposed site is located at the eastern hypoxic/anoxic basin of the Gulf where the water depth ranges from 40 to 60 m. Alternatively the GMM could be deployed at water depth of 25 m in order to monitor the oscillation of the oxic/hypoxic interface.
6.3 Bibliography for Greek lagoons


