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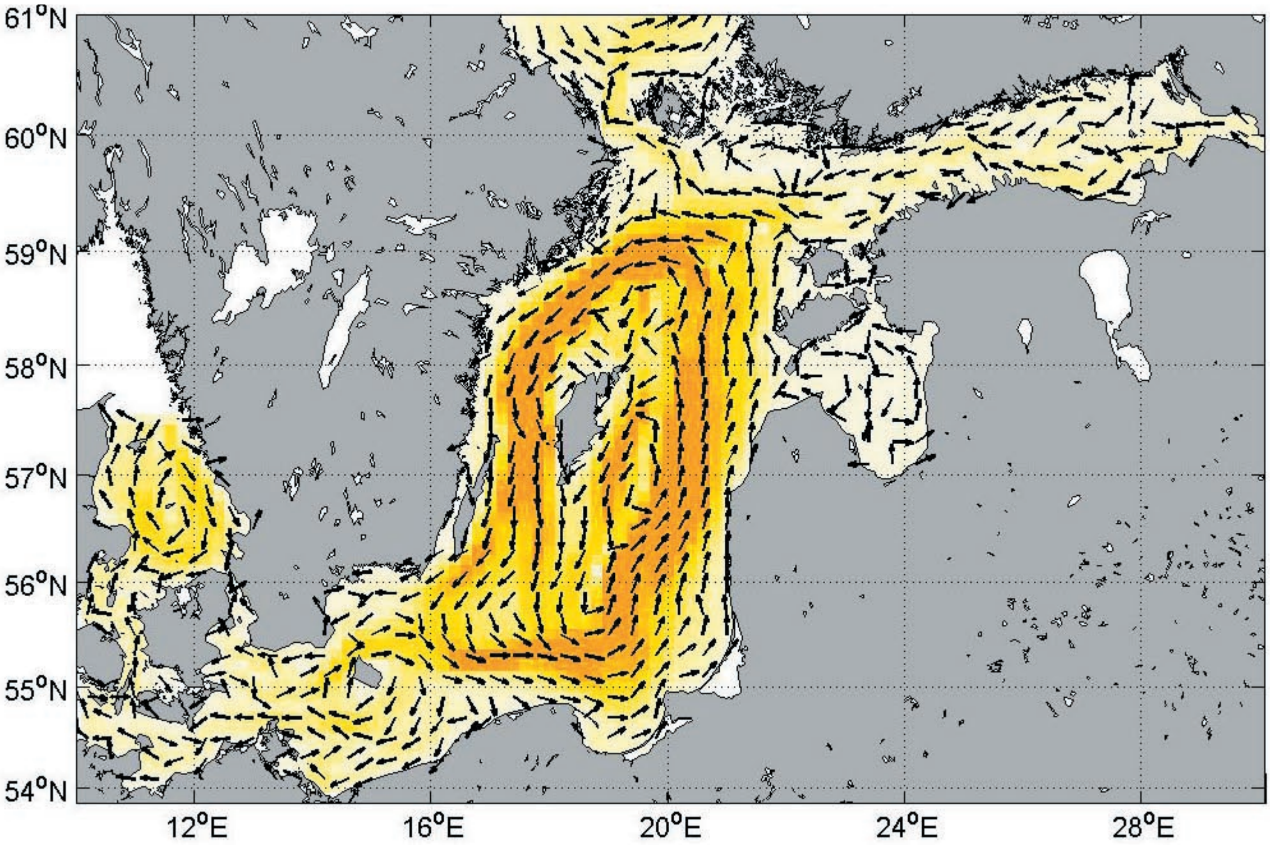

Transports and budgets of oxygen and phosphorus in the Baltic Sea

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Transports and budgets of oxygen and phosphorus in the Baltic Sea

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Front page: Model calculations of inorganic phosphorus indicate a clockwise rotation of phosphorus around Bornholm and a counter-clockwise rotation around and east of Gotland. The direction of the transport is indicated by the arrows and the amount of phosphorus is indicated by the colour in the background.

Summary
In this report we present budgets of oxygen and phosphorus for the deeper layers of the Baltic proper. The budgets give calculations of sedimentation, erosion and horizontal and vertical transports based on model simulations. The fluxes of oxygen and phosphorus as well as trends in contents have been computed.

Contents

1. Area description

The Baltic Sea is a strongly stratified semi-enclosed basin. Its horizontal and vertical salinity gradients are the result of the large freshwater supply from rivers and net precipitation and of the reduced water exchange with the world ocean (Fig. 1).

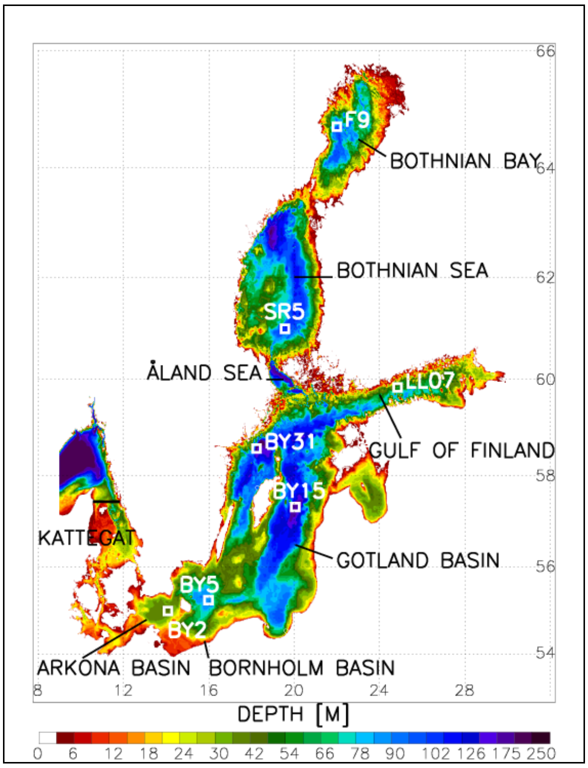


Figure 1. *Overview of the model domain. The black line indicates the open boundary in the northern Kattegat. The color bar shows depths in meter. Monitoring stations are indicated by white squares.*

The climate of the 20th century is characterized by an average salinity of about 7.4 and a freshwater supply including river runoff and net precipitation of about 16 100 $m^3 s^{-1}$. The average in- and outflows of the Baltic Sea amount to 16,100 $m^3 s^{-1}$ and 32,200 $m^3 s^{-1}$, respectively (applying the well-known Knudsen formulae with surface and bottom layer salinities of 8.7 and 17.4, respectively).

The large-scale horizontal circulation is characterized by cyclonic gyres (Fig. 2) and the vertical circulation is driven by the inflow of high-saline water from the Kattegat. The bottom water is usually only replaced after so-called Major Baltic Inflows. However, small and medium-strength inflows are important as well since they may renew intermediate layers of the Baltic proper halocline. During inflow events the high-saline water spills over the shallow sills of the Baltic Sea entrance area into the Arkona Basin and Bornholm Basin. Both dense bottom flows and cyclonic eddies renew the deep water of the eastern Gotland Basin. From the Gotland Deep the flow continues via the Northern Deep either into the northwestern Gotland Basin or into the Gulf of Finland. The mean ages of inflowing Kattegat water varies from about 10 years in the Arkona deep water to more than 40 years in the northern Baltic surface waters (Meier, 2007). Present knowledge about the renewal of the Baltic Sea deep water is summarized by Meier et al. (2006).

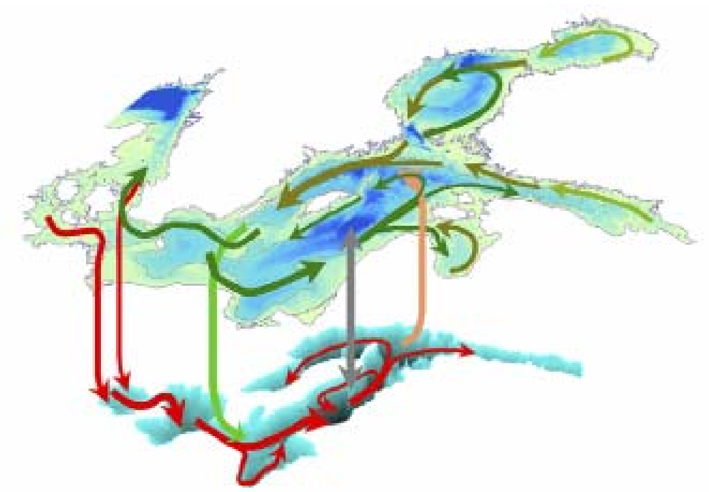


Figure 2. *Schematic view of the large-scale circulation in the Baltic Sea (from BACC, 2008). Green and red arrows denote the surface and bottom layer circulation, respectively. The light green and beige arrows show entrainment. The grey arrow denotes diffusion.*

2. Model description

The model system

The model system is based on the Swedish Coastal and Ocean Biogeochemical model (SCOBI) and the Rossby Centre Ocean circulation model (RCO) (Eilola et al., 2008; Eilola and Meier, 2006; Gustafsson et al., 2008; Marmefelt et al., 1999; Meier et al., 2003; Meier and Kauker, 2003). The model domain of the RCO-SCOBI model covers the Baltic Sea including the Kattegat (Fig. 1) with a 6 nm horizontal resolution and a maximum depth of 250 m in the present set-up. The vertical resolution of the model is 41 levels with an increasing layer thickness from 3 m in the surface layers to 12 m in the deep Baltic Sea.

Model forcing and setup

The circulation model simulates the time period from 1902 to 1998. A spin-up was first run from 1902 with reconstructed atmospheric forcing and river discharge data till 1998 (Kauker and Meier, 2003). The results from the end of the spin-up were used as initial conditions for the simulations presented here. The analysis of the results covers 30 years at the end of the simulation period (1966-1995).

Average atmospheric nitrogen deposition was computed from estimates for every 5th year of the period 1980-2000 and distributed over the surface areas of 6 sub-basins, the Bothnian Bay, the Bothnian Sea including the Åland archipelago sea, the Gulf of Finland, the Gulf of Riga, the Baltic proper including the Bornholm and Arkona basins, and the Kattegat including the Danish straits, the Belt seas and the sound. Atmospheric phosphorus deposition was based on a constant value from Areskoug (1993). The rivers in the RCO model include the 30 most important coastal segments of the Baltic Sea and incorporate all freshwater runoff and nutrient supplies from land to the sea. The climatological (1970-2000) monthly mean nutrient concentrations of the rivers were mainly based on the data set collected by Stålnacke (1999).

Atmospheric and river data were extracted from the Baltic Environmental Database (BED) via the internet based software NEST (http://nest.su.se/nest/). Averaged point sources of municipal and industrial discharges (HELCOM, 1993, 1998, 2004) were computed from 1990, 1995 and 2000 for each country and divided equally between national rivers in each basin. 50% of the total supply was assumed organic for both N and P. In Table 1 the modeled nutrient supply to the Baltic Sea during the period 1969-1998 is summarized. The phosphorus supply from rivers to the model varies from about 19 000 ton year^{-1} to 34 000 ton year^{-1} and the nitrogen supply varies from about 364 000 ton year^{-1} to 632 000 ton year^{-1}. The 10-year running mean shows a periodicity of about 28 years due to varying river runoff during the period 1902-1998. The nutrient supply from the atmosphere and point sources are constant.
The open boundary conditions in the northern Kattegat were based on profiles of climatological (1980-2000) seasonal mean nutrient concentrations from the station Å17 in the eastern Skagerrak (data from the Swedish Oceanographic Data Centre (SHARK) at the Swedish Meteorological and Hydrological Institute, see http://www.smhi.se).

Table 1: *Average (1969-1998) biologically available nutrient supply (ton/year) of total nitrogen (TotN) and phosphorus (TotP), and dissolved inorganic nitrogen (DIN) and phosphorus (DIP) to the Baltic Sea including the Kattegat (excluding Göta Älv).*

	TotN	**TotP**	**DIN**	**DIP**
Rivers	504 800	26 500	416 500	14 300
Point sources	44 800	6 600	34 500	3 700
Atmosphere	298 000	2 500	298 000	2 500
Total	847 600	35 600	749 000	20 500

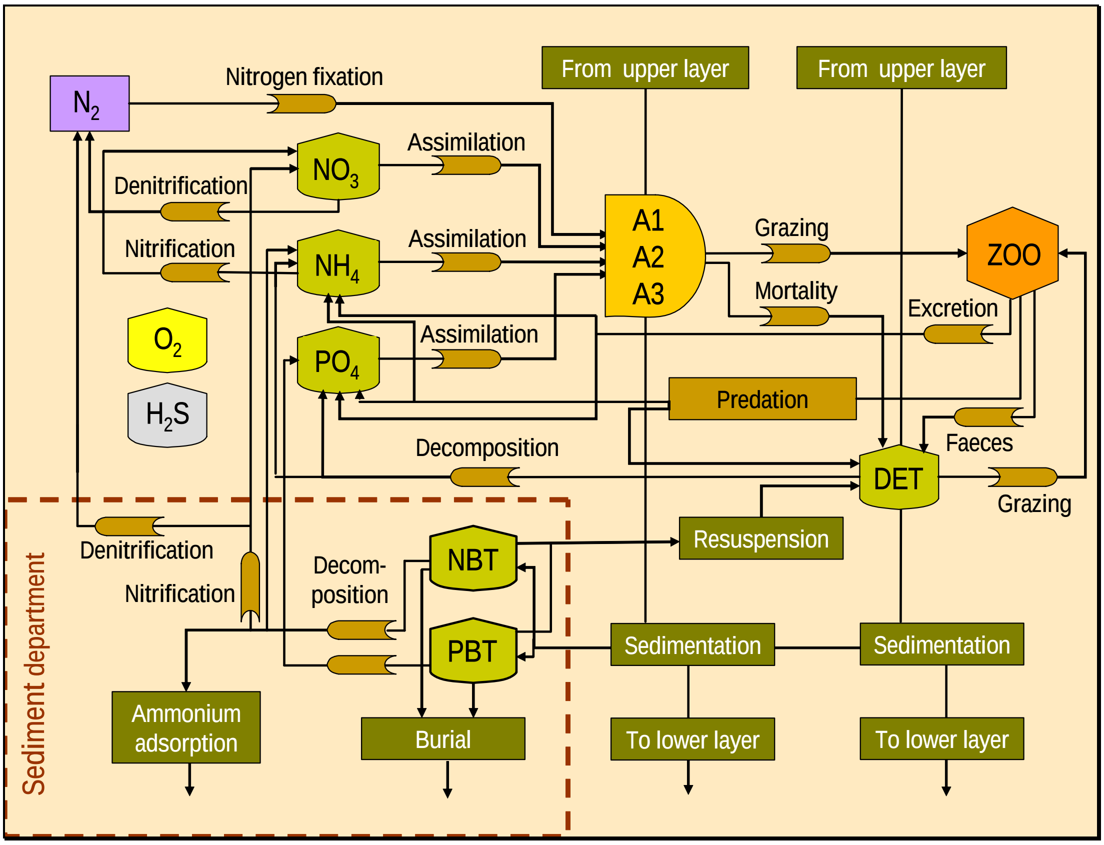


Figure 3. *The SCOBI model. Sediment variables and processes are shown in the lower left frame. Note that in the figure the process descriptions of oxygen and hydrogen sulfide are simplified for clarity*.

The SCOBI model (Fig. 3) contains inorganic nutrients, nitrate (NO_3), ammonium (NH_4) and phosphate (PO_4). Particulate organic matter consists of phytoplankton (autotrophs), detritus (DET) and zooplankton (ZOO). The carbon (C), nitrogen (*N*) and phosphorus (*P*) content of autotrophs, zooplankton and detritus are described by the Redfield molar ratio (*C:N:P=106:16:1*). Primary production assimilates nutrients by three functional groups of autotrophs, diatoms (A1), flagellates (A2) and cyanobacteria (A3). Besides the possibility to assimilate inorganic nutrients the modeled cyanobacteria also has the ability to fix molecular nitrogen (N_2) which may constitute an external nitrogen source for the model system. Production of zooplankton faeces and predation on zooplankton produces particulate organic matter which together with dead autotrophs adds up to the pool of detritus in the model. Decomposition of detritus as well as excretion of nutrients from zooplankton and predator activities produces nutrients in its mineralized forms NH_4 and PO_4. Diatoms, flagellates and detritus may sink to lower layers or add to the sediment department while cyanobacteria are neutrally buoyant in the model (zero sinking speed). The sediment contains nutrients in the form of benthic nitrogen (NBT) and phosphorus (PBT). The sediment module includes aggregated process descriptions for oxygen dependent nutrient regeneration, denitrification and adsorption of ammonium to sediment particles. When the bottom stress exceeds critical values, re-suspension from the sediments to the overlying water occurs. A fraction of the sediment nutrient pool is removed by permanent burial. Anaerobic decomposition of organic matter is first carried out by denitrifying bacteria when nitrate is available and then by sulphate reducing bacteria which produce hydrogen sulphide (H_2S) that is included as negative oxygen in the model. About half of the inorganic nitrogen (ammonium) produced in the sediments under anoxic conditions is permanently adsorbed to sediment particles. An oxygen dependent fraction of the mineralized phosphorus in the sediments is adsorbed to sediment particles while the rest is released as a flux of phosphate to the overlying water. The phosphate adsorption process may however reverse when the water turns anoxic and no adsorption occurs. Then some of the previously adsorbed phosphorus may also be released and added to the flux of mineralized phosphorus to the overlying water.

3. Transports and budgets

The Baltic Sea is divided into 13 sub-basins according to Fig.4. The names of the sub-basins are presented in Table 1. Positive transports are defined southward. The present report deals with phosphorus and oxygen budgets for the Baltic proper (including the Arkona Sea, the Bornholm Sea, the East Gotland Sea, the North West Baltic proper and the Gulf of Finland). Each sub-basin is divided vertically into 4 layers according to RCO depth ranges shown in Table 2.

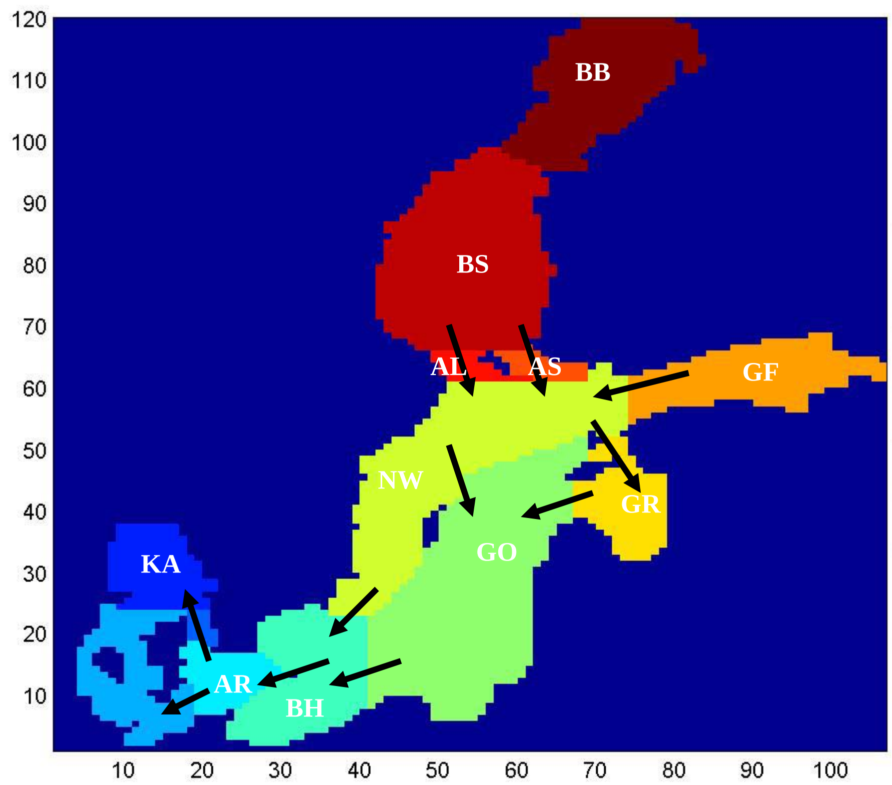


Figure 4. *Division of the model area into 13 sub-basins.*

Table 1: *Names of sub basins*.

Basin name	Abbreviation	Basin number
Bothnian Bay	BB	14
Bothnian Sea	BS	13
Åland Sea	AL	12
Archipelago Sea	AS	11
Gulf of Finland	GF	10
Gulf of Riga	GR	9
North West Baltic proper	NW	8
East Gotland Sea	GO	7
Bornholm Sea	BH	6
Arkona Sea	AR	5
Belt Sea	BS	4
The Sound	OR	3
Kattegat	KA	2
Skagerrak	SK	1

Table 2: *Depth ranges of vertical layers. The actual number of active vertical layers depends on the depth of each sub-basin. Maximum depth of the RCO model is 250m*.

Vertical box No	Depth range	Comment
1	0m - 30m	Surface layer
2	30m – 68m	Above permanent halocline
3	68m – 120m	In the halocline layer
4	120m – 459m	Deep water

Model results were saved every 6th hour for the time period 1902 to 1995. The last 30 years of the model run were analyzed. Annual average advective transports of biochemical substances and biogeochemical fluxes were computed from post processing of the 6-hourly snapshots. In order to obtain a good description of more complex and high-frequent processes of the biogeochemical fluxes, the sedimentation, re-suspension and photosynthetic production of organic matter were summed up in a 2-dimensional grid for each time step during the model run. Vertical fluxes of substances between the lower layers were obtained by means of mass conservation. The annual average vertical transports were thereby computed by the difference between the observed inter-annual changes of average contents and the annual average supplies from advection and biogeochemical fluxes.

The lower layer oxygen dynamics are illustrated by the variability of the annual average oxygen concentration in the lower layers (below 68m) of each sub-basin. The annual average biological oxygen demand (consumption) is also computed and compared with the annual average supply of oxygen by advection and diffusion processes. For clarity, oxygen consumption is defined as the oxygen equivalent needed to fully oxidize the organic matter decomposed in the sediments and in the water of the model. In the actual model run the oxygen used for oxidation may become supplied from nitrate via nitrification as well as from sulphate reducing bacteria. The long-term annual averages (1966-1995) and the standard deviations of the content in the water and sediments, and the biogeochemical fluxes of dissolved inorganic phosphorus (*DIP*), organic phosphorus (*orgP*) and oxygen (*OXY*), respectively, are computed. A T-test at significance level 0.05 is performed on the 30-year dataset to investigate the possibility of a linear trend for the annual average contents of *DIP*, *orgP* and *OXY* as well as for the annual average oxygen consumption. The sediment content in the table of organic phosphorus includes all fractions of benthic phosphorus. The corresponding physical characteristics (*PHYS*) of the water volumes, sediment areas and surface areas of the vertical boxes and the physical transports between the vertical boxes and the horizontal boundaries of the sub-basins are also computed.

4. Phosphorus biogeochemistry and hypoxia

Phosphate dynamics and sediment fluxes are much controlled by the oxygen conditions (e.g. Conley et al., 2002) and the correlation between these variables is indicated by the phosphate-oxygen diagram in Fig. 5. There is an increase of phosphate concentrations with decreasing oxygen concentrations and a very rapid increase when the water becomes hypoxic-anoxic. The figures in this section are from Eilola et al. (2008) who give a thorough discussion about the issue.

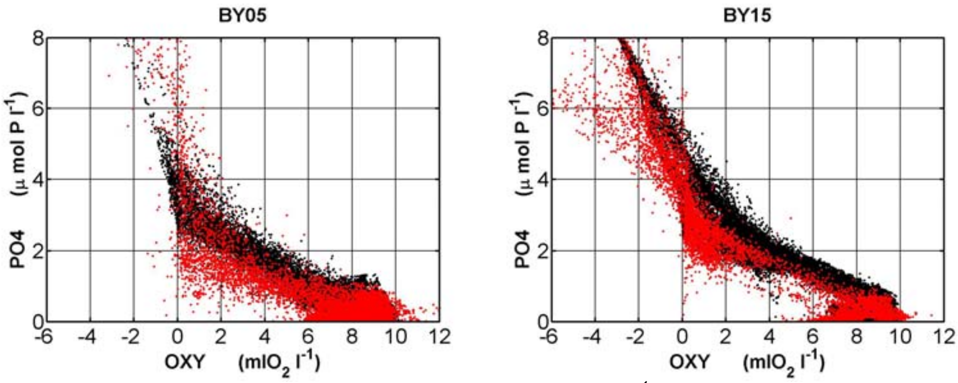


Figure 5. *Phosphate concentrations (µmol P l^{-1}) versus oxygen concentrations (ml O_2 l^{-1}) in the Bornholm Deep (BY5) and the eastern Gotland Deep (BY15). Black dots show model results and red dots show observations in the period 1969-1998.*

The spatial correlations between modeled low bottom water oxygen concentrations and the DIP content are shown in Fig. 6. The vertically integrated DIP content also depends on the depth of the water column which partly explains the very high DIP content values in the deepest parts of the Baltic Sea.

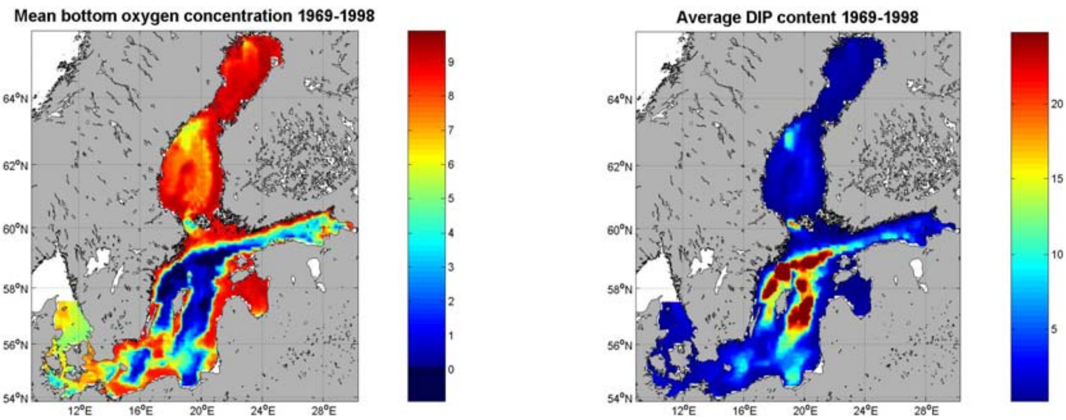


Figure 6. *Mean bottom water oxygen concentrations (ml O_2 l^{-1}) (left) and vertically integrated DIP content (ton DIP km^{-2}) (right) in the Baltic Sea during 1969-1998.*

The natural increase of phosphorus supplies from land due to increased river runoff since the early 1970s explained much of the long-term increase of phosphorus content in the Baltic proper (Fig. 7). Another significant fraction of the increase was explained by the release of phosphorus from increased anoxic areas during the period.

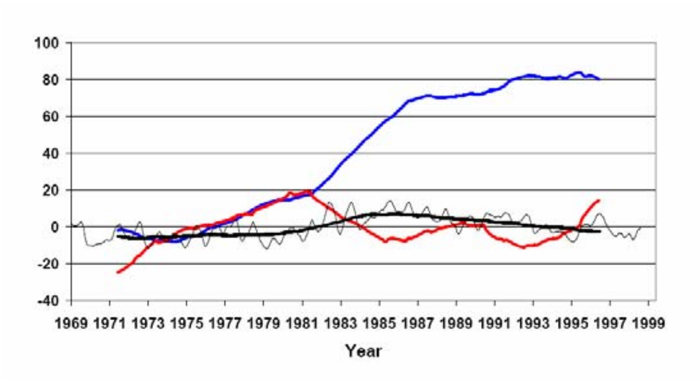


Figure 7. *5-year running mean anomalies of anoxic area (103 km2) (black line), DIP content (blue line), and phosphorus content in the sediment (red line) (103 kton P) of the Baltic proper (including the Gulf of Finland and the Gulf of Riga). The thin black line shows the 3-month running mean of anoxic area. The simulated anomalies are calculated relative to the mean values of 1969-1998. From the sediment phosphorus content a long-term trend is removed.*

The short-term (i.e. interannual) variability of the phosphorus content in the Baltic proper is mainly explained by oxygen dependent sediment fluxes which are influenced e.g. by the variations of hypoxic area (Fig. 8).

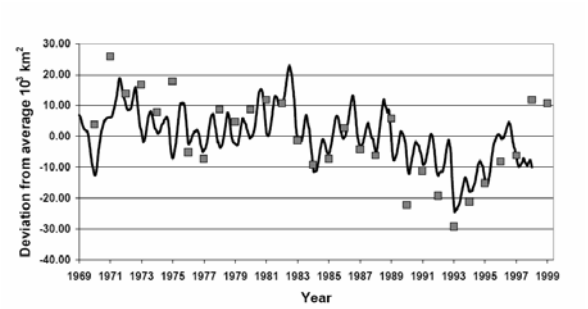


Figure 8. *Anomalies of hypoxic area (10^3 km^2) in the Baltic proper (including the Gulf of Finland and the Gulf of Riga). Black lines show model results (3-month running mean) and grey squares show results (average January-March) from Table 1 in Conley et al. (2002). The simulated anomalies are calculated relative to the mean values of 1969-1998.*

5. Results

The results for the Arkona Sea (5), the Bornholm Sea (6), the East Gotland Sea (7), the North West Baltic proper (8) and the Gulf of Finland (10) are presented. The temporal evolution of the oxygen demand and the oxygen supply of the lower layers of the basins are first discussed, and then the budgets of physical transports, *orgP*, *DIP* and oxygen are presented for each sub-basin. Note, the maximum depths in the Arkona Sea, Bornholm Sea, and Gulf of Finland are smaller than the lower boundary of the third box level (120m).

5.1. Lower layer oxygen dynamics

Oxygen dynamics and the development of oxygen concentrations in the deeper layers of the sea are determined by the oxygen demand by the oxidation of decomposed organic matter and the oxygen supply by natural oxygen transports by advective and diffusive processes. Oxygen concentrations in the water may change when the supply and the oxygen demand differ. This is illustrated by periods when the yellow area and the purple areas differ in the figures 9-12. The difference is quantified by the blue area. For example, when the oxygen demand is larger than the oxygen supply then the blue area is negative and this causes the oxygen concentrations to decline. Hence, in these cases the blue area indicates the extra oxygen needed to combat an oxygen deficit in the model. The opposite situation occurs when the blue area is positive. A trend in the oxygen concentrations is obtained if the long-term average of the blue area is non-zero.
From the results one may also note that during stagnation periods the halocline layer in the Baltic proper is ventilated better causing an increased oxygen concentration in that layer whereas the lower layer is characterized by oxygen deficiencies.

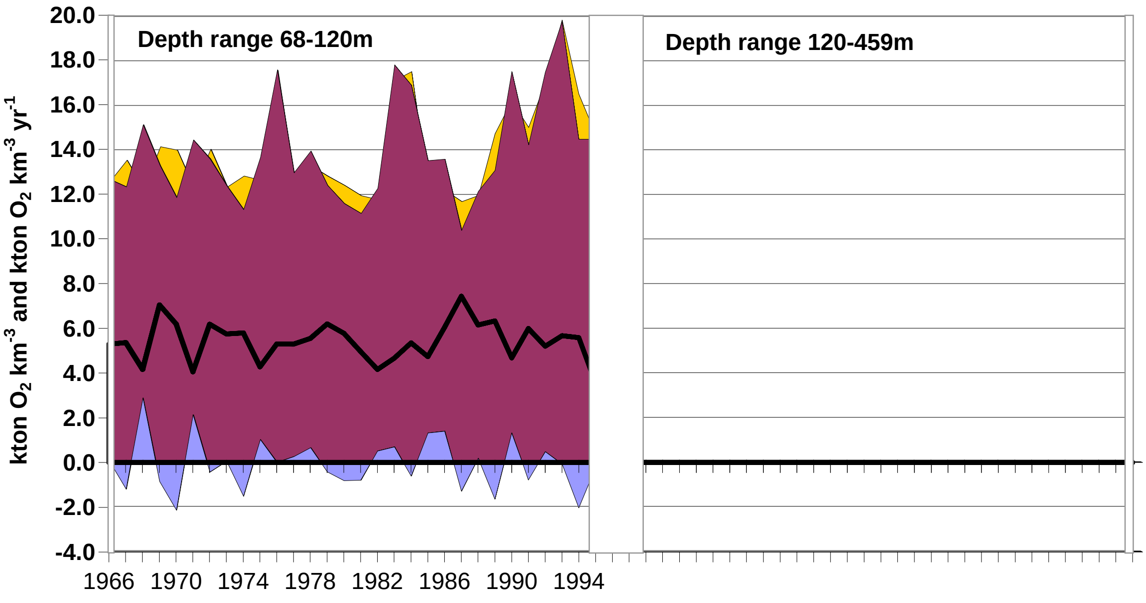


Figure 9. *Oxygen concentration (black line), oxygen consumption (yellow area) and oxygen supply (purple area) in layer 3 (left) of the Bornholm Sea (Basin 6). The difference between the oxygen supply and oxygen consumption is shown by the blue area. Units: Oxygen concentration is given in kton O_2 km^{-3} and the rate in kton O_2 yr^{-1} km^{-3}.*

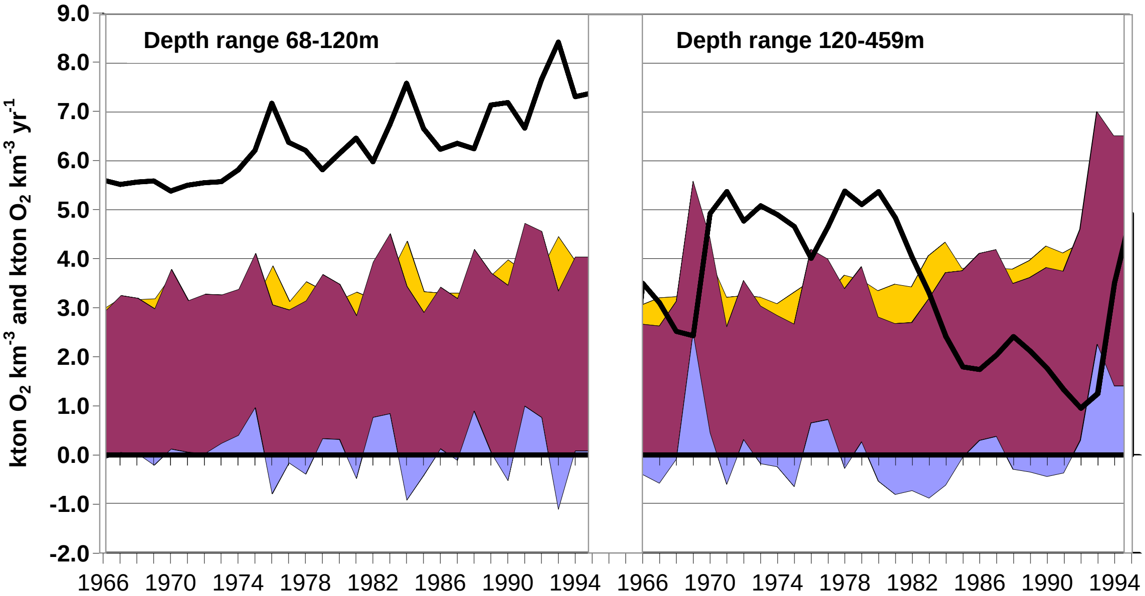


Figure 10. *Oxygen concentration (black line), oxygen consumption (yellow area) and oxygen supply (purple area) in layer 3 (left) and 4 (right) of the East Gotland Sea (Basin 7). The difference between the oxygen supply and oxygen consumption is shown by the blue area. Units: Oxygen concentration is given in kton O_2 km^{-3} and the rate in kton O_2 yr^{-1} km^{-3}.*

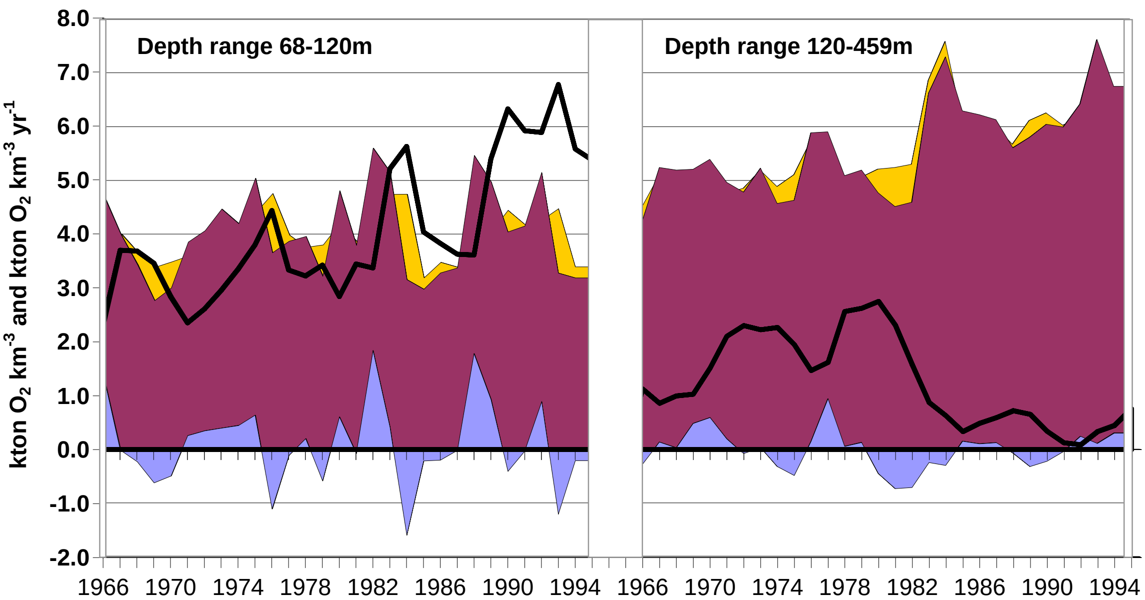


Figure 11. *Oxygen concentration (black line), oxygen consumption (yellow area) and oxygen supply (purple area) in layer 3 (left) and 4 (right) of the North West Baltic proper (Basin 8). The difference between the oxygen supply and oxygen consumption is shown by the blue area. Units: Oxygen concentration is given in kton O_2 km^{-3} and the rate in kton O_2 yr^{-1} km^{-3}.*

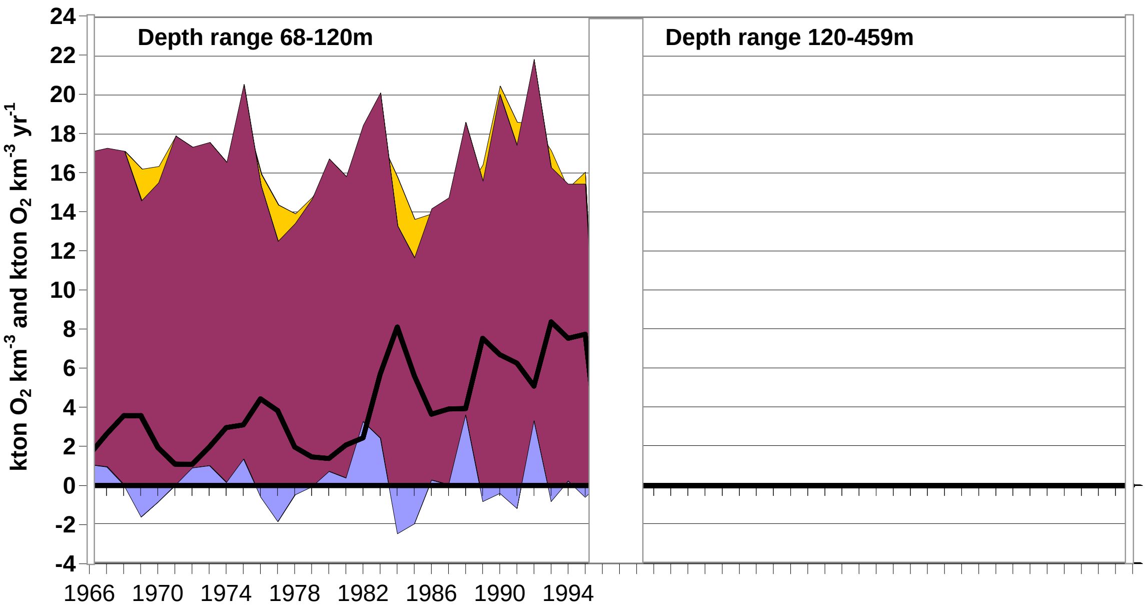


Figure 12. *Oxygen concentration (black line), oxygen consumption (yellow area) and oxygen supply (purple area) in layer 3 (left) of the Gulf of Finland (Basin 10). The difference between the oxygen supply and oxygen consumption is shown by the blue area. Units: Oxygen concentration is given in kton O_2 km^{-3} and the rate in kton O_2 yr^{-1} km^{-3}.*

5.3 Introduction to section 5.3.-5.7

The contents of the tables are defined below. The sign of the vertical and horizontal flows are defined positive in the direction from the right to the left, and downwards in the figures. Flows in the opposite directions are defined negative.

For each vertical layer the *PHYS* table shows:

1. Water volume in km^3.
2. Surface area of the upper interface between the vertical boxes in km^2.
3. Surface area of the sediment in km^2.
4. Horizontal inflow (from the right in the figure) in km^3 yr^{-1}. The number of the corresponding up-stream basin is shown.
5. Horizontal outflow (to the left in the figure) in km^3 yr^{-1}. The number of the corresponding down-stream basin is shown.
6. Vertical inflow from the upper layer in km^3 yr^{-1}.

For each vertical layer the *orgP* table shows:

1. Average water layer concentration of *orgP* in mmol P m^{-3}.
2. Water content of *orgP* in kton P.
3. Long-term trend of annual average water content in kton P yr^{-1}.
4. Sediment content of *orgP* in kton P.
5. Long-term trend of annual average sediment content in kton P yr^{-1}.
6. Phosphorus sedimentation of *orgP* in kton P yr^{-1}.
7. Phosphorus re-suspension of *orgP* in kton P yr^{-1}.
8. Phosphorus burial in the sediments in kton P yr^{-1}.

9. Phytoplankton production of *orgP* in kton P yr^{-1}. The vertically integrated production is accumulated in the surface layer of the table.
10. Pelagic mineralization of *orgP* to *DIP* in kton P yr^{-1}.
11. Horizontal inflow (from the right in the figure) of *orgP* in kton P yr^{-1}.The number of the corresponding up-stream basin is shown.
12. Horizontal outflow (to the left in the figure) of *orgP* in kton P yr^{-1}.The number of the corresponding down-stream basin is shown.
13. Vertical inflow of *orgP* from the upper layer in kton P yr^{-1}. The vertical inflow includes physical diffusion and advection as well as the sinking of organic matter.

For each vertical layer the *DIP* table shows:

1. Average water layer concentration of *DIP* in mmol P m^{-3}.
2. Water content of *DIP* in kton P.
3. Long-term trend of annual average water content in kton P yr^{-1}.
4. Release of *DIP* from the sediment in kton P yr^{-1}.
5. Phytoplankton production uptake of *DIP* in kton P yr^{-1}. The vertically integrated uptake is accumulated in the surface layer of the table.
6. Pelagic mineralization and release of *DIP* in kton P yr^{-1}.
7. Horizontal inflow (from the right in the figure) of *DIP* in kton P yr^{-1}.The number of the corresponding up-stream basin is shown.
8. Horizontal outflow (to the left in the figure) of *DIP* in kton P yr^{-1}.The number of the corresponding down-stream basin is shown.
9. Vertical inflow of *DIP* from the upper layer in kton P yr^{-1}.

For each vertical layer the *OXY* table shows:

1. Average water layer concentration of *OXY* in mlO_2 l^{-1}.
2. Water content of *OXY* in kton O_2.
3. Long-term trend of annual average water content of *OXY* in kton O_2 yr^{-1}.
4. Consumption of *OXY* in the sediment in kton O_2 yr^{-1}.
5. Long-term trend of *OXY* consumption in the sediment (kton O_2 yr^{-1}) yr^{-1}.
6. Consumption of *OXY* in the water in kton O_2 yr^{-1}.
7. Long-term trend of *OXY* consumption in the water (kton O_2 yr^{-1}) yr^{-1}.
8. Horizontal inflow (from the right in the figure) of *OXY* in kton O_2 yr^{-1}.The number of the corresponding up-stream basin is shown.
9. Horizontal outflow (to the left in the figure) of *OXY* in kton O_2 yr^{-1}.The number of the corresponding down-stream basin is shown.
10. Vertical inflow of *OXY* from the upper layer in kton O_2 yr^{-1}.

5.2. Arkona Sea

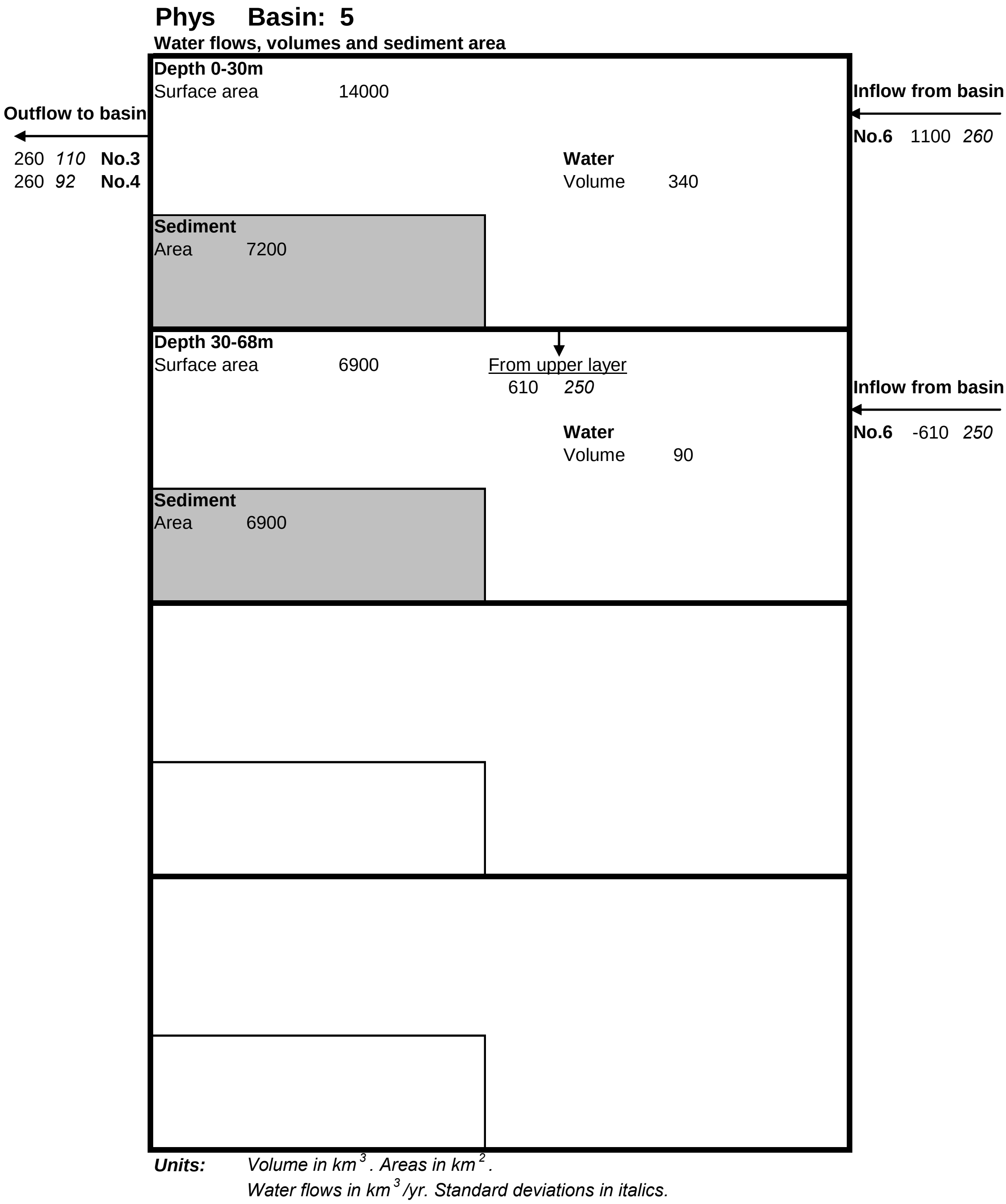
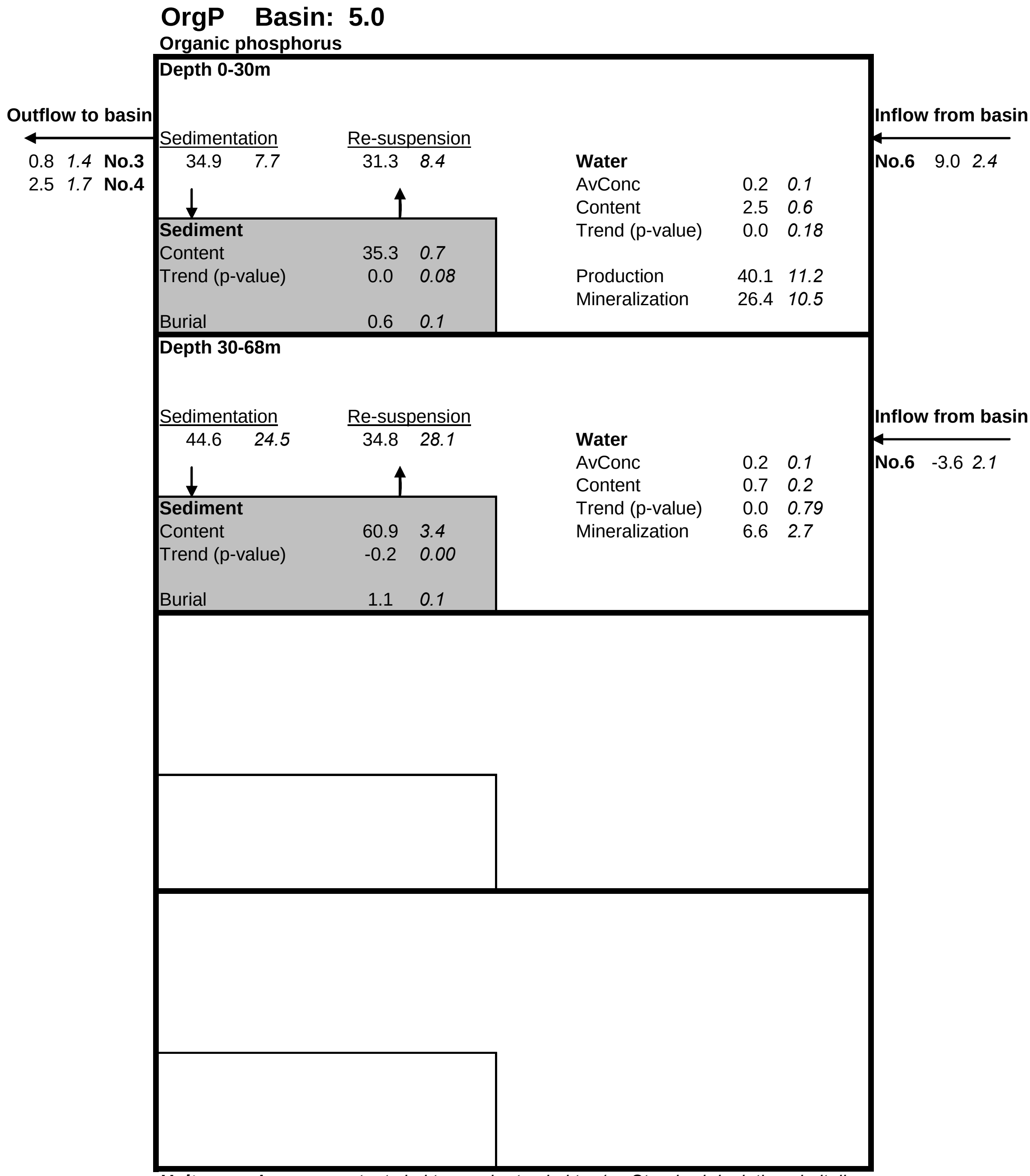
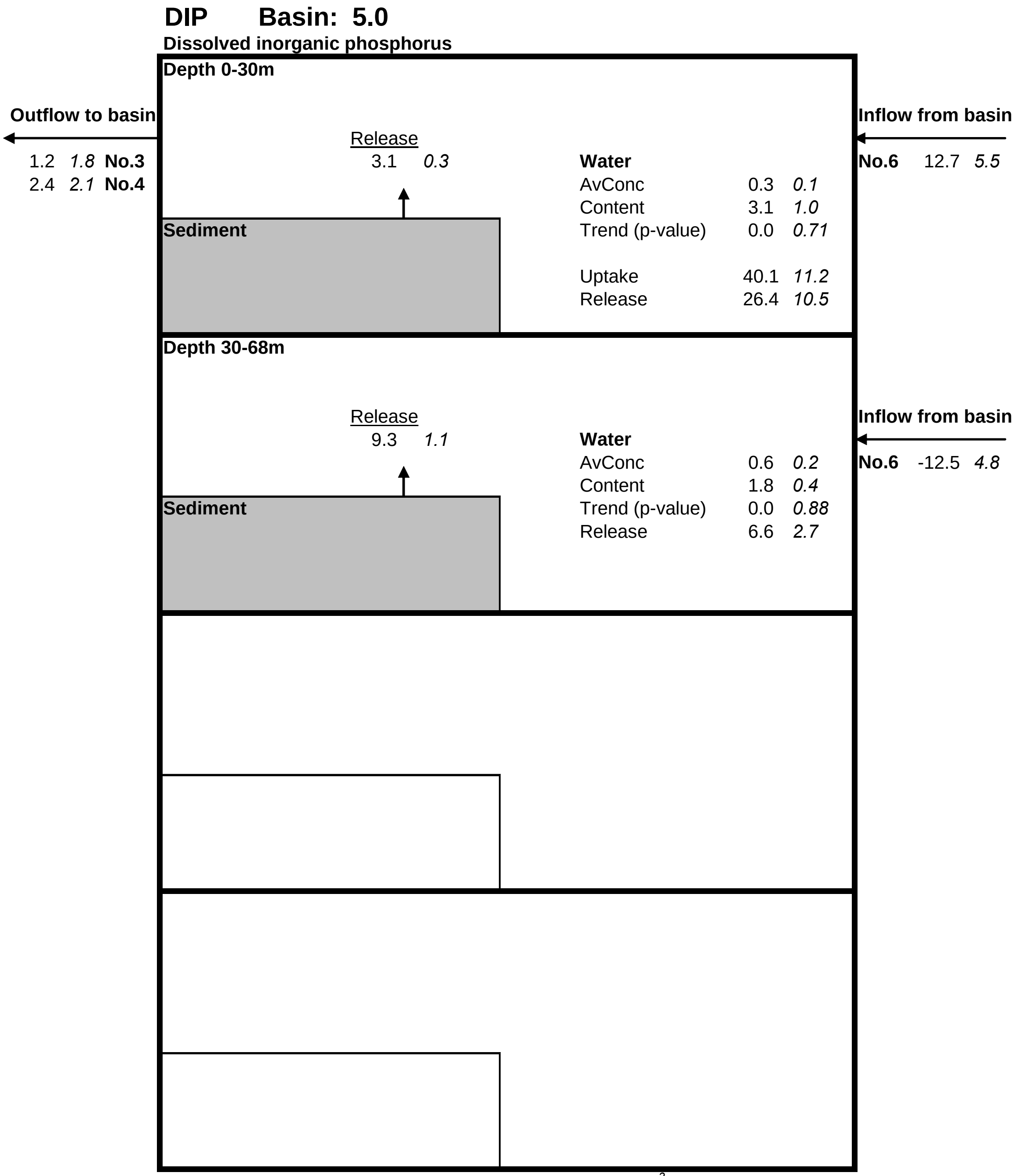


Figure 13. *Physical characteristics and transports of the Arkona Sea.*



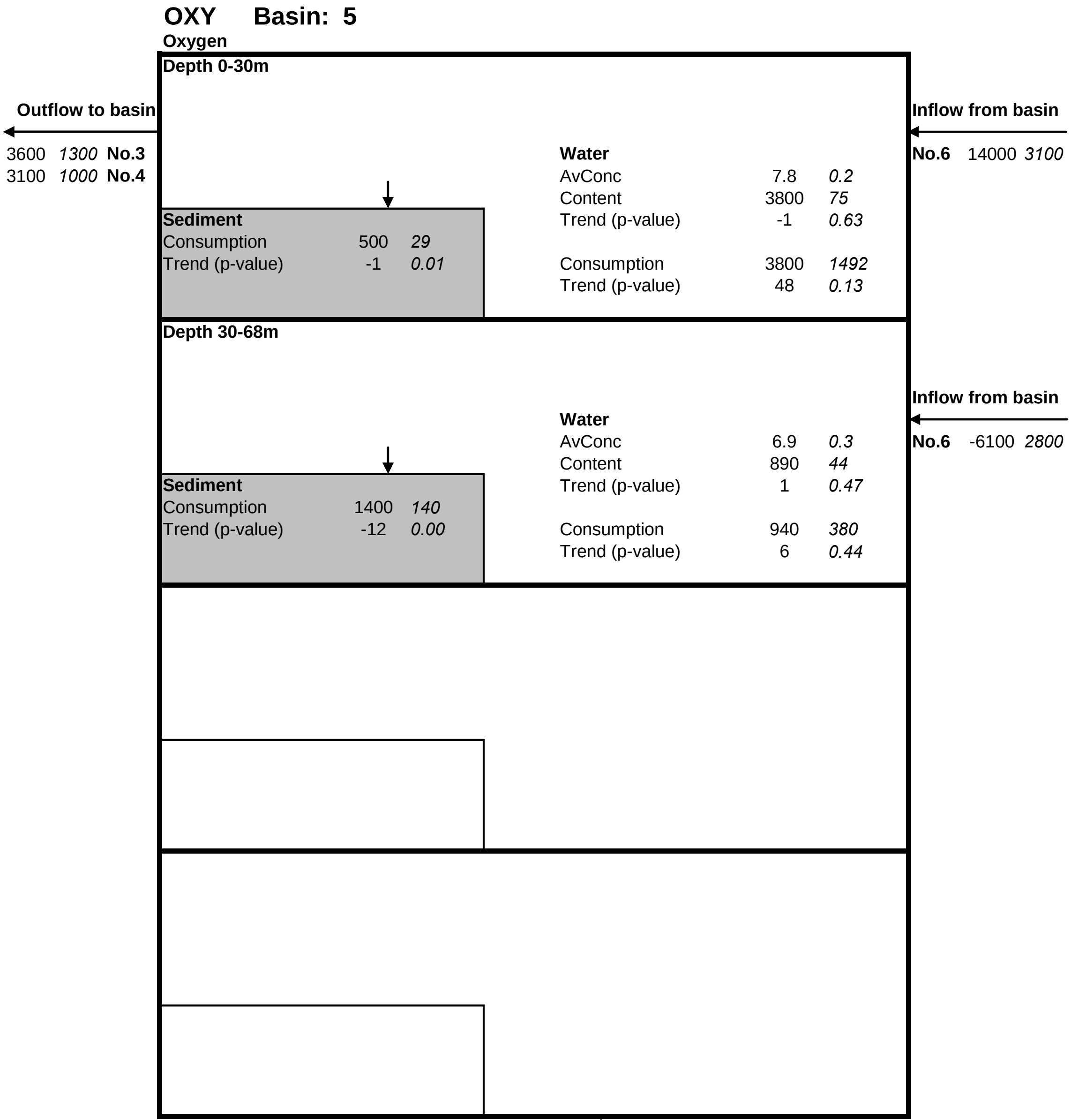
Units: *Average contents in kton and rates in kton/yr. Standard deviations in italics.*
Trend in kton/yr. P-value at significance level 0.05 in italics.
Production may take place in 30-68m but is accumulated in 0-30m in the table

Figure 14. *Organic phosphorus budget in the Arkona Sea.*



Units: *Average concentration (AvConc) in mmol DIP m^{-3}.*
Average contents in kton and rates in kton/yr. Standard deviations in italics.
Trend in kton/yr. P-value at significance level 0.05 in italics.
Uptake may take place in 30-68m but is accumulated in 0-30m in the table

Figure 15. *Dissolved inorganic phosphorus budget in the Arkona Sea.*



Units: *Average concentration (AvConc) in ml O_2 l^{-1}.*
Average contents in kton and rates in kton/yr. Standard deviations in italics.
Trend of content in kton/yr. P-value at significance level 0.05 in italics.
Trend of consumption in (kton/yr)/yr. P-value at significance level 0.05 in italics.

Figure 16. *Oxygen budget in the Arkona Sea.*

5.3. Bornholm Sea

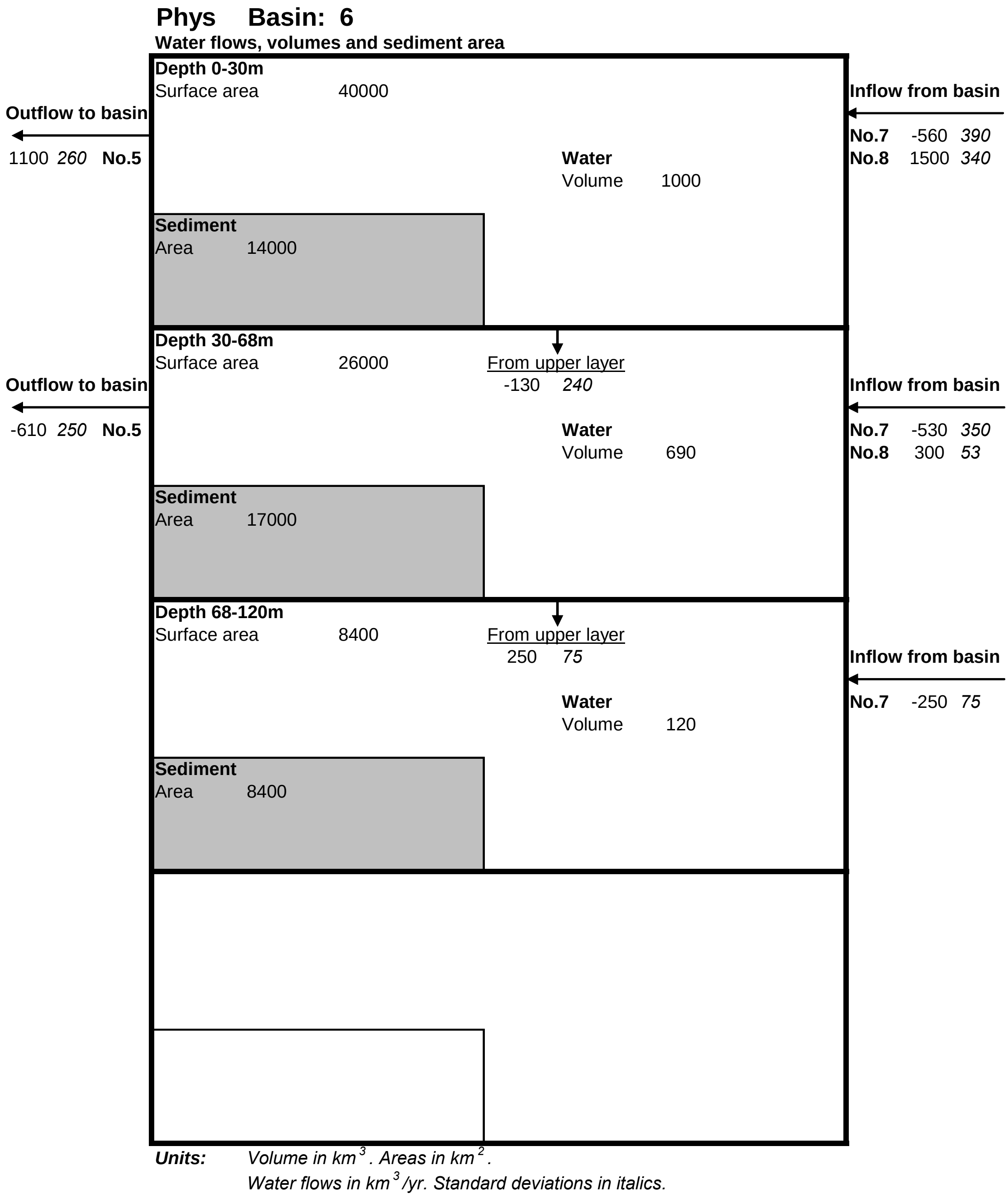


Figure 17. *Physical characteristics and transports of the Bornholm Sea.*

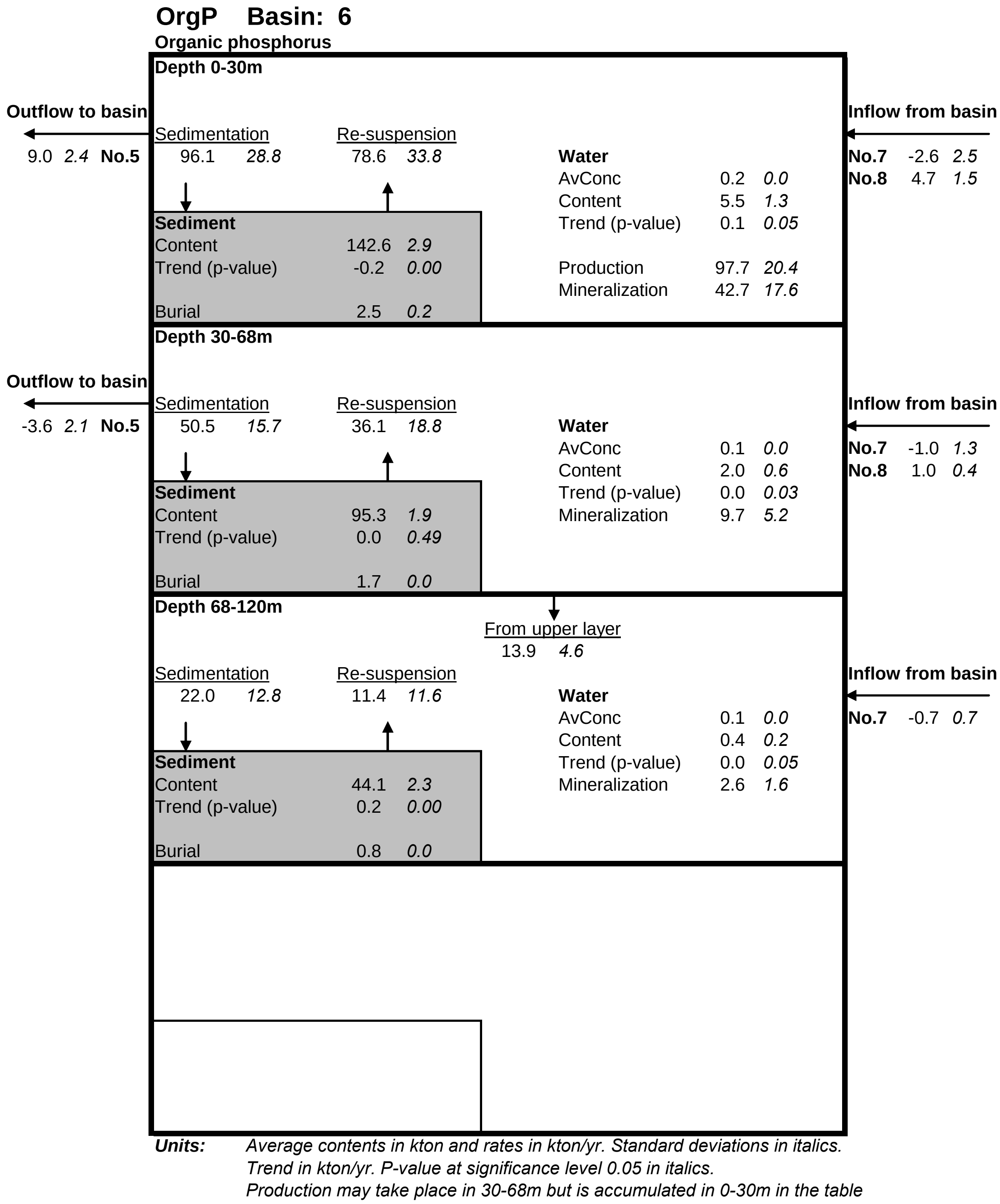
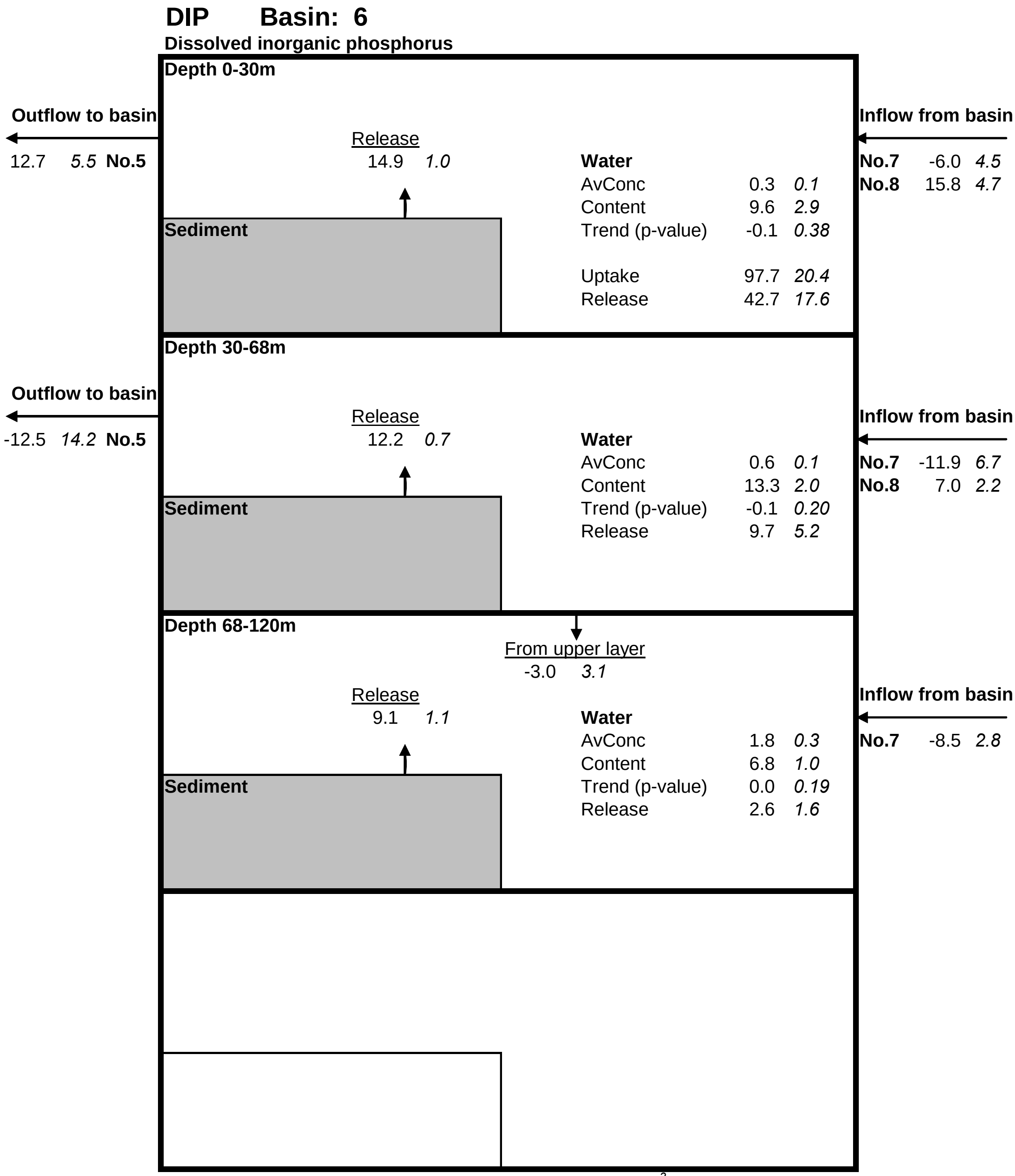
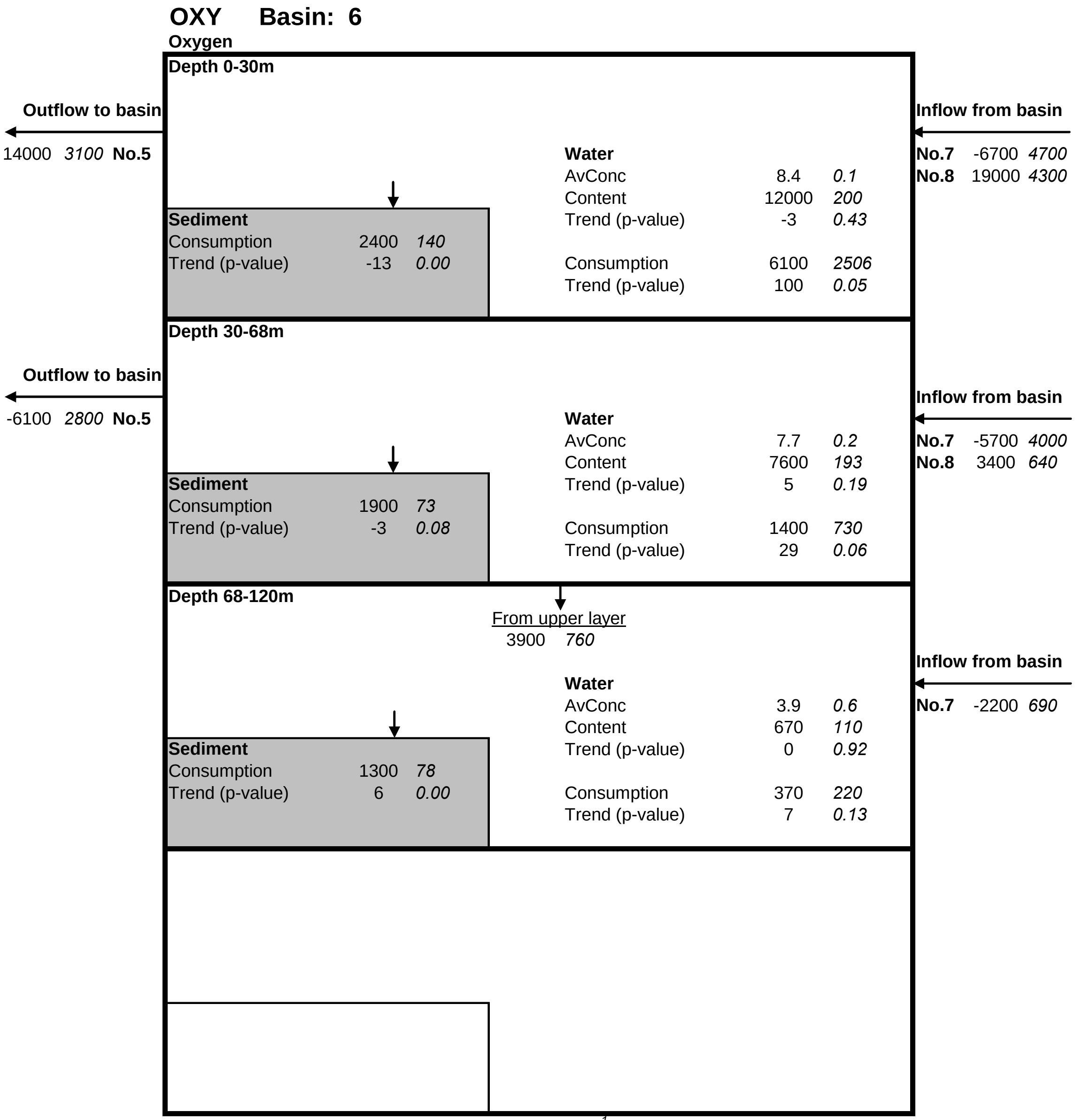


Figure 18. *Organic phosphorus budget in the Bornholm Sea.*



Units: *Average concentration (AvConc) in mmol DIP m^{-3}.*
Average contents in kton and rates in kton/yr. Standard deviations in italics.
Trend in kton/yr. P-value at significance level 0.05 in italics.
Uptake may take place in 30-68m but is accumulated in 0-30m in the table

Figure 19. *Dissolved inorganic phosphorus budget in the Bornholm Sea.*



Units: *Average concentration (AvConc) in ml O_2 l^{-1}.*
Average contents in kton and rates in kton/yr. Standard deviations in italics.
Trend of content in kton/yr. P-value at significance level 0.05 in italics.
Trend of consumption in (kton/yr)/yr. P-value at significance level 0.05 in italics.

Figure 20. *Oxygen budget in the Bornholm Sea.*

5.4. East Gotland Sea

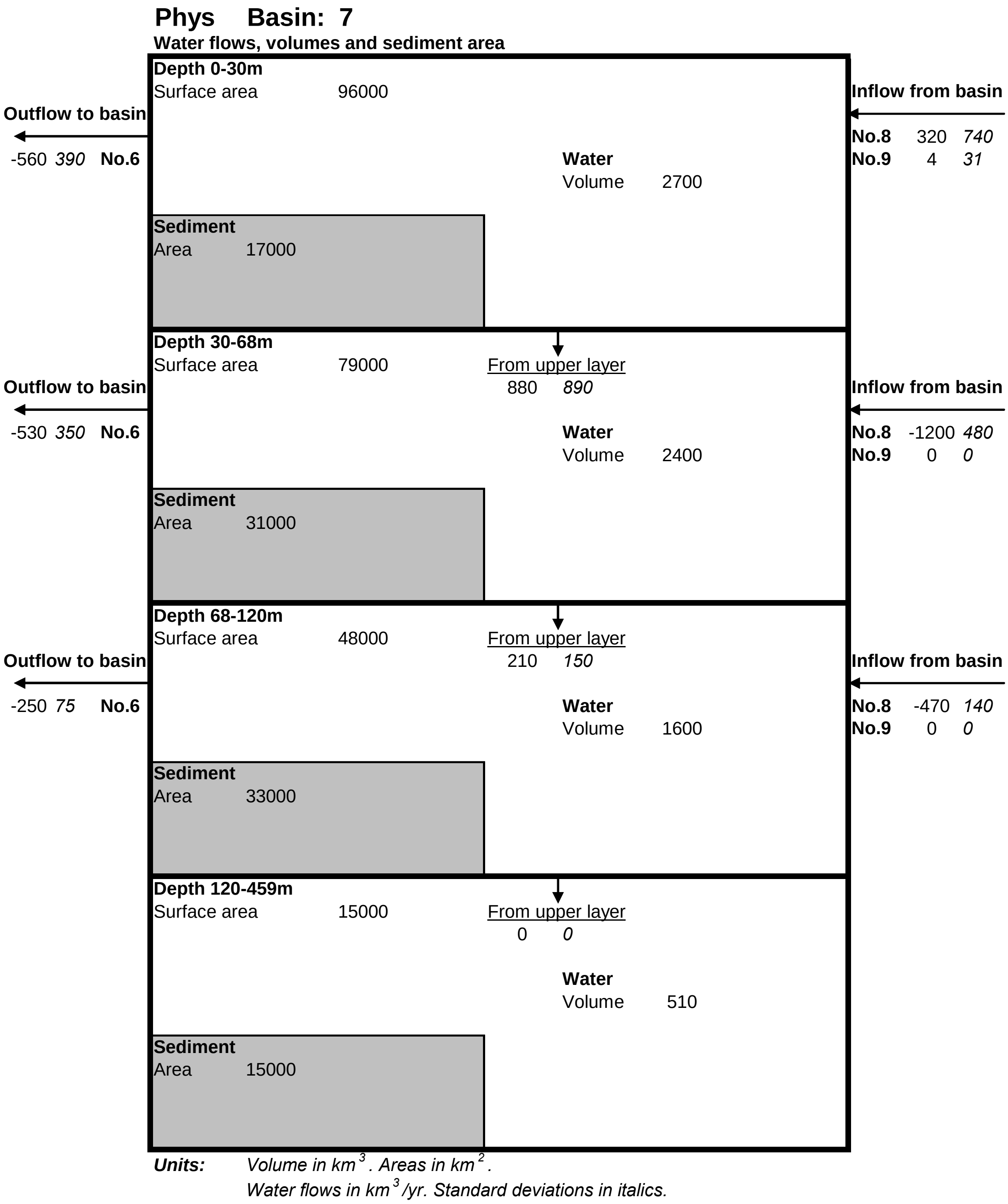
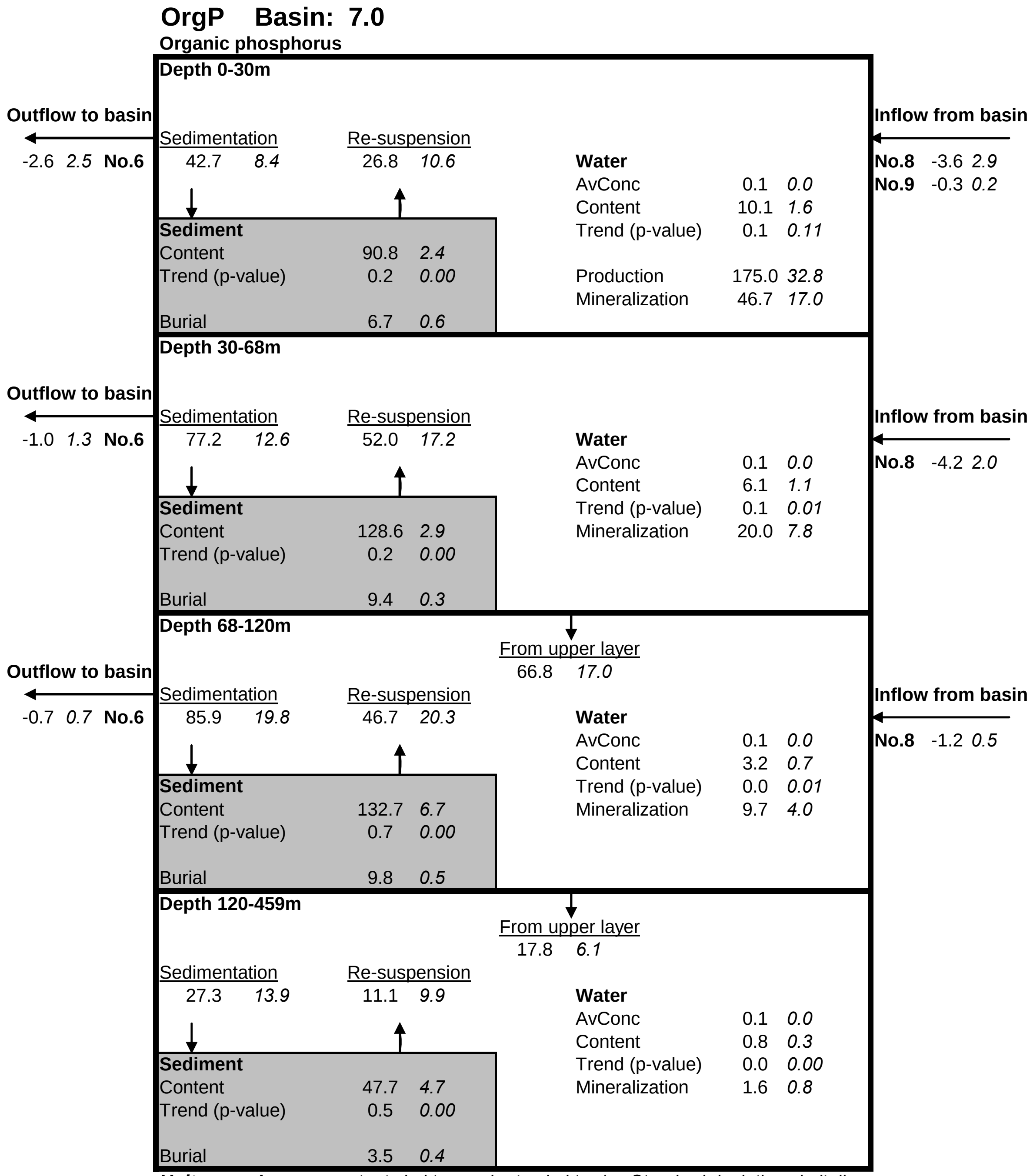
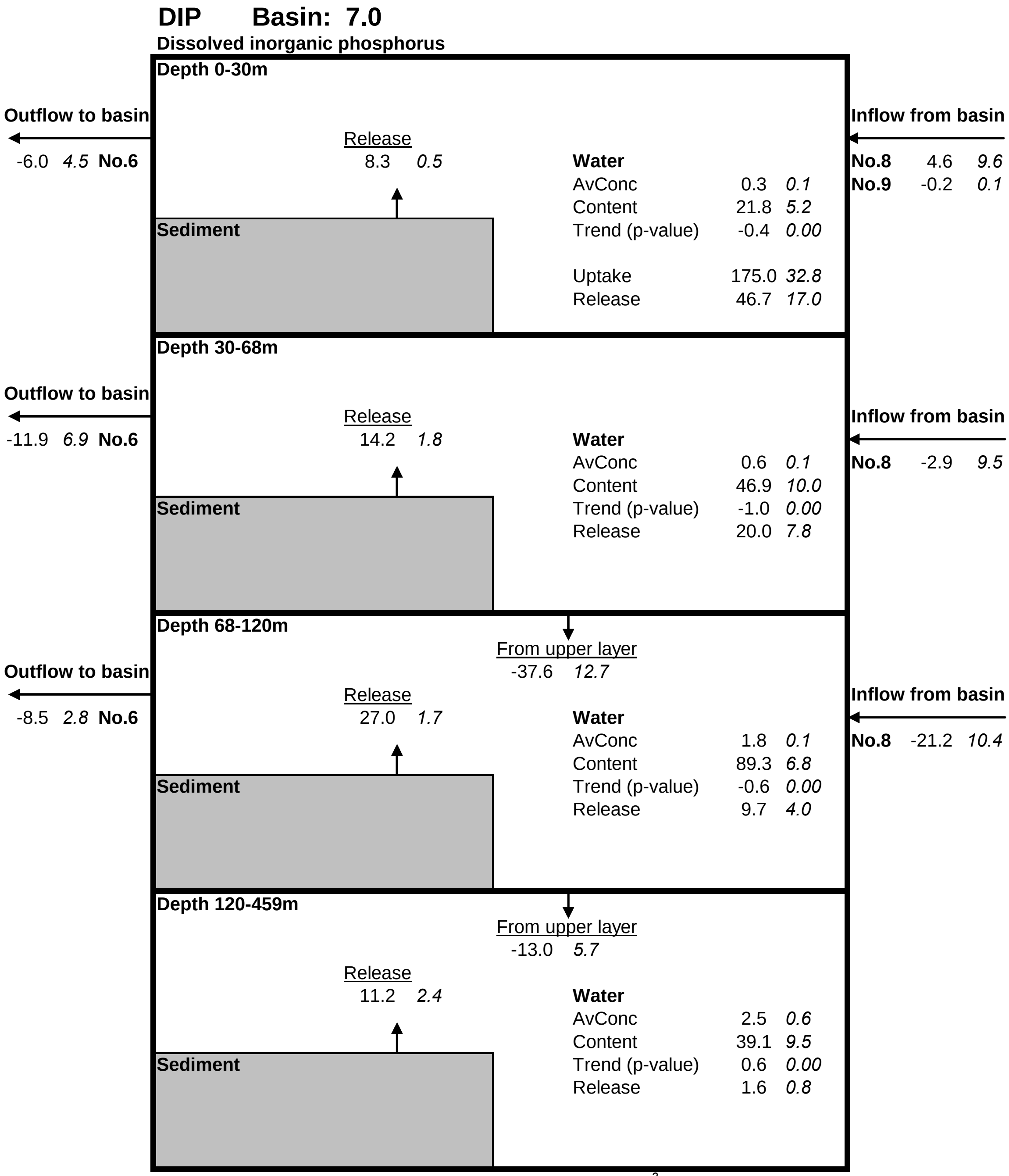


Figure 21. *Physical characteristics and transports of the East Gotland Sea.*



Units: *Average contents in kton and rates in kton/yr. Standard deviations in italics.*
Trend in kton/yr. P-value at significance level 0.05 in italics.
Production may take place in 30-68m but is accumulated in 0-30m in the table

Figure 22. *Organic phosphorus budget in the East Gotland Sea.*



Units: *Average concentration (AvConc) in mmol DIP m^{-3}.*
Average contents in kton and rates in kton/yr. Standard deviations in italics.
Trend in kton/yr. P-value at significance level 0.05 in italics.
Uptake may take place in 30-68m but is accumulated in 0-30m in the table

Figure 23. *Dissolved inorganic phosphorus budget in the East Gotland Sea.*

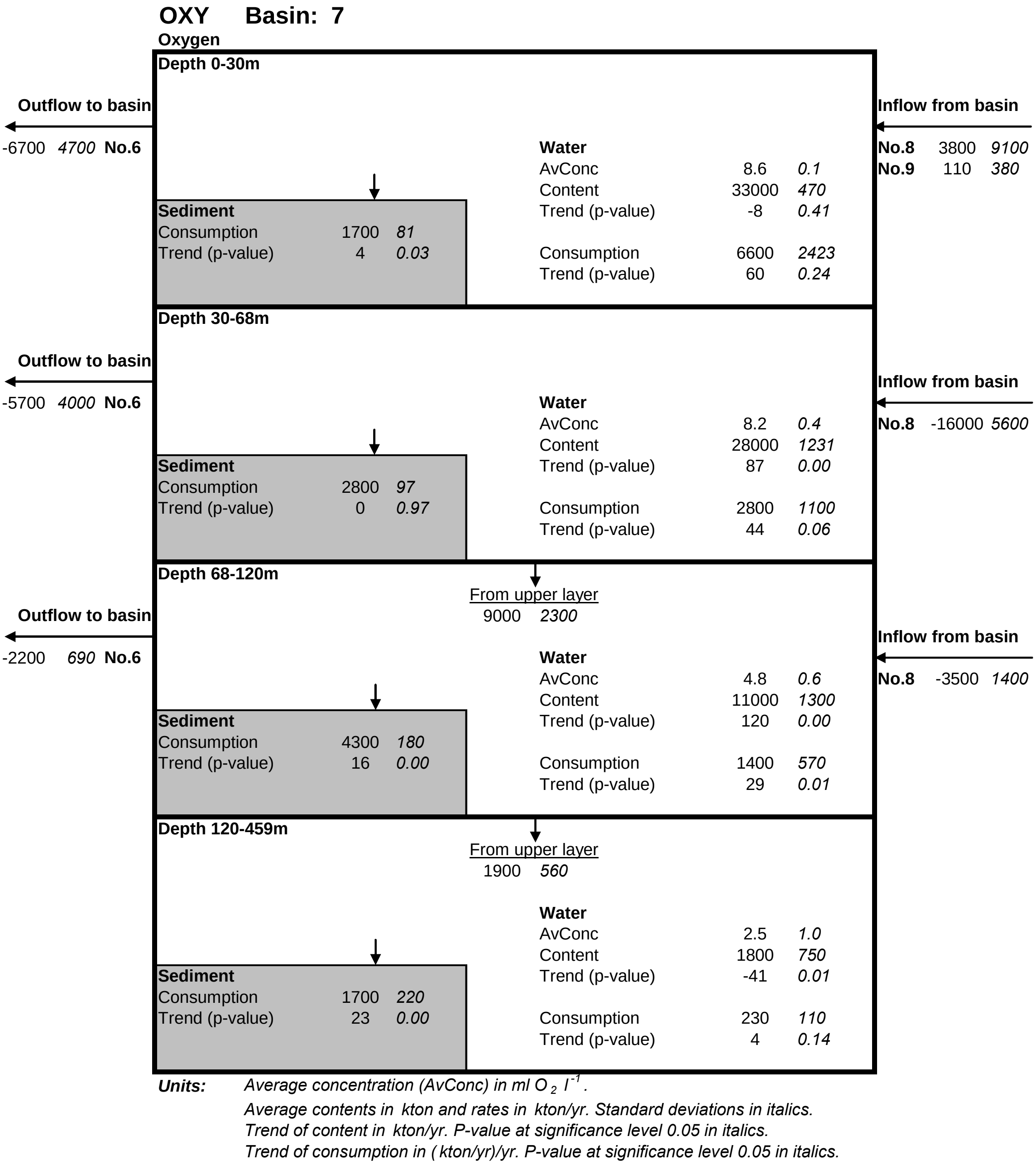


Figure 24. *Oxygen budget in the East Gotland Sea.*

5.5. North West Baltic proper

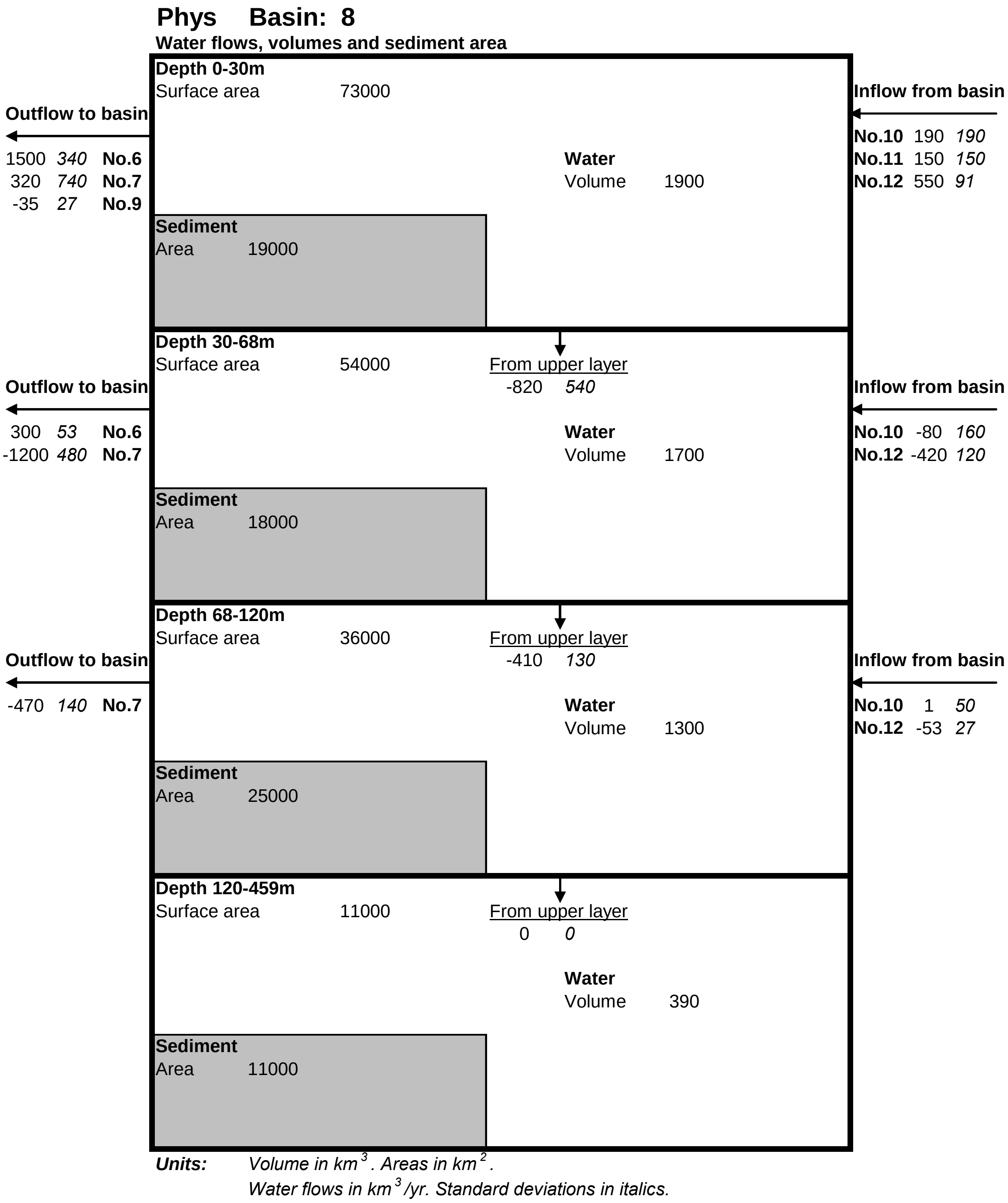


Figure 25. *Physical characteristics and transports of the North West Baltic proper.*

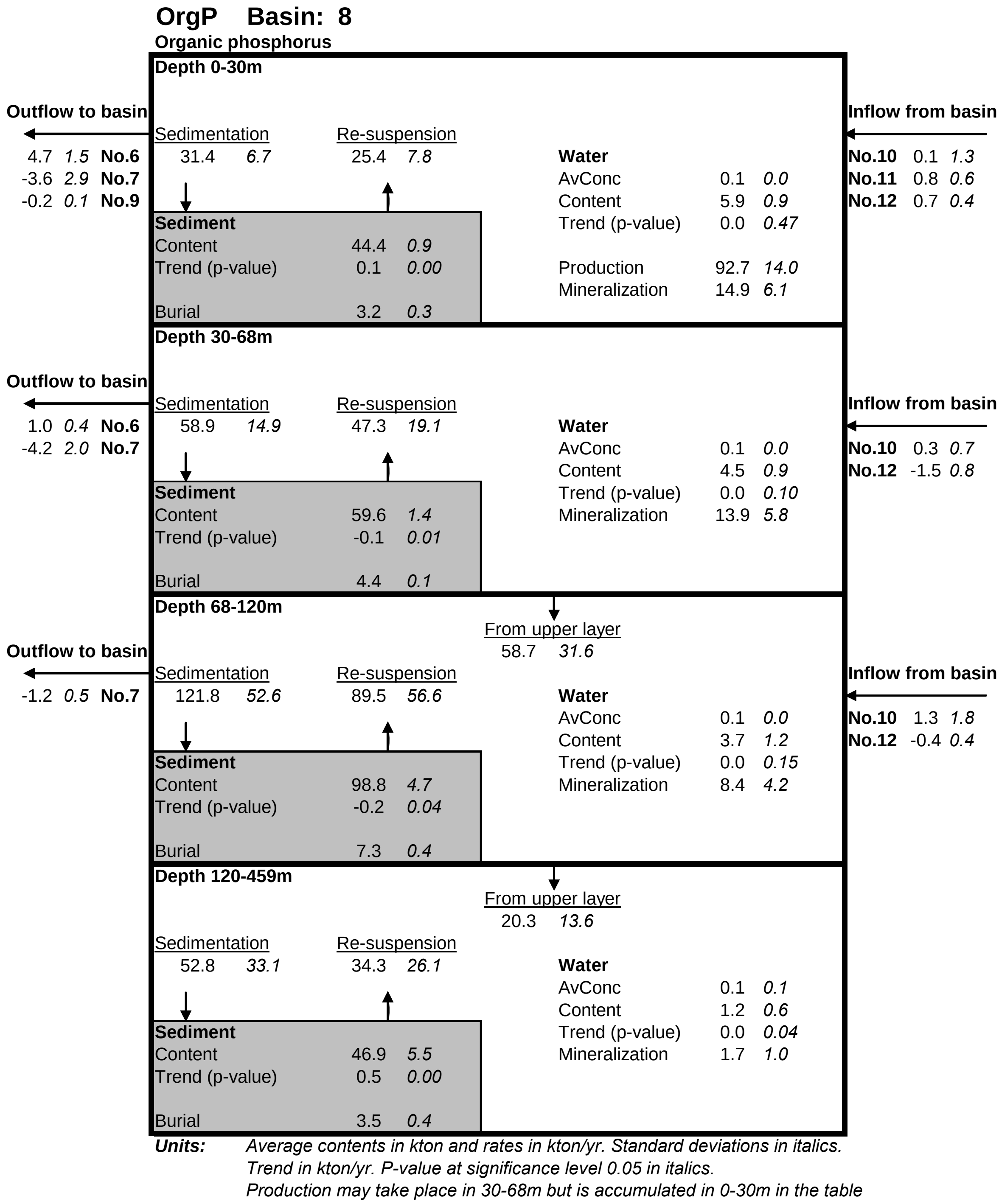
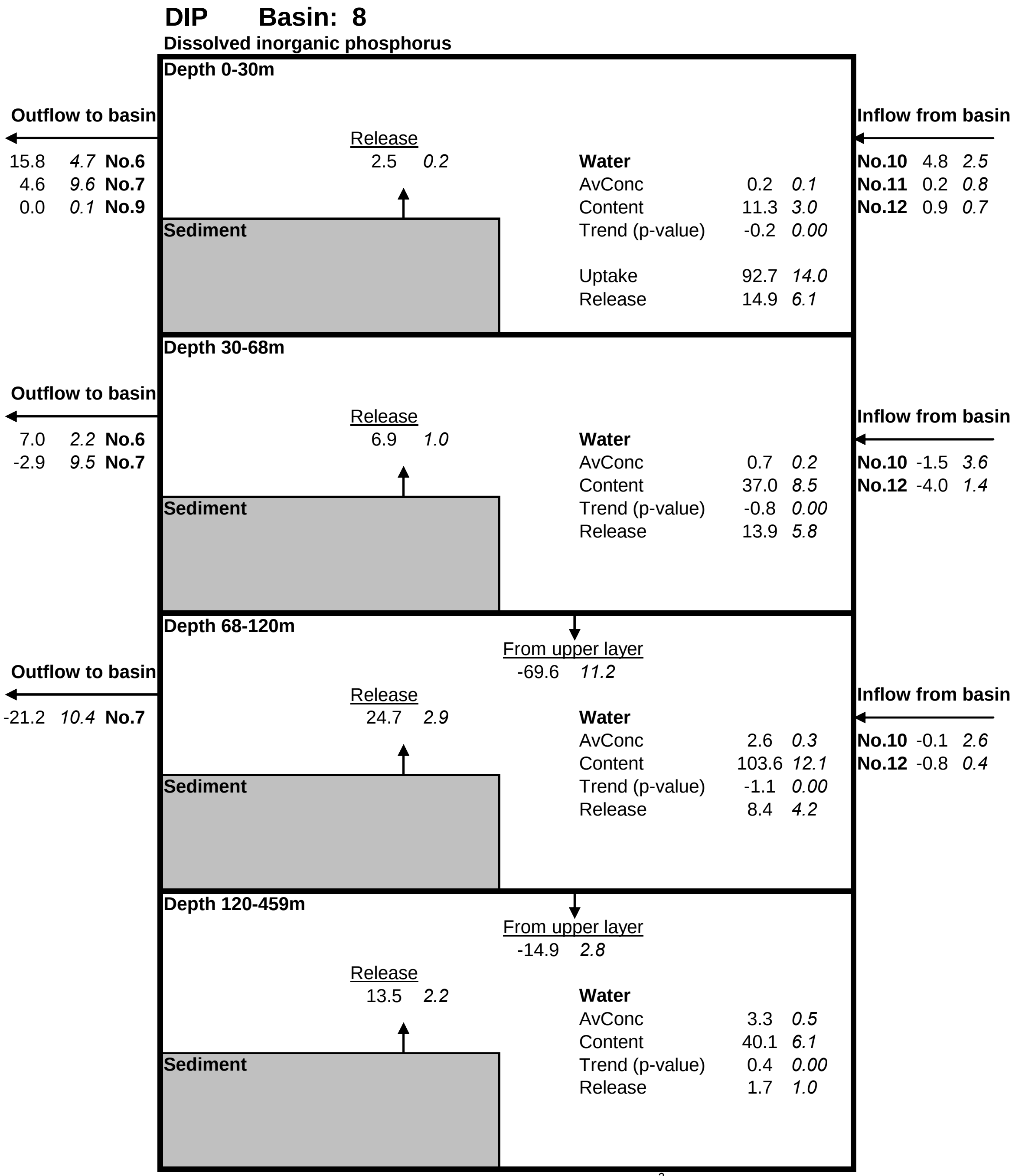


Figure 26. *Organic phosphorus budget in the North West Baltic proper.*



Units: *Average concentration (AvConc) in mmol DIP m^{-3}.*
Average contents in kton and rates in kton/yr. Standard deviations in italics.
Trend in kton/yr. P-value at significance level 0.05 in italics.
Uptake may take place in 30-68m but is accumulated in 0-30m in the table

Figure 27. *Dissolved inorganic phosphorus budget in the North West Baltic proper.*

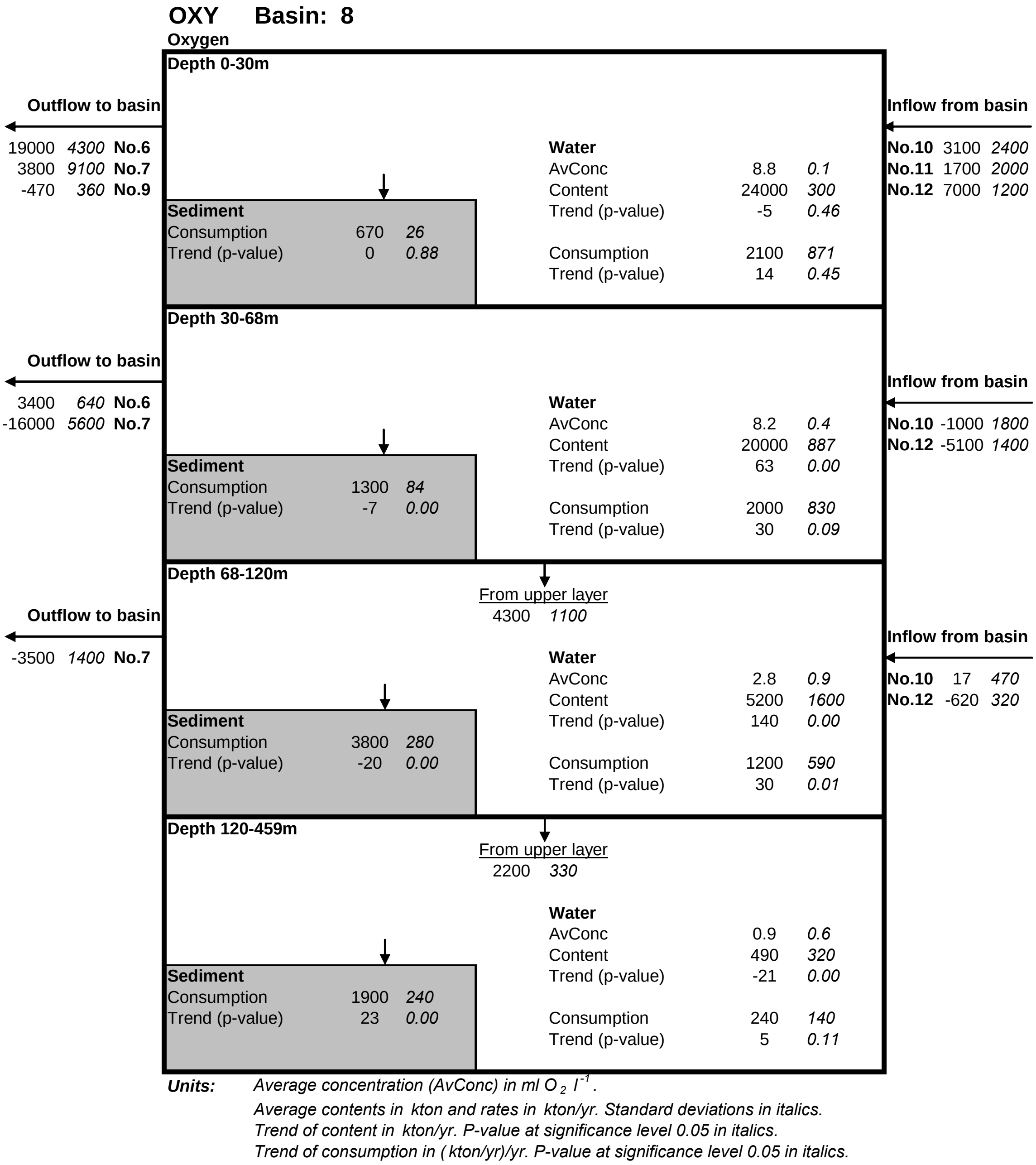


Figure 28. *Oxygen budget in the North West Baltic proper.*

5.6. Gulf of Finland

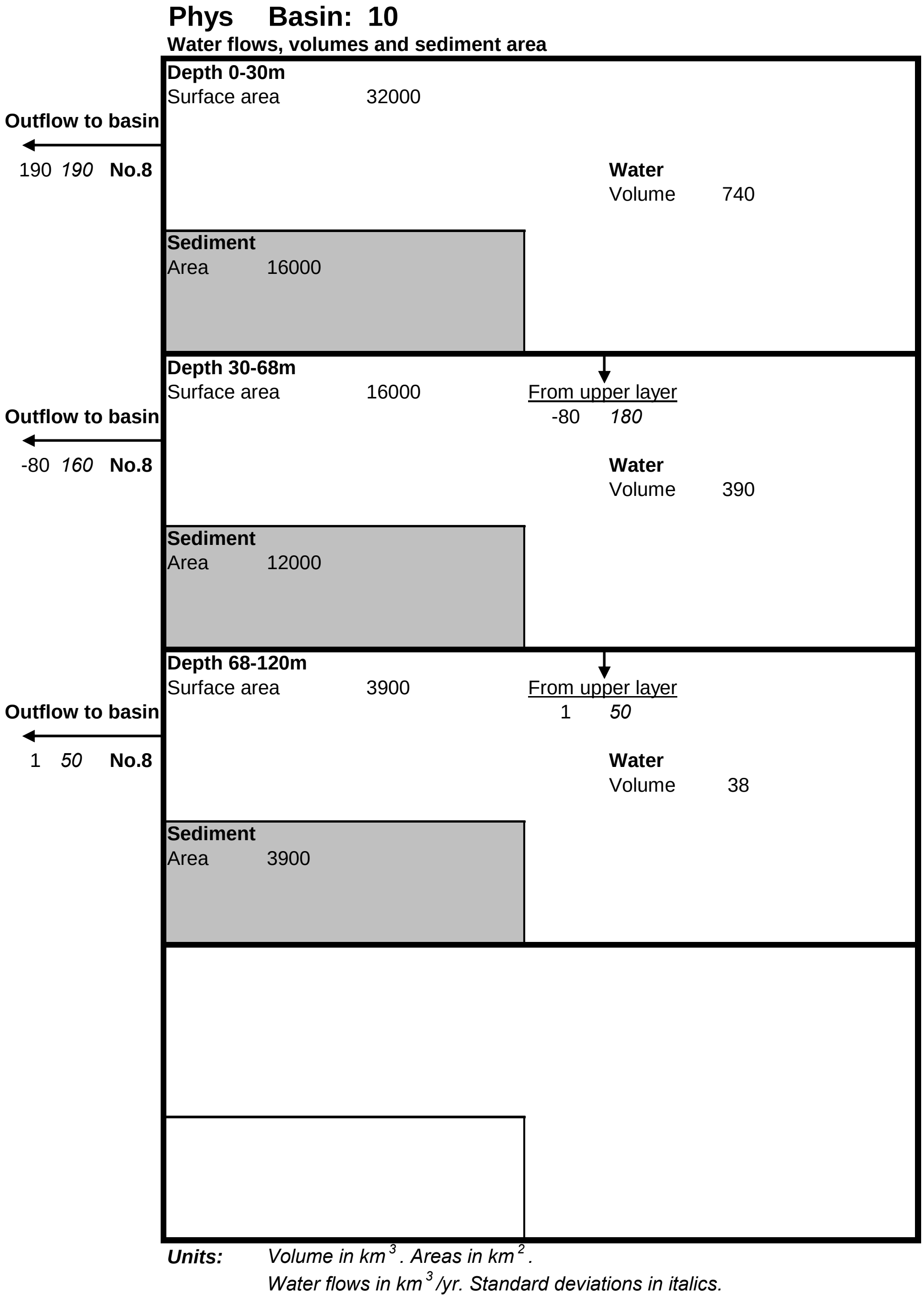
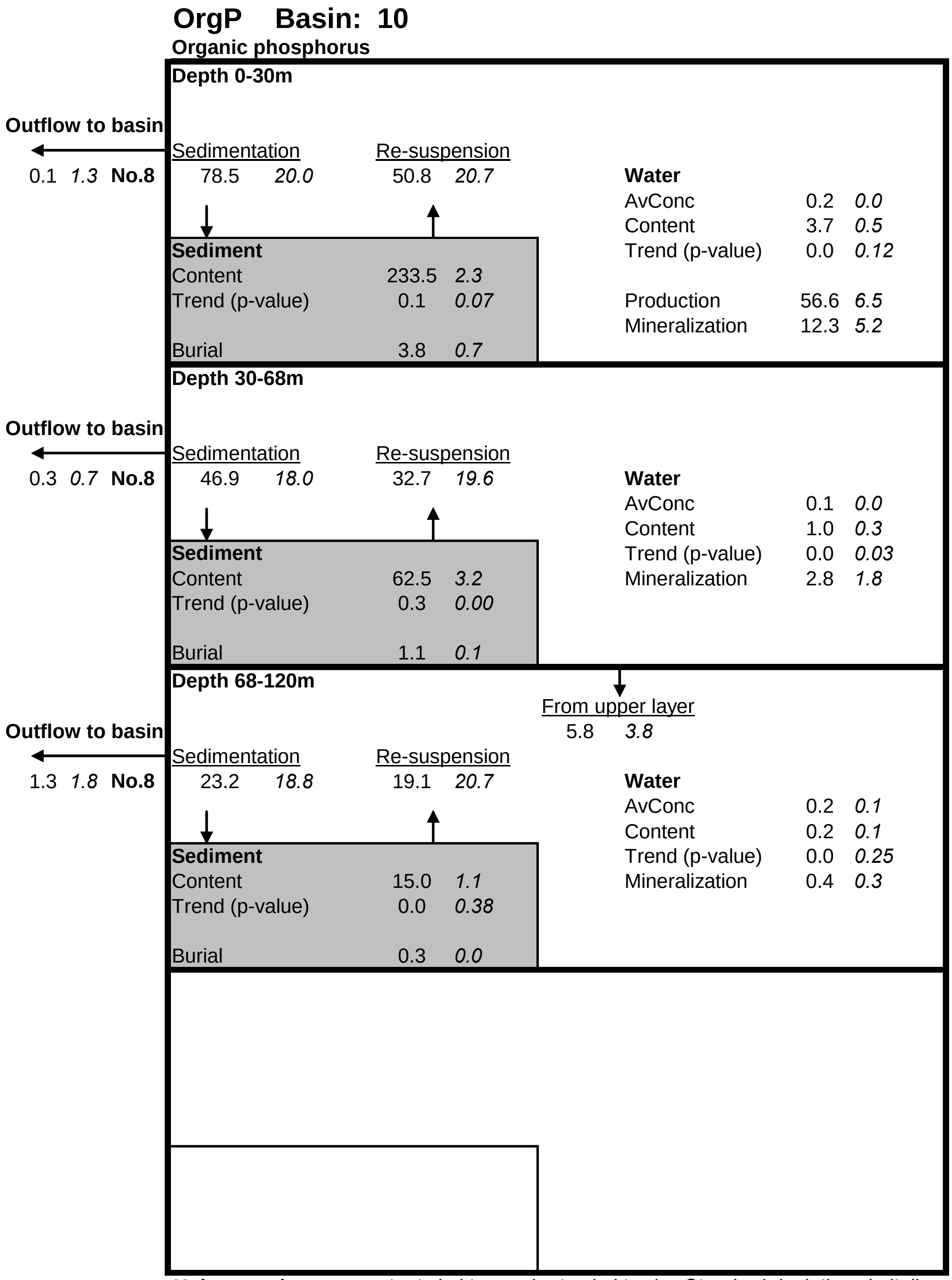
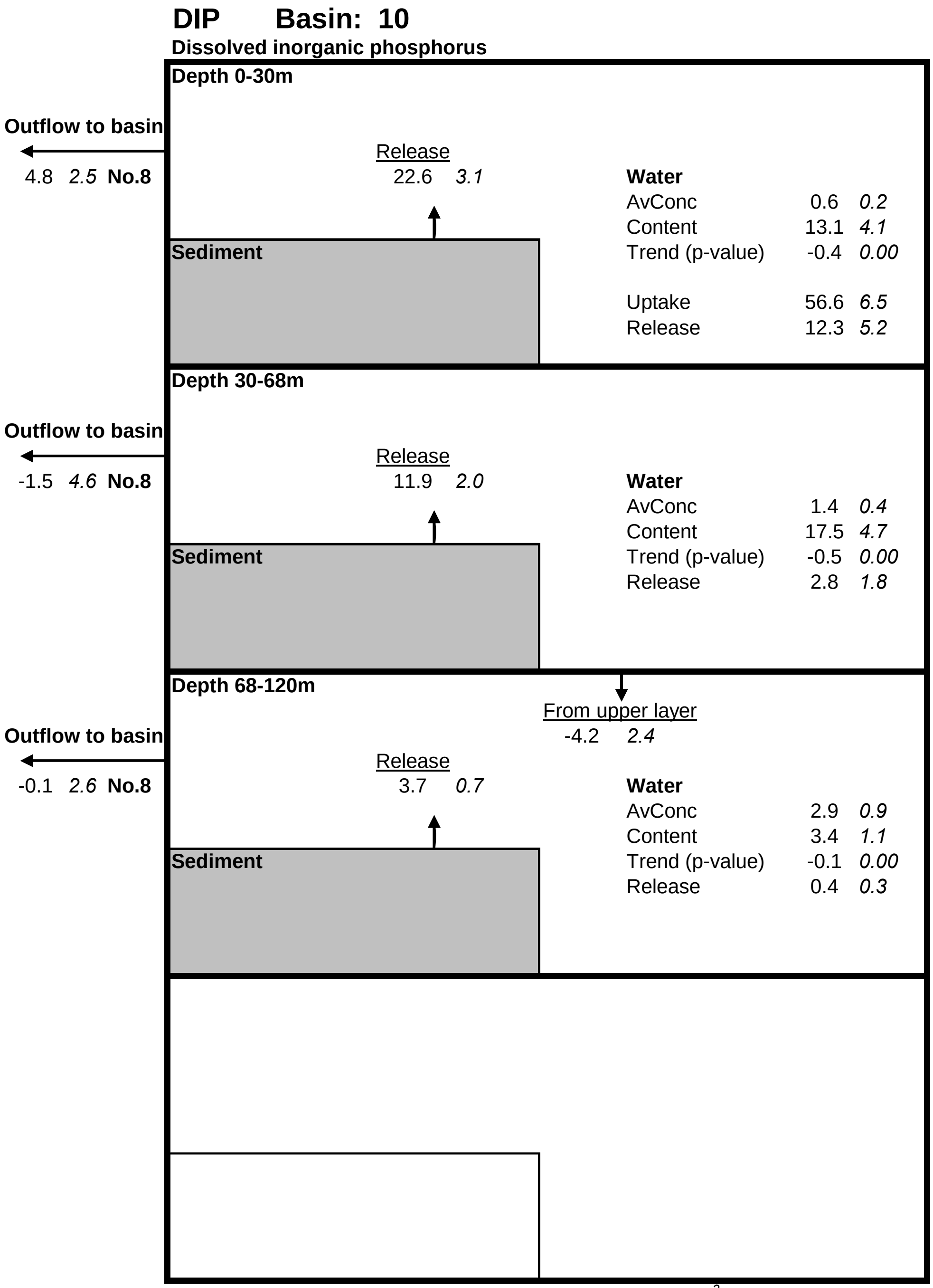


Figure 29. *Physical characteristics and transports of the Gulf of Finland.*



Units: *Average contents in kton and rates in kton/yr. Standard deviations in italics.*
Trend in kton/yr. P-value at significance level 0.05 in italics.
Production may take place in 30-68m but is accumulated in 0-30m in the table

Figure 30. *Organic phosphorus budget in the Gulf of Finland.*



Units: *Average concentration (AvConc) in mmol DIP m^{-3}.*
Average contents in kton and rates in kton/yr. Standard deviations in italics.
Trend in kton/yr. P-value at significance level 0.05 in italics.
Uptake may take place in 30-68m but is accumulated in 0-30m in the table

Figure 31. *Dissolved inorganic phosphorus budget in the Gulf of Finland.*

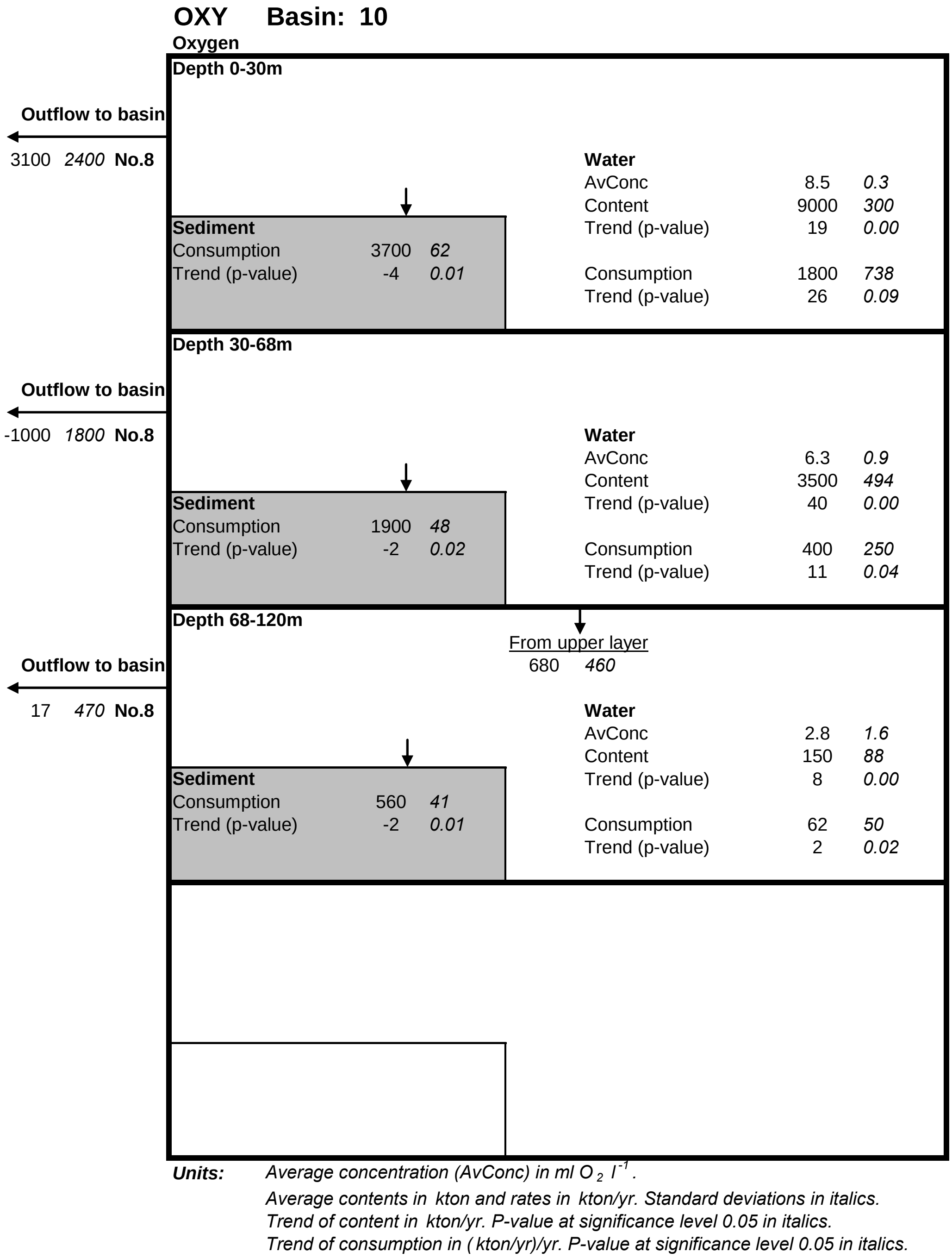


Figure 32. *Oxygen budget in the Gulf of Finland.*

6. Discussion

The transports of inorganic and organic phosphorus and oxygen between the sub-basins and the different depth layers are summarized in Fig.33, Fig.34 and Fig.35. The two upper boxes are merged into one box and cover the depth range 0-68m.

Phosphorus is in general transported to the lower layers by the vertical flow of organic matter. A large fraction of the downward flux of organic matter is deposited in the sediments together with organic matter originating from re-suspended sediments. Re-suspension is often about 50% or more of the sedimentation with largest values often found in the upper layers. This indicates that the sedimented organic matter is on average re-suspended at least once before its final deposition.
One may note from Fig.33 that the average vertical transports of organic matter are usually about an order of magnitude larger than the horizontal transports. This shows that the main source of organic matter in each sub-basin has its origin within the actual sub-basin. The horizontal transports of organic phosphorus are mainly directed towards the north (Basin 8), except in the south where phosphorus is transported from North West Baltic proper to the Bornholm Sea. There is also a net export of organic matter to the Belt Sea and the Sound as well as to the Åland Sea and the Archipelago Sea.

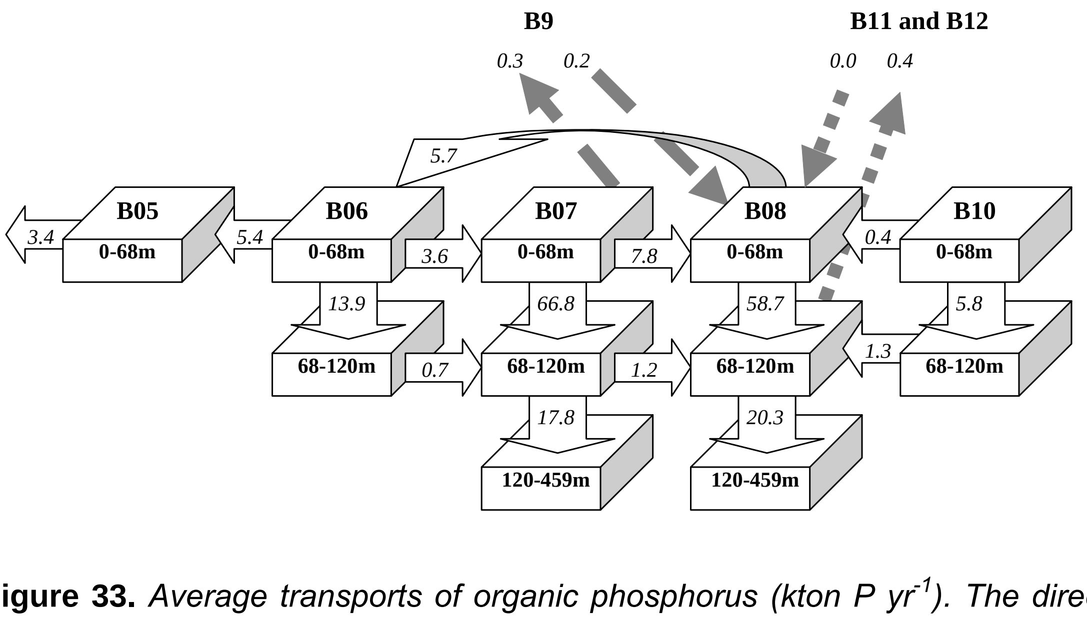


Figure 33. *Average transports of organic phosphorus (kton P yr^{-1}). The direction of the arrows indicates the direction of the transports. The number of each sub-basin is denoted by B05-B12 according to definitions in section 3. Basins 3 and 4 are not shown. Transports between Basin 8 and Basins 11 and 12 are merged into the dotted grey arrows. The dashed grey arrows indicate transports between the surface boxes of Basin 9 and Basins 7 and 8, respectively. Transports between Basin 8 and Basin 6 are shown by the curved arrow. Transport between Basin 5 and Basins 3 and 4 are merged into the leftmost arrow.*

Decomposition of organic matter takes place in the water and mainly in the sediments of the deeper layers. Inorganic phosphorus is then released to the water and transported upwards in the water column. It is noteworthy that there is a northward horizontal transport of DIP in the lower layers which accumulates into the upward flux of DIP in Basin 8. This DIP flux is larger than the downward flux of organic phosphorus (Fig.33). A large fraction of DIP is circulated southward through Basin 8 to Basin 6 and then back to Basin 7 again. There is also a net export of DIP to the Belt Sea and the Sound as well as to the Åland Sea and the Archipelago Sea.

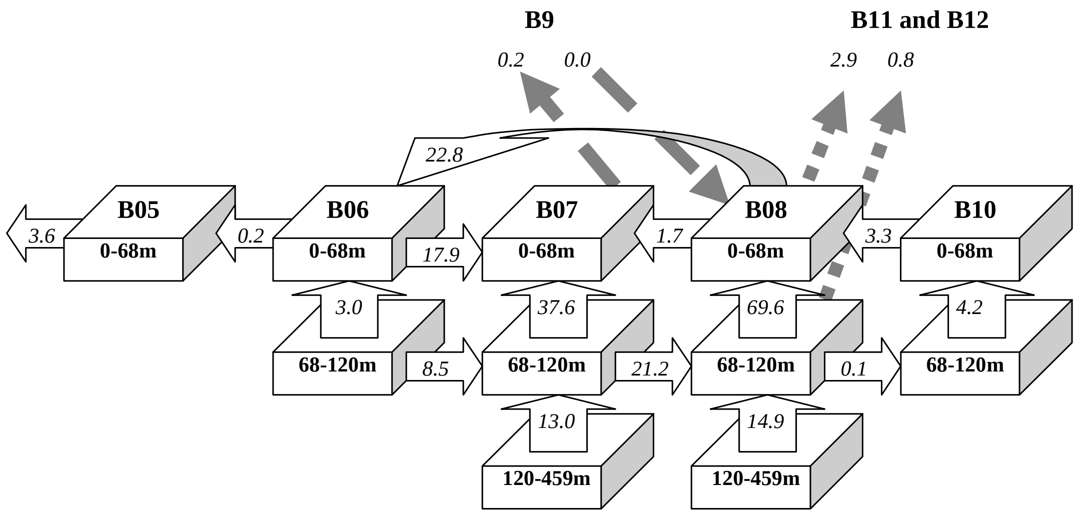


Figure 34. *Average transports of dissolved inorganic phosphorus (DIP) (kton P yr^{-1}). The direction of the arrows indicates the direction of the transports. The number of each sub-basin is denoted by B05-B12 according to definitions in section 3. Basins 3 and 4 are not shown. Transports between Basin 8 and Basins 11 and 12 are merged into the dotted grey arrows. The dashed grey arrows indicate transports between the surface boxes of Basin 9 and Basins 7 and 8, respectively. Transports between Basin 8 and Basin 6 are shown by the curved arrow. Transport between Basin 5 and Basins 3 and 4 are merged into the leftmost arrow.*

Air-sea interaction transfers oxygen from the atmosphere to the surface layers of the sea. Diffusive and advective transports bring the oxygen to the lower layers where it is consumed by the oxidation of decomposed organic matter. The net deepwater transports depend on the strengths of horizontal and vertical oxygen gradients. These are mainly set by the rate of decomposition of organic matter and the physical transport capacity why the average transports of oxygen (Fig.35) follow much the flux pattern of organic matter. The negative trends of oxygen in the deepest layers of Basin 7 and 8 (Figs. 24 and 28) however suggest that the average oxygen supply during the investigated period is slightly less than the demand by oxygen consumption.

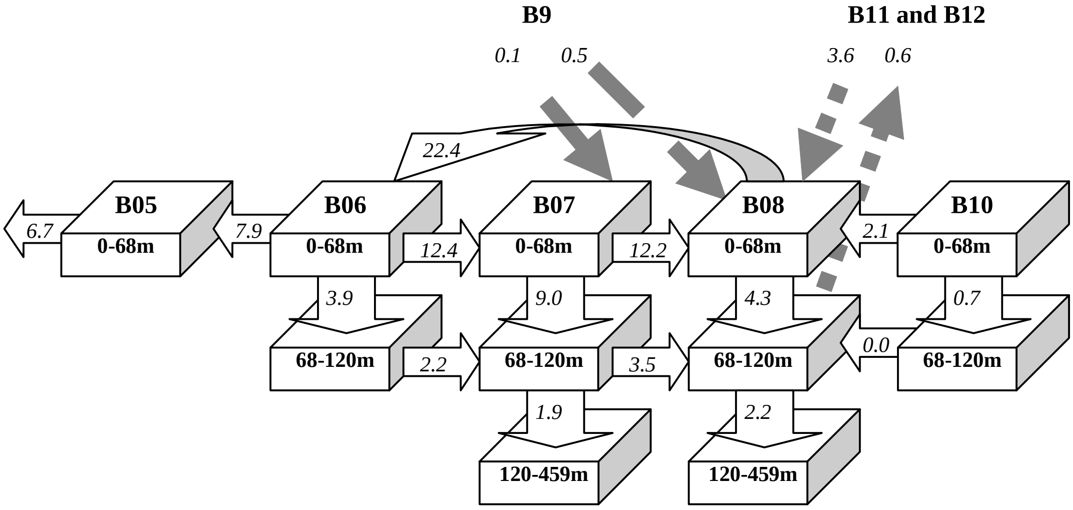


Figure 35. *Average transports of dissolved oxygen (10^3 kton O_2 yr^{-1}). The direction of the arrows indicates the direction of the transports. The number of each sub-basin is denoted by B05-B12 according to definitions in section 3. Basins 3 and 4 are not shown. Transports between Basin 8 and Basins 11 and 12 are merged into the dotted grey arrows. The dashed grey arrows indicate transports between the surface boxes of Basin 9 and Basins 7 and 8, respectively. Transports between Basin 8 and Basin 6 are shown by the curved arrow. Transport between Basin 5 and Basins 3 and 4 are merged into the leftmost arrow.*

Oxygen concentrations in the water decline when the oxygen supplied by advection and diffusion is less than the demand by the decomposition of organic matter. This is illustrated by periods when the yellow area is larger than the purple area in Figs. 9-12. In order to combat the oxygen deficit, which usually occurs in discrete time periods, the amount of extra oxygen needed to support the modeled oxygen supply is 0-2.5 kton O_2 yr^{-1} km^{-3} depending on the actual sub-basin and the actual depth layer. In order to further improve the oxygen conditions the oxygen supply has to be larger than the oxygen demand for a time period. The time period of improvement is defined by the rate of supply and the anticipated level of minimum oxygen concentration. Thereafter it is necessary to continue to keep an oxygen supply that on average may meet the oxygen demand. Gustafsson et al. (2008) simulated with two models a number of engineering methods to improve oxygen conditions in the Baltic proper. In one of the cases oxygen was added to the deeper layers with an artificial source. Their simulations required about 2-6 $x10^6$ ton O_2 yr^{-1} to keep the concentrations above 2 mlO_2 l^{-1} which is a desired oxygen minimum level from a biological point of view.

7. Acknowlegements

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