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The effect of floating houses on water quality

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Abstract: The need of an adaptive sustainable solution for the increased land scarcity, growing urbanization, climate change and flood risks resulted in the concept of the floating urbanization. In The Netherlands this new type of housing attracted the interest of local authorities, municipalities and water boards. Moreover, plans to incorporate floating houses in the urban planning have already been developed. However, the knowledge gap regarding the potential effect on the water quality halts the further development of the floating houses. This paper shows the results of a water quality measurement campaign, as part of the national program "Knowledge for climate", at a small floating houses project in Delft and serves as a case study for addressing the environmental-ecological knowledge gap on this topic.

Keywords: Adaptation to climate change; Floating houses; Water quality;

Introduction

In the near future two of the challenges urban areas will face are: the growing agglomeration of population and climate change. The growing agglomeration of population in urban areas leads to a continuous process of conversion of rural land into urban land. Since urban areas are mainly impervious, they suppress water infiltration, generating an imbalance in the urban water cycle. Regarding the climate change, it is expected to produce an increase or decrease of temperatures and more heavy rainfall events. Keeping in mind the uncertainty that characterizes climate change, a sustainable adaptive plan is of high importance (Howe et al. 2011).

In the Netherlands, coastal cities are facing the possibility of flooding from river and sea level rise, as well as an increase in pluvial floods. On top of this, land scarcity is another of the problems that urban planners have to face. Currently, legal requirements demand that 10% of the development should be kept for water storage (Nilessen and Jeroen 2011). This requirement opens a way for a new adaptive urban development model in the Netherlands: Floating houses.

Although the aspects regarding the design, construction and selection of materials for floating houses have been investigated, there are a number of other aspects, such as the large-scale application of floating houses, the development of an urban planning, the potential impact of floating houses on water quality and ecology etc., that are still not resolved nor investigated (De Graaf 2012):

The environmental knowledge gap is an important obstacle for further development and application since local government authorities appear to be reluctant to issue building permits for floating houses, while their effects on the water quality are still unknown. Additionally, the current legislation of the water boards allows only a 10% covering of the water bodies, which consequently hampers the deployment of floating houses on a larger scale (Hoefnagel and Raaphorst 2013).

The installation of floating houses directly produces the following effects, see **Figure 1**: blockage of sunlight and shadow, reduction of the air-water interface area (open surface), change in wind stress, change of water flow and sedimentation transport (Kitazawa et al. 2010; De Graaf 2012; Hartwich 2014). A description of the potential effects on water quality is given below.

- The blockage of sunlight and shadow not only affects the temperature of the upper layer of the water body but also reduces the production of oxygen by photosynthesis (Burdick and Short 1999). On the other hand, the reduction of the available air-water interface reduces the oxygen that is transferred from the air to the water. The above can lead to lower oxygen levels, which can eventually result in dead organic material that contributes to the turbidity, which in turn influences sunlight penetration. In addition, the dead organic material, due to the lower oxygen levels, will settle to the sediment increasing the nutrients concentration as well as the sediment oxygen demand. This can result in the development of a low dissolved oxygen zone below the floating houses (Penning et al. 2003; Kitazawa et al. 2010).

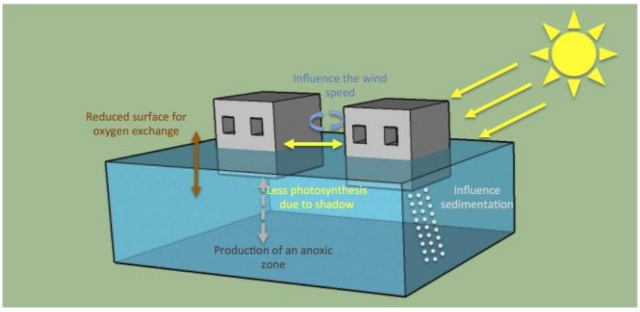

Figure 1: Schematics of the effects of floating houses on a water body.

- Wind, as a major mechanical energy source, can influence the circulation and turbulent mixing of a water body (Ji 2008). Wind is characterised by temporal and spatial variations therefore its influence on the water body will not be homogeneous. The presence of floating houses can influence the wind pattern since air is compressed as it passes between two adjacent houses. As it is compressed it is accelerated, resulting in an increased wind speed. The magnitude of this increase depends on how much the air is compressed. Furthermore the wind can also be blocked by the presence of floating houses. The façade opposite to the one facing the wind experiences lower winds.

- Finally, the underwater surface of floating houses or other floating structures is suitable for the development of sessile organisms. This is something that can influence water quality, even more in cases where the water state is more eutrophic and stagnant (Kitazawa et al. 2010). Finally, part of the floating houses penetrates the water column and the underwater façade creates a no flow boundary. The distance between two floating houses can be critical since they create a partially confined water column. Since the water in a pond has limited flow, the oxygen transfer by diffusion or dispersion can be slower and eventually can create unsuitable conditions for the aquatic life.

Water quality is described by chemical, physical and biological properties and the interactions among them and the surrounding environment. For example, meteorological conditions, inflows and outflows from the system can be predominant factors in determining the water quality (Ji 2008). This makes water quality a complicated issue to study. For that reason the current research focuses primarily on dissolved oxygen and secondarily on water temperature and turbidity because of their influence on dissolved oxygen levels. Dissolved oxygen is an important indicator for the survival of the aquatic life and is essential for many chemical reactions. Therefore, monitoring the fluctuations of the oxygen levels as well as the factors that affect theses fluctuations is important for assessing the ecological status of the water body.

Due to the limited available literature on this subject and the increased interest in integrating floating houses in urban planning, the scope of this paper is an initial investigation on the possible effects of floating houses on dissolved oxygen levels. The research will address the following statements:

- The shadow of the floating houses reduces the available sunlight, lowering dissolved oxygen levels in their vicinity due to reduced photosynthesis.
- Depending on their orientation, wind tunnel effect can be produced by the floating houses increasing the turbulence of the water. This increases the mixing in the column, which reduces the dissolved oxygen vertical gradient.
- Below the floating houses a hypoxic area is created and oxygen is transferred laterally by the adjacent water column. This lowers the dissolved oxygen levels in their vicinity.

Material and Methods

A pilot project of the Water Board of Delfland and the municipality of Delft, at Harnaschpolder, the Netherlands, will serve as a case study. Harnaschpolder is located at the west part of the Netherlands between The Hague and Rotterdam, see **Figure 2**. This area is a former greenhouse land converted to urbanization and is planned to accommodate 1300 residents. The pilot project consists of five floating houses in a shallow pond of approximately 1.5m mean depth and deepest depth of 2.5m, at the location of the floating houses. The floating houses have an immersion depth of approximately 1.6m. The total surface of the pond is 5.800 m^2, while the occupation by floating houses was set at 10% by the Water Board of Delfland.

Figure 2: Location of the floating houses in Harnaschpolder (left) and a panorama of the floating urbanization (Source: Hoogheemraadschap Delfland and own picture).

The measurement campaign took place in two periods: from July to September 2013 and from August to September 2014, while two measurement locations were chosen such that they represent a confined area (floating houses) and an open water surface. On the first measurement campaign two types of measurements were performed, namely discrete and continuous. For the discrete measurements a Hydrolab MS5 water quality multi-probe was used, see **Figure 3**, measuring at every 0.5m from the water surface, in order to obtain a vertical profile. For the continuous measurements a pair of CTD divers, see **Figure 3**, were installed in the floating houses and the open surface locations at depths 0.7 and 2.0m, measuring depth, temperature and conductivity. Finally, water transparency was measured with a Secchi disk, see **Figure 3.**

On the second measurement campaign a remote controlled underwater drone (Thunder Tiger Neptune SB-1) was employed, see **Figure 3**. The underwater drone was equipped with: (i) water quality sensors for collecting data of dissolved oxygen, temperature and turbidity, (ii) a high definition camera for collecting footage of the aquatic life below the floating houses and (iii) a CTD-driver which served as an indication of the vertical location of the drone (Lima et al. 2015).

Figure 3: Measurements equipment from left to right: Hydrolab MS5 probe, CTD diver, Secchi Disk and Thunder Tiger Neptune SB-1 underwater drone.

The observations are useful but they are not enough to describe the hydrodynamic, biological and physical processes that are involved in the water quality modelling, and in particular the dissolved oxygen budget. Additionally, to address the research questions and evaluate the measurement data it is important to understand these processes. Therefore, a numerical model will assist in this task since it can provide a higher spatial and temporal resolution and give a better insight into the contribution of each effect in the dissolved oxygen budget. The expression used in the numerical model is a simplified vertical one dimensional dissolved oxygen budget equation, see expression (1), which combines the transport of dissolved oxygen within the water column with the production and consumption of dissolved oxygen biochemical processes, see **Figure 4**.

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left(k_z \frac{\partial C}{\partial z}\right) + P + F_s - D - R - S_s \qquad (1)$$

Where: C is the dissolved oxygen concentration [mg/L], k_z is the turbulence diffusivity in the z direction [m^2/d], P is Photosynthesis [mg/(L d)], F_s is Reaeration [mg/(L d)], D is Decomposition [mg/(L d)], R is Respiration [mg/(L d)] and S is the Sediment Oxygen Demand [mg/(L d)].

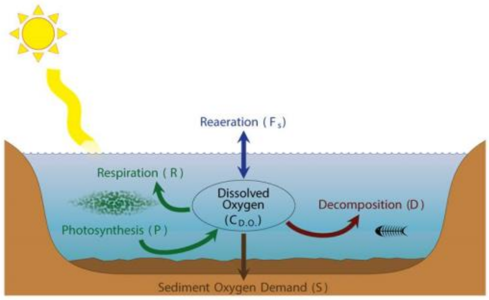

Figure 4: Conceptual model of the dissolved oxygen source/sink terms.

Results and Discussion

Throughout the measurements, the average water transparency value was 28 cm. This value is used to estimate the approximate depth up to which light penetration occurs, and consequently photosynthesis is active. As a rule of thumb, this penetration depth is equal to the double of the water transparency depth (Hasadsri and Maleewong 2012). Therefore, it is expected that the upper 56 cm of the water column will be influenced by light penetration.

The average values of the dissolved oxygen vertical profile show that during the measurement period the location situated between the floating houses exhibit the lowest values up to the first 1m, see Figure 5. These values account for a reduction of 10% (~1 mg/L) in comparison to the open space

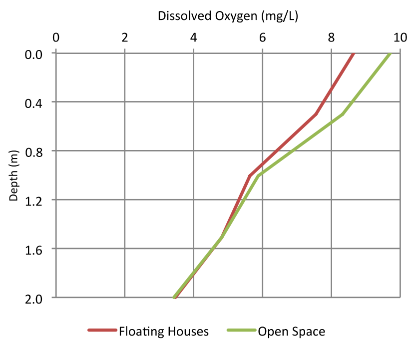

Figure 5: Averaged vertical profile of dissolved oxygen, July-September 2013.

The measurements of the underwater drone indicated that covering the water surface by the floating houses resulted in lower dissolved oxygen levels, see **Figure 6**. The differences between the open space and below the floating houses are 1.7 mg/L and 3.3 mg/L for the depths 1.5-2m and 2-2.5m respectively. Therefore there is a reduction of 19% and 40% respectively. These lower dissolved oxygen levels could be also attributed to the presence of clay sludge at the bottom of the water column, which creates anoxic conditions (Lima et al. 2015). Unfortunately, the highly turbid conditions of the water body in Harnaschpolder limited the acquisition of images of the possible development of aquatic life below the floating houses.

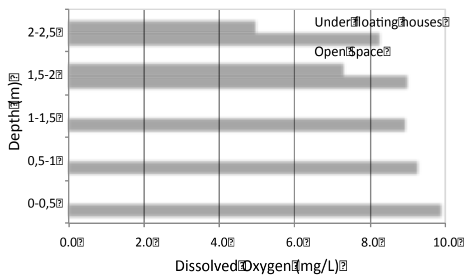

Figure 6: Average dissolved oxygen levels from drone measurements, August - September 2014.

The diurnal plots of dissolved oxygen show that although the dissolved oxygen was initially equally distributed along the vertical profile it began to deviate during the day, with the upper 0.5m of the water column having the larger variations. Additionally, in the course of the day the open space gained more oxygen than the floating houses, which can be attributed to the fact that the open space was more exposed to solar radiation than the floating houses.

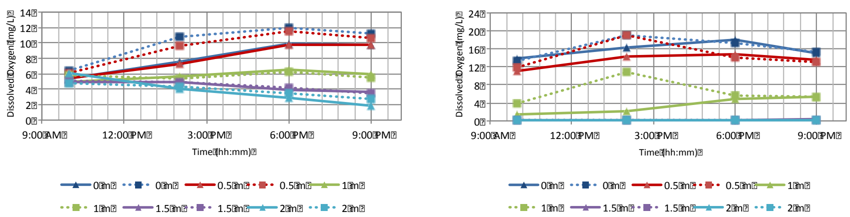

Figure 7: Diurnal Patterns of Dissolved oxygen 31st of July (left) and 2nd of August (right), (solid line: floating houses, dotted line: open space).

In order to study the influence of wind speed on dissolved oxygen levels mixing within the water column we need to have continuous and large amount of data. The only available data meeting these criteria were the water temperature measurements. Since the distribution mechanism of dissolved oxygen is similar to heat transfer (Antonopoulos and Gianniou 2003). The dissolved oxygen mixing was studied by the temperature differences of the two measuring depths at the open and floating houses locations. As can be observed in Figure 8, for the higher wind speeds we have a smaller dispersion of temperature differences, since higher winds lead to higher turbulence in the water body and in turn this enhances the mixing. Regarding the different positions and the mixing, we observe that the floating houses location has a smaller dispersion of water differences for wind speeds in the range of 6m/s and 12m/s Therefore, it appears that it is experiencing more mixing by the wind compared to the open water surface.

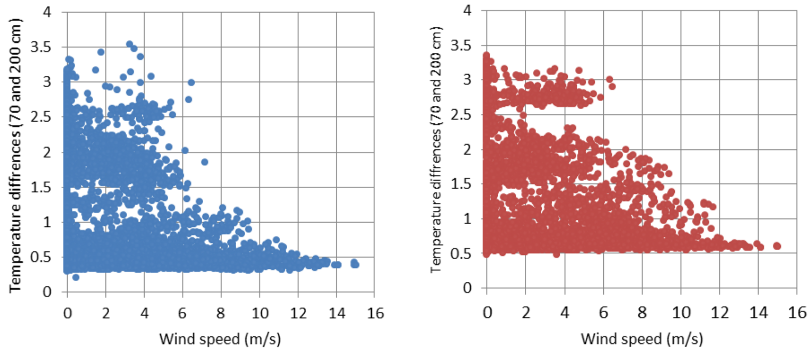

Figure 8: Correlations between wind speed and temperature differences between 70 and 200 cm in the two measuring locations (Floating houses left, Open Space right).

After calibrating the unknown parameters of the biological and chemical processes of expression (1) with the measured data, we were able to identify the main terms that contribute to the dissolved oxygen production and consumption. With this knowledge we can isolate the external factors that interfere with these terms and estimate their impacts. The two external factors in this case were the shade produced by the floating houses and the increased wind speed and diffusion coefficient due to the wind tunnel effect between two floating houses.

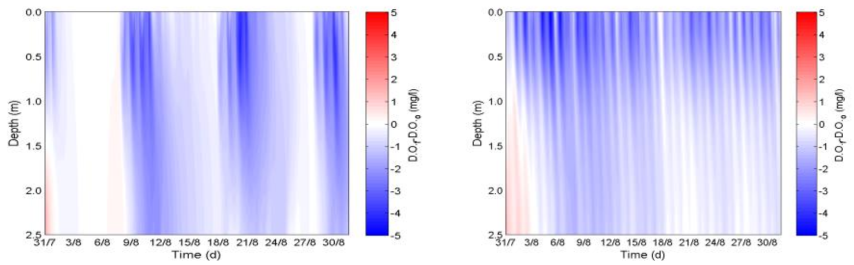

Figure 9: Numerical dissolved oxygen differences between floating houses (DO_f) and open space (DO_o) for shade effect (left) and wind tunnel effect (right).

Figure 9 left shows the results of the simulation with the shade factor. It is observed that the differences between the floating houses and the open space range between ± 1 mg/L, except from some days where the upper part of the water column between the floating developed considerably lower dissolved oxygen levels compared to open space. The results of the simulation with the wind tunnel factor are depicted in **Figure 9** right. Since both locations have the same amount of oxygen produced by photosynthesis, no shade factor, we see that the increased wind speed increased the reaeration coefficient and therefore the upper part of the water column between the floating houses developed lower dissolved oxygen levels with respect to the open space. Furthermore, the increased diffusion coefficient resulted in a higher flux of dissolved oxygen levels to the lower parts of the water column between the floating houses.

From this study it was not possible to clearly identify which of the effects is predominant. First because our model is characterised by knowledge uncertainty, and secondly because both effects take place in the same region of the water column (top layer). Furthermore, both effects play similar roles on average, changing from day to day depending on the wind speed, wind direction and available solar radiation.

Conclusions

Based on the results from the measurements at the floating houses of Harnaschpolder, the effects on dissolved oxygen level are small (~10% less dissolved oxygen between the floating houses) and are located on the upper part of the water column. The presence and orientation of the floating houses can influence the dissolved oxygen levels and water temperature on the adjacent area of the floating houses by shadow (hindering of photosynthesis) and wind tunnel effect (increased mixing), but the effect is temporary. The deprivation of oxygen exchange with the atmosphere, by the cover of the surface from floating houses, resulted in lower dissolved oxygen levels but did not reach critical conditions, less than 5mg/L. This has been confirmed at other locations as well (Boogaard and Graaf 2014).

Given the type of water body, a small shallow pond with high turbidity and low circulation flow, it is encouraging to see that during the measurement periods the water quality was not critically affected by the presence of the floating houses. However, having in mind the complexity of the interactions among the water quality parameters and the influence of the surrounding environment it is recommended to continue and improving the monitoring campaign.

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