Ecosystem and assimilative capacity of rivers with control structures

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Abstract

This research studies the impact of water level control structures on self-assimilative capacity of rivers and on their ecosystem. Constructing a water level control structure in a river reach will alter its hydraulics which will impact its water quality, thermal regime and fish habitat. A mathematical model is developed to simulate the river hydraulics, water quality, temperature, and fish habitat. The diurnal dissolved oxygen concentrations are investigated to see their impact on the fish. A case study of a Nile River reach was studied, to investigate the impact of the existence of the Esna barrage on the water quality in its upstream reach. The barrage has negative impacts on the upstream self-assimilative capacity of the rivers. The waste load that the river could take was only 54% from that load when there was no barrage and at low flow conditions. At high flow conditions this load changed to 78%. The diurnal DO variation was simulated and it was concluded that the diurnal photosynthesis has an effect on the diurnal cycle of the DO. The barrage has a positive effect on the fish habitat. The weighted usable area (WUA) of Tilapia fish is doubled in case of the barrage existence. The barrage causes a slight decrease in the water temperature. The average change in the diurnal temperature for the studied reach in the month of June is about 0.13ºC difference between the cases of existence and nonexistence of barrage.

Keywords: self-assimilative (self-purification) capacity, hydraulic structure, mathematical modeling, dissolved oxygen concentrations, photosynthesis and respiration, fish habitat, thermal regime and water temperature.

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1 Introduction

Control structures, such as weirs and barrages, constructed on a river will change the hydraulic regime of that river by increasing water depths and reducing velocities in the zones of developed backwater curves. This modified hydraulic regime impacts water quality due to changes in the transport and decay processes of pollutants along the rivers. Thus the pollutants' load will have different impact on the water quality after constructing the control structure as compared to its preconstruction stage. The modified hydraulic regime also impacts the thermal regime and the fish habitat in the river.

Although the construction of dams across rivers, usually entail in-depth socio-economic and environmental impact studies, water level control structures are usually governed by their economic feasibility with limited attention to their in-stream environmental impacts. An example of the studies done on the economic impacts of dams is the one done by Mc Cully [1], which studied in detail the economic and political aspects of large dams. Numerous researchers investigated the effects of hydraulic structures, which create impoundments behind them like dams, on the water quality. Hildyard et al. [2] as an example studied the environmental effects of large dams. There were rare studies investigating the effect of the water level control structures, such as, barrages and weirs on the water quality and its ecosystem. Eid [3] is among the rare researchers who investigated the impact of barrages on both water quality and fish habitat in rivers. However Eid used a simplified prismatic river section and considered only atmospheric reaeration and ignored photosynthesis. Eid studied the impact of barrages on fish habitat but the study was done on a theoretical fish. Many studies such as by Song et al. [4] and Candara et al. [5] were done to simulate water temperatures from air temperatures, but they didn't imply the effect of hydraulic structures on the water thermal regime. Eid studied this impact, but the simulated water temperature was assumed to obey a linear relation and the lag time between water and air temperature wasn't considered.

This paper studies the impact of water level control structures on the self-assimilative capacity of rivers and assesses possible changes in their ecosystem and fish habitat. In order to do so, water quality indicators were developed aiming to express the impact in a quantifiable manner.

2 River simulation model

The impact of constructing a water level control structure across a river is numerically modeled. The model consists of two main sub-models; a hydraulic sub-model and a water quality sub-model. The water quality sub-model consists of a dissolved oxygen simulator along with its components such as biological oxygen demand, reaeration, photosynthesis, and respiration. Two additional sub-models were developed; the temperature sub-model; and the fish habitat sub-model.

2.1 Hydraulic sub-model

The hydraulic sub-model simulates backwater curves, velocities and areas for a controlled river reach of any geometrical shape using the standard-step method.

2.2 Dissolved oxygen (DO) sub-model

The DO sub-model simulates all available sources and sinks (except NBOD and SOD). A mass-balance equation is solved as follows:

$$C_{i+1} = C_i + \frac{\overline{A}\Delta x\left\{\overline{P_a} + \overline{K_a\left(C_s - C\right)} - \overline{K_d L} - \overline{R}\right\}}{Q_i} \tag{1}$$

where; C_i and C_{i+1} = DO concentrations at sections i and $i+1$ in mg/L respectively; $\overline{A}$ = average flow area at sections i and $i+1$ in m^2 ; Δx = length increment in m; Q_i = river flow rate in ${m^3}/{day}$, $\overline{P_a}$ = average daily O_2 production due to photosynthesis mgDO/L.day, K_a = volumetric reaeration coefficient in day^{-1}, K_d = decomposition rate of CBOD, C and C_s = actual and saturation DO concentration in mg/L, L = average ultimate CBOD concentration, and R = DO depletion due to respiration in mgDO/L.day

The sources and sinks of eqn (1) are averaged over Δx, and calculated as follows: The Carbonaceous Bio-Chemical Oxygen Demand (CBOD) at the end of Δx is estimated from L_i and the average decay or loss rate "K_r" in Δx by

$$L_{i+1} = L_i e^{-K_{r_{i+1}}\left(\frac{\overline{A}\Delta x}{Q_i}\right)} \tag{2}$$

The average K_r accounts for both the decomposition rate of CBOD in stream, K_d , and the settling rate of CBOD, K_s .

$$K_r = K_d + K_s \tag{3}$$

The decomposition rate K_d is estimated by Thomann [6] as a function of the average water depth, y in meters.

$$K_d = 0.3\left(\frac{Y}{8}\right)^{-0.434} \tag{4}$$

The settling rate K_s is related to the settling velocity of the suspended organic matter in m/day Chapra [7]:

$$K_s = \frac{V_s}{Y} \tag{5}$$

The exchange of air at the water surface makes use of the "two film theory" and its rate is estimated from Thomann [6]:

$$\text{Reaeration} = K_a\left(C_s - C\right) \tag{6}$$

The volumetric reaeration coefficient, K_a is calculated using the O'Connor-Dobbins formula:

$$K_a = 3.93\frac{V^{0.5}}{Y^{1.5}} \tag{7}$$

where; V = average velocity in m/s; and Y = average depth in m.

The essence of photosynthetic process centers about chlorophyll $_a$ containing plants which utilize radiant energy from the sun, convert water and carbon dioxide into glucose, and release oxygen. Thus production of oxygen proceeds only during daylight hours. The variation of light and hence photosynthesis can be idealized by a half sinusoid function, from day to day. Thus swings in oxygen can be induced by diurnal light variations. The photosynthesis over the control volume is estimated by Thomann [6]:

$$P_a = \left[a_{op} G_{\max} (1.066)^{T-20} P \right] G(I_a) \tag{8}$$

where; P_a = average daily growth production (photosynthesis) in mgDO/L.day; a_{op} = mg of DO per µg of chlorophyll $_a$; P = phytoplankton chlorophyll in µg/L; $G_{\max}$ = maximum growth rate of the phytoplankton at 20ºC in day^{-1}; T = water temperature in ºC; $G(I_a)$ =light attenuation factor over depth and one day (Unitless)

Respiration is the process by which organisms take up oxygen and discharge carbon dioxide in order to satisfy their energy requirements and is estimated by:

$$R = a_{op} (0.1)(1.08)^{T-20} P \tag{9}$$

where; R= phytoplankton respiration in mgDO/L.day.

In addition to the atmospheric reaeration that occurs in the river, another reaeration process takes place across control structures. The control structure will form a hydraulic jump in the water and thus allows more air to enter into the stream. This process has a positive effect on the DO concentration at the downstream side of the structure. Structure reaeration is calculated by Gameson's equation: Alabama Department of Environmental Management [8]

$$r = 1 + 0.11(a)(b)(1 + 0.046(T))\,\mathrm{h} \tag{10}$$

where; r = ratio of upstream DO deficit to downstream deficit; a = water quality factor; b = structure aeration coefficient; T = water temperature, ºC; h = water level difference across the dam, ft

2.3 Temperature sub-model

Water temperature is vital for fauna and flora of water; and for chemical and biological reactions in rivers. Water temperature depends on air temperature and on hydraulic parameters of rivers; such as, depth of water, and geometry of river sections. Constructing a water level control structure alters the hydraulic regime of water and thus may alter its thermal regime.

Heat transferred at the air-water interface is the major factor that induces variation in water temperature. Response coefficients representing the rate of water temperature variation with respect to the air temperature variation were found to correlate well Song [4].

Candara et al. [5] studied some rivers in Texas and concluded that large streams have a small diurnal temperature change. Water temperature and its change depend on the water depth. Heinz et al. [9] revealed that the time lag which exists between the air and water temperatures varies linearly with the depth of the river. He studied water temperature simulation as a result of the lag time between the air and the water temperatures. The study was on 11 streams in the central U.S. (Mississippi River basin) and a linear equation correlating seasonal water temperature to seasonal air temperature was formed. Diurnal simulation of water temperature using air temperature was done by expanding the equation of Heinz et al. [9] to accommodate the diurnal water temperature changes. This is described via eqns (11) to (13)

$$Tw(t) = A + \frac{\Delta Tw}{\Delta Ta} * Ta(t-\delta) \tag{11}$$

where; the time t and the time lag δ are in units of days and temperatures are in °C. This equation shows that the water temperature calculated at time t is a function in the air temperature at the time t less the lag time. To calculate the lag time δ the following equation is used:

$$\delta = \frac{\tau}{2\pi} * \tan^{-1}\left(\frac{2\pi * depth}{\tau * \alpha}\right) \tag{12}$$

where; τ = cyclic period over which the study is done (here 24 hours); α = thermal diffusivity coefficient: $\alpha = \frac{K}{C_p * \rho}$; K = Surface heat exchange conduction coefficient between the air and the water in W $/m^2$.°C; Cp = the specific heat of water in W.S/kg. C ; ρ = density of water in kg/m^3 ;

$$\frac{\Delta Twater}{\Delta Tair} = \frac{1}{\sqrt{1+\left(\frac{2*\pi*depth}{\tau*\alpha}\right)^2}} \tag{13}$$

2.4 Fish habitat sub-model

Fish is affected greatly by the hydraulic parameters; such as, depth and velocity of water which are affected by water level control structure. In this research the Tilapia genus of fishes is studied because it is the most widely spread fish in the Nile in Egypt. The general theory behind fish habitat modeling is based on the fact that aquatic species will react to changes in the hydraulic environment. The indication of the effect of the water level control structure on the fish habitat is expressed as the weighted usable area that the fish will live in. A suitability index measures the conditions that are suitable for the fish to live under. It has an upper bound "1" which reflects the optimum conditions for a certain kind of fish, whereas, the lower bound "0"represents the critical conditions for the fish. Fish habitat is assessed by three suitability indices accounting for depth, velocity and substrate availability. Calculation of the 2-D velocity distribution across a section; as well as, the average velocity of the section is carried out using Manning's equation with the local depth within a particular cell Habitat Modeling [10]. The weighted usable area reflecting fish habitat(is weighted according to the load of each suitability index parameter) and is given by:

$$WUA = \sum_{j=1}^{n} A_{cell_j} * d_{index_{cell_j}} * V_{index_{cell_j}} * S_{index_{Cell_j}} \tag{14}$$

where S is the substrate (food).

3 Assessment of the self-purification capacity and ecosystem

The self-purification capacity of a river is its capacity to accept different waste load concentrations without significantly changing its original quality. To assess the impact of water level control structures on the self-assimilative capacity of rivers in a quantifiable manner, many indicators were developed.

Waste loads from point sources at different sections along that river are introduced and DO concentrations in the river are kept at a constant level of 5mg/L. Waste loads are estimated at different hydraulic cases.

The effects of temperature and photosynthesis on the diurnal DO variation are tested. Downstream DO concentration as a result of reaeration across the water level control structure is also calculated.

The presence of a water level control structure in a river or a waterway not only affects the water quality of that river, but it also affects the whole environment and ecosystem in the reach where it was constructed. So as indicators to this impact, the fish habitat and the thermal regime of the river are studied. Water temperature is important because it affects the biological and chemical processes in the water and thus the CBOD and the DO concentrations. Existence of a water level control structure will alter water temperature in a controlled river reach. To study this effect, the diurnal change in water temperature is simulated for the four main hydraulic cases.

Each kind of the fish has its own physical conditions, such as water velocity and depth and the substrate (food) of fish, under which it can best survive. Water level control structures in rivers alter their hydraulic regime and hence the physical factors that affect the fish population. This effect is assessed through calculating the WUA of fish for both cases of existence and non-existence of the structure.

4 Case study Nile River (Aswan-Esna reach)

The case study investigates the effect of Esna barrage on the water hydraulic regime; as well as, on water quality upstream the barrage from Esna to Aswan.

4.1 Hydraulic simulation of Aswan-Esna reach (upstream the barrage)

The Esna-Aswan reach is 157.9 km long. The peak discharge of the High dam is about 2500 m^3/s (high flow) and occurs in July, whereas, the minimum discharge is about 1500 m^3/s (low flow) and occurs in January. Available river sections are every 5 km and interpolation was used to generate sections every 100 m in order to do hydraulic calculations via the standard step method in an accurate way. Manning coefficient is assumed to be constant (n=0.0287) throughout the simulated reach. The studied reach was simulated under four main hydraulic cases: Cases 1 and 2 study the existence and the non-existence of Esna barrage respectively at low flow conditions; Cases 3 and 4 study the existence and non-existence of barrage respectively at high flow conditions.

4.2 Self-purification capacity and waste load at Aswan-Esna reach

Two scenarios were simulated to compare between different cases of waste loadings (W.L). Scenario 1 uses the DO as a function of only CBOD and reaeration. Scenario 2 adds photosynthesis and respiration to the DO. Figure 1 shows an example of waste load distributions over the studied reach. Table 1 summarizes all the waste loading cases. Figure 1 shows the distribution of the waste loads over the studied reach for case 1 and scenario 1.

Table 1: Simulation of the waste loads for different scenarios.

	Case 1	**Case 2**	**Case 3**	**Case 4**
W.L(kg/day)	1405	2612	2118	2705
	Scenario 1	Scenario 1	Scenario 1	Scenario 1
W.L(kg/day)	5684	6218	10971	11768
	Scenario 2	Scenario 2	Scenario 2	Scenario 2

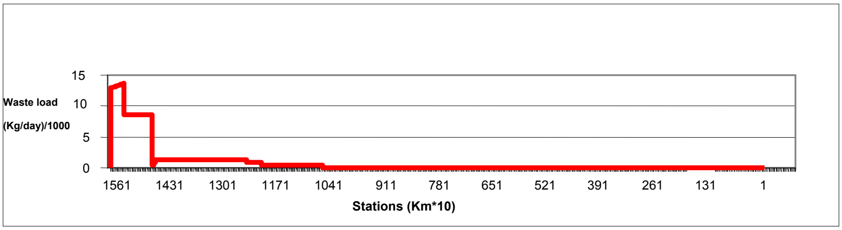

Figure 1: Waste loads at case 1 and scenario 1.

4.3 Diurnal dissolved oxygen

DO concentration changes during the 24 hours of the day because of change in water temperature and the change in photosynthetic action of plants throughout the day. Minimum DO concentrations usually occur in the early morning, and maximum concentrations occur in the early afternoon. In the simulation a section with average properties (hydraulically and water quality) was taken using simulated diurnal water temperature. The simulation compared the diurnal DO at cases of existence and non-existence of the barrage. To see the effect of the photosynthesis on the diurnal DO, a trial was done using only the CBOD and the reaeration in calculating the DO as opposed to another trial using the photosynthesis.

4.4 Reaeration across the barrage (downstream DO concentrations)

Gameson equation simulated DO concentrations downstream of the barrage. The calculations which are done under low flow conditions revealed an upstream DO concentration of 8.02 mg/L, an upstream DO deficit/ downstream DO deficit of 3.90, and a downstream DO conc. of 8.49 mg/L.

4.5 Simulation of the ecosystem at the Aswan-Esna reach--- fish habitat

The weighted usable area (WUA) of Tilapia fish was calculated in both cases of barrage existence and non-existence. Suitability indices of depth and velocity for Tilapia were constructed based on actual values. Substrate of Tilapia consists for the greatest part of phytoplankton which dwells in the first 1.5 m below water surface. Thus the optimum depth for Tilapia is 1.5 m. The critical depth is 9 m. The optimum velocity is 0.3 m/s, and the critical is 0.6 m/s. The suitability index for the substrate is taken as unity. The WUA in case 1 is 31236.8 m^2, whereas in case 2 it is 17061.93 m^2. Figure 3 compares between the WUA of cases 1 and 2 for the whole studied reach. The curve of case 1 is always higher than that of case 2.

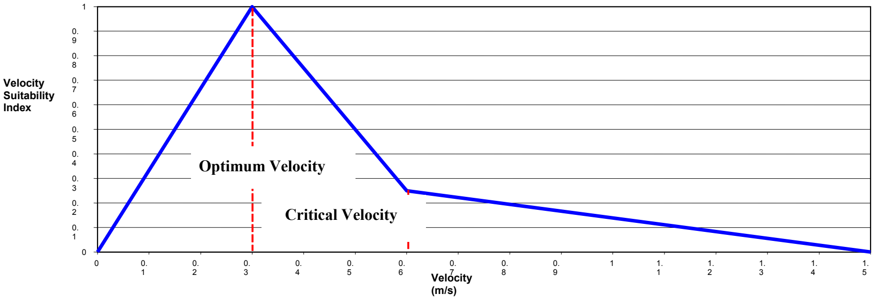

Figure 2: The velocity suitability index for the Tilapia fish.

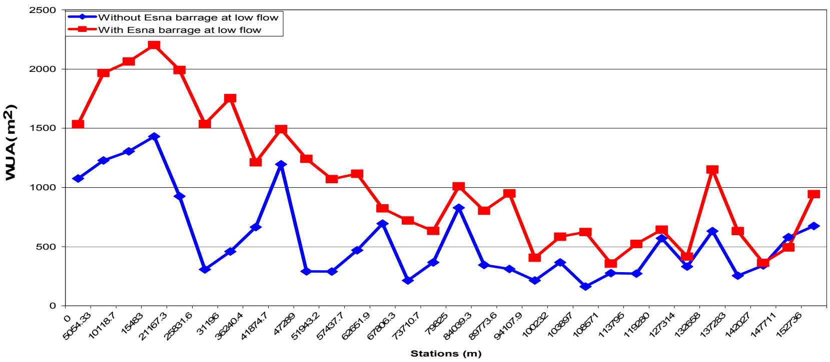

Figure 3: WUA of Tilapia in both cases of with and without Esna barrage.

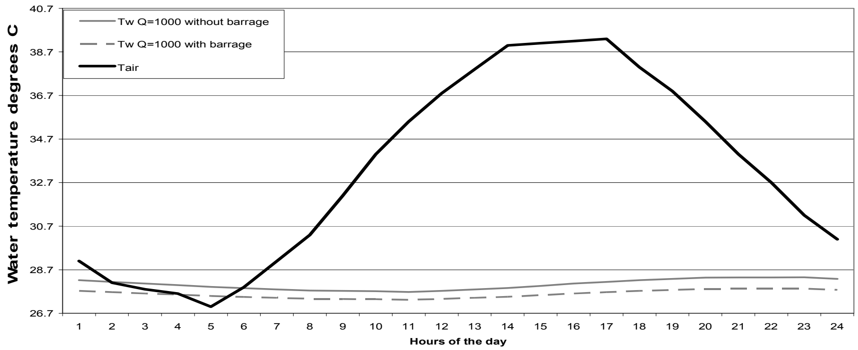

Figure 4: Diurnal air and water temperature at the average section and for the cases of with and without barrage at low flow.

4.6 Simulation of the water temperature

The effect of Esna barrage on the thermal regime of water was tested. The simulation of the diurnal variations in the water temperatures on a day of the month of June was done for one section that is representative for the whole reach. This section is taken as the section with the average depth throughout the whole reach. The simulation is done for the previously mentioned, four main hydraulic cases. It is observed that the sinusoidal diurnal water temperature curve follows the air temperature curve but with a lag time between water and air temperatures. This lag time increases with increased depth. Figure 4 shows the diurnal air temperature curve along with the diurnal water temperature curves at both cases 1 and 2. In case 1 the lag time between air and water temperatures is 5.842 hours, whereas in case 2 it was 5.791 hours. The curves show that in case 2 the diurnal water temperature is higher than in case 1. So in case 2 the maximum water temperature during the whole day is 28.4°C, whereas in case 1 it decreases to reach 27.8°C. This indicates that the existence of the barrage causes a decrease in water temperature. When operating under high flow conditions the diurnal water temperature further decreases. So in case 4 the maximum water temperature during the whole day is 27.5°C, whereas in case 3 it decreases to reach 27.3°C.

5 Summary and conclusions

The drawn conclusions are general for any water level control structure, but the calculated percentages are of the Esna barrage case study:

1. The barrage has negative impacts on upstream self-assimilative capacity of rivers. In case of barrage existence, the waste load that the river could take was only 54% from that load when there was no barrage and at low flow conditions. At high flow conditions this load changed to 78%. Those results were obtained when only considering the CBOD and the reaeration effects. When adding the effect of the average daily photosynthesis, and respiration the percentages were changed to be 91% and 93% respectively. Thus photosynthesis has positive effect on the self-assimilative capacity of water; also high flow conditions will lesson the negative effects of the barrage. As for the diurnal DO variations, it is found to be affected by diurnal water temperatures and photosynthesis values.
2. The barrage raises the DO concentration downstream by 6% from its upstream concentration value.
3. The barrage causes a slight decrease in diurnal water temperature. The average change in diurnal temperature between the cases of with and without barrage is 0.13°C and at high flow and 0.44°C at low flow respectively.
4. The WUA of Tilapia was doubled in case of having the barrage.

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