International Journal of GEOMATE, May., 2021, Vol.20, Issue 81, pp.146-152
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2021.81.GX315
Geotechnique, Construction Materials and Environment

# INFLUENCE OF LIGHT ON A MICROBIAL RIVER WATER ECOSYSTEM AND ITS SELF-PURIFICATION POTENTIAL

*Fumitake Nishimura[1], Yuki Koike [2] and Michiko Masuda [3]

[1] Department of Environmental Engineering, Kyoto University, Japan; [2] Department of Civil and Environmental Engineering, Ehime University, Japan; [3] Department of Civil Engineering, Nagoya Institute of Technology, Japan

*Corresponding Author, Received: 17 July. 2020, Revised: 31 Aug. 2020, Accepted: 13 Jan. 2021

**ABSTRACT:** Self-purification in rivers is mainly conducted by microorganisms attached to the river bed. To enhance the self-purification capacity, several processes or technologies have been proposed to improve the river water quality and preserve biodiversity. From the environmental engineering perspective, finding influential parameters and their effective control are effective in improving river water quality. However, there are numerous parameters affecting the self-purification capacity of rivers, and quantitative evaluations of these parameters have not been completed. In this study, the influence of light on both the microbial river water ecosystem and its self-purification capacity were investigated. Lab-scale experimental facilities (artificial river) were set, and artificially contaminated river water was introduced to the system. Furthermore, through a mass balance analysis, we realized that the clean river water conditions might be affected more by sunlight compared to water contamination; this is due to the large relative intensity of organic carbon loading by photosynthesis.

*Keywords: Self-purification, River ecosystem, Mass balance analysis, Photosynthesis*

## 1. INTRODUCTION

To preserve the water environment in both urban and catchment areas around a river section, sewerage is an important facility and plays an important role. However, sewerage development requires not only a considerable development cost, but also a long time. For example, it took 38 years to increase the coverage from 30 % (at the end of FY1980) to 79 % (at the end of FY2018) in Japan [1]. In areas where the sewerage system has not been developed, the ratio of domestic contaminants to the total contaminant load into enclosed water areas, such as lakes and inner bays, is higher [2]. Furthermore, reducing the amount of contaminant discharged by individual households is difficult; therefore, direct purification in rivers, channels, lakes, and bays is being carried out to reduce the loading rate until new developments emerge for sewerage systems [3,4]. Among the direct purification methods, the contact oxidation process has attracted attention and has been adopted in many places because it enhances the natural purification function and appears to be environment-friendly [5]. However, good results are not always obtained because proper design and operating factors have not been sufficiently clarified. Operational and design parameters in the system are the inlet water quality, water flow rate, hydraulic retention time (HRT), dissolved oxygen concentration (DO), and water temperature. Light irradiation is one such type, where, during the direct purification process in the river, it is practically not designed to block sunlight. There are some cases where light irradiation has been examined as a design factor in the design of direct purification [6–8], but few cases and studies, including treatment processes, have not been sufficiently conducted. However, the effects of light (mainly visible light) on the treatment results should be fully considered, taking photosynthesis into account.

In this study, we investigate the effects of light irradiation on biota, which is the main component of purification, during the treatment process using a laboratory-scale contact oxidation system. The amount and number of microorganisms in the treatment process, their activity, DO, and the concentration of organic and inorganic substances in the treated water were monitored to evaluate the effects of light.

## 2. MATERIALS AND METHODS

The schematic of the experimental equipment is shown in Fig. 1. The experimental water channel was made of acrylic and the width, height, and length of the channel were 1, 4, and 200 cm, respectively. In the water channel, a fiber carrier (Chisso Filter Co., Ltd., Japan, material: polyethylene/polypropylene mixture, fiber length of 64 mm, specific gravity of 0.90 to 0.96, which is

easy to fix for retaining biota) was packed. The thickness of the incorporated fiber carrier was 1 cm and attached to the channel bottom. The packing density of the fiber carrier was 0.031 g/cm$^3$. The organisms used in this study were collected from Okawa, Miyamae River, and irrigation channels in Matsuyama City, Ehime Prefecture, Japan, which were inoculated at 25 cm intervals from upstream to downstream. Three experimental channels were prepared, two of which were set under the light conditions (hereinafter referred to as cases L-1 and L-2) while the other was set under dark conditions. (hereinafter referred to as Case D). These three channels were installed on the same shelf, and the entire shelf was surrounded by a blackout curtain. Under the light conditions, white fluorescent lamps were used to irradiate the upper part of the channel with an illumination intensity of 3000 Lux every 12 h. Under dark conditions, the water channels were covered with aluminum foil to block the light. The water temperature in the water channel was set to 25 °C by contacting silicon tubes on both sides of the water channel (inner diameter: 8 mm × outer diameter: 1 mm) with circulating water at 30 °C inside the tube. Table 1 lists the composition of the artificial wastewater used in these experiments. The wastewater continuously flowed into the experimental channels at a rate of 100 mL/h. The dissolved organic carbon (DOC) of the artificial wastewater was set to 20 mgC/L, assuming a small-to-medium-sized river in a city where sewerage development was delayed. HRT was estimated to be 188 min as a result of the tracer experiment using NaCl, which indicated that the average water level of the channel was 1.56 cm. The experimental equipment was operated for 90 days during the winter season.

Table 1 Composition of artificial wastewater

| Substrate | Concentration | Substrate | Concentration |
|---|---|---|---|
| NaCl | 1.32 mg/L | $NaHCO_3$ | 38.3 mg/L |
| $KH_2PO_4$ | 3.72 mg/L | $MgSO_4 \cdot 7H_2O$ | 1.64 mg/L |
| KCl | 2.68 mg/L | Dextrin | 15.2 mg/L |
| $NH_4Cl$ | 19.1 mg/L | Bacto peptone | 32.7 mg/L |

The DOC was measured as the amount of dissolved organic matter in each channel, and the number of viable and total bacteria were measured as the amount of biomass over time. Then, on day 90, to understand the conditions inside the channel in detail, the channel was divided into four sections, i.e., I to IV, as shown in Fig. 2, from the artificial wastewater inflow section. For the division of the sections, visual observation of both the algae green density and water depth in the channel on day 73 were considered. The suspended solids (SS), viable cell count, total cell count, zooplankton population, Chl-*a* concentration, and total dehydrogenase activity of each category were measured. For the measurement of the number of bacteria and zooplankton population, the sampling points shown in Fig. 3 were provided in each compartment. Syringes were used for the sampling. Samples mixed with dissolved and suspended matter from both the fiber carrier and channel wall were collected and used for the measurement of SS, Chl-*a* concentration, and total dehydrogenase activity.

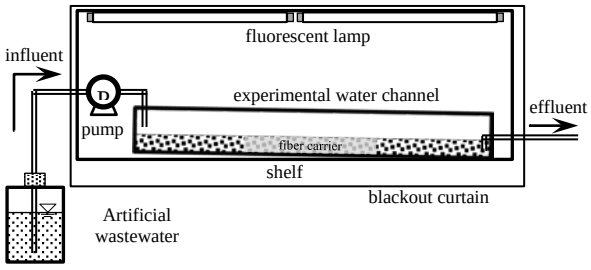


Fig. 1 Schematic diagram of experimental setup

## 3. RESULTS AND DISCUSSION

### 3.1 Removal capacity of organic matter and accumulated materials in channels

Fig. 4 shows the daily change in the DOC in the inflow and outflow water of each case. From day 3 after the start of the experiment, the DOC almost the

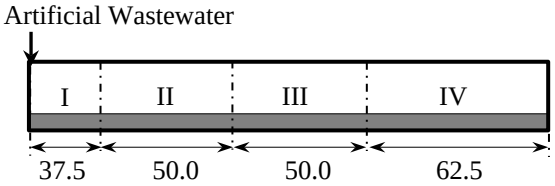


Fig. 2 Section of the waterway (unit: cm)

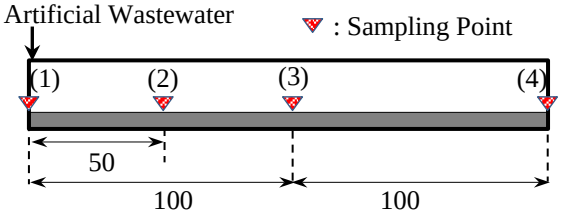


Fig. 3 Points of sampling (unit: cm)

ranged from 3 to 6 mg C/L, and there was no difference in the removal efficiency of organic substances in the entire channel resulting from the effect of light irradiation.

Fig. 5 shows the SS and its composition in each section. Under dark conditions, the SS increased slightly in section II, but decreased as it flowed down. At light conditions, it did not decrease as much as at the dark condition, whereas in some sections it increased to the same level in sections III–IV. The amount of accumulated organic matter in the entire canal ranged from 120 to 130 mg C in the two cases under the light condition, whereas the amount in the dark condition was 50 to 60 mg C, which was approximately 50 % or less than the light condition. We suggest that organic matter easily accumulates under light conditions due to photosynthesis.

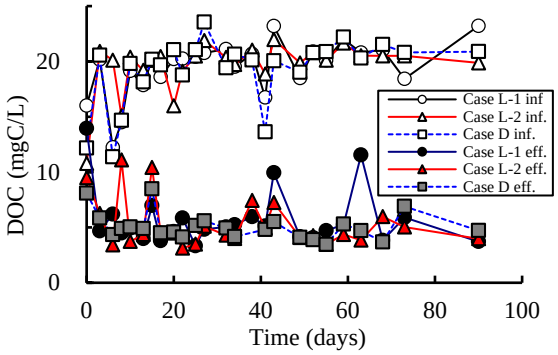


Fig. 4 Time series of DOC in the influent and effluent

### 3.2 Biota in the channel

Fig. 6 shows the total and viable cell counts at each section. There was no difference in the total and viable cell counts under both dark and light conditions, and the numbers decreased as they flowed downstream. Between sections I and IV, the number of viable cells decreased by one order of magnitude and the total number of cells decreased by two orders of magnitude. In section I, where the loading rate of the organic matter load was higher, the environment became anaerobic, whereas under light conditions, the presence of purple bacteria was

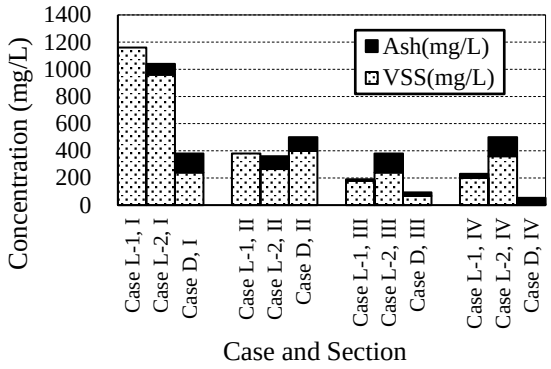


Fig.5 SS and its composition at each section

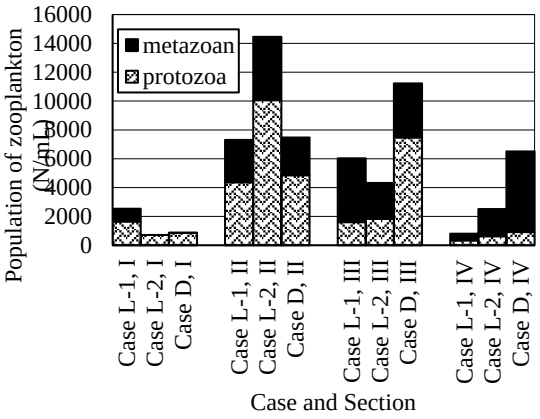


Fig.7 Population of zooplankton at each section

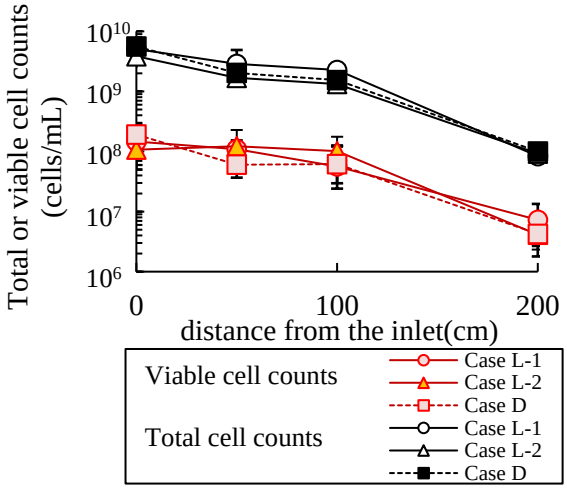


Fig. 6 Total and viable cell counts at each point

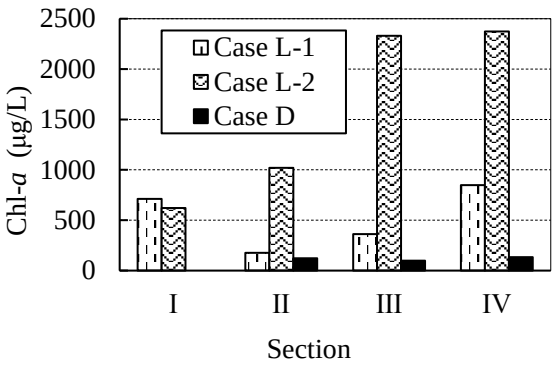


Fig. 8 Concentration of Chl-*a* at each section

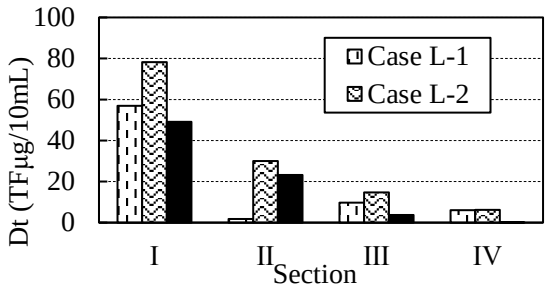


Fig. 9 Dehydrogenase activity at each division

observed.

Fig. 7 shows the population of zooplankton. In section I, the population tended to be small in all cases. We considered that it was difficult for zooplankton to live in section I owing to the anaerobic condition. The proportion of metazoans increased as they flowed under both light and dark conditions.

The Chl-*a* concentration at each division is shown in Fig. 8. A greater number of algae was confirmed in section IV, where the organic matter load was low. The algae inoculated at the beginning of the experiment remained in sections II to IV. We considered that the main component of SS in sections I and IV was microbial communities and algae, respectively. Fig. 9 shows the total dehydrogenase activity in each section. The activity

Table 2 Expression of the carbon conversion of the standing crop

| Symbol | Item | Equation |
|---|---|---|
| $C_P$ | Algae | $C_P = b \cdot (P/1000) \cdot (V/1000)$ |
| $C_B$ | Bacteria | $C_B = B \cdot a \cdot w_B \cdot V$ |
| $C_{Z1}$ | Protozoa | $C_{Z1} = Z_1 \cdot a^* \cdot w_{Z1} \cdot V$ |
| $C_{Z2}$ | metazoan | $C_{Z2} = Z_2 \cdot a^* \cdot w_{Z2} \cdot V$ |
| $C_O$ | Abiotic organic matter | $C_O = D_1 \cdot (V/1000)$ |

*: (C/protozoan dry weight), (C/bacterial dry weight) were used for (C/metazoan dry weight)

Table 3 Carbon transfer process and expression

| Process | Equations |
|---|---|
| Death of bacteria | $R_1 = k_B \cdot w_B \cdot a \cdot B$ |
| Death of algae | $R_2 = k_P \cdot (P/1000) \cdot (V/1000) \cdot b$ |
| Death of protozoa | $R_{3\text{-}1} = k_{Z1} \cdot w_{Z1} \cdot a \cdot Z_1 \cdot V$ |
| Death of metazoan | $R_{3\text{-}2} = k_{Z2} \cdot w_{Z2} \cdot a \cdot Z_2 \cdot V$ |
| Degradation of abiotic organic matter by bacteria | $R_4 = B \cdot r_1 \cdot V$ (assuming 1 cell = 1 CFU) |
| Predation of algae by metazoans | $R_5 = a \cdot r_2 \cdot Z_2 \cdot w_{Z2} \cdot V$ In case $R_5 > C_P$, $R_5 = A \cdot r_3 \cdot (V/1000)$ |
| Primary production by algae | $R_6 = r_4 \cdot c \cdot (P/1000) \cdot (V/1000)$ |
| Bacterial predation by zooplankton | $R_7 = r_5 \cdot a \cdot Z \cdot V$ |
| Inflow into the section | $R_8 = D_1 \cdot (Q/1000) \cdot 24$ |
| Outflow to the outside | $R_9 = D_2 \cdot (Q/1000) \cdot 24$ |

*A*: Algal biomass/algal biomass (literature value)( = $C_P/e$)
$D_1$: DOC at the previous section (mgC/L)
$D_2$: DOC in the effluent (mgC/L)
*P*: Chl-*a* (μg/L)
*B*: viable bacteria count (CFU/mL)
$Z_1$: Protozoa population (N/mL)
$Z_2$: Metazoan population (N/mL)
*Z*: Zooplankton population (N/mL) (= $Z_1 + Z_2$)
*V*: Volume of the section (mL)
*Q*: flow rate (mL/h)

Table 4 Literature values for the calculation of the carbon transfer and storage

| Symbol | Content | Values | reference |
|---|---|---|---|
| $k_B$ | Rate constant of self-decomposition (Bacteria) | 0.25 (1/d) | [9] |
| $k_P$ | Rate constant of self-decomposition (Algae) | 0.007–0.07 (1/d) | [9], [10] |
| $k_{Z1}$ | Rate constant of self-decomposition(protozoa: Ciliata) | 0.15 (1/d) | [12] |
| $k_{Z2}$ | Rate constant of self-decomposition (metazoan: Rotatoria) | 0.15 (1/d) | [12] |
| $r_1$ | Intake activity of organic compounds by bacteria | 1.2–7.7 ($\times 10^{-12}$mgC/(cell·d)) | [13] |
| $r_2$ | Filtration rate of rotifer | 0.6–1.5 (1/(mgDW·d)) | [14] |
| $r_3$ | Carbon transfer rate with intake of algae by zooplankton | 0.000045 (mgC/d) | [15] |
| $r_4$ | Primary production rate | 53.0 (mg-carbohydrate/(mgChl-*a*·d)) | [16] |
| $r_5$ | Predation rate of bacteria by zooplankton | 0.000012 (mgBacteria/(N-zooplankton·d) | [17] |
| $w_B$ | Dry weight of bacteria | | [18] |
| | (*Escherichia coli*) | $4.0 \times 10^{-10}$ (mg/cell) | |
| | (*Alcaligenes faecalis*) | $5.56 \times 10^{-10}$ (mg/cell) | |
| $w_{Z1}$ | Dry weight of protozoa (Ciliata) | | [18] |
| | (*Colpoda steinii*) | $1.20 \times 10^{-6}$ (mg/N) | |
| | (*Tetrahymena pyriformis*) | $1.39 \times 10^{-6}$ (mg/N) | |
| | (*Colpidium campylum*) | $1.60 \times 10^{-6}$ (mg/N) | |
| | (*Vorticella microstoma*) | $3.85 \times 10^{-6}$ (mg/N) | |
| $w_{Z2}$ | Dry weight of protozoa (Ciliata) | | [19] |
| | (*Brachionus angularis*) | $8.9 \times 10^{-5}$ (mg/N) | |
| *a* | C/(Dry weight of bacteria) | 0.531 | [20] |
| *b* | C/Chl-*a* | 49 | [21] |
| *c* | C/carbohydrate | 1.1 | [21] |
| *e* | Algal amount | 0.0009 (mgC/L) | [15] |

tended to be higher under light conditions, and the difference in sections III and IV was notable.

### 3.3 Carbon balance in the channel

Considering these experimental results, we can conclude that the treated water quality did not differ between light and dark conditions; however, the amount of organic carbon accumulated in the channel was higher under light conditions than under dark conditions due to photosynthesis. In particular, we suggest that the effect of light cannot be ignored when the amount of inflowing organic matter is small and the load due to photosynthesis is large.

Fig. 10 and 11 show the carbon balances of cases L-2 and D in section IV, respectively. Boxes indicate living organisms and abiotic organic matter that compose the ecosystem while arrows indicate the carbon transfer rate. The numbers attached to the arrows and boxes indicate the ranges in the quantity of each process or state variables. The box size and thickness of the arrow are based on each quantity. The extant amount was calculated using the carbon conversion formula listed in Table 2 based on the measured value. The inflow and outflow amounts are actually measured values. The amount of carbon transfer was calculated using the formula listed in Table 3 based on each existing amount. Table 4 lists the literature values used to determine each quantity.

The abundance of algae was approximately 10 times larger under light conditions than under dark

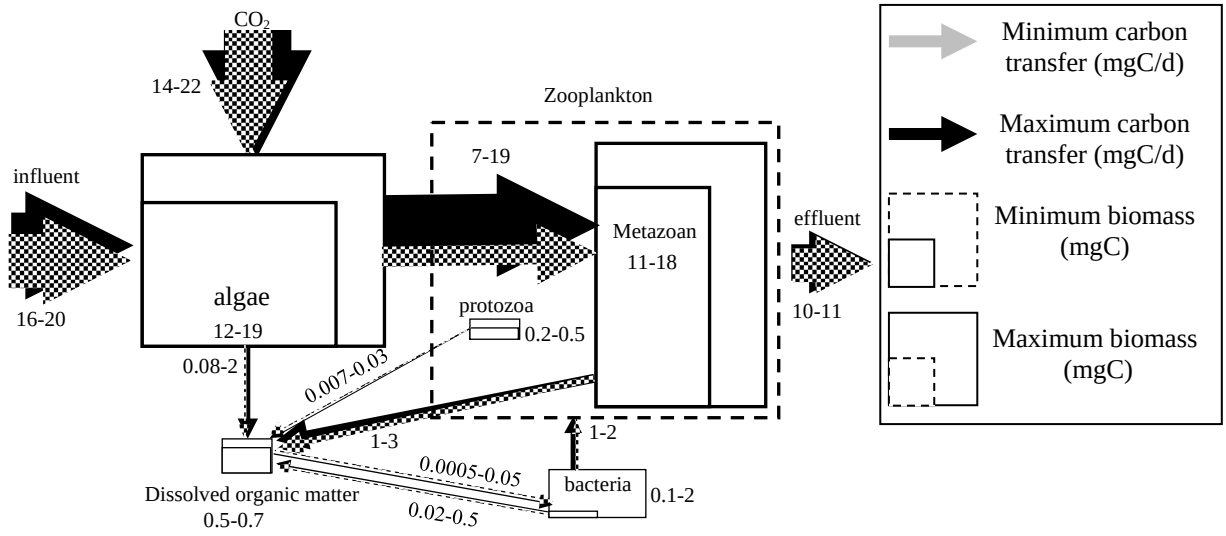


Fig. 10 Mass balance of carbon (Case L-2, section IV)

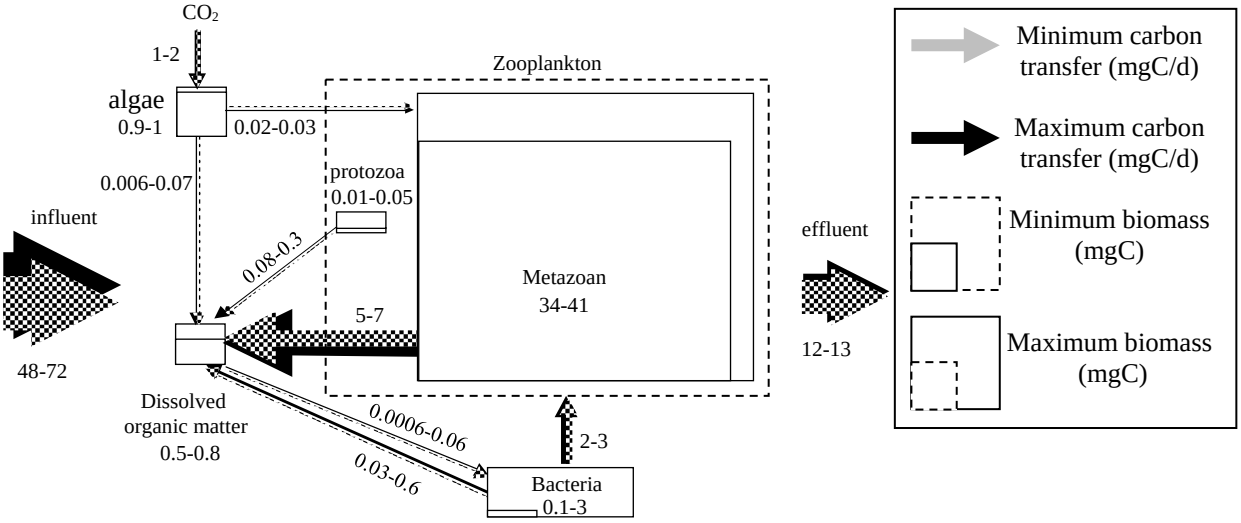


Fig. 11 Mass balance of carbon (Case D, section IV)

conditions. In terms of the carbon transfer, the primary production was approximately 10 times, the predation of algae was 100–1000 times, and the death of algae was 10–1000 times larger under light conditions than under dark conditions.

We suggest that light irradiation activates primary production by algae and increases the existing amount. The algae predation amount of zooplankton and the production of abiotic organic matter due to algal death increase accordingly.

## 4. CONCLUSIONS

In this study, the influence of light irradiation on the carbon balance in the process of contact oxidation treatment for wastewater containing organic matter was discussed. The results obtained in this study are as follows:

1) There were no clear effects of light irradiation on the organic matter removal capacity of the entire channel, but the amount of accumulated organic matter in the channel under light conditions was almost double that under dark conditions.

2) Light irradiation had an effect on the biota in the channels, including the presence of photosynthetic bacteria and the number of algae, but no effect on the number of bacteria.

3) According to the carbon balance analysis in the channel, we suggest that light irradiation increased the load of organic compounds due to photosynthesis 10 times greater than that under dark conditions, such that the effect of light irradiation cannot be ignored when the inflow amount of organic compounds is relatively small. In the case of nutrients, such as nitrogen and phosphorus, in the water, internal production by algae can have a larger impact on the behavior and dynamic state of organic compounds.

## 5. ACKNOWLEDGMENTS

We wish to thank the staff and students at the laboratory of Ecology, Faculty of Science, Ehime University for their assistance in conducting the experiment. We would like to thank Editage (www.editage.com) for English language editing.

## 6. REFERENCES

[1] Ministry of Land, Infrastructure, Transport and Tourism, Japan. http://www1.mlit.go.jp/common/001273126.pdf (in Japanese)

[2] Ministry of the Environment, Japan. https://www.env.go.jp/council/09water/y0917-01/mat05.pdf (in Japanese)

[3] C. Junjun, M. Jian, J. Wei, C. Jinquan, L. Xuan, J. Bohua, W. Haiming, Treatment of heavily polluted river water by tidal-operated biofilters with organic/inorganic media: Evaluation of performance and bacterial community, Bioresource Technology, Vol.279, 2019, pp.34-42.

[4] Y. Sheng, Y. Qu, C. Ding, Q. Sun, R.J. Mortimer, A combined application of different engineering and biological techniques to remediate a heavily polluted river, Ecol. Eng., Vol.57, 2013, pp.1-7.

[5] Jibo Xiao, Shuyi Chu, Guangming Tian, Ronald W. Thring, Lingzhou Cui, An Eco-tank system containing microbes and different aquatic plant species for the bioremediation of N,N-dimethylformamide polluted river waters, Journal of Hazardous Materials, Vol.320, 2016, pp.564-570.

[6] R.J. Craggs, A. Zwart, J.W. Nagels, R.J. Davies-Colley, Modelling sunlight disinfection in a high rate pond: Ecological Engineering, Vol.22, No.2, 2004, pp.113-122.

[7] C. Schultz-Fademrecht, M. Wichern, H. Horn, The impact of sunlight on inactivation of indicator microorganisms both in river water and benthic biofilms, Water Research, Vol.42, No.19, 2008, pp.4771-4779.

[8] Chawalit Chaiwong, Thammarat Koottatep, Chongrak Polprasert, Comparative study on attached-growth photobioreactors under blue and red lights for treatment of septic tank effluent, Journal of Environmental Management, Vol.260, No.15, 2020, 110134.

[9] Eckenfelder jr., W. W., and O'Connor, D. J., Biological Waste Treatment. Pergamon Press, Oxford- London- New York- Paris, 1961, pp.22-42.

[10] DePinto, J.V. and Verhoff, F.H., Nutrient regeneration from aerobic decomposition of green algae, Environmental Science and Technology, 11, 1977, pp.371-377.

[11] Takuya Okubo, Mitsumasa Okada, Akihiko Murakami, Characteristics of purification in Small channels, Journal of Japan Society of Water Environment, Vol.16, No.4, 1993, pp.261-269.

[12] Shigeo Fujii, Isao Somiya and Toshiyuki Shiraki, Studies on the Effect of Phytoplankton and Zooplankton on Self-Purification in Eutrophicated Water, Journal of Japan Society of Water Environment, Vol.15, No.6,1992, p.347.

[13] Edited by Isao Somiya, Purification mechanism of nature(Shizen no Joka Kiko, in Japanese) , 1995, p.127, Gihodo Shuppan.

[14] Edited by Yoshiro Iwasa, Engineering limnology, p.318, Sankaido publishing, ISBN: 9784381008121 (in Japanese).

[15] Shigeo Fujii, Isao Somiya and Toshiyuki Shiraki, Studies on the Effect of Phytoplankton

and Zooplankton on Self-Purification in Eutrophicated Water, Journal of Japan Society of Water Environment, Vol.15, No.6, 1992, p.397.(in Japanese)
[16] Edited by Yoshiro Iwasa, Engineering limnology, 1990, p.322, Sankaido publishing, ISBN: 9784381008121 (in Japanese)
[17] Ryuichi Sudo, Biology for wastewater treatment (Haisui syori no seibutu gaku, in Japanese), 1977, p.180, The Industrial Water Institute.
[18] Ryuichi Sudo, Biology for wastewater treatment (Haisui syori no seibutu gaku, in Japanese), 1977, p.171, The Industrial Water Institute.
[19] Jürgens K, Arndt H, Zimmermann H, Impact of metazoan and protozoan grazers on bacterial biomass distribution in microcosm experiments, Aquatic Microbial Ecology, Vol.12, No.2, 1997, pp.131-138.
[20] Edited by Isao Somiya, Purification mechanism of nature(Shizen no Joka Kiko, in Japanese), 1995, p.19, Gihodo Shuppan.
[21] Edited by Yoshiro Iwasa, Engineering limnology, 1990, p.320, Sankaido publishing, ISBN: 9784381008121. (in Japanese)