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Modelling the recruitment effect in a small marine protected area: the example of saltwater lakes on the Island of Mljet (Adriatic Sea)

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This paper analyzes potential recruitment effect of endangered bivalve Pinna nobilis *in a small marine protected area-Little Lake (Adriatic Sea). A box model has been applied for the estimation of residence time of the lake, forced by tides only at the open end of the lake system. The residence time of Little Lake was estimated to be 54 days. In our approach we assumed that* P. nobilis *larvae may be found in the surface waters only during the night, thus restricting their outgoing from the lake to about 7-8 hours per day in the June-August period, as the larvae need some time to reach surface waters. Therefore, the equivalent residence time of the larvae in Little Lake is estimated to be about 160-185 days. Knowing that the bivalve larva phase lasts between 3 and 5 weeks, one may estimate that only 11 to 22% of the larvae, respectively, leave Little Lake. From a conservation standpoint these low values imply a special level of protection within Mljet National Park. In addition, future climatic changes will affect the recruitment of* P. nobilis*, not only due to sea level rise but also with temperature and other changes which may influence its reproduction phase and larvae transport.*

Key words: mollusca, salt lakes, water budget, recruitment, modelling, Adriatic Sea

INTRODUCTION

Marine protected areas are important from the standpoints of fisheries management, marine ecology, and conservation biology. They are, regardless of their size, associated with higher values of density, biomass, organism size and diversity (HALPERN, 2003). Besides local protection, such areas can potentially enhance marine living resources through the net emigration of post-settlement animals (‘spill-over effect’) and the net export of larvae (‘recruitment effect’) (TEWFIK & BÉNÉ, 2003). The majority of previous studies, dealing with the effectiveness of the marine protected areas, have focused on fish populations and changes in their distribution in relation to protection levels (e.g. RUSS *et al.,* 2003; DOMEIER, 2004; ABESAMIS & RUSS, 2005; CLAUDET *et al.*, 2006; FLOETER *et al.*, 2006; KAPLAN, 2006), while a smaller number of studies have focused on invertebrates (e.g. TEWFIK & BÉNÉ, 2003; MACE & MORGAN, 2006; PURCELL & KIRBY, 2006), and particularly on bivalves (e.g. CASU *et al.*, 2006).

The existence of barriers, created through the spatial configuration of habitat, may significantly affect dispersal patterns and thus influence community dynamics and resource sustainability (TEWFIK & BÉNÉ, 2003). Further, the recruitment effect is conditioned by the ability of ocean currents to move larvae out of the protected area and allow for settling in nearby regions (DOMEIER, 2004). It is also important to note that the persistence of populations within reserves is necessary if reserves are to provide benefits (LOCKWOOD *et al.*, 2002).

The saltwater lake "Malo jezero" (henceforth Little Lake) on the island of Mljet was one of the first established marine reserves in the world. The western part of the island of Mljet, including Little Lake and the nearby "Veliko jezero" (Big Lake), was already protected under the category of National Park in 1960. In addition, all of its marine flora and fauna have gained an additional level of protection in 1976 under the Croatian Law of Nature Protection. The lake is very isolated from open Adriatic waters and presents a unique ecosystem (BENOVIĆ *et al.*, 2000).

Pinna nobilis is the largest marine bivalve in the Mediterranean Sea and is threatened and endangered by the reduction and loss of its natural habitat, increased anthropogenic inputs into coastal waters as well as by the collection of shells by amateur divers (VINCENTE, 1990; ZAVODNIK *et al.*, 1991). In Croatia, this species is protected since 1977. *P. nobilis* can live for over 20 years (RICHARDSON *et al.*, 1999; ŠILETIĆ & PEHARDA, 2003; RICHARDSON *et al.,* 2004) and attain sizes of up to 120 cm (ZAVODNIK *et al.*, 1991). In Little Lake the density of *P. nobilis* in *Cymodocea nodosa* meadows appears to be higher than in other areas of the Adriatic and Mediterranean Seas making this lake a unique phenomenon that deserves special attention (ŠILETIĆ & PEHARDA, 2003).

Using modelling tools, this paper analyzes potential recruitment effects of bivalve *P. nobilis* in neighbouring areas next to Little Lake, Adriatic Sea, through the exchange of water mass between Little Lake, the neighbouring Big Lake and the open sea. In addition it evaluates the potential effects of climate change on the recruitment.

MATERIAL AND METHODS

Study area

Little Lake (Fig. 1) is a natural phenomenon of karstic depressions filled by seawater about 5,000 years ago (WUNSAM *et al.*, 1999). It is connected to a saltwater lake, Big Lake, through a shallow and narrow channel, which in turn is connected to the surrounding open sea through a somewhat deeper and wider channel. Little Lake has a maximum depth of 29.4 m and a total area of 0.241 km^2 (Table 1) (VULETIĆ, 1953).

Bivalve larvae characteristics

In the western Mediterranean, *Pinna nobilis* reproduces in the summer period, from June to August (DE GAULEJAC, 1995). Since these are the only data available on the reproduction cycle of *P. nobilis*, and this species is listed as endangered in Croatia, these data was used for modelling larvae movement in Little Lake. For the length of *P. nobilis* larval life we considered in our calculations an estimate that the length of larval life in marine bivalves varies between three and five weeks, depending on environmental factors such as temperature, salinity and food ration

Table 1. Bathymetric characteristics of Little Lake used in the box-model

Little Lake bathymetric characteristics	
Lake area P (m^2)	241 000
Lake volume V (m^3)	3 349 000
Channel width a (m)	2.0
Channel depth h (m)	0.8
Big Lake bathymetric characteristics	
Lake area P (m^2)	1 450 000
Lake volume V (m^3)	58 000 000
Channel width a (m)	10.0
Channel depth h (m)	2.5

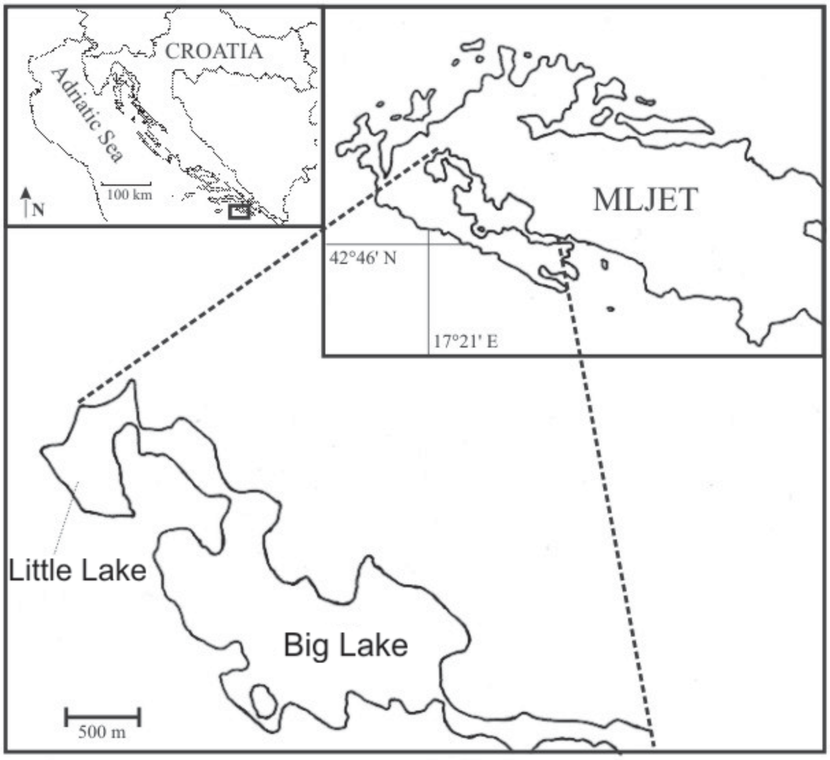

Fig. 1. Geographic location of the investigated area

(GOSLING, 2003). Further, we took into account that bivalve larvae may have some control over their vertical distribution (CRAGG, 2006), and that during darkness larvae move up into the surface waters, while during the day they move to less illuminated deeper waters (GOSLING, 2003).

Lake-sea water exchange and physical modelling

Quantification of the dispersal of *Pinna nobilis* larvae from Little Lake during its reproduction period may be modelled by a simple box model with a channel connecting the lake

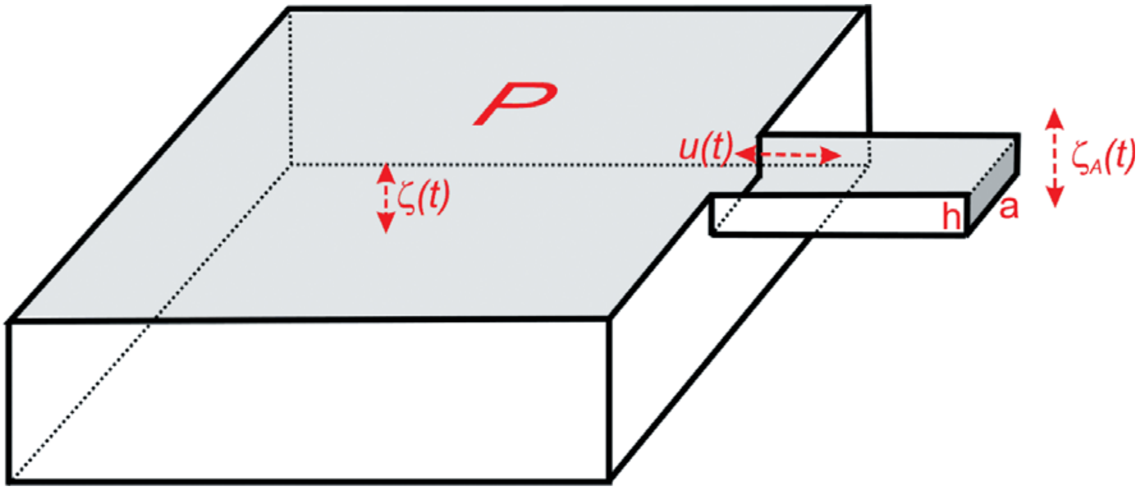

Fig. 2. Scheme of the box-model domain used for modelling of Little Lake residence time

and the outer basin (Fig. 2). Such physical modelling will result in the estimation of residence time and of the water quantity that is leaving the lake and carrying larvae.

However, as Big Lake is also separated from the open sea by a 2.5 m deep and 10 m wide channel, the same modelling approach will be used for the modelling of the sea level changes in Big Lake. The continuity equation in a box may be derived from the shallow-water approximation (e.g. CUSHMAN-ROISIN, 1994; STEWART, 2002)

$$\frac{dV(t)}{dt} \equiv P\frac{d\zeta(t)}{dt} = ahu(t) \qquad (1)$$

where $V(t)$ is volume of the lake (in m^3), being a function of time t (in s), P is the area of the lake (in m^2), $\zeta(t)$ is the lake level (in m), $u(t)$ is the current speed in the connecting channel (in m s^{-1}), and a and h are channel width and depth (in m), respectively. The equation simply declares that the change of lake volume is proportional to the volume of the incoming (or outgoing) water.

The second equation describes the dynamic pressure (so-called Bernoulli's equation, e.g. JOHNSON, 1998) at the channel ends which is equal to the static pressure due to the differences in lake and sea heights

$$\rho\frac{u^2(t)}{2} = \rho g\left[\zeta_A(t) - \zeta(t)\right] \qquad (2)$$

where ρ is the density of the water, g is gravity (9.81 m s^{-2}) and $\zeta_A(t)$ is ambient sea level (in m). This equation assumes the steady state in the channel, what is a fair assumption regarding the timescale of the tidal cycle (12, 24 h) versus the timescale of the passage of a particle through the connecting channel (a few minutes at the largest).

It should be stressed that the friction in the connecting channel may be strong during large currents, and may decrease the current and exchange between two basins. However, we do not consider these effects critical for the zero-level modelling approach, especially as the estimates of *P. nobilis* spillover rates are presumably affected more by the assumptions in larvae dynamics than in water mass dynamics (see next chapter).

The set of two differential equations (1) and (2) with two unknown variables (u and ζ) may be combined, leading to the quadratic differential equation in ζ

$$\left(\frac{P}{ha}\right)^2 \frac{1}{2g}\left(\frac{d\zeta(t)}{dt}\right)^2 + \zeta(t) = \zeta_A(t) \qquad (3)$$

This equation has been solved numerically through a finite difference scheme (e.g. SPIEGEL, 1971). The time step was chosen to be 60 s, resulting in stability of the numerical scheme.

First we applied eq. (3) to Big Lake and the outer sea system (Little Lake is neglected in this step, being substantially smaller than Big Lake), being connected through a 10 m wide and 2.5 m deep channel. The computed sea level changes in Big Lake served as an input $\zeta_A(t)$ to the estimates of the changes in Little Lake, following the same methodology and eq. (3). The parameters in both box model runs are given in Table. 1.

Although the entire Mediterranean is low-tidal area, the dominant process driving Adriatic sea level changes during summer are the tides (e.g. VILIBIĆ, 2006). Tidal currents are particularly strong in the narrow channels, where they can exceed 1 m s^{-1}. Therefore, the open-end of the channel has been forced by tides only and $\zeta_A(t)$ is computed by using a tidal synthesis (e.g. SHUREMAN, 1941; BELL *et al.*, 2000) during a perpetual year. Seven harmonic constituents were used (M_2, S_2, K_2, N_2, K_1, O_1, P_1), which are significant for the Adriatic (e.g. POLLI, 1960) and are used in official tide tables (HYDROGRAPHIC INSTITUTE, 2005). The harmonics reported at Dubrovnik have been used, as being practically the same as those modelled for the Mljet area (e.g. JANEKOVIĆ & KUZMIĆ, 2005).

The residence time is estimated simply by equalling the volume of the lake with the integrated transport of the outgoing current through the connecting channel. We are aware that such an approach does not count on the re-transport of the same water during the subsequent tidal cycles, but this issue is even not fully relevant for the dynamics of the *P. nobilis*, due to their daily vertical migration (GOSLING, 2003). For more accurate estimates, hydrodynamic ocean modelling should be used, including a particle model that accounts for the vertical movements of larvae.

RESULTS AND DISCUSSION

Recruitment effect estimates

Fig. 3 gives a snapshot of sea level $\zeta_A(t)$ and lake level $\zeta(t)$ time series obtained by the model for both Big Lake and Little Lake. Bathymetric parameters *P*, *a* and *h* are estimated from high-resolution bathymetric data surveyed by the Hydrographic Institute, and listed in Table 1.

One may notice that both channels are behaving as a filter at tidal frequencies, allowing just a fraction of tides to enter into the lakes. However, a much stronger effect occurs in the channel between Little Lake and Big Lake. It can be visually observed in Little Lake (Hrvoje MIHANOVIĆ, personal communication), although no sea level measurements were carried out in the area. Nevertheless, the reproduction of the phenomenon by our model indicates additional reliability of the model and results are used for the quantification of the dispersal of *Pinna nobilis* larvae out of Little Lake. Additional verification of the model may be done by comparing the currents with the ones observed between 1951 and 1954, in the frame of extensive hydrographic investigations conducted in the area (BULJAN & ŠPAN, 1976). Namely, they visually estimated the current speed in the connecting channel to be up to 2 m s^{-1}, which is in agreement with the model result that gives the maximum current in a year of 1.9 m s^{-1}.

These results may be used for the estimation of Little Lake residence time, particularly during the *P. nobilis* reproductive phase, and a quantification of the recruitment effect may be reached. However, one should take into the account that, although box-modelling properly describes major physical characteristics of the lake system, many objective shortcomings may

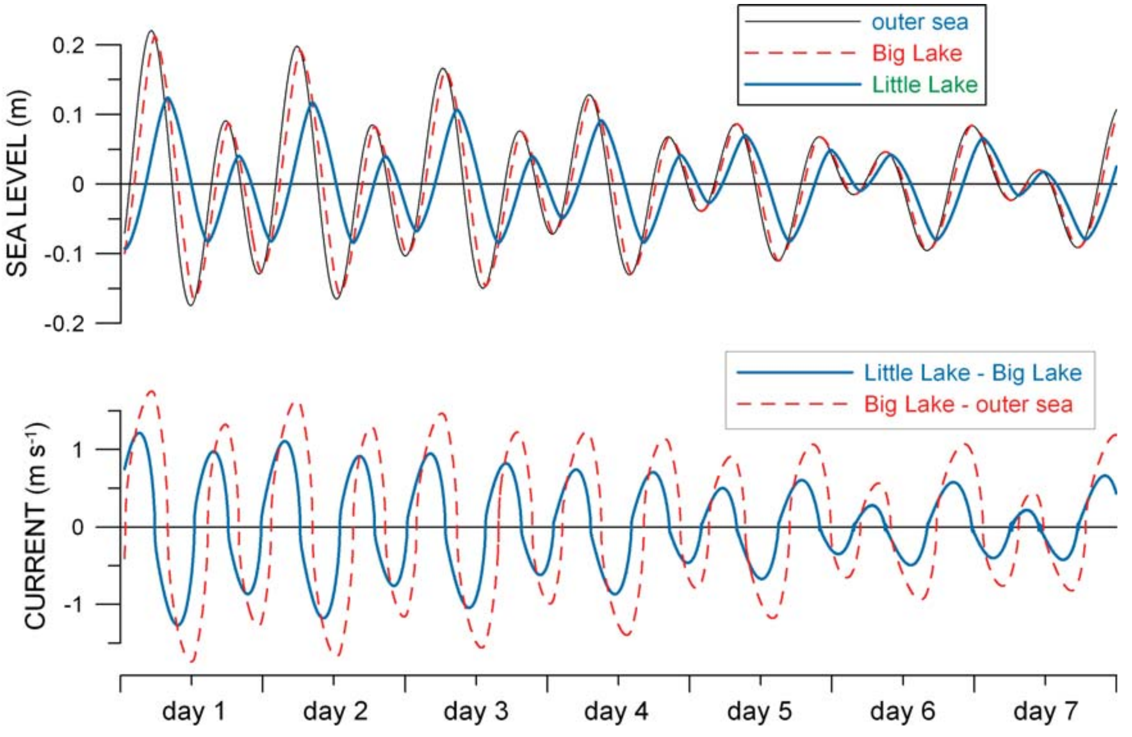

Fig. 3. Sea level time series synthesized for the outer sea (thin full line) and modelled for Big Lake (dashed line) and Little Lake (thick full line), and currents in the connecting channels during a week

influence the estimation of lake residence time, such as: (i) seasonal changes in stratification (BULJAN & ŠPAN, 1976) which acts as a separator between surface and bottom layers, and decreases the residence time of the upper layer during summertime, and (ii) multiple incoming and outgoing of the same surface waters through the channel, bringing a fraction of the out-flowed water back to the lake, and therefore increasing the residence time of the lake waters. Yet, we believe that such an approach gives an insight to the *P. nobilis* spill-over, which should be confirmed and more accurately quantified by applying advanced hydrodynamic models.

Let us comment here on the model results in the frame of *P. nobilis* larvae properties. One may estimate residence time of Little Lake to be 54 days. However, according to GOSLING (2003) bivalve larvae exhibit daily migrations and tend to spend daylight hours in less illuminated parts of the water column and night-time in the surface waters. Taking this into account, we can assume that *P. nobilis* larvae may be found in the surface waters only during night, which restricts their outgoing from the lake to about 7-8 hours per day (the night is approx. 8-9 hours long in the June-August period, and the larvae need some time to reach surface waters). Therefore, the equivalent residence time of the larvae in Little Lake is estimated to be about 160-185 days. Knowing that the bivalve larva phase lasts between 3 and 5 weeks, one may estimate that 11 to 22% of the larvae, respectively, leave the Little Lake.

Unfortunately there are no empirical measures of distribution of *P. nobilis* larvae in Mljet lakes. The only study that analyzed the distribution of bivalve larvae in general, in this area, found that there is a higher abundance of bivalve larvae in Little Lake than in Big Lake (BENOVIĆ *et al.*, 2000). However, previous studies found significant differences in distribution of adult *P. nobilis* between two lakes. For example, in a study conducted in a second part of the 1970s, DRAGANOVIĆ (1980) did not find *P. nobilis* in Little Lake, while in Big Lake it was very rare. During a SCUBA survey conducted in the summer of 1996, OREPIĆ *et al.* (1997), ŽERLIĆ (1999) and ŠILETIĆ (2006) found *P. nobilis* ranging in size from about 30 to 40 cm, while smaller animals were not recorded. In the summer of 1998, the occurrence of small individuals was noticed as well as an increase in the population density in Little Lake (ŽELIĆ, 1999; ŠILETIĆ & PEHARDA, 2003). In 1998 and 1999, PEHARDA *et al.* (2002) conducted a visual census survey in Little lake and found *P. nobilis* at depths down to 15 m and with an average density of 0.17 ind m^{-2}. The highest densities of 0.90 ind m^{-2} were recorded between 5 and 10 m in *Cymodocea nodosa* meadows (PEHARDA *et al.*, 2002). In Big Lake in 1998 and 2000, *P. nobilis* densities were lower than in Little Lake and closer to typical Mediterranean values (ŠILETIĆ & PEHARDA, 2003). Population recovery in Little Lake that occurred after the study of DRAGANOVIĆ (1980) can be attributed to the legal protection of *P. nobilis* under the category of endangered species.

Data presented above suggest significant shifts in the spatial distribution and abundance of *P. nobilis* adults that occurred in the twenty-year period from the late 1970s to the late 1990s. Although these shifts can mostly be attributed to the legal protection of *P. nobilis* that occurred in 1973, they were at least partially influenced by changes in ecological conditions and particularly by recruitment effects. Modelling data on the export of *P. nobilis* larvae obtained in this study suggest that the majority of larvae stay within Little Lake, while only between 11 to 22% of them leave Little Lake. While according to previous studies Little Lake has a higher abundance of adults, results of this study indicate that from a conservation standpoint, it deserves a special level of protection within Mljet National Park. Further, taking into account that *P. nobilis* is a long-lived species (RICHARDSON *et al.*, 1999, ŠILETIĆ & PEHARDA, 2003, RICHARDSON *et al.*, 2004) and that bivalve fecundity in general increases with size and age (GOSLING, 2003), special attention should be given to the conservation of bigger and older individuals in Little Lake and the prevention of poaching of such individuals.

Projections for the future

Apart from the present situation, one may wonder about the consequences of climate changes and sea level rise in such a vulnerable habitat, highly influenced by any changes occurring at its entrance. If one applies a moderate rise of sea level of 25 cm, which is half the projected global sea level rise (IPCC, 2001), equivalent residence time decreases to 125-150 days as estimated by the box model, enabling the leakage of 13-26% larvae to the outer sea. That approach assumes the same sea level rise values both in the lake systems and in the outer sea. In the case of a 50 cm sea level rise, the percentage of outgoing larvae would rise to 15-29% and in the case of an extreme scenario (90 cm sea level rise), the percentage rises slightly more, to about 16-31% of the total *P. nobilis* larvae as estimated by the box model. Such a nonlinear decrease in lake residence time is a result of weakening of the tidal filtering between Little Lake and Big Lake (Fig. 4). Also, one can see that the tidal filtering between Big Lake and the outer sea vanishes as sea level rises. Therefore, the currents are weaker but the cross-section is larger, resulting in a slight increase in transport and volume exchange through the connecting channel.

Changes in sea level rise will most likely be linked to changes in seawater temperature, which in turn might alter seasonality of *P. nobilis* reproduction. Further, recent studies have shown that both abiotic and biological responses to global climate change will be substantially more complex than previously thought and that changes in ocean chemistry may be more important than changes in temperature (HARLEY *et al.*, 2006). Analysis of shifts in distribution of species in north-west Mediterranean marine caves showed that Mediterranean marine biodiversity is already under threat from global warming (CHEVALDONNÉ & LEJEUSNE, 2003). However, since many of these changes that could affect recruitment of marine organisms are unknown, we propose Mljet lakes as excellent experimental sites for evaluating the potential effects of global climate change on the marine environment.

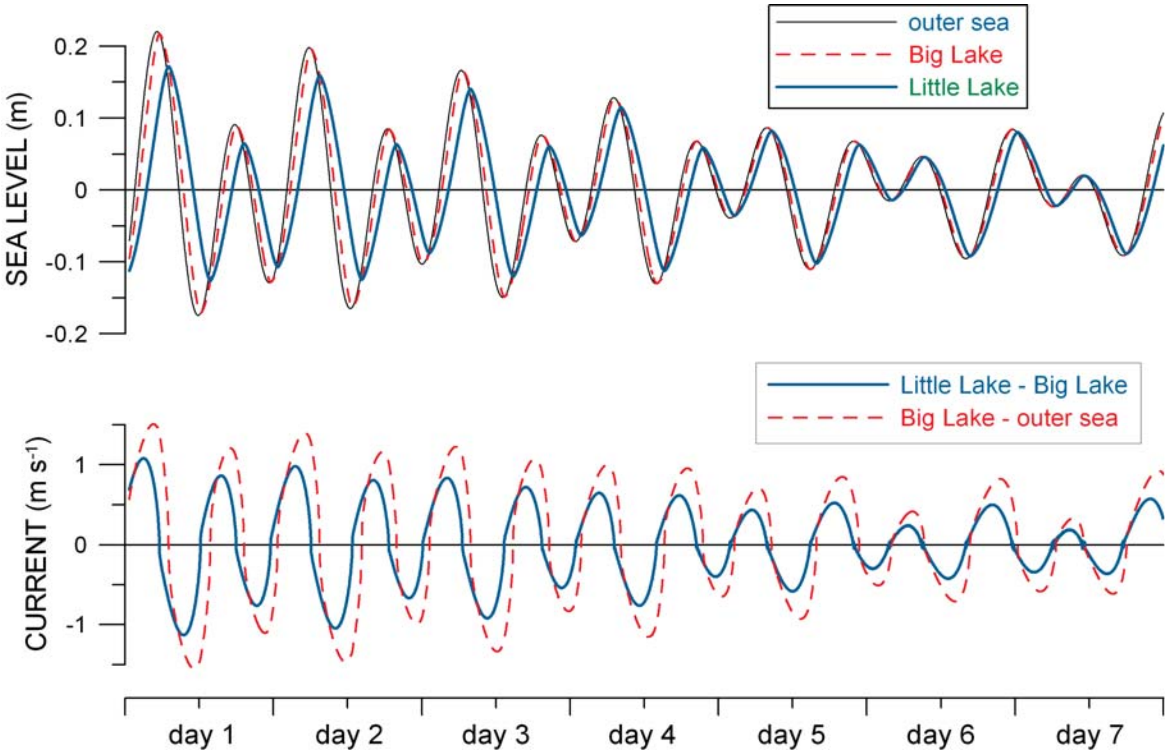

Fig. 4. As in Fig. 3, but assuming a sea level rise rate of 50 cm

CONCLUSIONS

Although being simple and not including some of the dynamical properties of the investigated area (e.g. seasonal stratification, friction), we believe that our simple approach and use of a box model may be useful for describing lake-sea exchange and recruitment effects in a small lake connected to an outer basin through a narrow entrance. Additionally, a more complex approach to the problem and advanced numerical modelling needs more input data on *Pinna nobilis* larvae reproduction, adult characteristics and distribution in the area, which are not yet available in the case of Little Lake and the surrounding region. However, the reliability of the model used is proven by reproducing some documented dynamic characteristics: the tidal filtering effect between Little Lake and Big Lake and the maximum currents in the connecting channel.

Our estimates of 11 to 22% *P. nobilis* larvae leaving from Little Lake to Big Lake and the surrounding area shows the importance of conservation and proper management of this species in its source area. However, this should be accompanied by appropriate *in situ* experiments and later by systematic monitoring, in order to obtain empirical estimates and to verify the approach and the model itself. After collecting a sufficient amount of quality data, the next step in modelling should include other effects (e.g. temperature, salinity, chemistry) which may affect the reproduction and settlement of *P. nobilis* in Mljet lakes. In particular, this should be carefully done when trying to predict *P. nobilis* interannual and decadal variations and trends which may be caused by local and regional climate changes, as the changes in sea level don’t affect substantially the recruitment of the larvae, those presumably being more influenced by climate trends and variations in temperature and ocean chemistry.

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Modeliranje iseljavanja ličinki u malom zaštićenom morskom području: primjer slanih jezera na otoku Mljetu (Jadransko more)

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SAŽETAK

U ovom se radu analizira mogućnost iseljavanja ličinki ugroženog školjkaša *P. nobilis* u malom zaštićenom morskom području–Malo Jezero (Mljet, Jadransko more). Pri izračunu vremena zadržavanja mora u jezeru primijenjen je model kutije, forsiran isključivo sa plimnim signalom na otvorenom kraju sustava jezera. Vrijeme zadržavanja mora u jezeru je procijenjeno na 54 dana. Pretpostavljeno je da se ličinke *P. nobilis* mogu naći u površinskom sloju samo za noćnih sati, što je ograničilo mogućnost iseljavanja iz jezera na 7-8 sati dnevno u razdoblju od lipnja do kolovoza, uz uvažavanje činjenica da je ličinki potrebno neko vrijeme da se uzdigne do površinskog sloja. Shodno tome, stvarno vrijeme zadržavanja ličinke je procijenjeno na 160 do 185 dana. Znajući da faza ličinki traje od 3 do 5 tjedana, procjena jest da samo 11 do 22% ličinki može napustiti Malo Jezero. Ovako niske vrijednosti impliciraju provođenje posebnih mjera zaštite Malog jezera u okviru Nacionalnog parka Mljet. Nadalje, predviđene klimatske promjene će utjecati na efekt iseljavanja *P. nobilis*, ne samo zbog promjene razine mora i režima izmjene vodenih masa u jezerima, već i zbog temperaturnih i drugih promjena koje mogu utjecati na reprodukcijsku fazu ličinke kao i na njezine sposobnosti gibanja.

Ključne riječi: školjkaši, slano jezero, vodena bilanca, iseljavanje, modeliranje, Jadransko more