

# NETLAKE toolbox for the analysis of high-frequency data from lakes



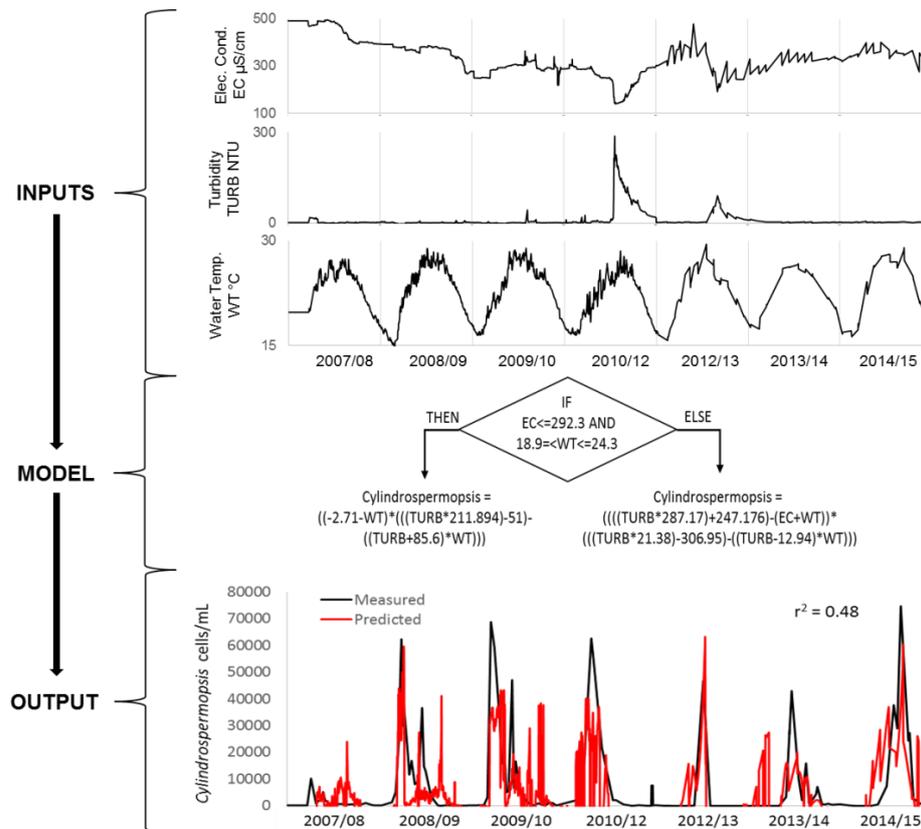
## Factsheet #11

### Inferential modelling of time series by evolutionary computation

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#### Objective

The hybrid evolutionary algorithm (HEA) has been designed: 1) to represent and forecast multivariate relationships between environmental conditions and population densities by inferential (IF-THEN-ELSE) models, and 2) to quantify ‘tipping points’ for population outbreaks by IF-conditions (Figure 1). During the course of hundreds of iterations, HEA discovers the ‘best-fitting’ model after optimising model structures by genetic programming and model parameters by differential evolution towards the lowest RMSE and highest  $R^2$  (Cao et al. 2013).



**Figure 1.** 20-day-ahead forecasting of *Cylindrospermopsis raciborskii* in Lake Wivenhoe (Australia) by means of inferential modelling based on HEA. The IF-condition suggests that fast population growth of *C. raciborskii* in Lake Wivenhoe may occur within the temperature range of 18.9 to 24.3 °C and at conductivity levels lower than 292 µS/cm.

The forecasting accuracy of inferential models by HEA suits early warning of population outbreaks. Ensembles of inferential models allow scenario analysis of how shifts in physical-chemical boundaries impact on aquatic communities. Meta-analysis of ‘tipping points’ and ecological relationships across lakes with the same stratification regime and trophic state allows the generalisation of knowledge inherent in complex ecological data.

### *Specific application*

**Quantifying ecological tipping points and relationships** has been demonstrated successfully by case studies for Lakes Müggelsee (Germany), Kinneret (Israel), Taihu (China) and Lajes (Brazil) (Recknagel et al. 2016; Recknagel et al. 2015; Recknagel et al. 2014; Recknagel et al. 2013). **Short-term forecasting and early warning** of cyanobacteria blooms as well as meta-analysis of tipping points have been demonstrated successfully by case studies for Lakes Wivenhoe, Somerset and Samsonvale (Australia) (Recknagel et al. 2014). **Spatially-explicit short-term forecasting** of cyanobacteria blooms has been demonstrated successfully by case studies for Lakes Lajes (Brazil), Taihu (China) and Wivenhoe (Australia) (Recknagel et al. 2015; Zhang et al. 2015; Cao et al. 2016).

### *Background*

The tool is available as user-friendly software written in C++. To use the tool requires basic programming skills. To execute evolutionary computations by HEA can be very time-consuming. It is therefore recommended to run HEA on supercomputers in cloud mode.

### *Type of data and requirements*

Ecological time series are recorded in .xls spreadsheets where rows contain input- and output parameters of interest (e.g. physical, chemical and biological data) for consecutive equidistant time steps. Since the HEA software learns from patterns, modelling of seasonal and inter-annual dynamics requires at least 3 years of data, but it generalises best with decades of data containing a wealth of patterns. If data are missing or have been measured at non-equidistant time steps, interpolation of data to the smallest measured time step is required (HEA licence includes a software tool for flexible linear data interpolation of time series). Whilst ‘day’ is the recommended time step for ‘several-day-ahead’ predictive modelling, there is no restriction to the choice of the smallest time step. Data for spatially-explicit modelling of same ecological attribute measured simultaneously at multiple sites has the same requirements as for modelling single-site data (HEA licence includes detailed manual and data examples for single- and multi-site modelling experiments).

The .xls spreadsheets need to be completed by specifying HEA control parameters such as numbers of inputs, outputs, generations, boot-strap loops etc. before being saved as Text (Tab

delimited) files. To run HEA, the HEA *exe*-file together with the Text file need to be submitted to a supercomputer.

### ***Basic procedures***

1. Prepare equidistant input and output data as well as HEA control parameters in .xls files before saving them as Text (Tab delimited) files.
2. Submit HEA *exe*-file together with Text file to supercomputer.
3. Review the modelling protocol documenting 10 'best fitting' models by: IF-THEN-ELSE rules, graphical validation, root mean squared error (RMSE),  $R^2$ , ranking inputs by sensitivity, input sensitivity functions.

### ***Pitfalls and tips***

- Since HEA ranks inputs by sensitivity after each run, noise from the least sensitive inputs can be removed for consecutive runs that may improve model validity.
- To avoid bias by relying on a single model, averages and Min-Max envelopes of an ensemble of 3 to 5 best-fitting models can be utilised for validation.
- Since HEA infers IF-THEN-ELSE rules for the underlying research question, the IF conditions reveal quantitative thresholds that explain causes for high and low output magnitudes.

### ***Further reading***

#### **Key References:**

Cao, H., Recknagel, F., Orr, P. 2014. Parameter optimisation algorithms for evolving rule models applied to freshwater ecosystem. *IEEE Transactions on Evolutionary Computation* 18: 793-806.

Cao, H., Recknagel, F., Bartkow, M. 2016. Spatially-explicit forecasting of cyanobacteria assemblages in freshwater lakes by multi-objective hybrid evolutionary algorithms. *Ecological Modelling*, 342, 97-112.

Recknagel, F., Adrian, R., Köhler, J., Cao, H. 2016. Threshold quantification and short-term forecasting of *Anabaena*, *Aphanizomenon* and *Microcystis* in the polymictic eutrophic Lake Müggelsee (Germany) by inferential modelling using the hybrid evolutionary algorithm HEA. *Hydrobiologia* 778: 61-74.

#### **Other useful references:**

Recknagel, F., Branco, C.W., Cao, H., Huszar, V.L., Sousa-Filho, I.F. 2015. Modelling and forecasting the heterogeneous distribution of picocyanobacteria in the tropical Lajes Reservoir (Brazil) by evolutionary computation. *Hydrobiologia* 749: 53-67.

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Recknagel, F., Ostrovsky, I., Cao, H. 2014. Model ensemble for the simulation of plankton community dynamics of Lake Kinneret (Israel) induced from in situ predictor variables by evolutionary computation. *Environmental Modelling & Software* 61: 380-392.

Recknagel, F., Ostrovsky, I., Cao, H., Chen, Q. 2014. Hybrid evolutionary computation quantifies environmental thresholds for recurrent outbreaks of population density. *Ecological Informatics* 24: 85–89.

Recknagel, F., Ostrovsky, I., Cao, H., Zohary, T., Zhang, X. 2013. Ecological relationships, thresholds and time-lags determining phytoplankton community dynamics of Lake Kinneret, Israel elucidated by evolutionary computation and wavelets. *Ecological Modelling* 255: 70-86.

Zhang, X., Recknagel, F., Chen, Q., Cao, H., Li, R. 2015. Spatially-explicit modelling and forecasting of cyanobacteria growth in Lake Taihu by evolutionary computation. *Ecological Modelling* 306: 216-225.

## Code

HEA has been coded in C++ language and is not yet freely available. The authors offer short courses on inferential and process-based modelling, and welcome collaboration on data processing and modelling (for more details please contact [friedrich.recknagel@adelaide.edu.au](mailto:friedrich.recknagel@adelaide.edu.au)).

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