Estuarine, Coastal and Shelf Science 148 (2014) 27–35

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Leaving the beaten track — Approaches beyond the Venice System to classify estuarine waters according to salinity

Thomas Taupp [a,*], Markus A. Wetzel [a,b,1]

[a] Institute for Integrated Natural Sciences, University Koblenz-Landau, Universitätsstrasse 1, 56070 Koblenz, Germany
[b] Department of Animal Ecology, German Federal Institute of Hydrology — BfG, Am Mainzer Tor 1, 56068 Koblenz, Germany

ARTICLE INFO

Article history:
Received 30 April 2014
Accepted 14 June 2014
Available online 21 June 2014

Keywords:
salinity gradient
salinity zones
macrozoobenthos
Venice System
Elbe Estuary

ABSTRACT

The Venice System is one of the best-known and most applied systems to classify waters with respect to salinity. It has often been subject to criticism because the criteria used to derive zone boundaries were not made explicit. Consequently, an alternative multivariate PCA method that aimed at identifying salinity zones by means of the salinity ranges preferred by species was introduced by Bulger et al. (1993). We tested the applicability of both methods using salinity and benthic macroinvertebrate data for the poikilohaline Elbe Estuary (Germany) from 1997 to 2012. This was done by comparing the resultant salinity zone limits from the two approaches with boundaries where significant community changes were found by means of cluster analysis. Only the Venice System polyhaline and limnetic zone boundaries, and the PCA method outer estuary zone limit, showed good agreement with the benthic community pattern. None of the other Venice System or PCA method zone limits reflected the benthic community patterns. Our findings suggest that zone limits can only be well determined from mean salinity at the inner and outer end of the estuary, where the variation of salinity is relatively low. In contrast, in the middle of the estuary variation in salinity is the better predictor of zone boundaries. Thus, application of the Venice System or the PCA method in poikilohaline estuaries, such as the Elbe, is not meaningful and their use should be limited to homoiohaline systems. For poikilohaline systems, we found cluster analysis to be a better tool to identify salinity-zone boundaries.

1. Introduction

Estuaries are transition zones, where saltwater and freshwater mix in varying amounts (McLusky and Elliott, 2004; Elliott and Whitfield, 2011). The resulting longitudinal salinity gradient is one of the main descriptive environmental factors (Telesh and Khlebovich, 2010; Elliott and Whitfield, 2011). This gradient is of crucial importance as it determines structural features of biota in aquatic systems (Rakocinski et al., 1997; Ysebaert et al., 2003; Telesh and Khlebovich, 2010; Basset et al., 2013). Occurrences of organisms along the salinity gradient are governed by their inherent physiological salinity tolerances and other ecological factors, such as availability of food or habitat within the species-specific salinity ranges (Guenther and MacDonald, 2012). Knowing the spatial distribution patterns of biota along estuarine gradients enables the derivation of zonation schemes and this may help to improve understanding of the underlying ecological processes (Bulger et al., 1993) and to develop tools for ecological quality assessments and mitigation strategies in estuarine management (Bulger et al., 1993; Ysebaert et al., 2003; Ghezzo et al., 2011).

Salinity zonation schemes have been proposed by several authors. According to den Hartog (1974), Redeke (1922, 1933) was the first to introduce a classification of brackish waters. He divided Dutch brackish waters into three chlorinity ranges, namely oligohaline, mesohaline, and polyhaline (for a comparison of salinity classifications see Table 1). This system was further developed by Välikangas (1933) based on plankton community surveys in the Baltic Sea. He divided the mesohaline zone into the meio- or β-mesohaline and the pleio- or α-mesohaline subzones because he observed a community change at the 8‰ isohaline. Later, the *Artenminimum* (species minimum) concept, based on macrozoobenthos data for the Baltic Sea, was introduced by Remane (1934). He argued that a zone with the lowest number of taxa in

* Corresponding author. Tel.: +49 (0) 261 287 2196; fax: +49 (0) 261 287 100 2196.
E-mail addresses: ttaupp@uni-koblenz.de (T. Taupp), markus.wetzel@bafg.de (M.A. Wetzel).
[1] Tel.: +49 (0) 261 1306 5842; fax: +49 (0) 261 1306 5152.

http://dx.doi.org/10.1016/j.ecss.2014.06.008
0272-7714/

Table 1
Boundaries of salinity classification schemes that influenced the development of the Venice System. Chlorinity values from Redeke (1922, 1933) were converted to salinity using the formula $S = 1.80655 \times Cl^{-}$ given by Fofonoff (1985). Salinity ranges are as presented in the original publications. Zones, defined by Dahl (1956) and the Venice System (1959), with salinities > 40 are not shown.

Source	Salinity classification				
Redeke (1922)	Freshwater <0.2‰	oligohaline 0.2–1.8‰	mesohaline 1.8–18.1‰	polyhaline >18.1‰	
Redeke (1933)	Freshwater <0.2‰	oligohaline 0.2–1.8‰	mesohaline 1.8–18.1‰	polyhaline 18.1–30.7‰	Marine >30.7‰
Välikangas (1933)	Freshwater <0.2(0.5)‰	oligohaline 0.2(0.5)–2(3)‰	meio- or (β)-mesohaline 2(3)–(8–10)‰	pleio- or (α)-mesohaline 8–16.5 (10–20)‰	Polyhaline >16.5‰
Remane (1940)	Freshwater <3‰	limnetic- brackish 3–5‰	Typical brackish 5–8(10)‰	Marine- brackish 8(10)–(15)16.5‰	Marine (15)16.5–35‰
Dahl (1956)	freshwater/homoiohaline <(0.1–0.5)	oligohaline/poikilohaline (0.1–0.5)-5‰	mesohaline/poikilohaline (5–8)–(15–20)‰	polyhaline/poikilohaline (15–20)–(25–30)‰	marine/homoiohaline 30–40‰
Venice System (1959)	Limnetic <0.5‰	oligohaline 0.5–5‰	mesohaline 5–18‰	polyhaline 18–30‰	Euhaline 30–40‰

brackish areas can be found at salinities between 5 and 8‰ and developed a biological salinity zonation scheme that differed considerably from those of Redeke (1922, 1933) and Välikangas (1933). For instance, he set the lower limit of the marine zone at 15–16.5‰ in contrast to approximately 30‰ in the aforementioned systems. To introduce a classification that also considers areas outside the Baltic, Dahl (1956) derived a system with boundaries based on investigations in different areas of the world (USA, South Africa, France, the UK, the Black Sea etc.). The most important difference to the systems by Redeke (1922, 1933) and Välikangas (1933) was that Dahl (1956) shifted the lower end of the mesohaline zone towards the oligohaline zone. In the course of a symposium on the classification of brackish waters, the Venice System was introduced and proposed for universal application (Venice System, 1959). It is rather similar to the classification given by Dahl (1956).

Today, the Venice System is one of the most widely-used and accepted systems for the classification of waters according to salinity. It also found its way into the recent European Water Framework Directive (WFD), in which its boundaries are used to sub-divide transitional surface waters (EC, 2000; Annex II, 1.2.3, System A). It has often been criticized as static and descriptive (den Hartog, 1974; Bulger et al., 1993; Attrill and Rundle, 2002). Furthermore, den Hartog (1974) stated that shifting the lower end of the mesohaline zone to the oligohaline zone rendered the Venice System 'inapplicable for the areas in North and West Europe'. In contrast, Boesch (1977) showed that the Venice System may be applicable in homoiohaline brackish systems like the Baltic Sea, whereas its application in tidally poikilohaline estuaries may not be meaningful. Bleich et al. (2011) also concluded that community changes of macrobenthic species in the homoiohaline Baltic Sea were consistent with the Venice System boundaries. Chainho et al. (2006), who studied the benthos in the northern branch of the poikilohaline Mondego River estuary (Portugal), also confirmed the observation of Boesch (1977), inferring that the Venice System was not applicable consistently to this type of estuary.

As an alternative approach to the controversial Venice System, Bulger et al. (1993) proposed a multivariate method of determining biologically-based salinity zones in estuaries. Their study relied on field data of the salinity tolerances of fish and invertebrates from Chesapeake Bay, USA (homoiohaline according to Boesch, 1977) and Delaware Bay which is a smaller version of Chesapeake Bay according to Bird (2010). Bulger et al. (1993) performed a principal component analysis (PCA) based on the salinity ranges of species. They found five overlapping salinity zones that had both similarities and dissimilarities to the Venice System. Based on their results, they suggested the application of their method in other estuaries in order to test its general applicability. So far, this method has been used, for instance, to develop an index of biological sensitivity of Gulf of Mexico species to changes in freshwater inflow (Christensen et al., 1997), and, in comparison with the results of a non-metric multidimensional scaling (e.g. Quinn and Keough, 2002) to explore evidence of distinct nekton-based salinity zones in estuaries in Florida, USA (Greenwood, 2007; Guenther and MacDonald, 2012).

Both the Venice System and the PCA method consider only the mean salinity. However, according to Dahl (1956), besides mean salinity, one of the most prominent characteristics of brackish zones in estuaries is the lack of stability in salinity, with its diurnal, seasonal, and annual fluctuations. He coined the terms 'homoiohaline' for water bodies with small fluctuations in salinity (in particular the freshwater and the marine zones) and 'poikilohaline' which he defined as brackish and estuarine waters that depend on the sea for their salinity conditions and lack stable salinity concentrations. In a more general sense, the terms homoiohaline and poikilohaline can be used to express relatively constant salinity with stable isohalines within an estuary and variable, unstable salinity, respectively (Venice System, 1959; Ghezzo et al., 2011). High physico-chemical variability is commonly regarded as the reason for estuaries to be species-poor (Elliott and Whitfield, 2011) because only few animals are physiologically able to adapt to the varying mixtures of saltwater and freshwater (McLusky and Elliott, 2004). According to Attrill (2002), the high degree of variation in salinity, rather than absolute salinity tolerance, is the most important factor influencing the distribution of biota in estuaries. This is why salinity zonation schemes that consider mean salinity alone may not be applicable under the prevailing conditions in poikilohaline waters.

Community patterns in poikilohaline estuaries reflect species responses to both, the mean salinity and the variation of salinity. Cluster analysis, in general, is an appropriate tool to identify distinct communities of biota, and several authors have applied this method in estuaries (e.g. Moreira et al., 1993; Ysebaert et al., 2000; Chainho et al., 2006; Wetzel et al., 2012). Consequently, based on salinity and benthic macroinvertebrate data collected over a period of 16 years in the poikilohaline Elbe Estuary (Germany) our aim was (1) to determine the spatial extent of the Venice System zones within the estuary, (2) derive an alternative salinity zonation scheme with the method proposed by Bulger et al. (1993), (3) compare both these zonation patterns with the boundaries of significant benthic community changes identified by cluster analysis, and (4) assess whether mean salinity or variation of salinity best determines community structure within the estuary.