A methodology for defining homogeneous water bodies in estuaries – Application to the transitional systems of the EU Water Framework Directive

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Abstract

A methodology is developed and tested for division of estuarine and coastal systems into water bodies for monitoring and management purposes. This division is often implicit in the choice of sampling stations and in pollution abatement measures applied to different locations – it is now an explicit requirement of European Union Directive 2000/60/EC (Water Framework Directive) and recommended by United States Agencies such as EPA and NOAA. The approach considers both natural characteristics and the human dimension, by means of a stepwise methodology, which considers, on the one hand, morphology and salinity distribution, and, on the other, appropriate indicators of pressure and state. In the present application, nitrogen and phosphorus loading was used as the pressure component and chlorophyll *a* and dissolved oxygen as indicators of state. The criteria for system division were defined based on (1) an adimensional shape factor and salinity classes for the natural component; and (2) a normalised pressure index and (ASSETS) eutrophication symptom classes for the human dimension. Water quality databases and GIS were used to develop spatial distributions for the various components, and the results were aggregated into a final water body division, using tidal excursion as a ''common sense'' test. The methodology was applied to three well-studied systems in Portugal, a tubular estuary (Mondego), a wide lagunal estuary (Sado) and a coastal barrier island system (Ria Formosa). Although a final definition of water bodies will usually be a policy decision, this type of approach for the division of coastal systems into management units scientifically informs the decision-making process.
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1. Introduction

EU Directive 2000/60/EC (European Community, 2000), commonly known as the Water Framework Directive (WFD), establishes that surface waters should be divided into Water Bodies (Fig. 1) which will be subject to monitoring in order to establish their Ecological Status. This is done through the assessment of a range of Biological Quality Elements and Supporting Quality Elements, that together lead to a classification into one of five Ecological Status classes, ranging from High Status to Bad Status. The WFD water bodies are management units, whose ecological status is considered spatially uniform; therefore the definition of such units necessarily includes a human dimension, reflecting both the significant pressures and the uniformity of state.

This definition poses a challenge, since it should be based on sound scientific grounding, accommodate the management

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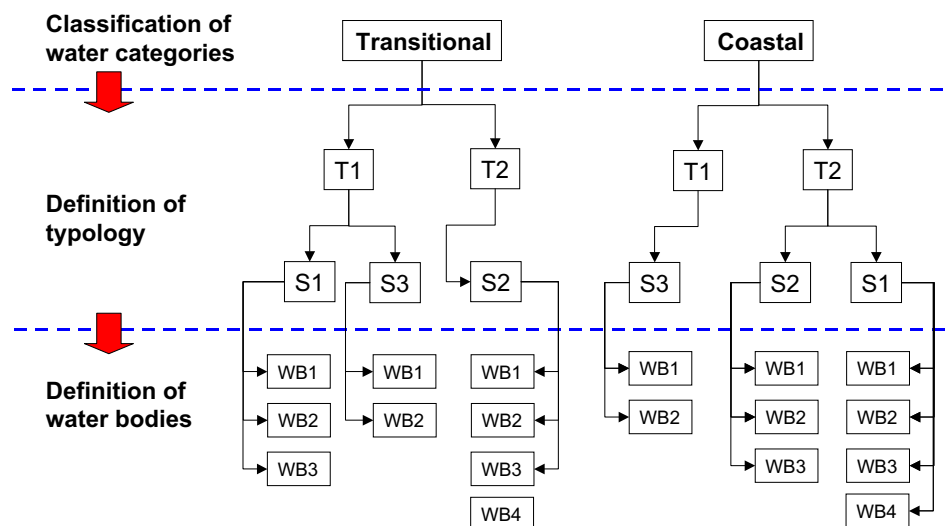 *E-mail address:* joao@hoomi.com (J.G. Ferreira).

Fig. 1. Summary of the process stipulated in the EU Water Framework Directive for definition of water bodies (T: types; S: systems; WB: water bodies).

requirement that pollution abatement measures are effective and verifiable at the water body scale, and be economically viable, avoiding a proliferation of management units. Additionally, while this methodology has been developed in order to facilitate the fulfilment of the requirements of the EU WFD it is formulated in such a manner that it should be broadly applicable and useful in all places that require monitoring, assessment, and management of coastal water bodies, such as in the US for fulfilment of requirements of the Clean Water Act (CWA, 2002).

Estuaries have historically been classified using a variety of approaches, including topography (Pritchard, 1952), morphology (Fairbridge, 1980), salinity structure (Pritchard, 1955; Cameron and Pritchard, 1963) and composite methods, which variously combine topography, salinity distribution and water circulation terms (e.g. Hansen and Rattray, 1966; Oey, 1984; Prandle, 1985; Jay and Smith, 1988). These approaches provide useful tools for assigning estuaries to different types. Although classification indices have not generally been used for this purpose, some of the underlying concepts may be applied to a sub-division of individual estuaries into homogeneous areas (e.g. Câmara et al., 1987; Cardoso da Silva and Carmona Rodrigues, 2004).

These schemes are designed to classify estuaries according to "natural" spatial divisions and, as a consequence, the effects of natural physical and chemical variants that might impede state comparisons are minimized. The classifications are, therefore, irrespective of watershed usage, anthropogenic pressure, and the state of the estuary, as assessed using environmental indicators such as chlorophyll *a* (chl *a*) or dissolved oxygen (D.O.). This allows for better interpretation of pressure effects, providing a strong basis for more focused and effective management strategies and efforts.

Estuarine and coastal managers have often used administrative and environmental dividers to define estuarine water bodies. Particularly, in the US, federal law mandates water body classifications to be based on human and environmental use

distinctions and prevailing water quality. These are usually thought to be amenable to similar management strategies within a class. For example, estuarine areas of significant ecological importance may form homogeneous administrative units, e.g. high-class waters with minimal impacts such as nature reserves, the delimitation of which is usually established through negotiation among stakeholders, including regulatory authorities.

A functional classification scheme will minimize the effects of natural physical and chemical variants, thus allowing for more meaningful comparisons of pressure and state conditions among similarly classified water bodies. In particular, nutrient loading pressures, and resulting state alterations in primary productivity and dissolved oxygen, have grown in prominence in recent years (Bricker et al., 1999, 2003; Driscoll et al., 2003; Galloway et al., 2003), and are primary human effects identified in the WFD. The relationship between land cover and nutrient loading is reasonably well established (Howarth et al., 1991, 1996; Carpenter et al., 1998; Creed and Band, 1998; Lewis, 2002), has been successfully modelled (Young et al., 1996; Viney et al., 2000; Grizzetti et al., 2003; Uncles, 2003) and is further tested in this methodology to define human pressures and state effects in Portuguese estuaries. These pressure and state variables can then be incorporated into the final water body classification scheme.

Additionally, there are several instances where a "natural" sub-division (e.g. into salinity classes) is used as a template for monitoring and environmental assessment, and the results are then presented as a map (e.g. NOAA, 1996, 1998; Wazniak et al., 2004) and/or aggregated into environmental quality indices (e.g. Bricker et al., 2003).

The objective of this paper is to develop, test and verify a semi-quantitative methodology that allows the division of estuaries (included in "transitional waters" in the WFD) and inshore coastal waters (e.g. coastal, lagoons, embayments, rias) into a meaningful set of water bodies, bringing together both natural criteria and the human dimension. Due to the differences in the scales of ecological processes and in the

management of ecosystems it may not be possible to develop a deterministic method that leads to just one final set of water bodies, instead the objective is to use a multi-criteria approach to provide an indication of the number and limits of water bodies which would be appropriate for a particular system. The end result of this analysis will always be subject to final policy decisions by managers, both as regards numbers and limits of water bodies.

In order to test the methodology, we have applied a range of data handling and modelling techniques to three coastal systems of different characteristics:

(a) A "tubular" estuary which has a one-dimensional circulation pattern;
(b) A wide estuary with a markedly two-dimensional (X−Y) circulation;
(c) A "dendritic" coastal barrier island system.

Vertical stratification is not considered in this classification since a water body by definition includes the whole water column.

2. Methodology

The methodology for division of transitional and restricted coastal waters into water bodies is illustrated in Fig. 2. The approach is applicable to estuaries and to restricted coastal areas such as lagoons or ria systems, and therefore includes transitional waters (sensu WFD) and some coastal water types.

The application of the natural and human influence criteria used for the water body division and the harmonisation processes are detailed below.

2.1. Natural characteristics

Morphology and salinity are natural factors that strongly influence the processes controlling the effect of human pressures on the state of water bodies. Morphological characteristics affect hydrodynamics and mixing, and salinity is a controlling parameter for biogeochemical processes. As a result, these factors were considered as primary dividers for the delimitation of water bodies. The morphological and salinity attributes are combined to identify the set of water bodies defined by these natural system characteristics.

2.1.1. Morphology

An adimensional shape factor (Eq. (1)) was used for morphological classification. This parameter reflects the dominance of interface or water column processes. For instance, when the ratio σ_i is high, benthic processes and water−atmosphere exchanges tend to control state.

$$\sigma_i = \log\left(\frac{w_i}{|\bar{z}_i|}\right) \tag{1}$$

where w_i is the mean width of section i (m) and z_i is the mean depth of section i (m).

A logarithmic transformation was used due to the wide range of ratios obtained, which can vary by two orders of magnitude.

The final morphological classification is obtained through an iterative process of (a) sub-division, and (b) analysis and aggregation.

2.1.1.1. Sub-division. Cross-sectional profiles are drawn from bathymetric data using a geographical information system
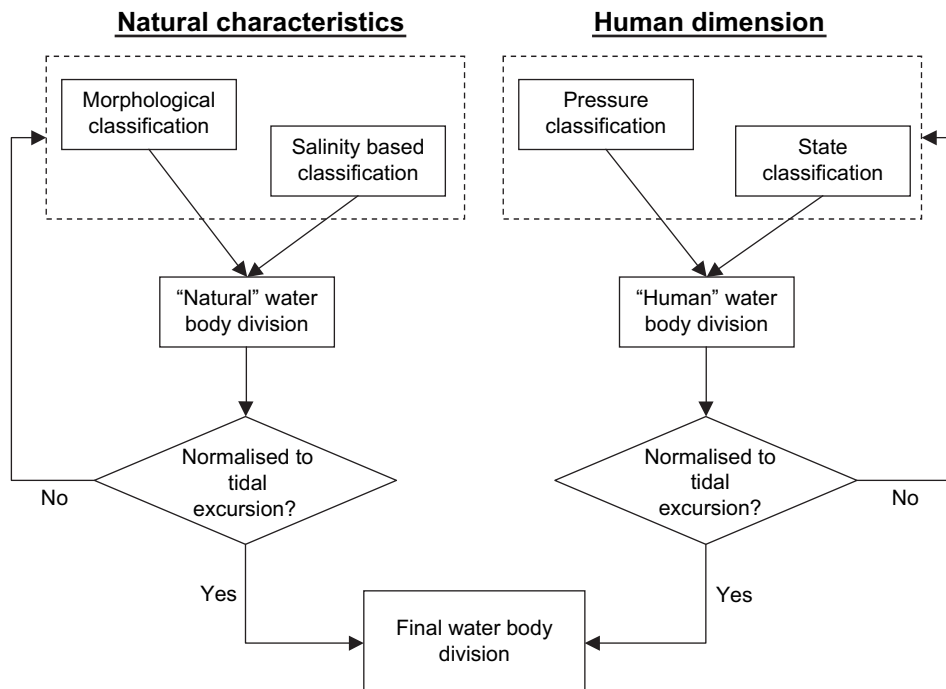

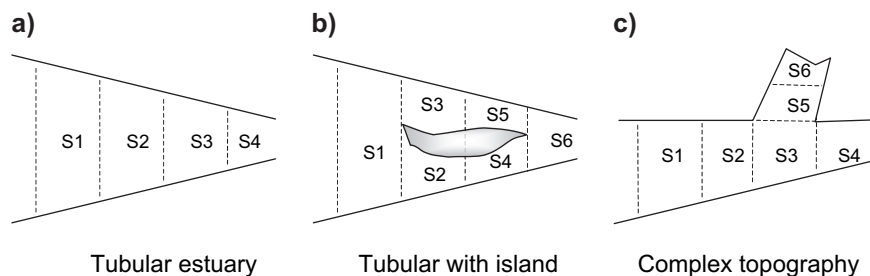Fig. 2. Stepwise definition of water bodies in transitional and restricted coastal waters.

Fig. 3. Plan view of longitudinal division into sections for different estuaries.

(GIS). The distance between sections is established as a function of the shape of the system – for a tubular estuary these are equidistant, but for systems with a more complex topography they may be heuristically determined (Fig. 3). The variable ϕ in Eq. (2) is sensitive to the number of sections used in the calculation: for a very small or very large number of sections the number of water bodies defined by $\phi > 30\%$ tends to 1. A sensitivity analysis was carried out to determine the appropriate number of sections (illustrated for the Mondego Estuary in Table 1) – the number of sections resulting in the highest number of water bodies is used. This provides the most detailed morphological division of a system, which may subsequently be aggregated through the application of other criteria.

The cross-sectional profiles are analysed in order to identify sub-units (Fig. 4): these would normally be considered separate when two (or more) deeper channels with an intertidal or island area between them occur (Figs. 3b and 4c).

2.1.1.2. Analysis and aggregation. The mean width w_i and mean depth z_i are determined by GIS for each section of the estuary. In areas where the system is split laterally into two or more sections (e.g. S2 and S3 in Fig. 3b and S1 and S2 in Fig. 4c) these are considered separately.

The shape factor σ_i is calculated for each section, and compared pair-wise to determine an aggregation index ϕ (Eq. (2)). Sections are aggregated longitudinally into water bodies when ϕ is below a threshold value. This critical value was defined heuristically to be 30%.

$$\phi_{i,i+1} = \frac{|\Delta\sigma_{i,i+1}|}{(\sigma_i + \sigma_{i+1})/2} \qquad (2)$$

Table 1
Sensitivity analysis of the number of morphology-derived water bodies as a function of the number of sections applied to the Mondego Estuary

N° of sections (comments)	N° of water bodies defined by $\phi > 30\%$
2 (estuary limits at the head and mouth)	1
4	1
7	1
20	2
40 (sections very close together)	1

where $\phi_{i,i+1}$ is the aggregation factor (no units) and $\Delta\sigma$ is the absolute difference between σ_i and σ_{i+1} (no units).

2.1.2. Salinity

A spatial framework based on salinity zonation was applied to provide an additional natural sub-division of water bodies within an estuary, complementing the morphological division. Three salinity classes were defined, based on the NOAA National Estuarine Inventory (NOAA, 1985, 1999): tidal fresh (0–0.5), mixing (0.5–25) and seawater (>25) zones, which broadly correspond to the Venice classification (Venice System, 1958). The threshold between the seawater and mixing classes (Venice system euhaline/mixohaline) was, however, adjusted to reflect changes in species distribution of floral and faunal communities along the salinity gradient.

Salinity for each station was determined from long-term salinity records and represents annual average values over the water column. The salinity zones were obtained using an inverse distance interpolator in the GIS based on the averaged salinity values for each station: tubular estuaries will normally be split into three zones and estuaries with a more complex topography and circulation may additionally be divided laterally. Although not all systems have all three zones, this allows a consistent approach for comparisons among highly diverse systems.

2.1.3. Harmonisation of the natural characteristics division

The results obtained through the application of morphology and salinity dividers are combined into a pre-final set of "natural" water bodies. In cases where the limits derived from morphology and salinity are close together, the pairs are considered as "bands", and a centreline is defined as a water body separator. In other cases, the combination of the two factors will potentially lead to more water bodies.

However, the tidal excursion is first used as a normalization test: if the length of a water body defined through morphology, salinity, or a combination of the two factors is less than the tidal excursion, its size is increased appropriately, which may lead to a decrease in the number of water bodies. The rationale for this test, which is also applied in the human dimension division, is to ensure that small areas are not considered as water bodies, since tidal circulation will cause the same water mass to be in two or more different water bodies. Given that a water body is defined in the WFD as
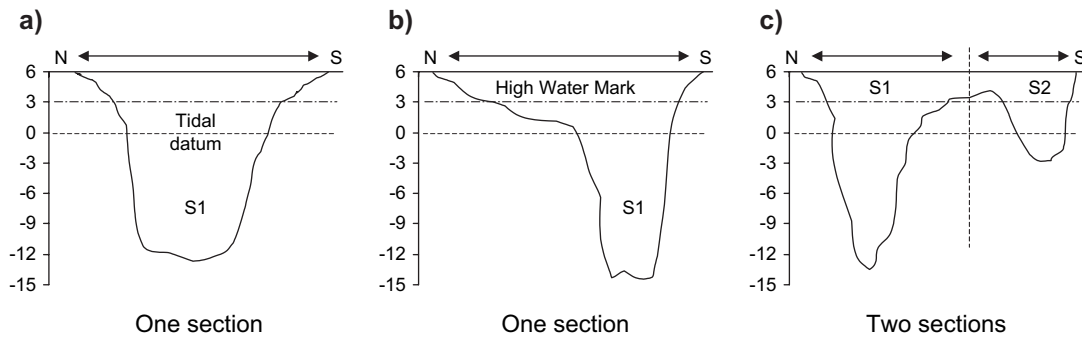
Fig. 4. Lateral division based on morphology, using transverse sections in a hypothetical estuary.

a management unit, where control measures on the significant pressures potentially result in a change in state, excessively small water bodies will be scientifically meaningless.

2.2. Human dimension

A guidance document on the application of the WFD to transitional and coastal waters (Vincent et al., 2003) provides the following orientation: "The need to keep separate two or more contiguous water bodies of the same type depends upon the pressures and resulting impacts. (…) Such an area of one type could therefore be divided into two separate water bodies with different classifications. If there were no impact from the discharge it would not be necessary to divide the area into two water bodies as it would have the same classification and should be managed as one entity." Both aspects are considered herein for water body division from an anthropogenic standpoint. The pressure factor provides an assessment of loading of the relevant substances to an estuary, and the state assessment allows a division in terms of impact of such discharges, based on a sub-set of appropriate metrics. These metrics are chosen from the list of WFD Biological Quality Elements (BQE) and Supporting Quality Elements (SQE). These are the same variables that are monitored for fulfilment of US Clean Water Act (CWA, 2002) requirements and used for the EU OSPAR Common Procedure (OSPAR, 2003) and thus the methodology detailed here should be broadly applicable.

2.2.1. Pressure

Determination of pressure on an estuarine system for the purpose of defining water bodies involves the following steps:

- Selection of the significant pressure, and choice of representative variables;
- Assessment and partitioning of loads;
- Normalisation, analysis and aggregation.

2.2.1.1. Selection of the significant pressure and representative variables. A variety of pressures may be considered in the application of the WFD for the purpose of defining water bodies and it appears appropriate that the most significant pressure should be selected. In the examples given in this paper nutrient

loading, with eutrophication symptoms (sensu Bricker et al., 2003) in the water bodies as a potential impact on state has been chosen.

2.2.1.2. Assessment and partitioning of loads. This may be done through a combination of different techniques, such as source inventories (Nobre et al., 2005) or modelling (Smith et al., 1997; Valiela et al., 1997, 2004; Kuo et al., 1999; Alexander et al., 2001, 2002; Lee et al., 2001). The Corine land cover database (EEA, 2005) was used (Fig. 5), and land use coefficients were applied to determine nitrogen and phosphorus loads. In order to partition the load discharging to different parts of an estuary, the watershed was divided into sub-basins using a digital terrain model (Fig. 5), and the final N and P loading was then determined for each section of the watershed.

2.2.1.3. Normalisation, analysis and aggregation. In order to determine the "pressure-defined" zones of an estuary, the following approach was used: (a) extend the section of each watershed to the estuary; (b) the N and P loading for each watershed sub-basin was normalised by dividing by the estuary shoreline length of the sub-basin; (c) the limiting nutrient for primary production was calculated from the Redfield ratio in the water column; and (d) a similarity index τ was defined heuristically, and used to aggregate contiguous lengths of the shoreline with similar pressure.

$$\tau_{i,i+1} = \frac{|\Delta\lambda_{i,i+1}|}{(\lambda_i + \lambda_{i+1})/2} \qquad (3)$$

where $\tau_{i,i+1}$ is the aggregation factor (no units); λ_i is the N load normalised per length of shoreline (kg Nutrient $yr^{-1} m^{-1}$) and $\Delta\lambda$ is the absolute difference between λ_i and λ_{i+1} (kg Nutrient $yr^{-1} m^{-1}$).

This index was calculated using Eq. (3); it is analogous to the approach used in the morphology component, but differs with regard to the selection of an optimum number of sections. Since the watershed sub-basin limits are defined hydrologically, thus establishing the respective shoreline lengths (Fig. 5) and the comparison is normalised to unit length there is no pre-selection procedure. Contiguous sub-basins with a value of $\tau < 100\%$ were aggregated pair-wise, providing a pressure-derived definition of water bodies.
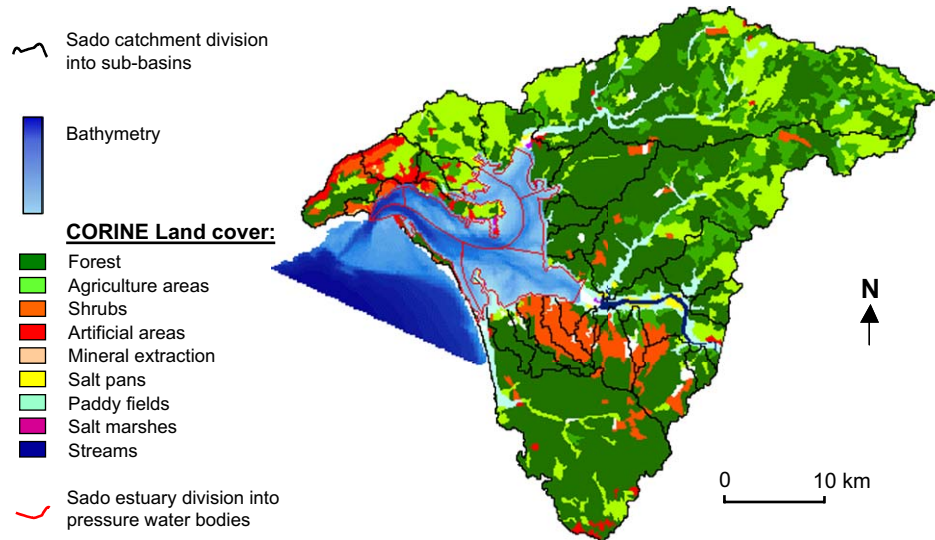
Fig. 5. Pressure aggregation based on Corine land cover mapping.

The normalization of watershed loads using shoreline length instead of estuarine area or volume was adopted in order to establish uniformity of loading (or not) along the shoreline to permit possible aggregation. The differential effects of such an aggregated loading (e.g. due to morphology or mixing) may lead to a subsequent separation based on the indicators of State.

2.2.2. State

The use of appropriate metrics of state to contribute to water body definition is justified because the relationship between pressure and state is strongly influenced by estuarine geomorphology, hydrodynamics and ecological structure. For instance, estuaries subject to similar nutrient-related pressure often exhibit totally different eutrophication symptoms, and in some cases, no symptoms at all. Factors such as water residence time (e.g. Ketchum, 1954; Lucas et al., 1999; Tett et al., 2003), tidal range (Alvera-Azcarate et al., 2003), stratification (Diaz, 2001), turbidity (May et al., 2003) and grazing (e.g. Cloern, 1982) play a major role in determining the nature and magnitude of symptom expression.

The approach followed in the present methodology consists of two steps:

- Selection of a sub-set of appropriate parameters;
- Data analysis and aggregation.

2.2.2.1. Parameter selection.
Appropriate parameters are chosen from the list of BQE and SQE. The relevance is determined from:

(a) Significant pressures — for instance, if these result in N and P discharge, water column chlorophyll *a* might be considered appropriate, whereas if the main issue is xenobiotic emissions, lead or mercury in sediments might be the element of choice;

(b) Key characteristics of the estuarine system — for instance, if eutrophication symptoms are the general category under consideration, opportunistic benthic macroalgae might be more appropriate than chl *a* for fast-flushing or strongly light-limited estuaries. For xenobiotics, benthic diversity or tissue contamination might provide relevant state characteristics.

2.2.2.2. Data analysis and aggregation.
Data on the relevant variables collected for an estuary (e.g. from field measurements or remote sensing) are assimilated at an appropriate time scale and plotted as GIS surfaces. Aggregation may be carried out by establishing concentration dividers for each variable, and using the overlapped surfaces to define the state component of water bodies. This may be done on the basis of established classification systems (e.g. MacDonald et al., 1996), or where these do not exist, using a heuristic approach.

In the present study, chlorophyll *a* (chl *a*) and dissolved oxygen (D.O.) were used as eutrophication symptoms, with data assimilated over a period of one year. Classification thresholds follow Bricker et al. (1999), using 90th and 10th percentile cut-off points for chl *a* and D.O., respectively (Bricker et al., 2003), as indicators of typically elevated (for chl *a*) and low (D.O.) values.

2.2.3. Harmonisation of the human dimension division

Harmonisation of the human dimension is carried out in a similar way to the natural characteristics division: pressure and state results are combined into a pre-final set of water bodies reflecting the human dimension. The water bodies defined through the analysis of state are used in two ways: (a) to link opposite shorelines where there is no significant gradient in state; and (b) to divide (or join) contiguous sections based
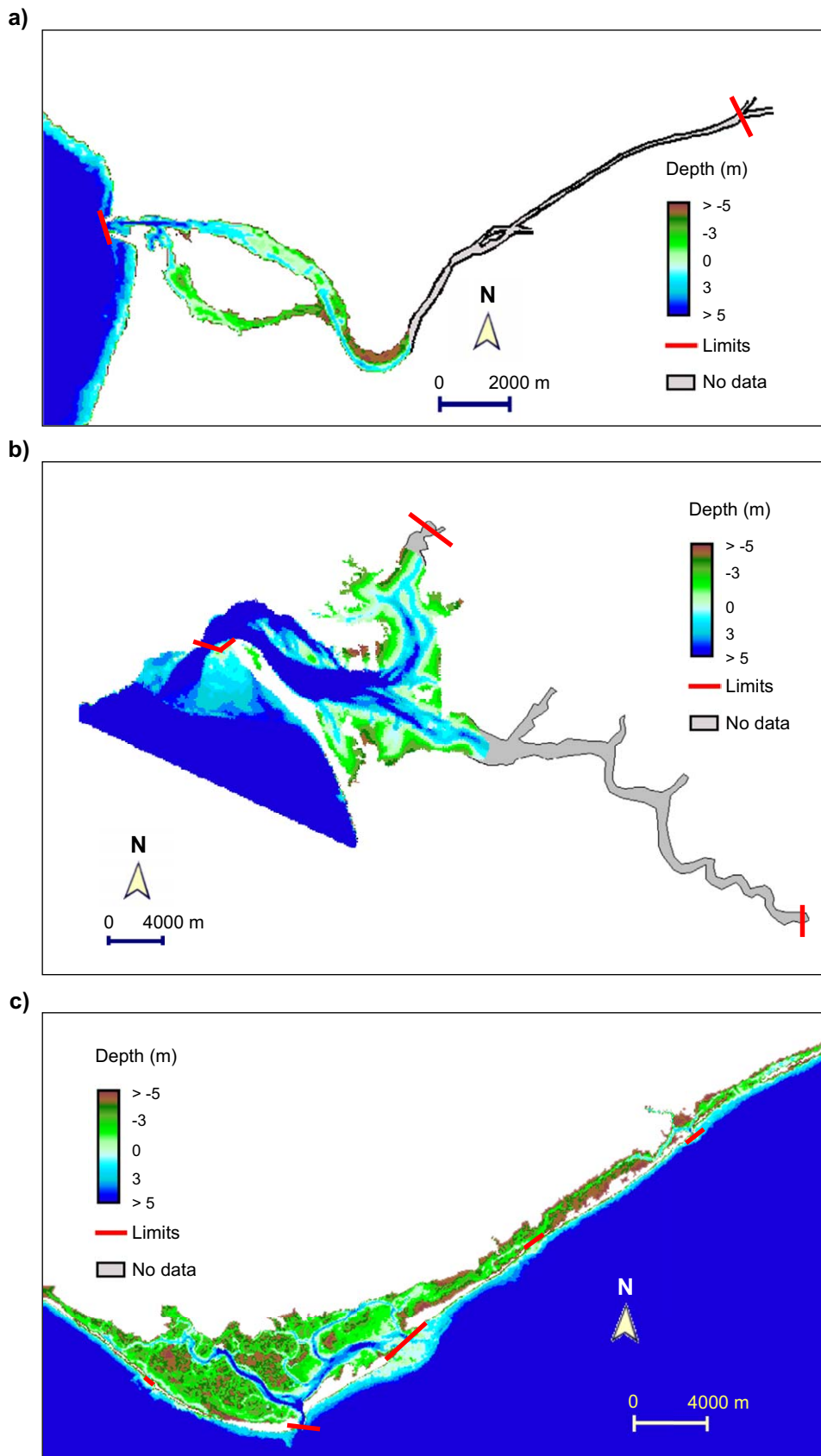
Fig. 6. Map of the systems used for case studies: (a) Mondego, small tubular estuary, (b) Sado, large coastal lagoon estuary and (c) Ria Formosa, coastal lagoon.

on pressures when there is (no) significant change in impact, following Vincent et al. (2003). As indicated previously, tidal excursion is also used as a normalization test (Fig. 2).

2.3. Final definition of water bodies

The final definition of water bodies for an estuary is obtained by combining and harmonising the natural and human components. Boundaries that are close together are aggregated as described previously, by considering a boundary "band" which is then reduced to a centreline. If required, the tidal excursion is used as a "common sense" test to define a final set of water bodies.

3. Case studies and discussion

Three contrasting systems from Portugal are presented as case studies to test the methodology, in order to highlight the various aspects of its application, including practical difficulties. These systems include two estuaries and one sheltered coastal system, belonging to two different WFD types (Bettencourt et al., 2003). They are all well-studied systems, for which appropriate data exist at adequate spatial resolution for a period of several years.

3.1. Description of test systems

The three systems (Fig. 6) selected to apply the methodology are (a) a small tubular estuary (Mondego); (b) a large coastal lagoon estuary with a 2-dimensional circulation, subject to torrential freshwater input (Sado); and (c) a coastal barrier island system with dendritic morphology (Ria Formosa). The main characteristics of the three systems are shown in Table 2, including (1) physical parameters which summarise the morphology and circulation, and provide an indication of

Table 2
Key features of the Mondego Estuary, Sado Estuary, and Ria Formosa (Ferreira et al., 2003)

Parameters	Mondego Estuary	Sado Estuary	Ria Formosa
Volume (10^6 m^3)	22	500	92
Surface area (km^2)	6.4	180	49
River flow (m^3 s^{-1})	80	40	–
Tidal range (m)	3.0	2.7	2.0
Mean water residence time (d)			
North channel	2	32	1
South channel	9		
Population	66,000	128,000	145,000
Nitrogen load (t yr^{-1})	143	3788	421
N load per unit area (g m^{-2} yr^{-1})	22.3	21.0	8.6
Phosphorus load (t yr^{-1})	27	837	83
P load per unit area (g m^{-2} yr^{-1})	4.2	4.7	1.7
Mean Redfield N/P (molar) ratio in the water column	11	4	14
ASSETS[a] grade	Moderate	High	Good

[a] For a description of ASSETS see Bricker et al. (2003); for classification of the three systems, see Ferreira et al. (2003).

system susceptibility; and (2) population data, nutrient loading, Redfield ratios and ASSETS eutrophication status (Bricker et al., 2003; Ferreira et al., 2003).

The three systems differ substantially in morphology, salinity structure, mixing characteristics, and water residence time. Anthropogenic pressure and state are also different, but in all three systems nitrogen appears to limit primary production (Table 2).

3.2. Natural characteristics

The division based on morphology is shown in Fig. 7, providing a first approach for the definition of water bodies. The morphological analysis of the similarity between contiguous sections using the ϕ criterion (Eq. (2)), results in the identification of five water bodies both in Mondego and Sado (Fig. 7a, b).

In shallow systems such as the Ria Formosa, with branched channels and large intertidal areas, it is rather biased to define cross-sections such as the ones drawn for the tubular systems. Fig. 7c, d show two possibilities for drawing sections and illustrate the difficulties, since the resulting sections would be meaningless for the division of intertidal areas. Additionally, the subsequent division into intertidal and channel areas and application of an adimensional shape factor and aggregation into a final morphological definition of water bodies is not adequate due to the heterogeneity of channels and intertidal zones, leading to an unmanageably large set of small water bodies. Instead it is proposed that the division of dendritic systems such as the Ria Formosa should be made using a heuristic criterion using drainage patterns evidenced by the bathymetry (Fig. 7e), resulting in this case study in 10 water bodies.

The salinity surfaces were calculated using data that cover all seasons and tidal situations. In the case of the Sado and Ria Formosa, the salinity distribution in the estuary is typical of a coastal lagoon and a single water body with salinity greater than 25 is considered in both cases. In the Mondego Estuary (Fig. 8), the morphologically defined WB1 and WB2 were merged into the natural WB1 using the tidal excursion criteria and also in agreement with the salinity division. On the contrary, the morphological WB4 was split into the natural WB3 and WB4 due to the salinity criterion.

The combination of the two natural factors led in the Sado and Ria Formosa to a set of water bodies dictated by the morphology. In the Mondego the natural water bodies result from the combinations of the morphological and salinity criteria.

3.3. Human dimension

Fig. 9 shows the application of the pressure metric for the Mondego and Sado estuaries. In both cases the water column Redfield ratio (in atoms) was below 16, suggesting the use of N as the element for analysis. For the Mondego, the τ threshold (Eq. (3)) distinguishes between sub-basins 1 and 2, and 1 and 5, with a τ value of about 160% in both cases. In the case of the Sado, all the contiguous sub-basin values have values of $\tau > 100\%$, suggesting the definition of six separate water bodies. In the case of the Ria Formosa this metric provides a division into 11 zones.
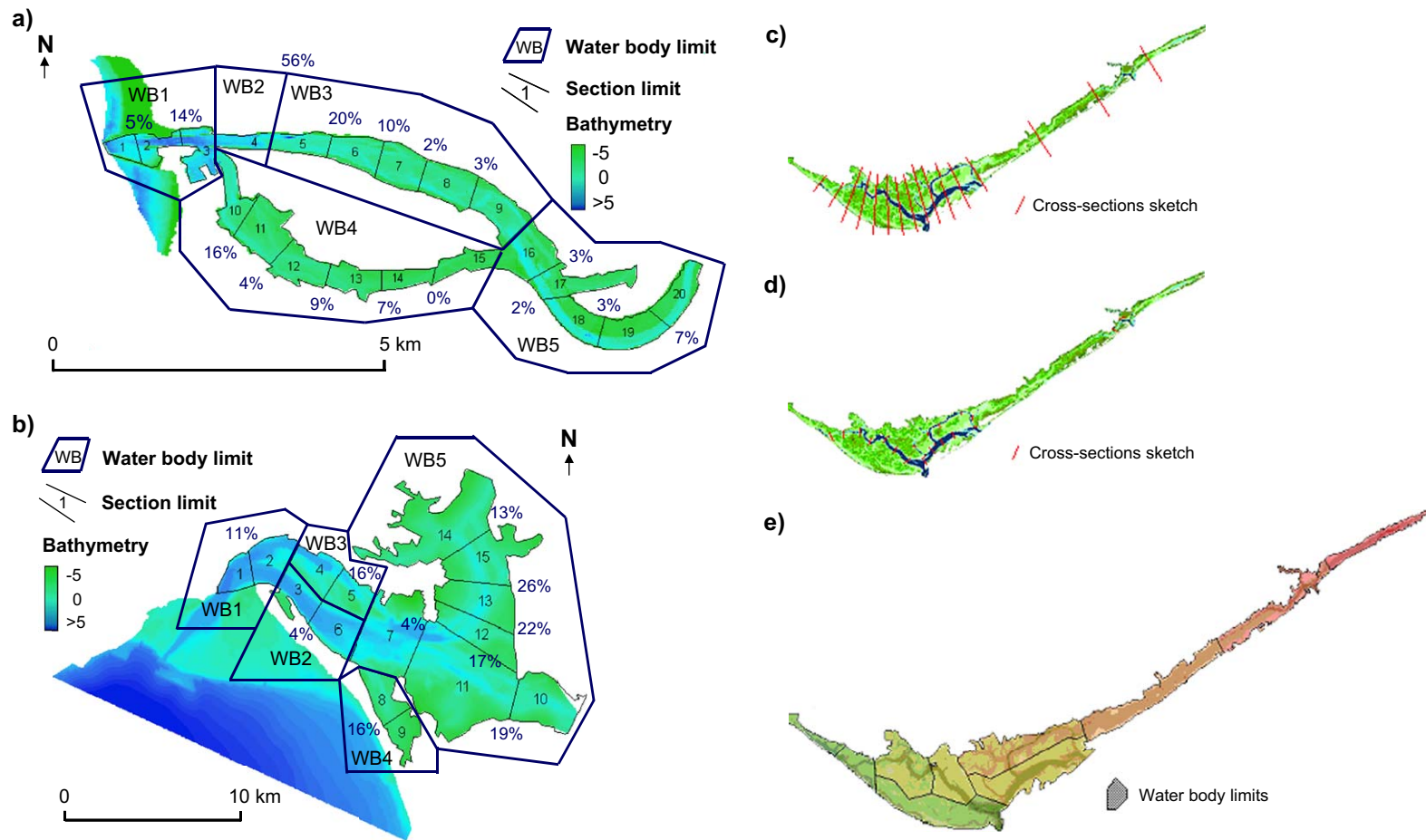
Fig. 7. Longitudinal division of the Mondego (a) and Sado (b) estuaries as an example for morphological analysis, showing GIS sections, ϕ values and definition of water bodies based on morphology. Three approaches are shown for the Ria Formosa, due to the difficulty in applying a quantitative approach to this type of system: a cross-sectional division based on (c) the whole system including intertidal areas; (d) only the sub-tidal channels; and (e) the final heuristic division.
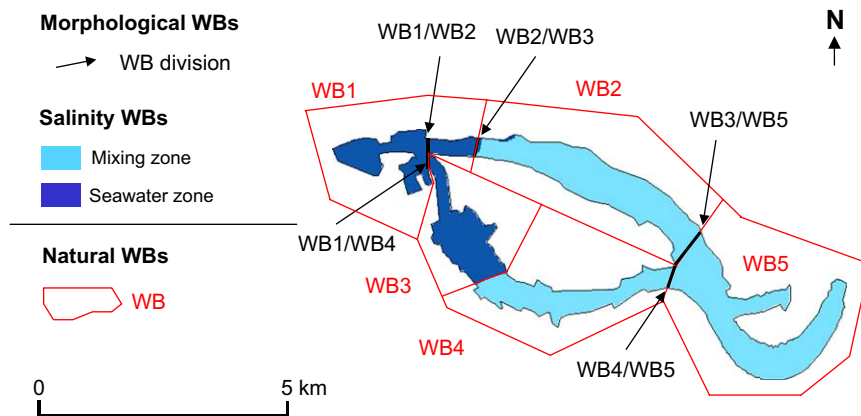
Fig. 8. Division of the Mondego Estuary into natural water bodies, combination of the morphological and salinity criteria.

The state was determined through the selection of appropriate BQE and SQE; since nutrient input was chosen as the relevant pressure, state was evaluated using chl *a* and D.O. as eutrophication symptoms as described in Section 2. The distribution of these variables in the Mondego and Sado generates a straightforward division into state water bodies since a single zone is defined using D.O. (all 10th percentile values are above 5 mg L^{-1}). Chl *a* defines two zones in the Mondego (shown by the State divider in Fig. 11a). In the Sado the complex distribution of chl *a* generates five distinct zones (see State assessment in Fig. 11b). The Ria Formosa case study is exemplified in Fig. 10. Both chl *a* and D.O. show that as regards state there is a distinct zone with lower water quality in the western part of the Ria (Fig. 10a, b). A state assessment
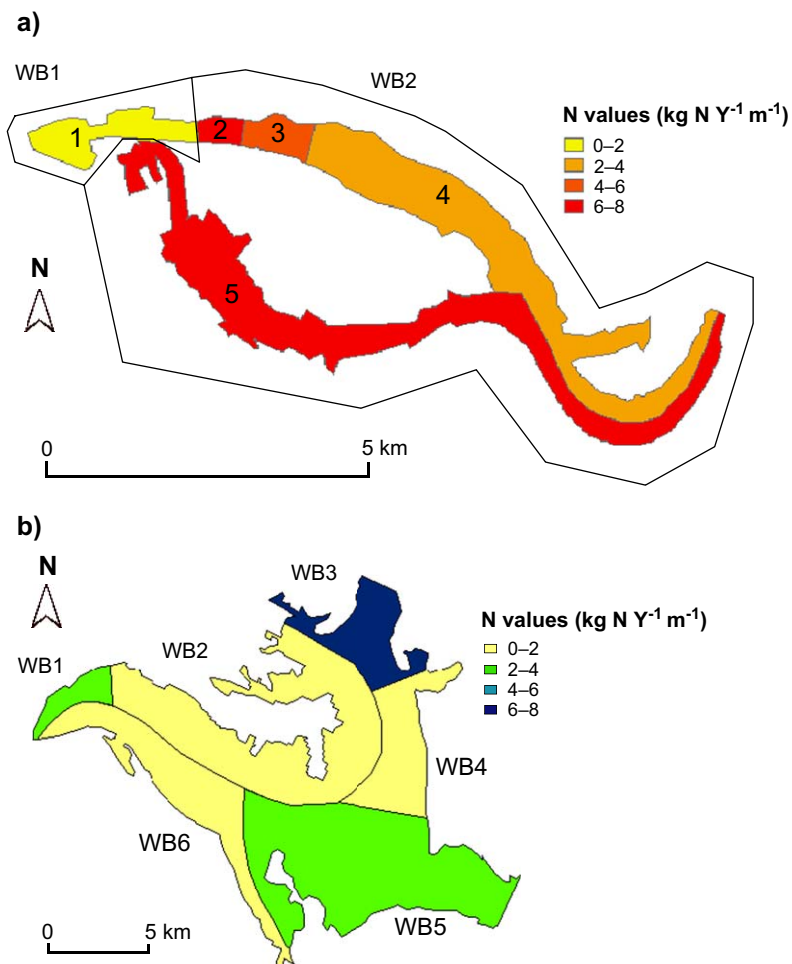

Fig. 9. Division of the (a) Mondego and (b) Sado estuaries based on watershed nutrient pressure.
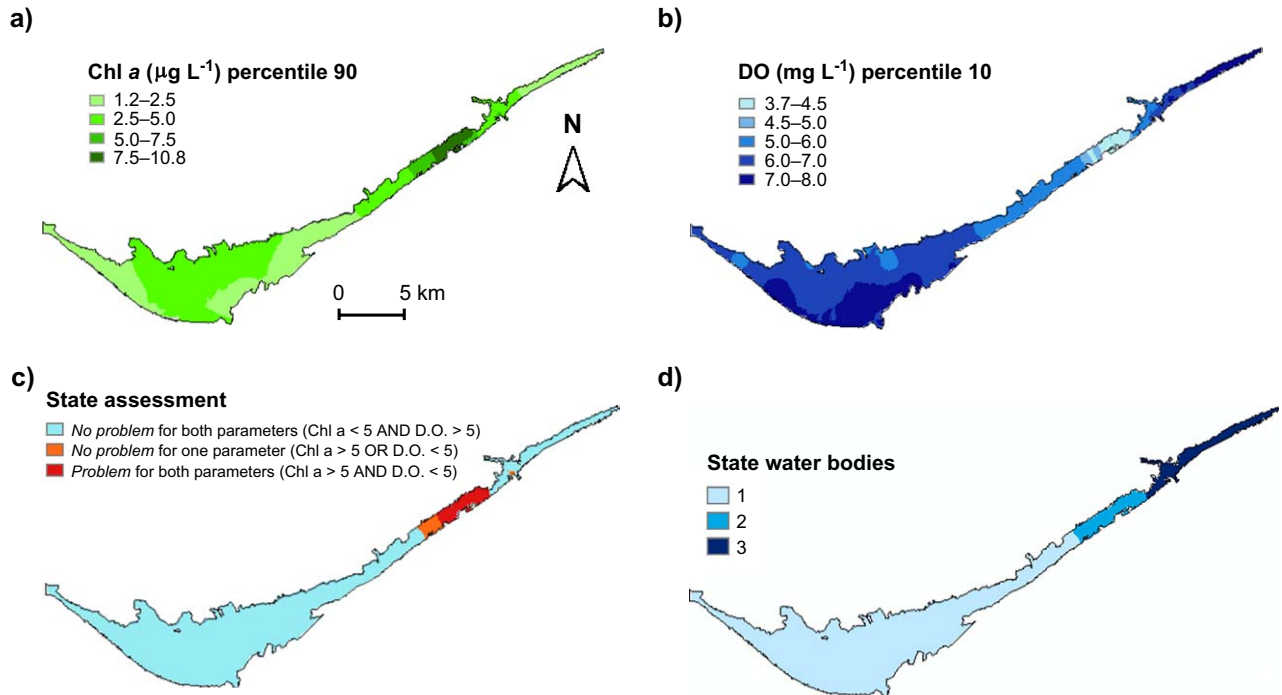
Fig. 10. Division of the Ria Formosa for State based on chl *a* and D.O. thresholds. Distribution of (a) chl *a* concentrations and (b) D.O. concentrations; (c) map algebra analysis results and (d) state water bodies.

was made by combining chl *a* and D.O. using map algebra (Fig. 10c). Pre-processing of the maps was done in order to convert continuous concentration data into binary data, No problem or Problem, regarding the ASSETS threshold of the No Problem class for these variables. The resulting state water bodies are shown in Fig. 10d.

In the Ria Formosa and Mondego it would be useful to include benthic primary producers in the state analysis as these have well-known issues of opportunistic macroalgal blooms but estuary-wide data were not available for this parameter.

In the Mondego Estuary and Ria Formosa the combination of pressure and state leads to the human dimension water bodies, three and 11, respectively, as shown in Fig. 11a, c. In the Sado Estuary the complex zones generated by the state criteria were used to divide or aggregate the ones obtained by the pressure criteria as illustrated in Fig. 11b, resulting in five human dimension water bodies.

3.4. Synthesis of natural and human characteristics

The aggregation of both natural and human dimension factors into the final water bodies is shown in Fig. 12 for the three case studies.

For the Mondego Estuary, the natural water body divisions correspond roughly to the human water bodies, except between WB3 and WB4 (shown in Fig. 8), leading to a set of four water bodies. As shown in Fig. 12a, the divider between WB1/WB2 changed to the centreline of the natural and human divisions. The dividers between WB2 and WB3 and between WB3 and WB4 were kept the same as in the natural water bodies, in this

case the centreline would generate an additional small water body that would be eliminated using the tidal excursion criterion. The divider between WB1 and WB4 exemplifies another exception where the centreline might not be used, instead the human division was used to avoid generating an awkward division due to the morphology of the system in this zone. The natural WB3 and WB4 (Fig. 8) were merged into WB4 since the human dimension criterion showed no difference between these.

In the case of the Sado Estuary, five water bodies are identified, the complex human dimension water bodies were harmonized with the natural ones as shown in Fig. 12b, aggregating the boundaries close together and using the tidal excursion to eliminate small water bodies. The complex zones defined by the state criterion were simplified into a final set of water bodies (WB3 and WB5).

In the Ria Formosa the combination of the natural (Fig. 7e) and human (Fig. 11c) water bodies would generate a large number of small water bodies. The final set of five water bodies (Fig. 12c) was obtained using the natural water bodies (defined according to drainage patterns) as a basis and the human dimension criteria for aggregation (e.g. WB2, WB3 and WB4 of Fig. 12c). The small water bodies that would be generated at the system limits were merged resulting in WB1 and WB5 (Fig. 12c).

4. Conclusions

The approach described in this paper provides a division of coastal systems (estuaries or restricted coastal areas such as lagoons or embayments) into a meaningful set of water bodies integrating both natural characteristics (morphology and
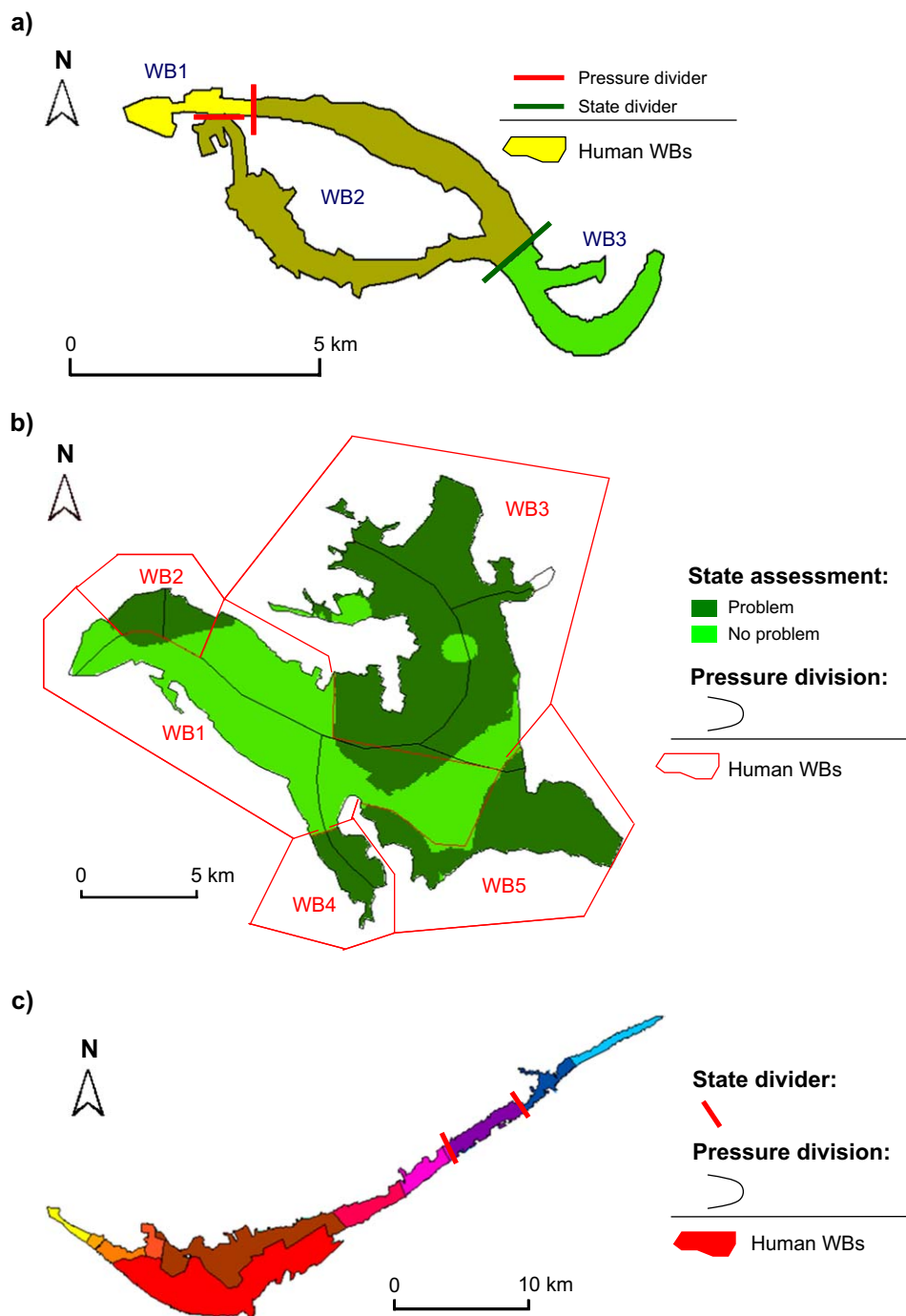
Fig. 11. Division of (a) Mondego, (b) Sado and (c) Ria Formosa, into human dimension water bodies, combination of the pressure and state components.

salinity) and management criteria (pressure and state). Thus, the application of the present methodology depends not only on the availability of natural attributes and water quality data but also on the knowledge of the significant pressures on a system.

The legislation currently enacted or under development in the EU and US (e.g. USEPA, 2001) for water quality management in transitional and coastal waters places a heavy burden on estuarine and coastal science, due to the difficulties inherent in its interpretation and application. These difficulties vary

from the precise legal definition of estuarine limits to the definition of appropriate type-specific reference conditions (e.g. Sagert et al., 2005; Ferreira et al., in press), and have serious repercussions on the definition of management measures, regulatory sanctions, etc.

For the definition of estuarine limits and related issues, Elliott and McLusky (2002) show how important the underlying science may be for the application of the EU Urban Waste Water Treatment Directive (UWWTD), which has been in force since 1991. Most of the interpretation questions between EU
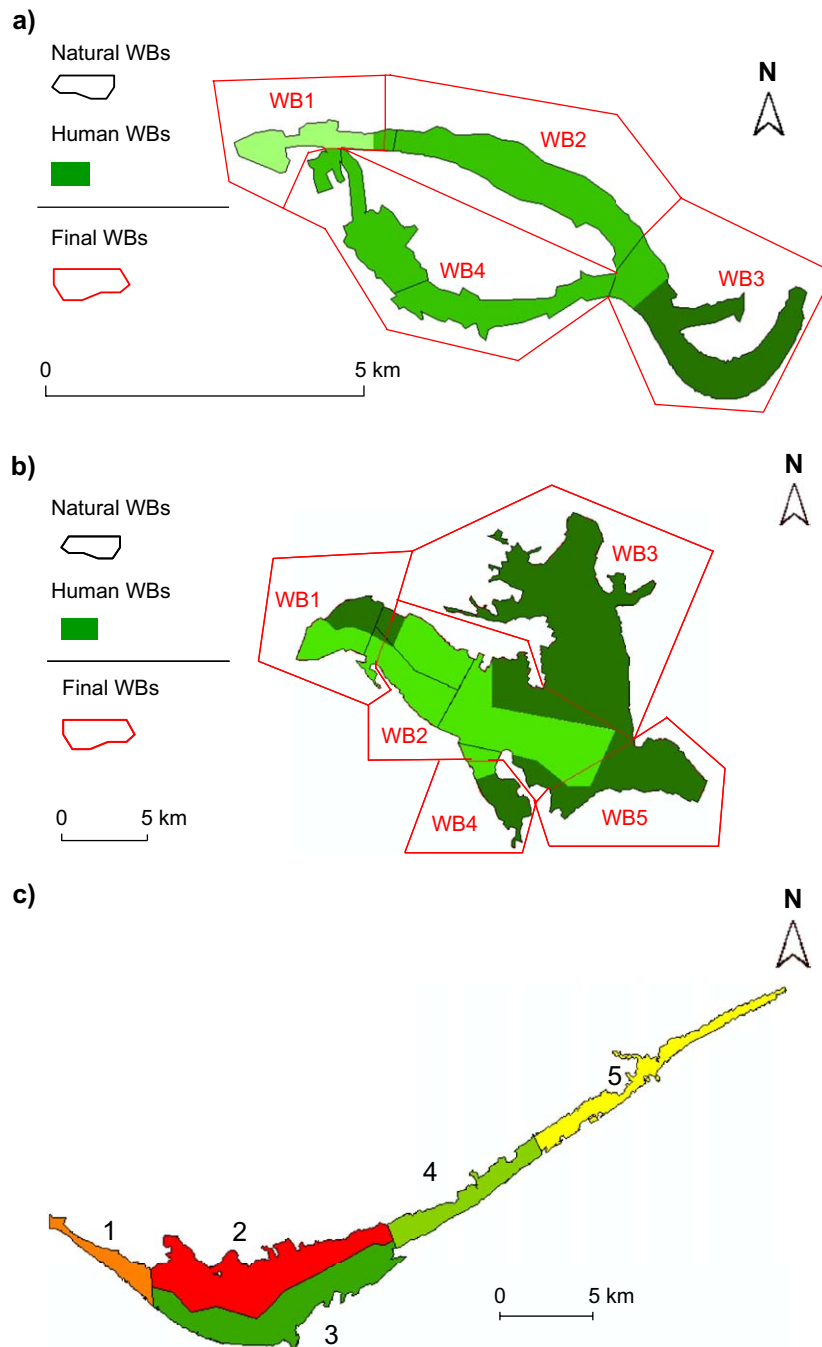
Fig. 12. Final definition of water bodies for the three case study systems.

Member States and the European Commission on the UWWTD have arisen in the past 10 years, and it seems reasonable to expect a similar lag with the WFD, but across a far broader range of issues.

Since the WFD is currently undergoing a series of steps of technical definition, guidance and harmonisation, this is the appropriate time for scientific discussion of many of these issues. This is particularly the case for estuarine systems, due to their transitional nature – reference conditions are particularly hard to define, due to, for example, the lack of pristine systems, the high level of noise-driven variability in most

estuarine signals, and the lack of an appropriate ecological paradigm to address issues such as biodiversity. The definition of water bodies in transitional waters for use as the "operational" units of the WFD (an approach which is also relevant to the US) presents an additional number of significant challenges: these include resolving (1) widely varying pressures (in magnitude and type) on different estuarine sections; (2) complex mixing patterns; and (3) the various manifestations of state change in different ecological compartments. For instance, "natural" pressures such as harmful algal blooms which develop, for example, due to upwelling relaxation in

offshore frontal systems, and are well described for the Iberian West coast (Fraga et al., 1988), North-West American coast (Wieters et al., 2003; Wetz and Wheeler, 2004) and the Benguela current (Andrews and Hutchings, 1980; Barlow, 1982; Brown and Field, 1985) are not immediately amenable to management measures (short of interdiction bans); estuarine science must play a key role in informing decision-makers on what may be identified as human influence responsive to management measures.

The authors hope that this paper will be seen as a contribution to the increased information of coastal management by science, playing a part in addressing the paradox expressed by Elliott (2000) as "…the scientific community is mostly working on very detailed and more narrow aspects whereas the managers require a holistic and ecosystemic approach, not necessarily at a very high level of detail."

Acknowledgements

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