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Effects of a specific climate scenario on the hydrography and transport of conservative substances in the Weser estuary, Germany: a case study

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ABSTRACT: The effects of a presumed climate scenario on the hydrography of the Weser estuary between Bremen (weir) and Robbensüdsteert (~10 km downstream of Bremerhaven) were investigated using numerical modeling. The results provide a basic approach for further studies addressing, for example, the utilization and ecology of the Weser estuary and the adjacent areas within the bounds of the winter dike. Morphological aspects are not considered in this paper. A rise in water level at the seaward boundary (high water +70 cm, low water +40 cm) propagates upstream only with some slight deviations. In the climate scenario, the subtidal volume and sublittoral for the section between the weir and Bremerhaven increase by about 6 and 7% respectively, while the tidal prism and eulittoral increase by about 16 and 52% respectively. Residence times of conservative water constituents are prolonged for fixed runoffs. These times also affect the water quality. The location of the upstream boundary of the brackish-water zone is located on average 2 km further upstream for fixed runoffs, possibly causing problems with marsh irrigation.

KEY WORDS: Weser estuary · Hydrography · Climate scenario

1. INTRODUCTION

Global climate has undergone considerable fluctuations in the past, as revealed by geological investigations. Presently, mean global warming is predicted for the future (e.g. IPCC 1996). Warming accompanied by a rise in sea level would have consequences on the hydrodynamic, morphological and ecological state of coastal waters and estuaries (e.g. Schellnhuber & Sterr 1993, Jones 1994). The possible types and magnitudes of changes in these systems are of interest to society and policy makers.

In the present paper a climate scenario for the year 2050, based on the work of von Storch et al. (1998) and described by Schirmer & Schuchardt (2001, this issue), is used to investigate consequences of global warming on the Weser estuary, Germany (Fig. 1). The different points of view concerning the existence and strength of climate change on a global or regional scale in the next 50 yr will not be an element of this paper, nor will the significance of the climate scenario chosen.

The Weser estuary is the lifeline of an economic and residential region. It is a navigational channel which receives urban and industrial sewage. Furthermore, it is used for irrigation and drainage of the Weser marshes. Changes in the hydrography (e.g. Wetzel 1987) and water quality and ecosystem (e.g. Busch et al. 1989) during the past 100 yr can partly be attributed to such utilization. Climate change may alter the system further and may also affect the ways in which the estuary is currently utilized. Kunz (1993) and Schirmer & Schuchardt (1993) reviewed the sensitivity of the Weser estuary to possible climate change. Climate change can result in changes in water levels and cur-

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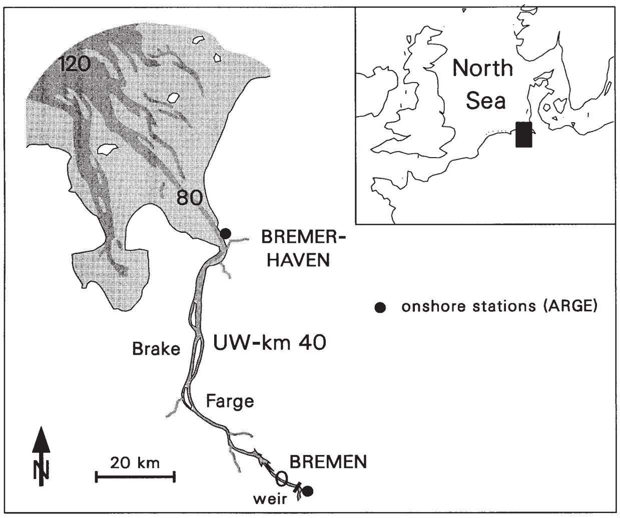

Fig. 1. Weser estuary, Germany. Official kilometer scale (UW-km) starts at bridge in Bremen, ~5 km downstream of weir. ARGE, Arbeitsgemeinschaft der Länder zur Reinhaltung der Weser

rents, temperature and freshwater runoff. These changes can influence the position and extent of flooding areas, the position of the brackish water zone, residence times and water quality. In addition, the estuary's ecosystem as well as its utilization could be influenced.

The interdisciplinary project 'KLIMaänderung und Unterweserregion' (KLIMU, Climate Change Impact on the Weser Estuary Region)—funded by the Bundesministerium für Bildung und Forschung and Freie Hansestadt Bremen—investigates the sensitivity of the hydrological, ecological and socio-economic properties of the Weser estuary and the adjacent regions with respect to the above-mentioned climate scenario. The project was designed within the 'Climate Change and the Coast' research program in order to provide a basic approach for decisions regarding water economy and management, as well as environmental policies, and to allow precautionary planning.

In the project the following different topics are considered (see Schirmer & Schuchardt 2001 for an overview): landuse, development scheme, ecometry (Universität Bremen, Bahrenberg et al. 1999, Elsner & Knogge 1999); groundwater (Universität Hannover, Meinken & Hoffmann, 1999) and water-resources management (Universität Braunschweig, Maniak et al. 1999) in the areas adjacent to the Weser estuary; coastal protection (Universität Hannover, von Lieberman & Mai 1999); hydrography and water quality of the Weser estuary (GKSS, Forschungszentrum Geesthacht); and ecology of the Weser estuary and the surrounding country (Universität Bremen, Osterkamp et al. 2001, this issue).

The hydrography and water quality of the Weser estuary were investigated with respect to utilization and to ecological impacts on the basis of numerical modeling. In order to qualify and, wherever possible, to quantify changes in hydrography and water quality due to the chosen climate scenario, the status quo was first established. Model simulations were conducted for the status quo and the climate scenario. Although coupling of hydrodynamic and morphodynamic models has gained interest during the last decade, it is not considered in this study. In the Weser estuary, bottom variations are caused by natural processes and by sporadic engineering works and repeated dredging carried out in order to maintain present utilization. Therefore, if natural morphological variations were to be considered, anthropological interference would also have to be taken into account. Anthropological alteration of river topography is a response not only to natural variations but also to independent political and economic decisions. However, while some alterations were investigated in the project in the form of scenarios, their results are not included in this paper. The results presented here are based on model runs using the same topography for the status quo and for the climate scenario.

In this paper, changes in the hydrographic variables between the status quo and the climate scenario are quantified. These results provide basic information for further investigations on the estuary's utilization and ecosystem, which are mainly considered by the other groups working within the project and are only briefly outlined here. A report concerning water quality is in preparation.

2. NUMERICAL MODELING, STATUS QUO MEASUREMENTS AND THE CLIMATE SCENARIO

The Weser estuary is separated into the 70 km long channel-like Lower Weser, between the weir in Bremen and Bremerhaven, and the 55 km long Outer Weser consisting of 2 tidal channels within the Wadden Sea. The research area covered the Lower Weser from the weir in Bremen and about 10 km of the Outer Weser, up to UW-km 80 (the gauge 'Robbensüdsteert', Fig. 1).

The tool used in this case study was a time-dependent, cross-sectionally averaged, numerical water-quality and transport model (Müller et al. 1992) in which 3-dimensional topography was included by parameterization. This model has been validated for the Weser estuary and used in various investigations. Although the estuarine system was simplified due to the cross-sectional averaging, field experiments performed in the Weser estuary indicated that the vertical and lateral gradients of the variables discussed (except current velocity) are small compared to their longitudinal variations. Higher-dimensional modeling enables the resolution of small-scale phenomena; however, it was not essential for this case study. This study focused on longitudinal and temporal variations, especially those with respect to freshwater runoff. Essential vertical and lateral phenomena (e.g. vertical profile of the current velocity) were parameterized.

The years 1991 and 1994 were chosen for the description of the status quo. These years are extremely different in view of freshwater runoff (Table 1): 1991 was dry, 1994 was wet. Furthermore, 1994 was relatively hot. Mean high water and mean low water were about 10 cm lower in 1991 and about 10 cm higher in 1994 when compared with the 10 yr average for 1985 to 1994 (Deutsches Gewässerkundliches Jahrbuch 1994). Therefore, a wide range of variation is covered.

Observed data were used for model input purposes as well as for comparisons with model results in the case of the status quo. The water level is measured at different tidal gauges (Wasser- und Schiffahrtsämter Bremen und Bremerhaven); low water and high water at 5 tidal gauges are published in the Deutsche Gewässerkundliche Jahrbücher. As part of the water-quality monitoring, salinity is recorded (mainly 14 d means for ~20 yr) at onshore stations in Bremen, slightly upstream of the weir, and Bremerhaven (UW-km 69.4). Additionally, nonsynoptic near-surface longitudinal transect measurements are carried out about once a month in well-developed ebb currents (Arbeitsgemeinschaft zur Reinhaltung der Weser, Bezirksregierung Weser/Ems, Außenstelle Brake, Senator für Bau und Umwelt Bremen).

At the seaward boundary of the model (UW-km 80) tidal cycles of observed water level and derived salinity were used. The tidal cycles of salinity were calculated from an empirical relationship between water level, runoff and salinity. This relationship was established on the basis of measurements scattered over several years and at diverse stations (Wasser- und Schiffahrtsamt Bremerhaven, Alfred-Wegener-Institut für Polar- und Meeresforschung Bremerhaven).

At the landward boundary (weir) daily values of freshwater runoff and salinity were used. Runoff values for 1991 and 1994 were taken from the 'Deutsche Gewässerkundliche Jahrbücher'. For salinity, annual cycles of daily values were derived from interpolation of the salinities at UW-km 0 observed during the longitudinal transects. These annual cycles correspond to those derived from the 14 d means at the weir.

In the model runs, daily or 3 h values of observed meteorological variables (e.g. wind speed and direction, see Müller et al. 1992) were incorporated. The model topography is based on cross-sectional measurements of the river with a longitudinal separation of 125 m and on longitudinal transect measurements (Wasser- und Schiffahrtsämter Bremen and Bremerhaven, Bundesanstalt für Wasserbau Karlsruhe). The set of cross-sections provides the basis for a curvelinear coordinate system. The heights of areas between mean water level and the winter dike are based on 1:5000 topographic maps (Deutsche Grundkarte).

The climate scenario chosen (Schirmer & Schuchardt 2001) assumes a mean sea level rise of 55 cm and a change in tidal range of 30 cm (high water +15 cm, low water –15 cm). Furthermore, it assumes an increase in temperature, frequency and intensity of storms and a change in precipitation. For the investigation described here, the sea level rise and the change in tidal range were considered at the seaward boundary. Seasonal changes of the freshwater runoff were taken into account at the landward boundary. These changes were calculated by the project group in Braunschweig on the basis of the changes in precipitation and temperature (Table 2). The mean and maximum runoffs increased for the climate scenario (Table 1); these increases took place in winter, spring and autumn.

The correlation between riverine salinity that is the result of salt inputs due to salt mining in the catchment area and freshwater runoff is not highly significant. This may be due to strong and irregularly changing salt inputs unrelated to runoff. Only about 30 % of the history of salinity can be accounted for by runoff variations. Therefore, the salinity values at the landward

Table 1. Freshwater runoff (m^3 s^{-1}) at Intschede (~30 km upstream of weir in Bremen). SQ, status quo; CS, climate scenario; MQ, long-term or annual mean; MLQ, MHQ, long-term average of annual minima and maxima respectively; LQ, HQ, annual minimum and maximum respectively. Values for SQ, Deutsche Gewässerkundliche Jahrbücher, Weser-/Emsgebiet (1991, 1994, 1996)

	SQ 1941–96		SQ 1991	SQ 1994	CS 1991	CS 1994
MLQ	125	LQ	74	135	75	135
MQ	325	MQ	214	503	237	587
MHQ	1250	HQ	940	1890	994	2007

Table 2. Climate scenario

	Precipitation (%)	Temperature (°C)
December, January, February	+15.7	+2.9
March, April, May	+22.1	+3.2
June, July, August	–6.0	+2.7
September, October, November	+12.2	+2.2

boundary used for modeling the status quo were also used for modeling the climate scenario.

With the lack of definite information about changes in salinity in the German Bight (Heyen & Dippner 1996), 2 different model runs were carried out. Firstly, the salinity used for the status quo at the seaward boundary was also used for the climate scenario. Secondly, the salinity at the seaward boundary was changed with respect to the assumed runoff changes using the aforementioned empirical relationship between water level, runoff and salinity.

3. RESULTS

In this section, results for the climate scenario are compared with those for the status quo; they are later discussed with respect to long-term trends and to the estuary's utilization and ecology. Changes in water levels, water volumes, flooded and non-flooded areas, transport of water and water constituents, and the position of the mixing zone are quantified.

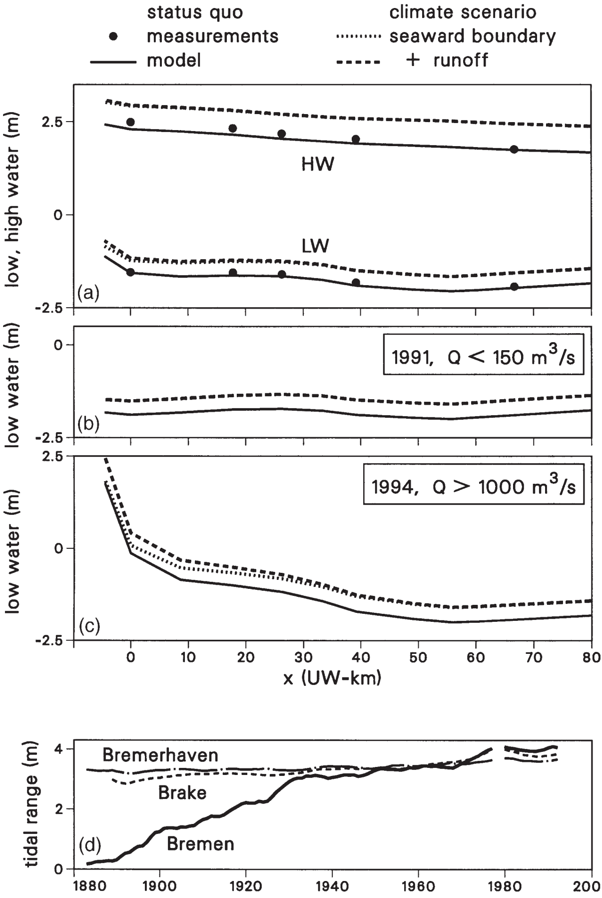

Fig. 2. (a–c) Longitudinal transects of water levels for the status quo and the climate scenario. Mean high water (HW) and mean low water (LW) averaged over 1991 and 1994. (•) Values based on data from 'Deutsche Gewässerkundliche Jahrbücher'. Mean low water for (b) low runoff, 1991, and (c) high runoff, 1994. (d) Time series of tidal range (5 yr running averages) at 3 locations. Averages are based on data from Wasser- und Schiffahrtsamt Bremen, Deutsche Gewässerkundliche Jahrbücher (1977–1997)

3.1. Water level and tidal wave propagation

Estuaries are often classified as either 'hypersynchronous', 'synchronous' or 'hyposynchronous' with respect to change in tidal range along their longitudinal section (LeFloch 1961, summarized in Nichols & Biggs 1985) caused by the opposing effects of frictional damping and concentration of energy due to convergence of channel cross-sections. Most estuaries belong to the hypersynchronous type, in which the tidal amplitude increases landward from the mouth before decreasing towards the river (Nichols & Biggs 1985). In the hypersynchronous Weser estuary the mean tidal range increases slightly towards Bremen—maximum tidal range around UW-km 0—and decreases towards the weir, ~5 km upstream of UW-km 0. In the status quo, the simulated tidal range was 3.5 m at the seaward boundary of the research area (UW-km 80), 3.9 m at Bremen (UW-km 0) and 3.6 m at the weir. These values are averages over the years 1991 and 1994. Averaged values for high water (HW) and low water (LW) which resulted from the modeling were up to 15 cm lower than those derived from measurements published in the 'Deutsche Gewässerkundliche Jahrbücher' (1991, 1994), as shown in Fig. 2a. This deviation was usually less than 20 cm for single values.

Upstream of Brake (UW-km 40), low water and tidal range in particular show a significant dependence on freshwater runoff. At the gauge in Bremen (UW-km 0), the simulated low water level was ~1.8 m higher for high runoffs (>1000 m^3 s^{-1}, 1994, Fig. 2c) than for low runoffs (<150 m^3 s^{-1}, 1991, Fig. 2b). There the tidal range was only ~2.9 m for high runoff but ~4.1 m during low runoff. During spring/neap tides the tidal range was ~0.5 m higher/lower in comparison with the mean tide.

For the climate scenario, firstly only the influence of the water level rise at the seaward boundary was analysed. The assumed low water rise of 40 cm at UW-km 80 resulted in a rise of 33 and 37 cm in Bremen for mean and low runoff conditions respectively (Fig. 2a,b). For high runoff (Fig. 2c) the low water rise of 40 cm decreased upstream of Brake, to 21 cm at Bremen. In contrast to the status quo, the pressure of the runoff became less noticeable due to the strengthened tidal wave. High water level changes in the model area differed only slightly from the 70 cm rise at UW-km 80.

Table 3. Ebb and flood durations (h.min, averaged over 1991 and 1994) for UW-km 80 and UW-km 0. SQ, status quo; obs, observed; sim, simulated; CS, climate scenario. SQ(obs), based on data from Deutsche Gewässerkundliche Jahrbücher (1991, 1994)

	SQ(sim) ebb	SQ(sim) flood	SQ(obs) ebb	SQ(obs) flood	CS ebb	CS flood
UW-km 80						
1991/94	6.17	6.08	6.17	6.08	No change assumed	
UW-km 0						
1991/94	7.17	5.08	7.21	5.04	7.10	5.15
<150 $m^3 s^{-1}$	7.07	5.18			7.01	5.24
>1000 $m^3 s^{-1}$	7.38	4.47			7.28	4.57

When the assumed changes in freshwater runoff (increased runoff of 10 to 15% in winter, spring and autumn) were also taken into account, the influence of runoff again became more noticeable in the inner part of the estuary, upstream of Brake. The changes in low and high water levels at Bremen (UW-km 0) were then 40 and 64 cm respectively (averages over 1991 and 1994, Fig. 2a). In high runoff conditions (Fig. 2c), the changes at Bremen slightly exceeded those at UW-km 80. The averaged tidal range was 3.8, 4.1 and 3.8 m at UW-km 80, Bremen and the weir respectively, for 1991/94. Differences in water levels between spring and neap tides corresponded to those for the status quo.

The flood duration decreases and the ebb duration increases in the upstream direction. In the status quo, the flood duration decreased from 6 h 8 min at UW-km 80 to 5 h 8 min at UW-km 0; the ebb duration increased from 6 h 17 min at UW-km 80 to 7 h 17 min at UW-km 0 (averages over 1991 and 1994, Table 3). Low water and high water occurred about 3 h 15 min and 2 h 15 min later, respectively, in Bremen than at UW-km 80. Deviations between simulated and observed times were ~10 min. In the case of low runoff (<150 $m^3 s^{-1}$, 1991) the ebb duration was shorter and the flood duration longer, and vice versa in the case of high runoff (>1000 $m^3 s^{-1}$, 1994).

In the climate scenario the mean ebb duration slightly decreased and the mean flood duration slightly increased upstream towards Bremen. For mean runoffs, the ebb duration at UW-km 0 was 7 min shorter and the flood duration 7 min longer in the climate scenario than in the status quo (averages over 1991 and 1994, Table 3). Similar changes occurred for very low and high runoffs.

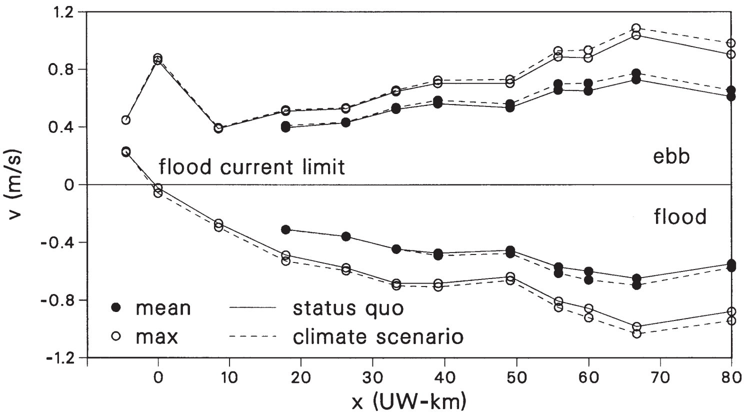

Fig. 3. Longitudinal transects of mean and maximum current velocity *v* during ebb and flood tide, simulated data, averaged over 1991 and 1994 for the status quo and the climate scenario. Mean values not given upstream of UW-km 17 because of shift in flood current limit

3.2 Current velocity and mixing intensity

In the status quo the maximum and mean current velocities during ebb or flood tide varied from ~0.7 m s^{-1} near Bremerhaven (UW-km 67) to ~0.4 m s^{-1} near UW-km 20. The respective maximum velocities were ~1 to 0.55 m s^{-1}. Due to the narrow crosssections the maximum ebb current velocity in Bremen near UW-km 0 increased up to 0.9 m s^{-1} (Fig. 3). These values are averages over the years 1991 and 1994; values within single tidal cycles can exceed 2 m s^{-1}. The flood current limit (upstream of which there is no flood current) is usually observed in the Bremen area and depends on the freshwater runoff. In the status quo, this limit varied from ~UW-km –3 to ~UW-km 10 for the long-term averages of the annual minimum and maximum runoffs (MLQ and MHQ, see Table 1) respectively.

In the climate scenario the mean and maximum current velocities during ebb or flood tide (averages over the years 1991 and 1994) increased by 1 to 7 cm s^{-1} (Fig. 3). Because of the assumed change in tidal range of 30 cm, the current velocity also increased at the seaward boundary. The highest changes (by 4 to 7 cm s^{-1}) between the status quo and the climate scenario occurred downstream of UW-km 55. For a fixed runoff, the flood current limit lay ~2 km further upstream.

The ratio of runoff per tidal period (average 1991/94) to tidal prism (see Section 3.3) can be used as a criterion for classifying mixing intensity in an estuary (e.g. Barg 1979). This ratio was about 0.08 for the status quo and for the climate scenario. According to the criterion, the Weser estuary was, on average, well-mixed for both cases. For the cli-

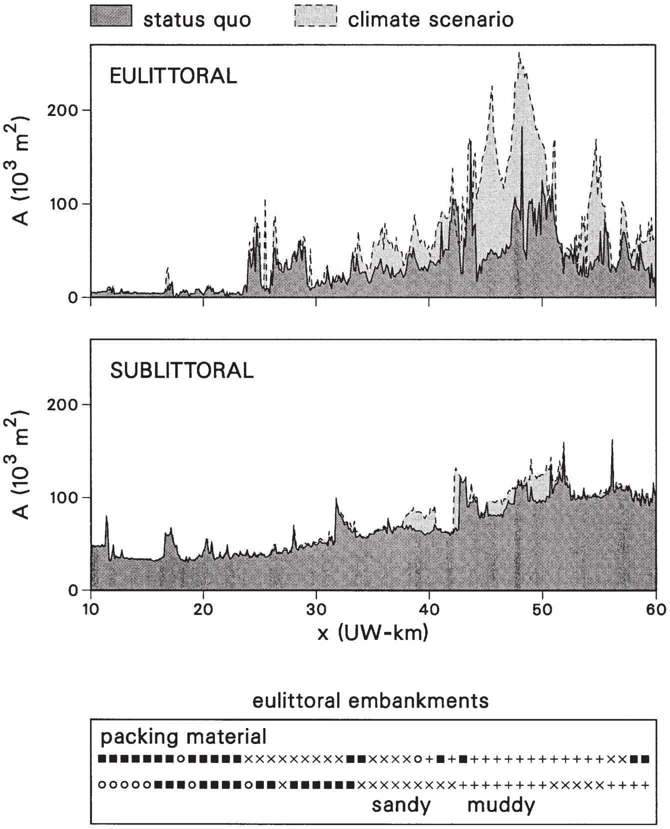

Fig. 4. Sublittoral and eulittoral between UW-km 10 and 60 for status quo and climate scenario. Rough classification of eulittoral embankmants also given, after Schuchardt et al. (1984)

mate scenario the change in the tidal prism was almost compensated by the assumed change in the freshwater runoff. Variations in mixing processes on a small scale were not investigated, and fixed parameters for these were used in the model.

3.3. Water volumes and flooded areas

Changes in water levels correspond to changes in water volumes and to the expansion of temporarily or permanently flooded areas. For the status quo, the subtidal volume (i.e. volume below low water) of 300×10^6 m^3 was $1.5 \times$ the intertidal volume or tidal prism (i.e. volume between low and high water) of 195×10^6 m^3. These values were calculated for the section between the weir and Bremerhaven (UW-km 70) for water levels averaged over 1991 and 1994 (see Fig. 2a). These averages almost correspond to the most frequently observed low and high water levels (i.e. the mode). For the climate scenario, the subtidal volume increased by ~6%, and the intertidal volume increased by ~16%. The low water rise of ~40 cm was restricted to steeper parts of the river bed, but the high water rise of ~70 cm also reached the shallower areas to the left and right.

For the status quo, the areas of the sublittoral and eulittoral were 42×10^6 m^2 and 24×10^6 m^2 respectively, for the above-mentioned section. The change in the sublittoral between the status quo and the climate scenario was relatively small (~7%, see Fig. 4). The change in the eulittoral for this section was more obvious; its area increased by ~52%. When the deviations between the simulated and observed average water levels were taken into account, the sublittoral and eulittoral for the status quo increased by ~2%.

3.4. Residence times

Changes in water level and propagation of the tidal wave also result in changes in residence times of water bodies and water constituents within the estuary and in transport times through the estuary towards the sea. Fig. 5a shows the simulated movement of a water parcel or a conservative substance for a runoff of 325 m^3 s^{-1} in the status quo. Such movements of water parcels for different runoffs were calculated by special model runs using a method described in Grabemann et al. (1996).

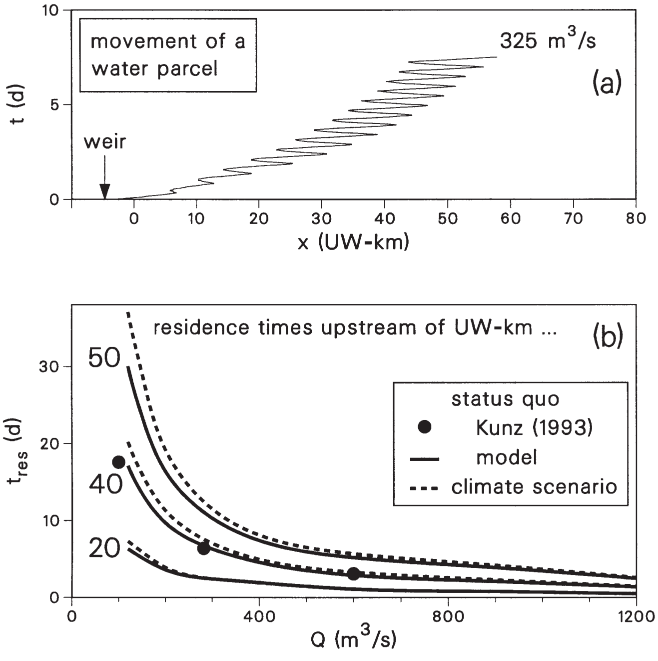

Fig. 5. (a) Simulated movement of water parcel for freshwater runoff 325 m^3 s^{-1}. (b) Residence times (t_{res}) upstream of UW-km 20, 40 and 50 calculated for status quo and climate scenario as functions of freshwater runoff

Residence times and transport times depend on the freshwater runoff. Simulated transport times that fit well with those derived from measurements are presented in Grabemann et al. (1996). Calculated residence times for the status quo are displayed in Fig. 5b. The residence time upstream of UW-km 40, for example, is defined as the time a water parcel needs from the weir up to its last passage at UW-km 40 (Fig. 5a). The times upstream of UW-km 20 and UW-km 50 were about 6 and 30 d respectively for MLQ and <3 d for MHQ. Residence times calculated from model simulations (Kunz 1993) fit well with those presented here.

For the climate scenario, residence and transport times were prolonged due to the more symmetric tidal wave. For MLQ the residence time upstream of, for example, UW-km 50 was about 8 d longer. The differences between the status quo and the climate scenario decreased for higher runoffs and upstream locations (Fig. 5b).

3.5. Position of the brackish water zone

The hydrographic changes also resulted in changes in the intrusion of marine salt water. The position of the brackish water zone (i.e. the mixing zone between marine and river water) depends on the freshwater runoff. This position, derived from longitudinal near-surface transect measurements, also displayed strong variability for fixed runoffs due to spring-neap differences, wind influence etc. This variability may be strengthened by the nonsynoptic nature of the transect measurements carried out during almost well-developed ebb currents. For fixed runoffs the positions of the upstream boundary of the brackish-water zone based on model simulations were in the range of those measured (Fig. 6a). For the status quo, the position of the boundary at about high water varied over about 35 km for low (MLQ) and very high runoff (1.5 × MHQ); it reached up to UW-km 35 for very low runoff (0.8 × MLQ, Fig. 6b). High water was chosen because the brackish-water zone is then in its most upstream position and salinities are highest at the mouths of irrigation channels (note that irrigation takes place during the hours around high water).

In the climate scenario, the upstream boundary of the brackish-water zone was located on average 2 km further upstream for fixed runoffs (Fig. 6b). This upstream displacement was derived from the simulations using status quo salinities at the seaward boundary. When the salinity at the seaward boundary was modified by the altered runoff, deviations to the status quo salinity were small and also led to upstream displacement of the brackish-water zone by about 2 km.

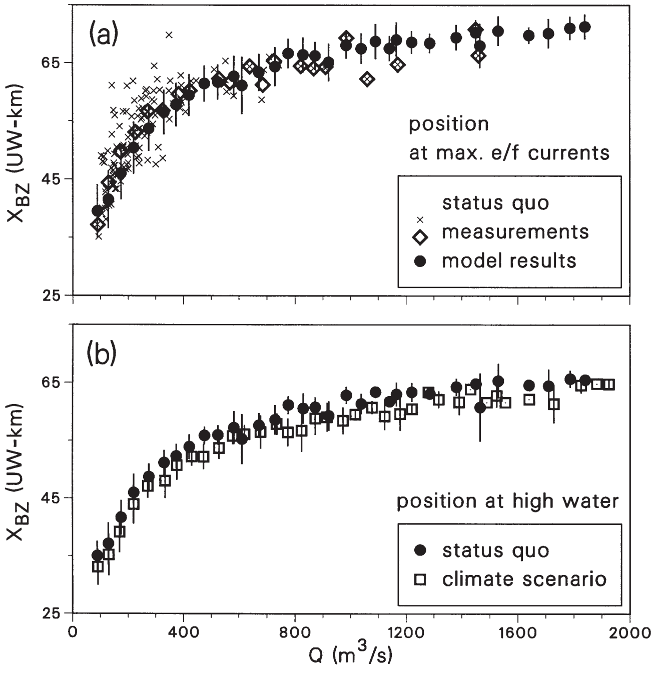

Fig. 6. (a) Measured (approx. ebb tide) and calculated (mean position for ebb and flood tides) positions of upstream boundary of brackish-water zone (x_{BZ}, for a salinity of 2.5) and (b) its calculated position at high water (in relation to Brake) for status quo and climate scenario as functions of runoff. In (a): (•) and (◇), means for given runoff intervals of 50 m^3 s^{-1}; vertical bars, standard deviations; (×), data derived from longitudinal transects (Senator für Bau und Umwelt Bremen and Bezirksregierung Weser/Ems, Außenstelle Brake)

4. DISCUSSION

During the last 100 yr the Weser estuary, especially the inner part, has been altered by engineering works in order to fulfill the requirements for navigation. These engineering works included funnel shaping, with deepening and broadening of the fairway, diminishing of river channel bifurcation, and construction of embankments and groynes (e.g. Dirkson 1986, Wetzel 1987). They have caused pronounced changes in hydrography. The propagation of river spates through the inner estuary towards the sea became better, but water levels during storm surges became higher (Dietze 1983). Significant changes in water level and tidal range (Fig. 2d), especially upstream of Brake (UW-km 40) as well as in ebb and flood durations, are due to accelerated upstream propagation of the tidal wave, which also became more symmetric in the inner part of the estuary (e.g. Hensen 1953, Wetzel 1987). In Bremen, the flood duration has become about 2 h longer and the ebb duration shorter during the last 100 yr.

In the climate scenario chosen, the water level change at the seaward boundary (UW-km 80) propagated only with slight deviations towards the weir in Bremen, and the tidal wave became somewhat more symmetric. This is a result of the 'hydraulic smoothness' of the inner Weser estuary. As a comparison, the difference in mean low water between 1968–1972 and 1976–1980 was 35 cm at UW-km 8.4; about ⅔ of this can probably be explained by the engineering works in the Lower Weser in the 1970s, with the remaining ⅓ possibly being partly due to water levels changes in the North Sea (Wetzel 1987). The Weser estuary's utility as a shipping channel would benefit from the presumed rise of water levels in the case of the climate scenario.

Water levels are also important with regard to coastal protection and drainage of the Weser marshes, which are the concern of the project groups in Hannover (Meinken & Hoffmann 1999, von Lieberman & Mai 1999) and Braunschweig (Maniak et al. 1999).

There are indications that the position of the flood current limit influences the strength of sedimentation in the Bremen harbor area at UW-km 4–8 (see Nasner 1997 for overview on sedimentation in the Bremen harbor area). Sedimentation is high in the harbor area when the flood current limit is near UW-km 0 than when the limit is near UW-km 5 (Lobmeyr et al. 1993). In the climate scenario there is no obvious displacement in frequency of the position of the flood current limit, despite a more pronounced maximum landward of UW-km 0 (Fig. 7). At the present stage of the investigation, no statements regarding changes in the sedimentation in the Bremen harbor area can be made.

In the course of the engineering works the shore length of the Lower Weser was reduced and today ~60% of the shore is covered by a variety of packing materials. The river surface and the riparian zone were reduced to one third and most of the backwaters, reeds and mudflats of high ecological value were lost (e.g. Busch et al. 1989). The biological production and self-purification processes mainly take place in the near-shore shallow-water zone (Schuchardt et al. 1984). The above-mentioned changes, together with the construction of dikes, influenced the occurrence and composition of different types of fauna and flora in the Weser and on the areas within the bounds of the winter dike (Schuchardt et al. 1984, Busch et al. 1989). In such locations, the duration and extent of flooding need to be considered. Furthermore, the areas within the winter dike are used in different ways, e.g. as cargo space in harbor areas or for agriculture. The assumed climate change may cause further alteration.

A significant increase in the eulittoral occurred downstream of UW-km 65, in the mesohaline Wadden Sea area. The largest changes in the eulittoral in the

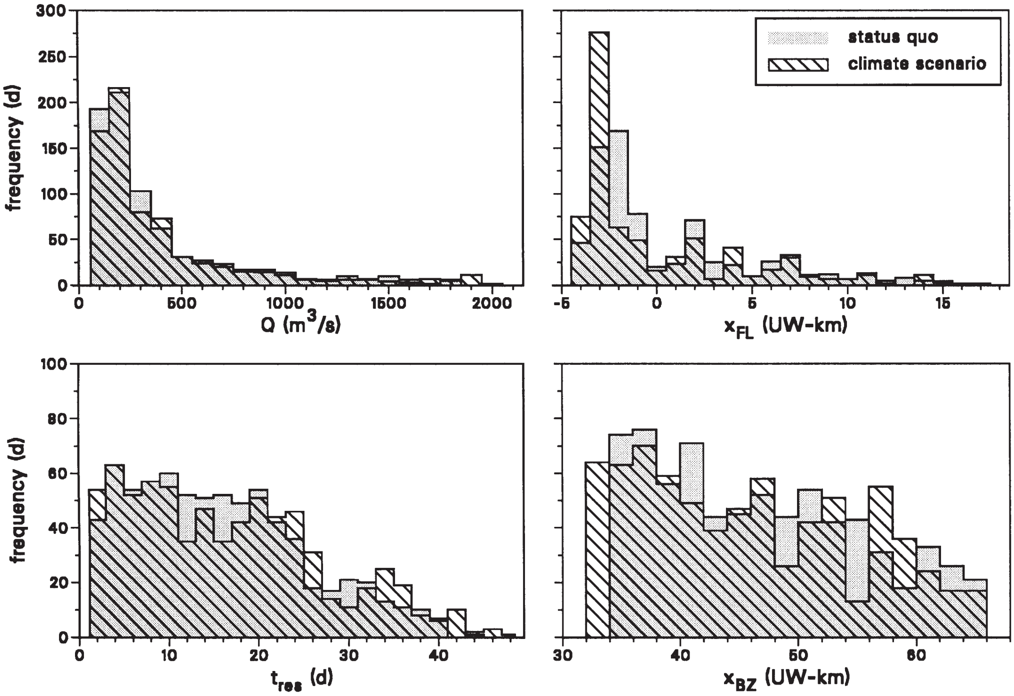

Fig. 7. Frequency distributions for freshwater runoff (Q) and derived variables: position of flood current limit (x_{FL}), residence time upstream of UW-km 50 (t_{res}) and position of upstream boundary of brackish-water zone (x_{BZ}) at high water (in relation to Brake, see Fig. 6), 1991/1994, for status quo and climate scenario

inner part of the estuary were in the section between UW-km 42 and 55 (Fig. 4), which belongs to the oligohaline. In this section the shores are more or less 'natural' (i.e. sandy or muddy) on both sides of the fairway. On the eastern shore upstream of UW-km 33, and on the western shore upstream of UW-km 24, there are both pile walls (e.g. harbor areas) and shores with steeper slopes, covered with a variety of packing materials. The eulittoral is small and showed almost no increase in area in the climate scenario.

The ecology and water quality would benefit from an increase in the eulittoral. On the other hand, the decrease in the supralittoral could reduce the regions used for agriculture (e.g. cattle grazing). Consequences of the eulittoral changes calculated influencing vegetation and agricultural landuse possibilities are reported in Osterkamp et al. (2001); implications for landuse of the supralittoral are discussed in Bahrenberg et al. (1999). The significant change in the eulittoral may alter if morphological processes are taken into account.

Transport and residence times of water bodies and their constituents are important with respect to wastewater inputs and self-purification processes. They are also important in predicting the time of arrival of a pollution cloud at sensitive locations, in order to alleviate potential negative impacts. It was shown that for the climate scenario the residence times are prolonged. With regard to their effects on water quality, the frequency distribution of residence times is also important. A significant but small increase in the frequency of long residence times was found (Fig. 7). This can have positive as well as negative effects on water quality. The biodegradation and nitrification of sewage inputs can take place within a shorter longitudinal range. However, within this range more oxygen can be consumed by self-purification processes. On the other hand, smaller loads of decomposable substances such as ammonium may reach the adjacent sea.

The longitudinal distribution of salinity — the position of the brackish-water zone — is important with respect to the irrigation of the Weser marshes used for agriculture and to littoral ecosystems. Due to the alteration of the water mass exchanges in the course of the engineering works, the brackish-water zone changed its position. The mean position of the zone initially moved downstream because of a loss of flooding areas (e.g. Hensen 1953). Then its mean position indicated a movement up-estuary (e.g. Hensen 1953, Grabemann et al. 1983) probably due to the following engineering works and a slight influence from water level changes in the German Bight since the 1970s (Siefert 1982, Führböter 1986).

In the climate scenario the brackish-water zone was displaced by ~2 km in the upstream direction for fixed runoff. A more upstream position of the zone was slightly more frequent (Fig. 7). Problems with irrigation of the marshlands may become relevant. For example, the mouth of a large and important irrigation channel is located at UW-km 51.5. For the status quo, the number of days with high water salinities >6 psu was ~170 for the dry summer, 1991 ½ yr (May to October) and ~30 for the wetter summer, 1994 ½ yr. For the climate scenario these values increased to about 180 and 80, respectively (salinity of 6 psu was chosen for this calculation because it was measured in an irrigation channel flowing into the Weser at UW-km 53, Kraft 1995). Due to the upstream movement of the brackish-water zone, treatment of Weser water might be necessary before it is usable for industrial purposes.

5. CONCLUDING REMARKS

Trends concerning tidal wave propagation and the position of the brackish-water zone in the Weser estuary, which started in the past due to engineering works, would continue in the case of the climate scenario chosen, but in a weakened form. Because of the 'hydraulic smoothness', water level changes at the seaward boundary would propagate upstream only with slight deviations. The maximum and mean current velocities during ebb and flood tide would increase by up to 7 cm s^{-1} (averages over 1991 and 1994). The subtidal volume and sublittoral for the section between the weir and Bremerhaven (UW-km 70) would increase by ~6 and 7% respectively, while the tidal prism and eulittoral would increase by ~16 and 52% respectively. Long residence times and a more upstream location of the brackish-water zone would be slightly more frequent, possibly affecting water quality and irrigation of the marshes.

The assumed climate scenario implies not only a change in water level and runoff but also a temperature increase (see Table 2). The effects of the combination of hydrodynamic and temperature dependent variables are only briefly outlined here. The strength of self-purification processes, the water quality and the use of the Weser estuary as a receiving body for waste heat and sewage may be influenced. Owing to the assumed temperature rise, the already restricted use of the Weser estuary as a receiving body for waste heat may have to be further reduced. A temperature increase will intensify self-purification processes. Together with prolonged residence times this can also affect the position and strength of nutrient peaks and oxygen minima occurring in the longitudinal transect as well as the use of the estuary as a receiving body for waste sewage. On the other hand, the assumed increase in the freshwater runoff during winter, spring and autumn would provide for a greater dilution of waste inputs and could relieve the tension in these seasons.

Additional work has been done in the course of the project concerning potential socio-economic and coastal protection responses to possible local effects of the climate scenario chosen. Effects of responses that could influence the hydrography and water quality (e.g. displacement of dikes, improvement of sewage treatment and industrial plants) have been investigated by additional simulations.

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