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Vegetation change in the Astrakhanskiy Biosphere Reserve (Lower Volga Delta, Russia) in relation to Caspian Sea level fluctuation

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Summary

During the twentieth century the level of the Caspian Sea dropped from -26 m (1930) to -29 m (1977) below global sea level and subsequently rose again to -26.66 m in 1996. We aimed to describe responses of the vegetation in the lower Volga Delta to these substantial sea-level changes using an analysis of historic vegetation maps produced by aerial photography and satellite imagery.

The sea level drop in the earlier part of the century was followed by rapid progression of the vegetation. The subsequent rapid sea-level rise in the 1980s did however not result in similarly rapid regression of the vegetation. This partial irreversibility of the vegetation response to sea-level change is explained by the wide flooding tolerance of the major emergent species, namely *Phragmites australis*. Floating vegetation increased in extent, most likely due to the increased availability of more favourable conditions, particularly for *Nelumbo nucifera*, a tropical plant reaching its northernmost distribution in the Volga Delta. This species increased in distribution from 3.5 ha in the 1930s throughout the entire Volga Delta to several thousands of hectares in the Astrakhanskiy Biosphere Reserve alone in the 1980s. The reported sea-level changes swept the ecosystems in the Astrakhanskiy Biosphere Reserve back and forth within the Reserve boundaries. At longer time scales, ten-fold greater sea-level change has been reported. The ecosystems for which the Reserve is renowned might be pushed completely out of the Reserve under these conditions. We therefore question whether the current Reserve will be sufficiently large to guarantee conservation of the biota in the lower Volga Delta at longer time scales.

Keywords: sea level change, vegetation distribution, remote sensing

Introduction

The wetlands of the lower Volga Delta located at the northern fringe of the Caspian Sea form a rich and unique ecosystem (Rusanov 1983; Skokova & Vinogradov 1986). With over 260 recorded species they form one of the richest bird habitats and nesting areas in the world (Isakov & Krivonosov 1969; Finlayson *et al*. 1993). They also host a large number of commercially-valuable fish species, amongst which are several species of sturgeon threatened by intensive poaching (Birstein 1996). The vegetation consists of emergent and aquatic vegetation including vast reedlands (*Phragmites australis*) as well as the isolated northernmost population of a tropical plant species, *Nelumbo nucifera* (plant nomenclature according to Flora Europaea [Tutin *et al.* 1964–80]). The biota of these wetlands is protected in the Astrakhanskiy Biosphere Reserve, which was established in 1919 and approved as a UNESCO Biosphere Reserve in 1984.

The lower Volga Delta is subject to substantial fluctuations in the water level of the Caspian Sea. A water level of about -26 m was registered during most of the nineteenth century and until 1930, but it then rapidly dropped, reaching a level of -29.01 m in 1977, corresponding to the lowest level in 200 years (Ignatov *et al*. 1993; Ragozin *et al*. 1996). Between 1977 and 1995 the water level rose again by 2.35 m. These fluctuations are explained by the fact that the Caspian Sea forms a closed basin, hence a balance between river discharge and precipitation on the one hand and water loss through evaporation on the other determines its water level (Ignatov *et al*. 1993).

The Volga Delta is also unique because of its extremely gentle onshore to offshore gradient of 5 $cm\,km^{-1}$, which is even more extreme than that of the Mississippi Delta (Kroonenberg *et al*. 1997). In this particular geomorphologic setting, a two to three metre sea-level change as reported above would result in a 40–60 km displacement of the boundary of the Caspian.

The distribution and species composition of aquatic vegetation are considered to be closely determined by hydrological conditions, both in freshwater (Spence 1982) and marine environments (Chapman 1974). Aquatic vegetation would therefore be expected to respond to changes in hydrological conditions such as water depth or the duration of flooding. Van Der Valk and Davis (1976), Toivonen and Nybom (1989), Wallsten and Forsgren (1989) and Nohara (1991), reported changes in freshwater vegetation due to water level change, while changes in salt marsh vegetation following tidal modifications have been reported by De Leeuw *et al.*

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(1994), Cramer and Hytteborn (1987), Beeftink (1987) and Roman *et al*. (1984). Because of this, you would expect pronounced changes in the vegetation in the lower Volga Delta. So far, however, no detailed description has been made of the response of the vegetation to the above-mentioned hydrological changes.

The objective of this study was therefore to describe changes in the vegetation of the lower Volga Delta and assess how these might relate to the changes in environmental conditions.

Materials and methods

Study area

The Astrakhanskiy Biosphere Reserve is situated in the lower Volga Delta, along the northern shore of the Caspian Sea (Fig. 1). It consists of three distinct areas approximately 140 km apart. The present study was executed in and around the Damchik area, located between 45°25′ and 45°55′ N and between 47°45′ and 48°00′ E. The Damchik area of the Astrakhanskiy Reserve covers approximately 30 000 ha. The study area further included some 20 000 ha of buffer zone and surrounding territory.

The study of the plant communities of the Reserve started in the 1920s. Dobrokhotova and Mikhailova (1938) and Dobrokhotova (1940) made the first detailed descriptions of vegetation in the 1930s. Regular and detailed observations on the dynamics of the vegetation have been made along transects since the 1960s. These observations described both the seasonal fluctuations and the long-term trends of the vegetation. The spatial distribution of vegetation remained virtually unknown since few vegetation maps were available. In this study we present a number of maps of the northern part of the Damchik area, the southern part of the Damchik area and of the island of Chistaya Banka (Fig. 1).

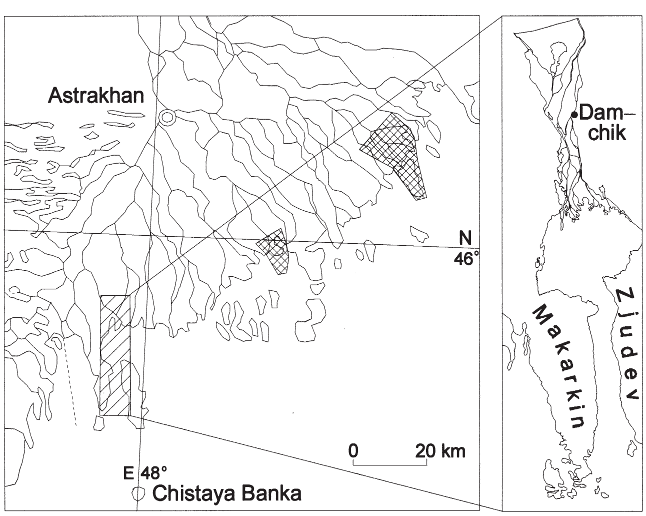

Figure 1 Diagrammatic map of the Volga Delta and location of the three parts (hatched) of the Astrakhanskiy Biosphere Reserve which from west to east are: Damchikskiy (the Damchik study area, enlarged in right hand figure), Trekhizbinskiy and Obzhorovskiy.

Aerospace materials and vegetation maps

The first reliable vegetation map of the northern part of the Damchik area is the one presented by Dobrokhotova and Mikhailova (1938), which we used to represent the state of the vegetation in 1935. We digitized the boundaries displayed in this map but adapted the vegetation categories to those of the other maps presented in this study.

The next three available maps were based on aerial photographs. The 1951 vegetation map of the northern part was prepared using 1:35 000 aerial photographs of 29 July 1951. The 1981 vegetation map was based on 1:25 000 aerial photographs of 9 May 1981. The 1989 vegetation map was prepared using 1:50 000 aerial photographs of 28 May 1989. For the latest map we additionally used Kosmos MK-4M colour space photographs of 19 June 1991 enlarged to a scale of 1:200 000 as well as KFA-1000 infra-colour space photographs taken by the Kosmos satellite on 31 July 1991.

The southern part of the area was covered by water in the 1930s. Hence, there were no aerial photographs or maps available from this period. The oldest vegetation map is from 1957, but the information it contained was insufficient to allow preparation of a reliable vegetation map. Furthermore, for this period, aerial photographs were not available for the southern territory.

The vegetation map of the late 1970s is based on the 24 August 1977 and 8 June 1978 Landsat MSS images. These represent two different seasons (spring and summer) and thus allowed us to discriminate between vegetation types with different phenology. Aerial photography of 9 May 1981 was used to make the photo-plan and map the boundary of the emergent vegetation. The vegetation map of the early 1990s is based on the Resurs MSU-E images of 30 June 1991 and 5 September 1992, as well as aerial photographs of 28 May 1989.

All the images were prepared for analysis according to the procedures described by Baldina *et al*. (1995). The aerial photographs were digitized, transformed and merged using ILWIS GIS software to create a georeferenced photo-mosaic. The photo-mosaic of 1951 included 21 images, that of 1981 used 50 images and that of 1989, 14 images. Their positional accuracy did not exceed two pixels (20 m). Space images were georeferenced with an estimated positional accuracy of about one pixel, 40 m and 80 m, for MSU-E and Landsat MSS respectively. All these transformed images were mutually coordinated with the help of a vector base map.

Field observations

For Table 1 we used various sources of field observations on the vegetation collected between the 1950s and the 1990s by A.F. Zhivogliad and other staff of the Reserve. These included descriptions of species composition and schemes of the spatial distribution of plant communities. Information and schematic maps based on observations from a helicopter in 1977 and 1978 (Rusanov 1983, 1993) were used for the late 1970s vegetation map. We ourselves described the vegetation

Table 1 Legend for the map of the Damchik area. Codes for environmental factors: Geomorphology: le = levees on older islands; in = interior of older islands; ed = places, encircled with artificial dams; sp = spits and new formed islands; dl = delta lakes; cb = coastal bays; a = aquatic part of the avant-delta; ia = islands of avant-delta. Inundation: n = normally not flooded; s = short: less then 1 month; i = intermediate: 1–2 months; l = long: 2–4 months; p = permanently: 12 months. Salinity of the soil: h = high; + = weak; − = absent; na = not applicable. Land-use: p = planted; g = grazing; m = mowing; a = agriculture; n = not used; na = not applicable. Codes for species names: Ap = *Aeluropus pungens*; Bu = *Butomus umbellatus*; Ca = *Carex acutiformis*; Cd = *Ceratophillum demersum*; Ce = *Calamagrostis epigejos*; Cs = *Calistegia sepium*; Ea = *Eleagnus angustifolia*; Er = *Elymus repens*; Lg = *Limonium gmelinii*; Nc = *Nymphea candida*; Nl = *Nuphar lutea*; Nn = *Nelumbo nucifera*; No = *Nitellopsis obtusa*; Np = *Nymphoides peltata*; Pa = *Phragmites australis*; Ph = *Phalaris arundinacea*; Pl = *Potamogeton lucens*; Pp = *Potamogeton pectinatus*; Rc = *Rubus caesius*; Sa = *Salix alba*; Se = *Sparganium erectum*; Sm = *Scirpus maritima*; Ta = *Typha angustipholia*; Tl = *Typha laxmannii*; Tn = *Trapa natans*; Tr = *Tamarix ramosissima*; Ts = *Trachomitum sarmatiense*; Vs = *Vallisneria spiralis*.

Map unit	*Geomor-phology*	*Inunda-tion*	*Sali-nity*	*Land-use*	*Vegetation description*
E1	le	s	−	p	Planted forests of *Populus alba*, *Populus* sp. and *Fraxinus excelsior*
E2	le	i	−	n	Medium aged dense forests (*Salix alba*, Ca, Rc)
E3	sp	l	−	n	Young dense forests (*Salix triandra*, Sa)
E4	ia	l	−	n	Open inland forests (*Salix alba*, Ca)
E5	le	s	−	n	Mosaic old open forests (*Salix alba*), meadows (Ca, Pa, Ce) and shrublands (Rc)
E6	le	n	+	g	Bushland (*Elaeagnus angustifolia*, Er)
E7	le	s	−	n	Mosaic of meadows (*Phragmites*, Ca) and shrubland (*Rubus caesius*, Ca)
E8	in	s	h	g	Mixture of saline grassland (*Sueada*, Ap, Sm, Lg) and brushland (Tr)
E9	le, in	n	h	g	Mixture of degraded meadows (Er, Ap) and bushland (Tr)
E10	le, in	s	+	g	Mixture of meadows (*Elymus repens*) with halophytes (*Scirpus maritimus*, Ap)
E11	ed	n	+	g	Mixture of meadows (Er) with halophytes (Ap) and bushland (Ea, Tr)
E12	in	i	+	m, g	Reed with herbs, grass and halophytic species (*Phragmites*, Tl, Er, Sm)
E13	le, in	s	+	m	Mixture of meadows (*Calamagrostis epigejos, Elymus repens*, Sm)
E14	le	s	−	m, g, n	Reed with sedges and herbs (*Phragmites*, *Carex*)
E15	in	i	−	m	Reed with grasses and herbs (*Phragmites*, *Phalaris arundinacea*)
E16	in	i	−	n	Mosaic of pure reed, reed with herbs and reed + grass (Pa, Ph, Ca, Ce, Ts, Cs)
E17	in, ia	i	−	n	Reedland without undergrowth (*Phragmites*)
E18	dl	l	−	n	Mosaic of reed, reed-mace, grasses (*Phragmites*, *Typha*, Ph)
A1	dl, a	l, p	na	na	Closed stands of emergents (*Typha* with little Pa)
A2	cb, ia	l, p	na	na	Closed stands of emergents (mainly *Phragmites* with little Ta)
A3	a	p	na	na	Almost closed stands of emergents (Pa, Ta) with submerged vegetation (Cd)
A4	a	p	na	na	Open stands of emergents (Pa, Ta) + floating (Nc, Np, Tn) + submerged (Cd)
A5	cb, a	p	na	na	Aggregated and isolated clones of emergents (Pa, Ta) with floating (Np, Nc) and submerged (Cd) vegetation
A6	cb, a	p	na	na	Aggregated and isolated clones of emergents (Pa , Ta) with *Nelumbo*, floating (Np, Nc) and submerged (Cd, No) vegetation
A7	a	p	na	na	Aggregated and isolated clones and fringes of emergents (Ta with little Pa) with submerged vegetation (Cd)
A8	a	p	na	na	Isolated clones of emergents (Pa, Ta) + floating (Np,Tn) + submerged (Cd)
A9	a	p	na	na	Isolated clones of emergents (Pa, Ta) with some patches of lotus (Nn)
A10	cb, a	p	na	na	Large clones of *Phragmites* and *Typha*
A11	a	p	na	na	Closed monospecific fields of lotus (*Nelumbo nucifera*)
A12	cb, a	p	na	na	More open fields of lotus (Nn) + Se + isolated emergents (Pa, Ta)
A13	cb, a	p	na	na	Fields of floating (Nl, Nc, Np, Tn) and submerged vegetation (Cd, Pp, No) with some lotus (Nn), Se and isolated clones of emergents (Pa,Ta)
A14	dl, cb	p	na	na	Fields of floating (Nl, Nc, Np, Tn) and submerged vegetation (Cd, Pp, No) with isolated clones of emergents (Pa,Ta)
A15	dl	p	na	na	Floating vegetation (Tn) with isolated clones of Ta
A16	c, a	p	na	na	Dense fields of submerged vegetation (Cd, Pp, No) with patches of floating vegetation (Np, Tn) and Se
A17	c, a	p	na	na	Submerged (Cd, Vs, Bu), sparse clones of floating species (Np), Se and Pa
A18	c, a	p	na	na	Open water with submerged vegetation close to bottom (Cd, Vs, Pp, Pl, Bu)
Fields	ed	n	−, +	a	Agriculture fields
Rivers					Rivers and fish pond

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of the study areas in 1994 in order to prepare the maps of 1989 and the early 1990s (Labutina *et al.* 1995).

Vegetation maps compilation

For the preparation of the 1990 vegetation maps presented, we used the methods outlined by Labutina *et al.* (1995). Different methods were applied to prepare the vegetation maps for the northern (terrestrial) and southern parts of the territory.

The main vegetation types in the northern part could easily be distinguished on the aerial photographs of 1981 and 1989, which were taken in the spring. The lower areas of the Delta islands, which were flooded at that time, had a dark tone, while the levees had a lighter tone. The photographs also revealed differences in vegetation structure such as various types of woody vegetation, reedlands and meadows. Mown grasslands outside the Reserve had a very bright tone. This level of detail was not visible from the satellite images. In particular, the narrow strips of woody vegetation on the levees could not be discriminated. We therefore decided to use visual interpretation of stereo-pairs of aerial photographs for the vegetation mapping. For 1951, only late summer aerial photographs were available. Consequently, the aquatic vegetation, which is optimally developed in late summer, could be distinguished relatively easily, while terrestrial vegetation types were more difficult to distinguish than on the 1981 and 1989 aerial photographs. The boundaries established during photo interpretation were digitized on-screen and the map units were then linked to field observations on species composition.

For the vegetation map of the southern part, both aerial photo-mosaic and satellite imagery was used. Visual on-screen interpretation of the aerial photo-mosaic taken in spring was used to map the distribution of emergent vegetation such as reed and reed mace. At that time, the emergent vegetation was clearly visible, while the other aquatic species had not yet developed. The main information sources for the mapping of aquatic vegetation were satellite images. We executed a supervised maximum likelihood classification of both the early and late summer images resulting in 11 classes. The satellite imagery allowed us to distinguish various density classes of *Nelumbo nucifera* as well as stands of *Phragmites australis* and *Typha angustifolia*, floating vegetation, submerged vegetation and open water. At the final scale of the map (1:100 000), the classified satellite images would have had pixel sizes of 0.4 mm, which exceed the desired level of detail in a cartographic product. We thus decided to generalize the patterns in the satellite images to a minimal map unit of 1 mm^2. We digitized these classified satellite images on screen and combined the information of the two seasons and results of photo-mosaic interpretation into one single map. The procedures have been described in more detail by Labutina *et al.* (1995). When generalizing in this way, there are inevitably groups of pixels that belong to different spectral classes and thus to different plant communities. This heterogeneity within map units was represented in the vegetation key, where many units were described in terms of a mosaic of plant communities. A uniform key for all vegetation maps for the whole period was compiled based on the key of the vegetation map of the 1990s (Labutina *et al.* 1995).

Finally we estimated the area (ha) covered by the different map units in and outside the Reserve in the various years. These areas were calculated using the GIS to overlay the vegetation maps with the boundary of the Reserve in the 1990s.

Vegetation change on Chistaya Banka Island

Chistaya Banka Island is located approximately 25 km south of the southern margin of the Damchik area. We monitored the vegetation changes between the end of the 1970s and the early 1990s using Landsat MSS and MSU-E imagery. We calculated the Normalized Differential Vegetation Index (NDVI; Mather 1987) for both images and then classified them in two classes: vegetated areas (NDVI > 0) and open water (NDVI < 0). We then overlaid the two maps, to reveal the changes in the size of the island.

Results

Water level fluctuations

In the first three decades of the twentieth century, mean annual Caspian Sea level showed minor fluctuations around 26 m below global sea level (Fig. 2). Between 1929 and 1941, it dropped from -25.88 m to -27.84 m; this corresponded to a reduction of 16 cm yr^{-1}. It then stabilized around -27.80 m

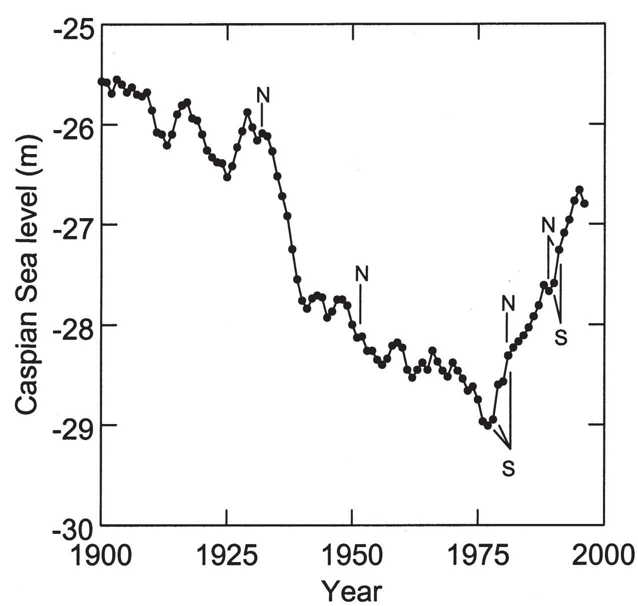

Figure 2 Mean annual water level (in m below global sea level) of the Caspian Sea between 1900 and 1996 (According to Mikhaylov 1997). Symbols (N, S) indicate the date of the maps of the northern (Figs 3 & 4) and southern (Fig. 5) part of the Damchik area respectively.

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until 1949. Another reduction of 7 cm yr^{-1} between 1949 and 1956 and another period of stabilization (around -28.25 m) followed this. The level of the Sea then dropped to reach a level of -29.01 m in 1977. Since 1978 the level of the Caspian once more increased to reach -26.66 m in 1996. This corresponded to an annual increase of 13 cm yr^{-1}. The maps presented in this study describe the vegetation in 1935, shortly after the onset of the drop in sea level, in 1951 when sea level had been reduced by 2 m, in 1979 and 1981 shortly after the historic low, and in 1989 and 1992 following ten or more years of rapid sea-level rise (Fig. 2).

Vegetation in the northern area

Figures 3 and 4 show four vegetation maps for the northern part of the Damchik area; the key is shown in Table 1. In 1935 various types of reedlands (Fig. 3, codes E16 and E17) dominated the area. *Salix triandra* and *S. alba* forests (E3) were present in the south along the coast. Open forests of *S. alba* (E5) occurred towards the north. In the northern part of the Reserve, Lake Damchik consisted of an area with floating vegetation (A14 and A15) surrounded by narrow strips of emergent vegetation (A1 and A2). The area to the south of the 1935 map (Fig. 3), which has not been mapped, is known to have consisted mainly of open water with some very sparse and isolated vegetation that appeared following the reduction of the waters in the early 1930s.

Comparison of the 1935 and 1951 vegetation maps (Fig. 3) reveals various changes. After 1935, a large area of new land emerged and by 1951, the coastline had moved towards the south, in some places by as much as 8.5 km. All of this newly-exposed land had been colonized by vegetation. Along the streams, these new areas were dominated by *Salix triandra* (Fig. 3, E3), while reedlands (E17, A2) developed further inland. In the south-west, a large bay called Sazanij Kultuk had formed. It consisted of various complexes of floating and submerged vegetation (Fig. 3, A14 and A15) bordered by strips of emergent vegetation intermingled with aquatic species (A2 and A5). Meanwhile the area of floating vegetation in Lake Damchik had been reduced, due to progression of emergent vegetation (Fig. 3, A1). The *Salix triandra* and *S. alba* forests along the former coastline (Fig. 3, E3) had changed to pure *Salix alba* forests (Fig. 3, E2). Small areas of halophytic vegetation not occurring in the 1935 map occurred in the northern part of the 1951 map (Fig. 3, E8). The 1951 map

Table 2 Area (ha) covered by the various map units inside and outside the Reserve boundaries according to the four maps (Figs 3 & 4) of the northern part of the Damchik area of the Astrakhanskiy Reserve. — = Area had not been mapped. Note that the extreme northern part of the area (1727 ha) had not been mapped in the 1981 map. Table 1 provides a full description of the map units.

Map unit	*1935*		*1951*		*1981*		*1989*	
	Inside	*Outside*	*Inside*	*Outside*	*Inside*	*Outside*	*Inside*	*Outside*
A1	160	—	159	99	275	3	0	0
A2	171	—	523	855	279	5	355	1
A5	0	—	1015	169	706	0	90	2
A6	0	—	0	0	20	0	92	16
A12	0	—	0	0	62	0	9	0
A14	26	—	795	30	275	35	96	11
A15	198	—	355	32	0	0	0	0
A18	864	—	1871	126	0	0	0	0
E1	0	—	0	0	12	0	24	5
E2	0	—	507	15	1042	74	1054	91
E3	452	—	403	73	61	18	90	0
E4	0	—	0	20	0	0	0	0
E5	67	—	133	12	328	47	328	98
E6	0	—	0	0	0	23	0	23
E7	0	—	584	0	550	6	548	38
E8	0	—	34	190	48	204	55	281
E9	0	—	0	0	0	28	0	80
E10	0	—	0	0	0	318	0	934
E11	0	—	0	0	0	155	0	120
E12	0	—	0	1831	119	2194	120	2277
E13	0	—	92	77	340	42	483	796
E14	44	—	0	1128	0	1152	0	1157
E15	0	—	0	0	594	3143	598	2730
E16	1562	—	1443	3600	2303	0	2307	0
E17	1154	—	1710	2364	1605	1084	2449	1101
E18	0	—	0	0	0	0	280	0
Fields	0	—	0	0	0	579	0	825
Rivers	664	—	531	129	383	105	345	139
Settlement	—	—	—	0	6	0	6	0
Total	5363	—	10 152	10 749	9007	9215	9331	10 726

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shows that various types of grasslands and reedlands (Fig. 3, E12, E14, E16, E17 and A2 and A5) dominated the vegetation around the Reserve.

Comparison of the 1951 and 1981 maps (Figs 3 & 4, respectively) reveals a further 500 m progression of the shoreline to the south. In these areas, pioneer forests (E3) are observed. Further in the north, the older forests of *Salix triandra* and *S. alba* (Fig. 3, E3) were replaced by forests of *Salix alba* (Fig. 4, E2), while part of the old *Salix alba* forests in the centre of the map had changed towards reedland. The vegetated area in Sazanji Kultuk had further expanded to the south, and the area covered by floating and submerged vegetation (Fig. 4, A14 and A15) had been reduced greatly. A similar trend is observed in Damchik Lake where the central area, which used to be dominated by unit A15 (Fig. 3) had been completely invaded by reed-mace (Fig. 4, A1). Outside the Reserve, almost all the natural reedlands had been replaced by reed with grasses and herbs meadows (Fig. 4, E15) which were mowed. In the north-east, outside the Reserve, the appearance of agricultural fields and various meadows with halophytes is discernible (Fig. 4, E10 and E11).

Comparison of the maps of 1981 and 1989 (Fig. 4) reveals that, apart from the appearance of some minor clones of reed and small spits with new *Salix triandra* and *Salix alba* thickets, the coastline did not progress any further towards the south. There was a further reduction of Sazanji Kultuk. Moreover, outside the Reserve, new agricultural fields and meadows with halophytes had appeared.

Table 2 displays the area covered by the various map units inside and outside the Reserve. The table shows the decline of the early successional *Salix triandra* and *S. alba* forests (E3), and an increase of the area covered by the late successional *S. alba* forests (E5).

Vegetation in the southern area

Figure 5 shows the vegetation of the southern part of the Damchik area in the late 1970s (1977–78) and the early 1990s (1991–92). No maps were available for the 1930s and 1950s. However, the whole area was flooded and devoid of emergent vegetation in the early 1930s. The first emergent vegetation started to appear in the late 1930s following the emergence of the islands of Makarkin and Zjudev (Belevich 1965). The vegetation map of the late 1970s shows areas, which started to be colonized by vegetation following the reduction of the Caspian Sea level.

In the late 1970s, the central parts of the islands were covered by reed-meadows (Fig. 5, E17), which due to the low sea level were flooded only during spring. Small *Salix alba* open forests occurred on the most elevated places. The more frequently and permanently flooded margins of the islands were occupied by reed and reed mace with aquatic species inbetween (Fig. 5, A2, A3, A4). *Typha angustifolia* was abundant there. More open vegetation, consisting of aggregated and isolated clones of reed and reed mace with other emergent, floating and submerged vegetation (Fig. 5, A5, A6, A7, A9, A11 and A12) covered the shallows around the islands. As you moved still further away from the centre of these islands, water depth increased. Ultimately, the emergent vegetation disappeared to give way to complexes of *Sparganium erectum* and floating and submerged species (Fig. 5, A16 and A17) in the area between the islands. Isolated and aggregated clones of reed and fields of lotus (A5, A8, A9, A11 and A12) started to form in the south of this area. There was some open water with submerged vegetation (Fig. 5, A18) in the central parts between the islands.

Comparison of the maps of the late 1970s and the early 1990s (Fig. 5) shows further changes in vegetation. The vegetation in the centre of the islands changed from E17 to A2, reflecting an increase in the duration of flooding. Inbetween the two islands there were two distinct changes. The most visible process was disappearance or decrease in area of communities with *Sparganium* and floating vegetation (Fig. 5, A16 and A17). Locally in the northern part of the fore delta, patches of lotus (Fig. 5, A12) had been replaced by open water with some submerged vegetation (Fig. 5, A18). At the same time, the area of emergent vegetation dominated by reed and lotus (A9, A11 and A12) increased in the southern part of the area. To the south-west of Makarkin there was an area where *Phragmites* increased in extent.

Table 3 shows the area covered by the various map units in the southern part of the Reserve. Noteworthy is the sum of the area inside and outside the Reserve covered by map units which included lotus in the 1991–92 map: 401 ha and 1413 ha

Table 3 Area (ha) covered by the various map units inside and outside the Reserve boundaries according to the two maps (Fig. 5) of the southern part of the Damchik area of the Astrakhanskiy Biosphere Reserve. Table 1 provides a full description of the map units.

Map unit	*1977–78*		*1991–92*	
	Inside	***Outside***	***Inside***	***Outside***
A1	45	0	0	0
A2	1951	321	7129	4288
A3	970	626	488	673
A4	284	216	0	0
A5	124	554	545	641
A6	120	157	216	2
A7	638	477	520	868
A8	536	1158	0	0
A9	463	467	673	1030
A10	90	161	112	140
A11	414	0	239	162
A12	299	97	823	590
A13	611	114	243	0
A16	1723	1216	968	911
A17	2796	1810	1281	601
A18	5111	3233	6513	3005
E3	0	2	11	9
E4	52	0	65	0
E17	3811	2847	69	434
Total	20 038	13 454	19 894	13 354

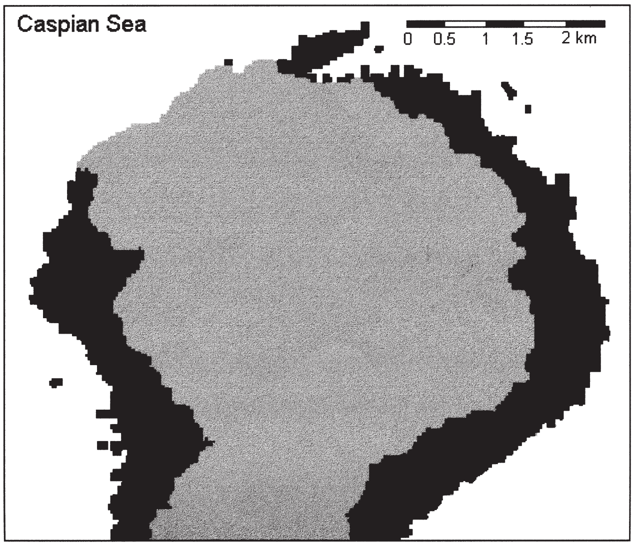

Figure 6 Diagrammatic map showing vegetation change on Chistaya Banka Island between 1978 and 1992. Grey represents areas covered by vegetation in 1978 and 1992. Black indicates areas that changed between 1978 and 1992 from vegetated into open water. White represents open water in both years.

respectively were mapped as units with dense (A11) and open (A12) fields of lotus, while another 2164 ha were mapped as units with a lower density of lotus (map units A6, A9 and A13).

Vegetation on Chistaya Banka Island

Figure 6 displays the shape of the Chistaya Banka Island area in 1978 and in 1992. There was a considerable reduction of the size of the island, in particular along the fringe, which was dominated by reed.

Land-use in the northern area

In the 1950s, most of the area outside the Reserve in the North of the territory was unused, although grazing occurred in the extreme northern part (Fig. 7). Mowing and grazing had extended southward in the map of 1981, and farmland occurred in the north-eastern part of the map (Fig. 7). The situation still prevailed in 1989 (Fig. 7), although more farmland occurred to the south.

Discussion

Impact of sea-level changes

During the course of the twentieth century, the Caspian Sea has shown an extremely rapid reduction of sea level followed by a similarly rapid sea level rise in the last decades of this century. It would be attractive to attribute these observed changes in the vegetation solely to these dramatic sea-level changes, but it should be borne in mind that it has been reported that the distribution of aquatic vegetation also changes under conditions of constant water levels (e.g. Weisner 1987).

The rate of transgression of the vegetation, however, was extremely high. The reduction of sea level exposed the islands of Makarkin, Zjudev and Chistaya Banka and led to the colonization of these islands by the vegetation. By 1977 the reedlands had reached the southern margin of Chistaya Banka, some 60 km south of the 1935 coastline. This corresponds to a shoreline progression of 1.5 km yr^{-1}. On a smaller scale, since 1935, there has been a 9 km southward progression of the coastline in the northern part of the territory, which included a strong southward advance of the *Salix* forests. In addition to this southward progression, there was a lateral progression. Areas of open water with a width of 1–2 km (Lake Damchik and Sazanij Kultuk) were closed within a couple of decades, corresponding to a shoreline progression of 10–200 m yr^{-1}. The rates of coastline progression in the Reserve were generally 10–1000 times higher than those reported for similar vegetation in waters with a constant level. Weisner (1987) for instance reported expansion rates varying between 0.03–0.96 m yr^{-1}, depending on the degree of wave exposure for *P. australis* in a stagnant Swedish lake. We therefore conclude that the drop in the Caspian Sea level was the overriding factor determining the observed rapid shoreline progression.

Sea water levels have been rising since the end of the 1970s, and a marked regression of the vegetation-water boundary was expected in response to this. Our results have shown such a regression of the vegetation on the island of Chistaya Banka. In the early 1990s we recorded water depths of 150–200 cm at the outer edge of the island, where the vegetation consisted mainly of *Phragmites*. This is above the reported maximum water depth tolerated by reed which ranges from 60 cm (Coops *et al.* 1994) up to 160 and 170 cm (Weisner 1987, 1991). Hence we conclude that the reduction in the size of the island of Chistaya Banka most likely reflected a gradual drowning and die off of the fringe of reed.

We failed, however, to detect a retreat of the emergent vegetation on the islands of Makarkin and Zjudev and along the southern coast of the northern part of the territory. Closer inspection of these areas in 1995 revealed that *Phragmites* grew in depths (1.5–1.8 m) close to the tolerance level reported by Weisner (1987, 1991). This suggests that a further significant rise of the waters might lead to a massive die off of *Phragmites* in the southernmost part of the Reserve.

Distribution of lotus

Our study demonstrated a strong increase in the distribution of lotus *(Nelumbo nucifera)*. At present the Damchik area alone has several thousands of hectares of lotus stands. Dobrokhotova (1938) reported only 3.5 ha of lotus in the western part of the Volga Delta in the 1930s, half of which was inside the Astrakhanskiy Reserve. A 70% increase in the area covered by lotus had occurred over the years preceding the study of Dobrokhotova (1938). Hence, at the start of the twentieth century, lotus must have been extremely rare in the Volga Delta.

Dobrokhotova (1938) described the habitat of lotus as shallow water depths on sandbanks slightly invaded by emer-

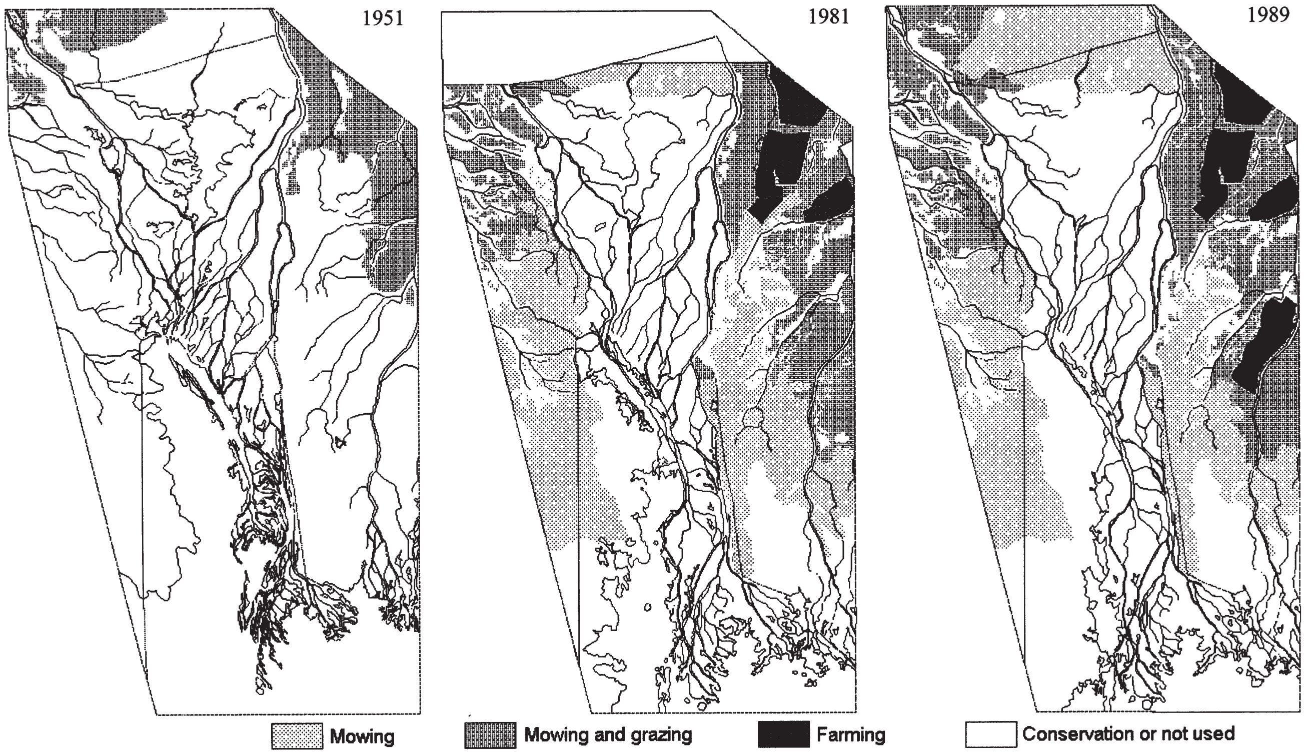

Figure 7 Distribution of main land-use types in the northern part of the Damchik area in 1951, 1981 and 1989.

gent species, shallow inlets along the Caspian Sea coast where water depth was about 50 cm, and river tributaries with water depths of about 150 cm up to 225 cm. Nohara (1991) reported that lotus tends to be restricted to water less than 150 cm deep. These shallow-water environments have become more widely available in the Volga Delta since the 1930s. In the 1970s most of the southern part of the territory was extremely shallow, with a water depth of 30–100 cm. As discussed above, these environmental conditions are very favourable for the spreading of lotus. We therefore suggest that the reduction in the Caspian Sea level increased the suitability of the area for lotus.

The current rise in the Caspian Sea level has led to increased water depths in the Volga Delta. So far, however, water depths in areas dominated by lotus do not exceed 200 cm during the floods in spring and 150 cm in summer. This might explain why most lotus populations still remain in good condition.

Impact of land-use

Our results revealed a pronounced change between the 1951 and the 1981 map in land-use of the area outside the Reserve boundaries. Areas not utilized before were used for grazing and haymaking in 1981. In the early 1960s, a paper mill was opened in Astrakhan, using reed harvested in the lower Volga Delta, including the areas surrounding the Reserve. The harvesting proved to be unsustainable; after 3–5 years the reedlands were completely degraded by the heavy machinery used for reed harvesting (Karzhavina 1970), and the vegetation changed into various grassland communities (Skripchinskiy 1970; Zhivogliad 1970). Reed harvesting was abandoned and the land was increasingly used for hay production. The map of 1981 displays this area where mowing replaced reed harvesting in the 1960s. Pilipenko and Zhivogliad (1991) and Finlayson *et al.* (1993), however, reported that, more recently, reed is starting to redominate since prolonged flooding makes haymaking impossible.

Another development was the establishment of farmland protected by dykes in the north-east of the area; this land-use pattern persisted into the early 1990s (Fig. 7). Recently, however, these agricultural fields are increasingly salinized because the groundwater table is rising as a result of the higher level of the Caspian Sea (Finlayson *et al.* 1993; Gennadiev *et al.* 1994). This salinization reduces the agricultural potential and ultimately leads to the abandonment of agriculture.

Vegetation changes and geomorphology

So far, the transgression of the shoreline and the displacement of plant communities have been discussed in relation to the change in Caspian Sea level. However, a proper understanding of the vegetation changes requires considering another peculiarity of the Caspian lowlands. In a geomorphologic sense, the Volga Delta is unique because of its extremely gentle onshore to offshore gradient of 5 cm km^{-1} (Kroonenberg *et al.* 1997). By itself, this gentle gradient would make the Delta sensitive to sea-level changes. It is, however, the combination of this gentle gradient with the

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extreme sea-level fluctuations which can best explain the remarkable transgression of the vegetation reported in this study.

Management

The Astrakhanskiy Biosphere Reserve was established in 1919 (Belevich *et al*. 1970). Since then the Caspian has gone through what looks to us like a major sea-level fluctuation, but geologically speaking, this has been only a minor oscillation. Over the past 100 000 years the level of the Caspian Sea has fluctuated between +50 m and –80 m, while fluctuations of up to 10 m have occurred in the Holocene (Svitoch 1991; Rychagov 1993). The Volga Delta has wandered to the north and to the south of its current position, corresponding to locations as far as 700 km apart (Belevich 1970; Kroonenberg *et al*. 1997). At larger time scales therefore, larger sea-level fluctuations may be anticipated. The red list species and unique ecosystems for which the Reserve was established (Belevich *et al*. 1970; Krivonosov & Rusakov 1991) can be expected to continue to shift in distribution up and down the shore and occasionally to be pushed out of the Reserve boundaries. Hence, we may question the long-term sustainability of the contribution of the Reserve towards the conservation of its ecosystems and biota. It may not be possible at all times to provide the habitat required for the conservation of these target species and ecosystems within the current boundaries of the Reserve. Extension of the Reserve boundaries both up and downshore should sustain the purpose for which the Reserve was established over a time scale of centuries.

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