Landscape Geochemistry of Soil Salinization and Alkalization

I. SZABOLCS

Research Institute for Soil Science and Agricultural Chemistry of the Hungarian Academy of Sciences, Budapest

It has been taken for granted for a long time that salt affected soils occur under arid and semiarid conditions and, even in handbooks and in reports of national and international organizations, the interrelation of soil salinity and environmental conditions is often considered in respect to the dry climate only. It is true that aridity promotes the processes of soil salinization and, under arid and semiarid conditions, the possibility of salt accumulation in soils and waters should always be taken into consideration, however, the accumulation of electrolytes in a soil is a complex process which cannot be interpreted as a simple consequence of climatic effects.

Modern landscape geochemistry [7], which has been developed from the classical geochemical aspects of pedology and the achievements of CLARKE [cit. 5], FERSMAN [5], VERNADSKY [17], POLYNOV [13] and others, may represent a holistic approach to the mass and energy flows which lead to the formation of salt affected soils. According to this approach besides the influence of the climate, the geochemical and the biogeochemical processes determining the mass flow that affects soil formation should be studied with particular care.

Comparatively few elements play a decisive role in the development of salt affected soils and their geochemistry must be described and accumulation or leaching in the landscape must be studied so that the preconditions of the occurrence of salinity and/or alkalinity affecting the soils, waters and vegetation in a given territory will be clearly established [8].

POLYNOV [13] interrelated the vegetation, soils, underlying rocks, water, geomorphology and geology and, by complex investigations, disclosed the qualitative and quantitative relationships between the factors of the geochemistry of the landscape. He considered the landscape as a dynamic system, which constantly changes resulting in natural processes of different and often opposite directions. Relict and newly arising factors take part in these changes and determine the directions of soil forming processes as well as the shape of the landscape as a whole. His interpretation of a landscape includes the interrelationships and interactions of the lithosphere, the hydrosphere and the daylight surface of these geospheres in contact with the atmosphere. He also emphasizes the effects of living materials, the biosphere, on the development and appearance of the landscape. All these factors, the matrix of their interrelations and influences determine the migration of elements in a given place [8, 10].

I. The main geochemical characteristics of elements and compounds causing soil salinity and alkalinity

There are only a few chemical elements and compounds which play a decisive role in the salinization and alkalization of grounds, soils and waters. They are as follows:

Cations	Anions
Ca^{2+}	Cl^-
Mg^{2+}	SO_4^{2-}
Na^+	HCO_3^-
K^+	CO_3^{2-}
	SiO_3^{2-}

Here and in this paper generally, the acid sulphate soils, and the problem of some toxic elements occurring in the different saline and alkali soils will not be discussed. Only the dominant elements and compounds regulating the mentioned processes will be interpreted.

The ions and compounds, the migration and accumulation of which lead to the formation of saline and/or alkali soils, behave diversely in the weathering processes taking place in the earth's crust.

In Table 1, according to Fersman [5], the places of the dominant elements in the sequences of extraction are demonstrated. The sequences with growing numbers indicate the decreasing mobility of elements during the weathering processes.

According to Fersman [5] the energy coefficient can be calculated on the basis of known lattice energies in inorganic salts. These values are called "experimental energy coefficients" and considered the most reliable ones. The energy coefficients of Fersman [5] are closely related to the sequence of the extraction of ions from minerals, to the rate of migration of ions, and to their ability to accumulate in sediments and soils.

In recent times the weathering of rocks has been the primary source of soluble salts getting into the natural waters, sediments and soils.

The geochemistry of salts in a certain place is determined by the mobility of the compounds formed and by the sequence of the precipitation of weathering products. The mobility of the rock forming elements depends on the following factors:

a) the stability of the crystalline network

b) the radius of ions formed during weathering

c) the charge of the ions formed during weathering

It is evident that the possibilities of translocation for weathering products depend mainly on their mobility.

From Table 1. it follows that the elements and compounds with a dominant role in salinization and alkalization are mainly in sequences I and II; in other words, they are capable of intensive migration. In spite of this, very diverse values can be measured as to the mobility of the mentioned compounds, and their occurrences in rocks and waters are similarly diverse. In Table 2. the relative mobility and ratio of nine elements and ions are set out according to Polynov [13].

Table 1

Sequence of ion extraction during weathering [5]

Sequence of extraction	Ions	Coefficient of energy	Sequence of extraction	Ions	Coefficient of energy	Sequence of extraction	Ions	Coefficient of energy
I.	Cl^-, Br^-	0.23	II.	Na^+	0.45	III.	SiO_3^{2-}	2.75
	NO_3^-	0.18		K^+	0.36			
	SO_4^{2-}	0.66		Ca^{2+}	1.75	IV.	Fe^{3+}	5.15
	CO_3^{2-}	0.77		Mg^{2+}	2.10		Al^{3+}	4.25

From Table 2. it is clear that there are great differences between the quantitative occurrences of the mentioned compounds and ions in rocks and waters as well as between the percentages of their relative mobility. The global situation is even more complex in respect of this problem if the average chemical compounds of the waters of rivers on different continents, as well as those of the oceans and seas are determined and studied.

Table 2

The relative mobility and average distribution of some elements and ions in rocks and waters

component or ion	Average composition of igneous rocks, %	Average composition of the mineral residue of river waters, %	Relative mobility of elements and compounds, %
SiO_2	59.09	12.80	0.20
Al_2O_3	15.35	0.90	0.02
Fe_2O_3	7.29	0.40	0.04
Ca^{2+}	3.60	14.70	3.00
Mg^{2+}	2.11	4.90	1.30
Na^+	2.97	9.50	2.40
K^+	2.57	4.40	1.25
Cl^-	0.05	6.75	100.00
SO_4^{2-}	0.15	11.60	57.00
CO_3^{2-}	—	36.50	—

In Table 3. the chemical compositions of ocean- and seawaters are given, and it may be seen that there are considerable differences in the values.

The Aral Sea contains only one third of the average salt content of the oceans and the Baltic Sea is even more diluted. Keeping in mind the very different environmental conditions of the seas (the Aral Sea is surrounded by a desert and the Baltic Sea has a humid climate), we have to recognize the importance of geochemical factors other than the climate.

Table 3. shows rather high SO_4^{2-} contents in the Caspian and Aral Seas while in the others the SO_4^{2-} concentration is very close to the average level of this compound in the oceans. It has to be mentioned that both seas with high SO_4^{2-} contents are in areas of intensive sulphate accumulation in rocks, waters and soils.

Table 3

The chemical composition of oceans and seawaters

Name	Salt %	Na^+	Mg^{2+}	Ca^{2+}	K^+	CO_3^{2-}	SO_4^{2-}	Cl^-	Br^-
		percentage of total ion concentration							
Oceans (average)	3.3—3.7	30.6	3.7	1.2	1.1	0.2	7.7	55.3	0.2
Aral Sea	1.07	22.1	5.4	4.5	0.1	0.1	31.3	35.6	—
White Sea	2.6—3.0	30.7	3.75	1.2	0.9	0.1	7.9	55.2	0.1
Caspian Sea	1.27	24.5	5.8	2.6	0.6	0.9	23.8	41.8	0.05
Gulf of Mexico	3.55	30.8	3.6	1.2	1.1	0.3	7.5	55.2	0.2
Baltic Sea	0.72	30.5	3.5	1.7	0.1	0.1	8.0	55.0	0.1
Mediterranean Sea	3.73	30.6	3.65	1.2	1.1	0.2	7.9	55.1	0.2
Black Sea	1.8—2.3	30.5	3.70	1.4	1.2	0.5	7.5	55.1	0.2

Remarkable differences can be found in the chemical compositions of river waters, too, on the different continents. (Table 4).

The data in Table 4. show that river waters in South America and Australia are twice as much diluted as the global average, and nearly three times as much as the waters of Europe. Even larger differences can be observed in the concentration of some cations and anions in the river waters. However, it is also

Table 4

Average chemical composition of river waters of continents

Continent	Dry residual p.p.m.	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	Na	Residual carbonate	SAR
		me/l							%		
North America	142	1.05	0.42	0.39	0.04	1.11	0.42	0.02	20.5	—	0.46
South America	69	0.36	0.13	0.17	0.05	0.58	0.10	0.14	24.1	0.095	0.35
Europe	182	1.55	0.47	0.24	0.04	1.56	0.50	0.20	10.4	—	0.24
Asia	142	0.92	0.47	0.24	—	1.30	0.18	0.25	14.8	—	0.29
Africa	121	0.63	0.32	0.48	—	0.69	0.28	0.39	34.3	—	0.70
Australia	59	0.20	0.23	0.13	0.06	0.52	0.05	0.28	21.0	0.098	0.28
Global average	119	0.78	0.34	0.27	0.05	0.96	0.26	0.21	20.8	—	0.37

clear from this Table that the river waters constitute good quality irrigation water on all continents, at least as far as their average values are concerned. From the above mentioned geochemical characteristics it can be concluded that the elements causing salinity on the continents are more concentrated in the seas than in the river waters [4].

On the other hand, sharp differences exist in the chemical compositions of the waters of different rivers. In Table 5., according to Kovda [11], salinity levels of the Volga and Amu Daria rivers are compared. While the latter flows through desert and semi-desert regions, the Volga collects its water from mainly non-arid territories.

Table 5

Collected salts in the catchement of rivers per year [11]

River	Catchement area, km^2	Airborne salts, t/km^2	Discharge to sea, t/year
Volga	1,401,949	2	8,000,000
Amu Daria	308,804	10	226,000,000

Table 5. clearly shows that tremendous amounts of soluble salts can be found in the water of some rivers traversing deserts and semi-deserts. The water quality problems must be studied individually in such cases in order to control the chemical composition of irrigation waters [3].

Table 5. also indicates that in many regions the quantity of airborne salts, too, should be taken into consideration. However, when comparing this amount with that of the salts collected and transported by the waters, we shall find that, with the exception of some seashore districts, the quantity of airborne salts is negligible.

Among the possible sources of salts, Kovda [11] also mentions the biological processes, particularly in arid regions, where the ash of halophytes may contribute to the salinity of soils and waters. However, it is difficult to say whether it is a cause or a consequence when speaking in terms of landscape geochemistry, because halophytes grow as a result of the intensive salinity of their environment.

Table 6

Average elemental composition of some igneous rocks [9]

Element	Concentration in p.p.m.			
	Ultrabasic rocks	Basaltic rocks	High Ca granitic rocks	Low Ca granitic rocks
Si	205	230	314	347
Al	20	78	82	72
Fe	94	86	30	14
Ca	25	76	25	5
Mg	204	46	9	2
Na	2	20	28	26
K	0.04	8	25	42
Ti	0.30	14	3.40	1.20
Mn	1.60	1.50	0.54	0.40
P	0.22	1.10	0.92	0.60

During the weathering of rocks and the translocation of the products of this process, the quantity of water-soluble substances is still insignificant. The average chemical composition of some igneous rocks, after Greenland and Hayes [9], is given in Table 6.

From Table 6. one can see that the different mobile compounds causing salinity may be found in the different igneous rocks in different proportions.

Table 7

Average chemical composition of igneous and sedimentary rocks in percentage

Components	Igneous rocks			Sedimentary rocks		
	Granite	Grandiorite	Basalt	Sandstone	Clay stone	Limestone
SiO_2	70.77	65.69	51.55	79.63	61.16	5.24
TiO_2	0.39	0.57	1.48	0.15	0.68	0.06
Al_2O_3	14.59	16.11	14.95	4.85	16.21	0.82
Fe_2O_3	1.58	1.76	2.55	1.09	4.23	0.55
FeO	1.79	2.68	9.10	0.31	2.58	0.55
Fe	2.50	3.31	8.86	0.99	4.96	0.43
MnO	0.12	0.07	0.20	Traces	Traces	Traces
MgO	0.89	1.93	6.63	1.18	2.57	7.96
CaO	2.01	4.47	10.00	5.59	3.27	42.97
Na_2O	3.52	3.74	2.35	0.46	1.37	0.05
K_2O	4.15	2.78	0.89	1.33	3.41	0.33
P_2O_5	0.19	0.20	0.30	0.08	0.18	0.04
CO_2				5.11	2.77	41.93

Magnesium, for instance, will be present mainly in ultrabasic rocks, while sodium in the granitic ones.

In Table 7. igneous and sedimentary rocks are compared in respect of their contents of different elements.

Table 7. shows that the chemical elements playing a governing role in salinization occur in sedimentary rocks in a percentage even lower than in igneous rocks. Furthermore both rocks completely lack the most common anion taking part in the process of salinization: chloride.

Table 8

Composition of some clay minerals in percentage

Components	Allophane	Kaolinite	Halloysite	Montmorillonite	Vermiculite	Illite	Chlorite
SiO_2	33.96	45.44	44.08	51.14	35.92	49.26	26.68
Al_2O_3	31.12	38.52	39.20	19.76	10.68	28.97	25.20
Fe_2O_3	traces	0.8	0.1	0.83	10.94	2.27	—
FeO	—	—	—	—	0.82	0.57	8.7
MgO	—	0.08	0.05	3.22	22.0	1.32	26.96
CaO	2.26	0.08	—	1.62	0.44	0.67	0.28
Na_2O	—	0.66		0.04	—	0.13	—
K_2O	—	0.14	0.2	0.11	—	7.47	—
H_2O	33.12	14.2	16.18	22.80	19.84	9.25	11.7

When studying the clay minerals which are considered as comparatively mobile substances within the soils, we shall find that their chemical composition also shows a very diverse picture. The sodium cations which are dominant and common in salt affected soils are represented in very low percentages, as can be seen in Table 8.

When we compare the data in Table 8. with the average chemical composition of the earth's crust, shown in Table 9. we shall find, that the percentages of such elements as sodium and calcium, which are important in respect of salinity, are much lower in most clay minerals than in the earth's crust.

From all these it follows that the elements and compounds causing salinity must be mobile in order to accumulate in soils and waters. The average composition of soils is always associated with certain amounts of sodium compounds in a non-mobile form. The percentage of non-mobile sodium is

Table 9

Average chemical composition of the earth's crust (After CLARKE [cit. 5])

Components	Percentage %	Components	Percentage %
SiO_2	59.07	Na_2O	3.71
Al_2O_3	15.22	K_2O	3.11
Fe_2O_3	3.10	TiO_2	1.03
FeO	3.71	P_2O_5	0.30
CaO	5.10	MnO	0.11
MgO	3.45	H_2O	1.30

usually the same in salt affected and non-salt-affected soils. The mobile (exchangeable and water soluble) sodium compounds, however, occur in different ratios in the saline and non-saline soils.

In Table 10. the amounts of the different forms of sodium compounds are shown in four types of soil. The first three, a solonetz and a solonchak-solonetz from Hungary and a salorthid from Syria, are salt affected. The fourth one, a

Table 10

The distribution of soil sodium compounds with different mobilities, me/100 g soil

Soil type	Depth of sampling, cm	Na^+		
		Total	Exchangeable	Water soluble
Solonetz	0— 5	69.6	8.5	8.6
(Hungary)	10— 21	126.0	11.5	19.0
	38— 48	71.9	12.6	13.5
	60— 68	141.0	14.7	30.7
	80— 90	121.5	7.7	2.3
Solonchak-solonetz	0— 2	138.5	1.1	6.1
(Hungary)	2— 11	150.0	6.3	6.8
	11— 26	96.0	6.5	14.3
	32— 47	122.0	4.3	10.4
	55— 67	104.5	4.9	3.7
	78— 89	116.0	3.5	1.9
Salorthid	0— 4	203.0	4.5	19.5
(Syria)	20— 30	232.0	1.0	20.1
	60— 70	219.0	12.9	9.4
	145—155	326.0	1.5	2.2
Calciorthid	0— 3	126.0	0.2	0.2
(Syria)	6— 12	165.0	0.2	0.1
	25— 30	184.0	0.7	1.1
	50— 55	123.0	1.0	2.0
	80— 85	168.0	1.5	3.5

calciorthid from Syria, is not salt affected. Consequently, the exchangeable and water soluble substances occur in rather high quantities in the first three while their level is low in the last soil profile. It is also clear from Table 10. that the non-mobile sodium compounds (total) are close in all soils.

II. The accumulation of soluble salts and the formation of saline and alkali soils in different landscapes

About 10% of the continents is covered with salt affected soils or with such types of the earth's crust where salt accumulation may easily provoke the salinization and/or alkalization of the soil cover. It does not mean that in the geological past other areas of our globe could not, or in the future will not be exposed to salt accumulation. On the contrary, the salinization and desalinization of different areas is an endless and continuous phenomenon resulting from geological alterations. At present, however, there are certain regions, landscape types, which are closely associated with contemporary salt accumulation, with the formation of saline or alkali soils.

Figure 1. shows the schematic diagram of the interactions between lithosphere (L), atmosphere (A), biosphere (B) and hydrosphere (H), after MATTSON [12]. The ABLH square represents the landscape, the P stands for the pedosphere. In the pedosphere, under the influence of different factors, different soils develop. For the development of a salt affected soil the accumulation of the mobile elements and compounds is necessary, as described earlier in this paper. A very large number of variations are possible, influencing the transport, horizontal and vertical distribution of water soluble products in the course of soil forming processes.

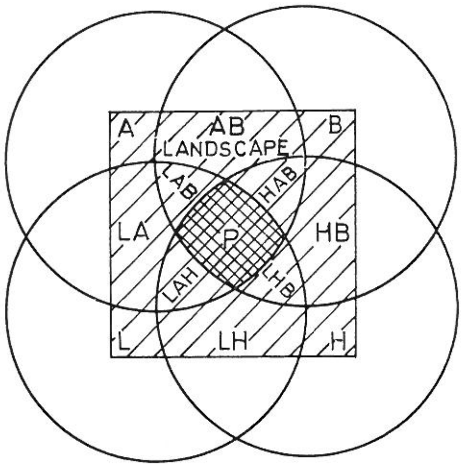

Fig. 1
Schematic diagram on possible interactions between Litosphere (L), Atmosphere (A), Biosphere (B), and Hydrosphere (H). ABLH = Landscape; P = Pedosphere (After MATTSON)

Polynov [13] describing the weathering processes and the geochemistry of continental sediments, distinguishes three characteristic types of the distribution of weathering products in saline depressions. Three types are not enough, of course, to account for all the possible patterns, but they are good examples of the different courses of salt accumulation under salt affected conditions.

Polynov [13] used the landscapes of the Gobi desert to demonstrate the different types of distribution of weathering products. In Section I of Fig. 2. the alluvial material with $CaCO_3$ content covers the elevations of the watershed, while sediments containing sulphates and chlorides occur in the depressions or in the saline lakes. The author explains that this is typical not only of the Mongolian regions of the Gobi, but also of several districts in Armenia, the Arabic Peninsula, Chile, Western Australia and the Kalahari desert in Africa.

Section II in Fig. 2, siallitic orthoeluvia, which was discovered by the author in river terraces in Northern Mongolia, illustrates the accumulation of calcareous sediments in slopes overlaying the sulphates and chlorides which can be found in the depressions. This type is very characteristic in the environment of saline lakes, in desert and semidesert regions.

In Section III of Fig. 2. the possibility of the accumulation of salts associated with lateritic rocks on the most elevated places of the landscape is demonstrated. According to Polynov [13] this type develops, apart from some regions in the Gobi, in Africa in the valleys of the rivers Kongo and Zambezi

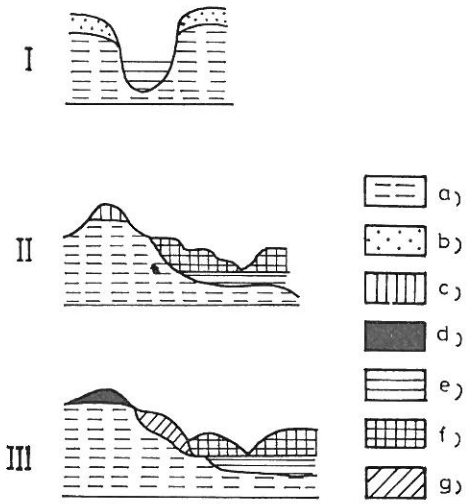

Fig. 2
Distribution types of weathering products in saline depressions (After Polynov). a) Primary rocks; b) calcareous eluvial rocks; c) siallitic rocks; d) allitic rocks; e) chlorid-sulphate sediments; f) carbonates; g) siallitic sediments

and in the Kalahari desert. Here, besides the accumulation of sulphates and chlorides in the depressions covered by carbonate sediments, a siallitic ring has also formed in the slope.

The geomorphology of the landscape plays a governing role in the distribution of materials in all the mentioned types. In most cases water is the main carrier, both on the surface of the soil and underground, transporting the salts toward the places of their accumulation. It is also mainly the water which removes the salts after the weathering processes from other territories, leaching out this way the soils and sediments.

Kovda [11] describes the different landscapes where the geochemical flow leads to the formation of salt affected soils in the USSR and other countries. Based on his grouping and other studies, the following types of landscapes can be listed as the geochemical regions of salt accumulation:

1. Salt dome. — Particularly in arid and semiarid areas, salt domes may occur near the surface. One example for this phenomenon is the Caspian Lowland, where domes consisting mainly of sodium chloride occur and saline soils dominated by this salt have developed. A similar phenomenon can be found in the Central Asian republics of the USSR and in Siberia in the basins of the rivers Enisei and Lena. Such domes form, as a rule, near salt mines, like in the valley of the river Arak in the Caucasus, and in the Pamir (Iran), and in other arid countries where NaCl occurs in large quantities. They are the formations of different geological epochs. Sometimes their extension is considerable, as large as 60—100 km^2.

2. Related to the type of salt accumulation described above are the ones of maritime origin. — In this group the old, young or recent maritime NaCl formations should be mentioned. Such saline grounds occur in many countries, not only in the dry regions, but practically under all climatic conditions, on sea shores, lagoons, etc. Several soil classification systems distinguish the maritime saline soils whose chemistry as well as geochemistry are dominated by the influence of NaCl. Similarly to the type described in point 1, saline or solonchak soils develop in these areas.

3. The deluvial type of salt accumulation. — Salt affected soils frequently occur on the slopes of mountains particularly if during weathering soluble salts form in considerable quantities which are then transported downwards. Many authors described this phenomenon, e. g. Kovda [11] in Central Asia, Armenia and Azerbaidzhan; Filipovski and Ciric [6] in Yugoslavia. For the formation of deluvial salt affected soils some barrier is necessary across the slope which prevents or hinders the removal of salts. Such barrier may be the specific shape of the slope or impermeable subsoil layers. As a rule, the soils belonging to this group do not occur in big massives but rather spotwise. According to the chemical composition of weathering products and waters, different types of salt affected soils can develop. In Italy, for instance, in Volterra near Florence, a typical solonetz can be found in consequence of the phenomenon described above. The deluvial type of salt affected soils may occur under practically any climatic conditions.

4. Salt accumulation in river deltas in steppe and desert regions. — There are vast territories covered by salt affected soils in and near river deltas in deserts and semideserts as well as in some steppe regions. It has to be repeated that, when speaking of salt affected soils, the acid sulphate ones are not included. Namely, acid sulphate soils occur in or near deltas in many regions, under the most diverse climatic conditions, for instance in humid tropics and in areas near the polar circle, etc. The landscape geochemistry of the formation of acid sulphate soils is, however, completely different from that of the salt affected soils discussed in this paper.

Kovda [11] describes three phases of delta development from the point of view of salt accumulation. In Fig. 3. the development of deltas is demonstrated.

During the formation and development of river deltas there are periodical and permanent changes in the base level of erosion. As a rule, this level is sinking resulting in changes not only of the topography, but also in the distribution of waterlogged spots and dry places. The migration of water and salts is also altered due to this process.

Phase I: Young alluvium is forming, temporary or permanent waterlogged spots develop, the water table is close to the surface. Practically no salt accumulation takes place in this phase, because the salt content of the groundwater is nearly the same as that of the river water, which is, under such conditions, always fresh.

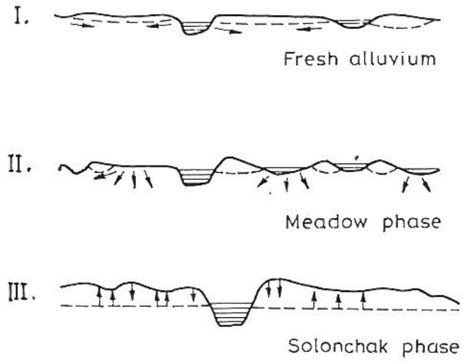

Fig. 3
Development of deltas and salt accumulation (After Kovda)
— — — Water table; arrows indicate the direction of salt movement

During Phase II, the topography of the delta changes. A certain differentiation and polarization of the waterlogged spots and the small "islands" of the developing delta ensues. The formation of small meanders and swamps starts. The formerly homogeneous alluvium changes into light and heavy sediments. This process does not yet result in salinization, though, as it is indicated in Fig. 3, the water migrates mainly downwards and meadow soils develop.

During Phase III, the topography changes again in and near the delta, as a consequence of which the flow of water decreases. The stagnant water in the small lakes and swamps gradually contacts the groundwater which, too, has a rather poor outflow. Because of the lack of outflow, the salt concentration of waters increases, the saline groundwater reaches the surface of the soil through capillary rise and solonchak soils develop.

Apart from the river deltas in arid and semiarid regions, this phenomenon frequently occurs in the river deltas of steppe areas. For instance, the river Volga can be characterized as non-saline, according to the chemical composition of its water, before its delta near Astrakhan. In the delta, however, the groundwater is saline (Table 11).

5. Salt accumulation in dry deltas in dry areas. — In deserts and semideserts, dry deltas are a very common feature of the landscape. The formation of dry deltas is a consequence of former or recent river activity, and it

Table 11

Salt content of the waters in the Volga delta, ppm

Origin of water	Dry residue	Cl^-	SO_4^{2-}	HCO_3^-	Ca^{2+}	Mg^{2+}	Na^+
Volga	310	20	80	80	60	10	20
Groundwater in delta	4910	320					

occurs as an alluvial fan of the river. However, there are certain differences between salt accumulation in maritime deltas and in dry ones. The most important among these differences is that while maritime deltas transport certain parts of the dissolved salts into the sea or ocean, dry deltas broadcast the salts into the land surrounding them. In the alluvial fan, the granulometrically smallest particles occupy the most distant places. In the case of a maritime delta, all these particles are transported to the sea. From this it follows, that in maritime deltas close to the outlet there is a certain zone of leaching, completely missing from dry deltas.

Rivers forming dry deltas in dry regions have a hydrological periodicity, but in ancient dry deltas the former river can sometimes hardly be traced, or only through the study of the alluvial fan, the stratification of sediments, etc.

Where a dry delta is permanently or periodically supplied with water, its flow can be divided into three zones:

1. Zone of the formation of the flow,
2. Zone of the transit of the flow,
3. Zone of the evaporation and salt accumulation,

It is a tremendous amount of salts which can accumulate yearly in a dry delta. For instance, according to Kovda [11], 264,000 tons of salt accumulate every year in the dry delta of the river Soch, and, according to Vasilev [In 11], 655,000 tons in that of the river Murgab.

In Fig. 4. the similarities and differences of salt accumulations of maritime and dry delta origin are schematically represented.

Fig. 4. shows that in dry deltas the total salt content of the flow remains practically in the soil, while in other deltas certain parts of the dissolved materials flow into the sea or ocean. Salt accumulation is consequently much more intensive in dry deltas.

6. Salt accumulation in alluvial plains and river terraces. — There are salt affected soils on all continents in alluvial plains and river terraces. This type of salt accumulation is probably the most common on our globe. In technical literature the different papers and books deal mainly with this type of the salinization and alkalization of soils. It is rational to discuss the problems of salt accumulation in alluvial plains and in river terraces together, because they can often not be divided by a marked borderline. Genetically even the main regularities of salt accumulation are similar in alluvial plains and river terraces.

Salt affected soils occur in alluvial plains under very diverse natural conditions. For instance, we can find vast salt affected alluvial plains in Yakutia above the polar circle under permafrost conditions, and nearly the same type of salinization and alkalization occurs near the equator in the humid tropics of Puerto Rico or Peru. Practically all the salt affected soils in Hungary belong to this type as well as the greatest part of European salt affected soils. Most of the alluvial formations of the big rivers of our globe, e. g. the Nile, Volga, Danube, Lena, Kongo, Mississippi, Murray, Rio Grande, Ganges, Tigris, Euphrates, etc. are more or less salt affected. This type of salt accumulation is important not only theoretically, but also practically. The methods for the utilization of salt affected soils have been elaborated and used mainly under such conditions. It is also in the alluvial plains and river terraces where the secondary salinization and alkalization of irrigated soils are most frequent [14].

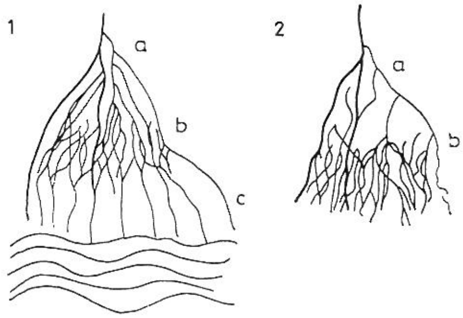

Fig. 4
Salt accumulation in maritime (1) and dry (2) river deltas (After KOVDA). a) Alluvium; b) salt accumulation; c) leaching

In consequence of the great diversity of salinization processes in alluvial plains and river terraces, the chemical composition of accumulated salts as well as the types of salt affected soils in these areas can be different. Solonchak soils dominated by sodium chloride or sulphate, or solonchak soils dominated by magnesium and calcium salts are common, but a large variety of solonetz or solod soils may also develop in this type of landscape. There are few general rules of salt accumulation related to the geomorphology or the climatical conditions of river valleys. The following are the most important of them:

a) On the northern hemisphere salt accumulation and the formation of salt affected soils in river terraces develop more frequently on the left bank of rivers, than on the right bank. The cause of this phenomenon is the shape of the terraces on the right and left banks, respectively, and their different salt and water regimes.

Fig. 5. shows the schematic picture of river terraces on the northern hemisphere.

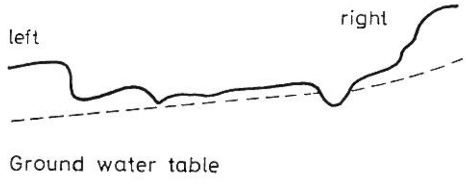

Fig. 5
Scheme of left and right hand terraces of rivers in the northern hemisphere

On the southern hemisphere the opposite phenomenon can be observed, as the terraces of the river Murray in Australia illustrate it so well.

b) In the terraces of the rivers and in their alluvial plains, salt accumulation is more frequent in the lower and middle courses of the rivers than along the upper course. This can only partly be explained with the different climatic conditions of the different parts of the river. For instance, the river Volga has its upper course in humid and the lower one in arid regions. But other rivers, like the Lena in Siberia, the Ganges in India and Bangladesh, are good examples of salt accumulation mainly along the middle course.

In river terraces, as a rule, salt accumulation is slight or does not occur at all in the first terrace. (Exceptions are irrigated lands, where secondary salinization often appears even in the first terrace.) Saline or alkali soils can mainly be found in the second terraces of rivers. Topographically they can develop both in small depressions and on the more elevated elements of micro- or mezorelief. The area of their occurrence depends on the local salt and water movements, on the results of the processes of periodical leaching and salt accumulation. Migrating solutions can sometimes concentrate in depressions and sometimes on the higher places encircling the depressions.

As in the various alluvial plains and river terraces, a very diverse chemistry of salts can be found, different types of salt affected soils may develop. The local environmental conditions determine the formation and chemical composition of soils. Depending on the river water and groundwater chemistry, the climatic and lithological conditions as well as on the topography and shape of the terraces, solonchak or solonetz soils may develop.

Many types of salt affected soils occur in the above described areas [15, 16] however, the sodic types of soils should be specifically mentioned. Most of these types may be found in alluvial plains and river terraces, as is the situation in Hungary. Mainly the same types dominate in piedmont regions, the proluvial-alluvial plain of Erevan, in the basin of the river Lena, in the valley of the Rio de la Plata in South-America, in the valley of the river Murray in Australia and in many other places.

7. *Salt lakes, salt marshes and swamps.* — This type of salt accumulation is related to the former one, particularly, when lakes and swamps are concerned. Temporarily or periodically waterlogged formations often occur in the river valleys and alluvial plains [2]. Salt lakes and swamps may transform into saline soils, but saline or alkali soils may also be temporarily waterlogged. The occurrence of saline soils is most common around salt lakes and swamps. Salt marshes are related to the salt accumulation types described in points 2., 4. and 5. Salt lakes, marshes and swamps occur on all continents, particularly in arid or semiarid regions. There are very large salt lakes, e. g. the Balkhash lake in the USSR or the Great Salt Lake in Utah, USA. There are small salt lakes in many deserts and alluvial plains as well as in river valleys. Their formation depends mainly on the hydrological conditions; both climate and hydrology influence their development or their desiccation. While a saline ground is under water, it can hardly be named soil. The environment of saline lakes and swamps is, as a rule, covered by salt affected soils. Often, these lakes and swamps desiccate partly or wholly and their saline bottoms appear.

The chemical composition of salts in the formations described above can be diverse, depending on the local environmental conditions. There are lakes where $NaCl$ or Na_2SO_4 dominates, whereas in others Na_2CO_3 prevails.

Partial or total desiccation often takes place in the alluvial plains. This process is going on at present in the Baraba plain in Siberia and partly the same was characteristic of the Hungarian Plain until its greatest part, the valley of the river Tisza was ameliorated and desiccated.

Some of the salt or saline lakes and swamps may have another origin. They can often be found in tectonic valleys, like the Fertő lake in Hungary, or they are of volcanic origin. Many authors [10, 11, 13, 16] share the opinion that artesian waters can also contribute, directly or indirectly, to the formation of saline lakes.

Although the types of landscapes discussed above do not present a full picture of all the possibilities of soil salinization and/or alkalization, the formation of saline and alkali soils, however, is related to one or more of these types in most cases.

The study of environmental conditions, the quantitative description of salinization and alkalization in a given area lead to the elaboration of up-to-date, economic methods for the utilization and reclamation of salt affected soils.

References

[1] BERG, I. Sz.: (Climate and life) [H] Akadémiai Kiadó. Budapest. 1953.
[2] CHAPMAN, J. V.: Salt marches and salt deserts of the world. L. Hill. London. 1960.
[3] DARAB, K.: (Qualification of irrigation waters and its experiences in Hungary) [H] MTA Agrártud. Oszt. Közlem. **35.** 167—174. 1976.
[4] DEGENS, E. T.: Geochemie der Sedimente. F. Enke. Stuttgart. 1968.
[5] FERSMAN, A. E.: (Geochemistry.) [R] Leningrad. 1934.
[6] FILIPOVSKI, G. & CIRIC, M.: Zemljista Jugoslavije. Beograd. 1963.
[7] FORTESCUE, J. A.: Environmental geochemistry. Ecological Studies No. 35. Springer. New York—Heidelberg—Berlin. 1980.
[8] GLINKA, K.: Die Typen der Bodenbildung. Bornträger. Berlin. 1914.
[9] GREENLAND, D. J. & HAYES, M. H. B.: The chemistry of soil constituents. Wiley and Sons. New York. 1938.
[10] KELLEY, W. P.: Alkali soils. Reinhold. New York. 1951.
[11] KOVDA, V. A.: (Origin and regime of salt affected soils) [R] Vols. I. II. Izd. Akad. Nauk. SSSR Moscow. 1947.
[12] MATTSON, S.: (Soil colloids) [R] Sel'hozgiz. Moscow. 1938.
[13] POLYNOV, B. B.: (Selected papers) [R] Izd. Akad. Nauk. SSSR Moscow. 1956.
[14] SZABOLCS, I.: Salt affected soils in Europe. Martinus Nijhoff, The Hague and Res. Inst. for Soil Sci. and Agric. Chem. of the Hungarian Academy of Sciences, Budapest. 1974.
[15] SZABOLCS, I.: Solonetz soils in Europe. In: European solonetz soils and their reclamation. (Ed.: SZABOLCS, I.) Akadémiai Kiadó. Budapest. 1971.
[16] SZABOLCS, I.: Review on research of salt affected soils. UNESCO. 1979.
[17] VERNADSKY, V. I.: (Chemical composition of biosphere.) [R] Nauka. Moscow. 1965.

Discussion

GIRDHAR, I. K.
Data given in Table 2. indicate that the relative mobility of Mg ion is even much lower than Na^+. May I know the possible reason for the lowest mobility of Mg ion in comparison to Na^+?
SZABOLCS, I.
The geochemical mobility of Mg is lower than that of Na because Mg is component in lattic layers of clay minerals, forms hardly soluble compounds.
YADAV, J. S. P.
The author has elaborated the importance of geomorphological features in influencing the nature of formation of salt affected soils in different areas of the world. This holds good

in many cases, but there are at the same time several situations where climatic conditions play a more dominant role in influencing the nature of formation of salt affected soils. In the Indo-Gangetic Plain in India the alkali soils dominated by carbonates and bicarbonates of sodium are found in the areas having annual rainfall more than about 450 mm, while the saline soils are occurring in areas having lower rainfall. Thus, the author may indicate if the climatic conditions will not be more important in such situations.

SZABOLCS, I.

The climate is one of the main factors of soil formation in general. The dry climate is favourable for the development of saline soils. However, the accumulation processes of salts in any place are influenced not only by climatical conditions, but by all factors of the geochemistry of the landscape. For instance, in very dry and hot deserts, like the Sahara, there are saline areas as well as non-saline areas, depending on local geochemical conditions. It is true that in most cases the extreme arid environment is associated with NaCl or Na_2SO_4 accumulation, while under more humid conditions the $NaHCO_3$—Na_2CO_3 type of alkali soils is prevalent.

SINGH, N. T.

What do you think, what is the reason for variation in shape of terraces along left and right banks of different rivers? Which conditions would favour accumulation of sulphates or chlorides in different lakes?

SZABOLCS, I.

It is the Ber-law that the shape of terraces along the left and right sides of rivers forms differently in consequence of the rotation of the Globe. It is valid if the river flow direction is north-south.

The local geochemical conditions determine which type — sulphate or chloride — dominates in the lake water. For instance in the Middle East or in the Soviet Central Asian Republics sulphate accumulation prevails in the soils as well as in the lakes. In the region of chloride accumulation or in lagunas, in lakes near to salt domes the chloride type of lake waters dominates, as well as chloride accumulation in soils.