Available online at www.sciencedirect.com
ScienceDirect
Quaternary International 173–174 (2007) 125–136

Uzboy and the Aral regressions: A hydrological approach

René Létolle[a,*], Philip Micklin[b], Nikolay Aladin[c], Igor Plotnikov[c]

[a]Université Pierre et Marie Curie, Paris, France
[b]Western Michigan University, Kalamazoo, USA
[c]Zoological Institute, Russian Academy of Sciences, Saint Petersburg, Russia

Available online 21 March 2007

Abstract

The Uzboy is an enigmatic dry river channel in Western Central Asia. This 750 km long channel regained life on several occasions after the end of the Würm glaciation (about 11,000 years BC), due to climatic episodes more humid than today and/or human deviations of the main course of the Amu Darya towards the west. Much of the Amu annual flow was diverted elsewhere. The discharge of Amu Darya in the Zaunguz desert accounts for the tens of km^3 of water the Uzboy was unable to convey away.

It appears reasonable to conclude that the Amu Darya could not carry more than 20–30 km^3 per year to the Sary Kamysh lake, due to the channel cross-section at Daryalyk and Daudan Darya, at a time when the total water output of Amu Darya to Aral was about 60–70 km^3 per year.

1. Introduction

The Uzboy is an enigmatic dry river channel in Western Central Asia (Fig. 1). Correctly mapped by Konshin in 1884, the geological setting of the Uzboy has been thoroughly studied by Kes from 1937 until recently (chapters in Tolstov and Kes, 1960; Tolstov, 1962; Andrianov, 1969; Kes and Klyukanova, 1999). For a brief review of the first discoveries, see Wood (1876), Morgan (1878), and Yusupov (1996, 2001). For a recent monograph, one may refer to Létolle (2000).

Although some authors assert, without any conclusive arguments, that the Uzboy never was a real river, Kes (1991, 1997) clearly demonstrated that it was an important river and a western branch of the Amu Darya. This paper establishes some hydrological parameters of the most recent characteristics of the Uzboy flow, in the Middle Ages, and especially in the XVIth century A.D., when the Aral suffered a regression of at least the same importance as the present one. This epoch is the best documented and geomorphological characteristics of the channel remain essentially unchanged since this time. The Uzboy was unable to carry all the Amu Darya's flow and other dissipative processes must have been operative.

This 750 km long channel (Fig. 1) regained life on several occasions after the end of the Würm glaciation (about 11,000 years BC), due to climatic episodes more humid than today and/or human deviations of the main course of the Amu Darya towards the west. Today this channel is dry except for several elongated small pools, which are fed by spring rain and snow, perennial springs from the Ust Urt plateau in the North and from sands of the Karakum desert in the SW, which is a reservoir of low transmissivity fed by southern waters, mainly from the slopes of Khopet Dag and inland deltas of the rivers Tejen and Murgab. Some of these pools are perennial.

At various times in the past, the rising level of the Caspian created a narrow gulf from the lower course of the Uzboy, up to 0 m a.s.l., but never during the last millennia. Most often when one refers to Uzboy, the Amu Darya running towards the Caspian Sea, this implies that the Amu was completely diverted towards the Caspian. But was only a part of its flow directed toward the Caspian, while the remainder flowed to the Aral, or elsewhere? Furthermore, is the relict bed of the Uzboy even able to carry the tens-of-billions of cubic metres of water it is supposed to have carried every year?

*Corresponding author. Tel.: +33 142372856; fax: +33 142372856.
E-mail address: rene.letolle@wanadoo.fr (R. Létolle).

1040-6182/$ - see front matter
doi:10.1016/j.quaint.2007.03.003

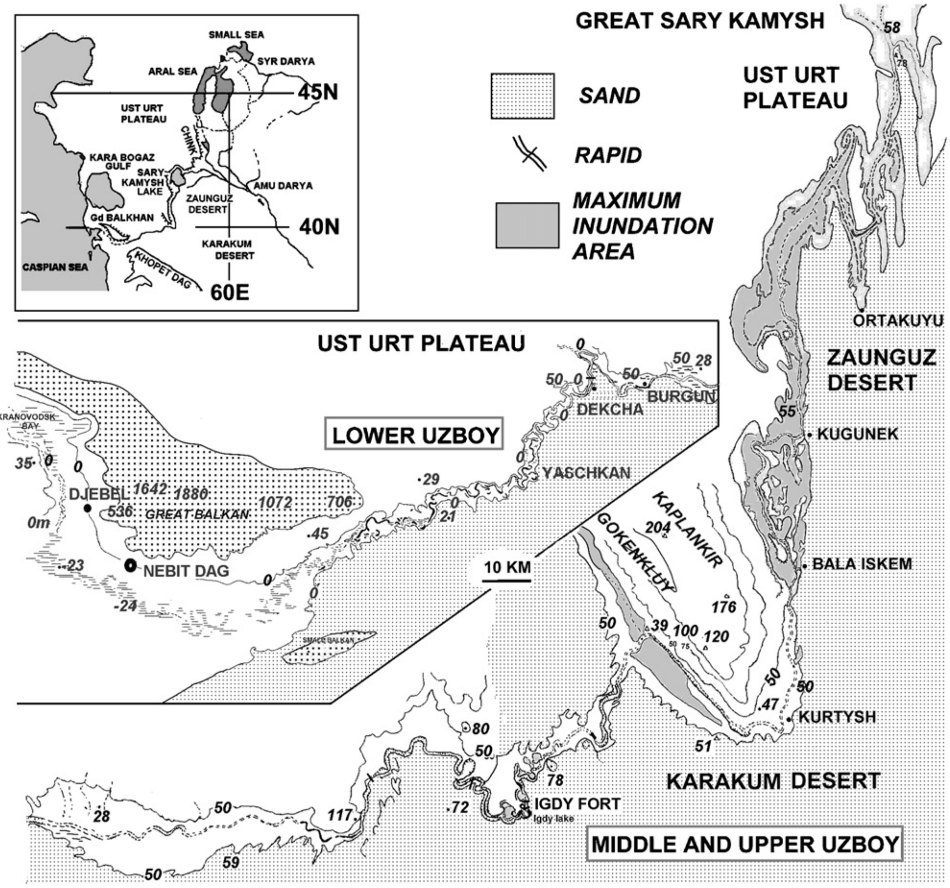

Fig. 1. General map of Uzboy, after 1:500,000 map of USSR origin.

Barthold (1910) states that Arab historians of the Middle Ages wrote that the Uzboy was a water course used by merchants who navigated it for centuries, and had to overcome several rapids. The route from the Caspian Sea left the Uzboy near Kurtysh (Fig. 1) to cross a part of the Karakum desert and reach the Saksenem station halfway from Khiva to Urgench. Jenkinson in 1548, arriving from Russia via the Ust Urt plateau, camped on the shore of Sary Kamysh (Fig. 1), the lake from which the Uzboy originates. He found the water ''fresh and sweete'' (*sic*), which proves that the lake was fresh water at this time, and consequently was exorheic. East of Urgench, the main course of the Amu running north and the current had been recently re-established, and ''was swifte''.

This study examines the flow capacity of the Uzboy during the last pre-Soviet recession of the Aral Sea in the XVth–XVIIth centuries. It uses sets of satellite photographs from NOAA, SPOT, Google Earth, XSAR radar pictures, and sets of ground photographs of various origins.

The present topographic configuration of the Uzboy was established in the XIXth century, except for minor changes linked with wind erosion and sedimentation (mobile sand dunes). The intent here is to determine what constraints hydrology imposes on the possibility of a complete diversion of the Amu Darya towards the Caspian Sea during the pre-historic and historic eras, as has often been asserted without proof. The main cause of several important regressions of the Aral Sea level cannot be attributed to climatic variations, such as the ''Little Ice age'', as is the case for Aral transgressions, although those are limited by the sill formed by the Amu Delta between the Aral and Sary Kamysh lake. The maximum altitude of this sill is 70 m a.s.l.

The idea that the Amu Darya flowed to the Caspian preoccupied historians for centuries. Konschin (1897), one of the first scientific explorersof western Central Asia, believed that the Uzboy could not have carried the entire Amu discharge, or even the largest part of it, to the Caspian Sea. Nevertheless, a common assertion today is that the flow of the Amu Darya was wittingly or unwittingly turned westward depriving the Aral of most of its water supply. This would imply that the total Amu Darya flow (Fig. 2), averaging 56 km^3 per year for the instrumental measuring period 1911–60 (before irrigation expansion severely depleted its flow) with a range of 30–70 km^3 per year and instantaneous values from 6560 to 325 m^3/s went to the Caspian Sea before the building of dams along the river and its tributaries in the second part of the XXth century.

Various authors, since Kes, have concluded that the Uzboy was unable to carry more than ~15 km^3 per year of

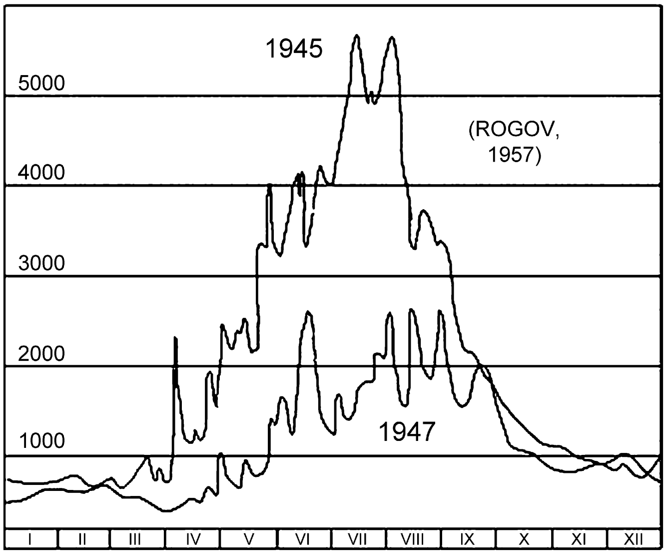

Fig. 2. Hydrogram of maxima and minima of Amu Darya (from Rogov, 1957).

the mean Amu flow. This paper presents a new study of the ability of the Uzboy to convey water. Most of the geographical information on the Uzboy comes from the magnificent works and maps of Kes, published in the proceedings of the Khorezm Expedition (Tolstov and Kes, 1960; Tolstov, 1962). Kes was able to differentiate the fluvial alluvium of the Holocene period (less than 10,000 years B.P.) from those of Pleistocene age (last glaciation and before). To this material are added some details from other authors (see Létolle, 2000), and from topographical documents.

2. Amu Darya/Sary Kamysh/Uzboy system

Today, irrigation drainage water originating from the Amu Darya flows to the Sary Kamysh depression through canals, which follow more or less ancient natural channels (Darya Lyk and Daudan Darya) (see Fig. 13), although the latter does reach the present lake. Sary Kamysh lake sits in an oval depression of tectonic origin, which was later affected by aeolian erosion during successive glaciations from 2 millions years ago to 10,000 BC. It was filled during the Holocene, partly by aeolian sand and dust, but mainly by alluvium of the Amu Darya delta, which choked the pre-existing lacustrine link between the Aral Sea and Sary Kamysh ("the Great Aral", Boomer et al., 2000). Subsequently, western branches of the Amu carved these geological formations and also, beneath them, those of Upper Tertiary and Lower Quaternary periods, creating the Darya Lyk canyon. These channels were inactive when the lake was discovered by the Petrosevich expedition in 1876, after the Russian army occupied Khiva. At that time, the Sary Kamysh lake was reduced to a series of small salt lakes of a total volume of 1 km^3, fed by karstic springs and scanty precipitation. In 1878, the lake was almost filled by a giant flood from the Amu Darya, which destroyed its western dikes. The lake received in its 2004 state approximately 5–6 km^3/year of drainage water, which stabilized its level at about 0 ± 2 m a.s.l. (Kes, 1997).

This corresponds to the equilibrium of inputs (essentially the Daryalik waters) with evaporation (about 1.2 m/year, Orlovsky, 1967; Kes, 1991), infiltration and springs being of little importance. Complete filling of the depression, to the southern edge at 58 m (53 m following Saparov and Golubchenko, 2001), should be possible in a few years with an input of at last 15–20 km^3/year. The minimum water input to keep the lake filled to its maximum level with no discharge to the Uzboy is about 9.5 km^3/year. When the Amu Darya completely filled up Sary Kamysh during the historical epochs, the area of the lake was 13,500 km^2, including its western annex, the Assake Kaudan (base at +29 m a.s.l.), with an area of 600 km^2 and a volume of 15 km^3. The Assake Kaudan can be filled from the Sary Kamysh only when the level of Sary Kamysh is higher than 50 m a.s.l.

The negative part of the water balance (evaporation) was about 12–13 km^3/year, all factors considered. When the Amu discharged into Sary Kamysh, it carried between 35 and 70 million m^3/year of sediments into the lake. These have mostly disappeared since the XVIth century, due to aeolian erosion, which is prevented when a temporary lake contains water. This explains why practically no old sediments are known in the Aral Sea itself.

2.1. Sary Kamysh overflow sill

The following discussion will consider first the hypothesis that most of the Amu Darya flow was carried by the Uzboy. Based on the detailed maps of Kes and photographs, the very flat channel leading to the Uzboy is estimated to be about 1000 m wide. The altitude of the sill between Sary Kamysh and the upper thalweg of the Uzboy, today, having been affected by substantial aeolian erosion, is a little higher than the isohypse at 50 m a.s.l. This creates for the upper course of the Uzboy, down to the Bala Ischem hamlet a very low slope (8 m for about 140 km, $= 5.7 \times 10^{-4}$).

The longitudinal profiles of western branches of Amu delta (Daryalyk) have greater slopes than those that approach the Aral Sea, and have sigmoidal form, which shows they have not attained their equilibrium profiles. On the contrary, the profile of the Uzboy itself is much nearer equilibrium, which shows its geological antiquity. The profile of those western channels is carved extensively in Holocene detrital sediments of the Amu, which were deposited when the present Amu delta (post glacial-Holocene) formed.

The first section of the Uzboy from the sill has a very indistinct morphology, with wide channels oriented more or less NW–SE, between *buttes-temoins* of Sarmatian rocks (limestones, gypsum marls and marine sands), remnants of the Ust Urt plateau, and elongated dune massifs separating solonchaks (Fig. 3). Some are located along the banks of

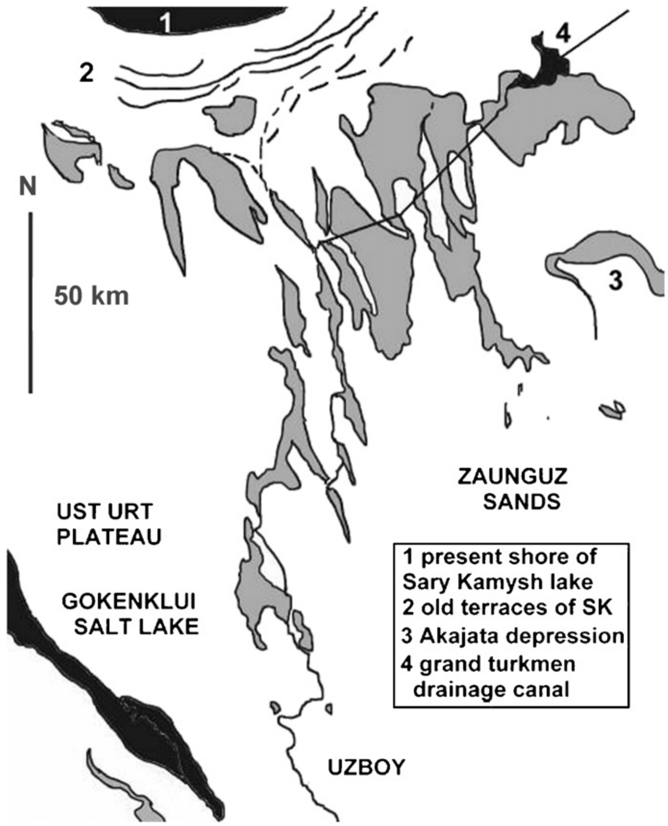

Fig. 3. Schematic geologic map of upper Uzboy, with lateral solonchaks.

the channel, poorly defined and invaded by recent dunes, down to the Kugunek locality where the bed begins to be clearly defined with steep banks. Today these solonchaks are fed by small karstic springs and especially by precipitation filtering through the sand and reappearing at the boundary between sand and the geological substratum. This is especially apparent on recent satellite images (2003–04), when precipitation was heavy.

Most of the discharge, however, poured towards the southeast of the Uzboy, forming several temporary channels that spread between the rows of dunes of the Zaunguz (Northern Karakum) desert dunes. Konschin (1897) and Moser (1885) had already observed that well-preserved channels from the region of Khiva and Urgench did not follow the western direction of Daudan and Daryalyk channels and lost themselves in the Zaunguz sands. Those forgotten channels will be discussed below.

It is possible to define the maximum possible output of Sary Kamysh, under the hypothesis of all Amu water going through the Sary Kamysh, as between 43 and 23 km^3 per year, deducting water lost to evaporation on the lake. When water reached the level of 53–58 m a.s.l., it poured as a thin sheet (sheet flow) towards the south. Every flood peak would be transmitted towards the south, with a few days delay, and would spread in the solonchak area south of Sary Kamysh, with only a part flowing towards the ill-defined originating channel of the Uzboy. Moser (1885) estimated that solonchaks in the southern area of the Sary Kamysh covered 20,000 km^2, including the dry bottom of the Sary Kamysh. Presently, the area of functional solonchaks south of Sary Kamysh, as determined from satellite images is about 600 to 800 km^2.

It is possible to estimate, at least semi-quantitatively, the characteristics of such water flows utilizing some empirical formulae (see Wohl and Enzel, 1995, for a detailed bibliography). Running water takes its energy from gravity: energy is lost by friction on the banks and the bottom of channels, and in rapids and waterfalls. As water is uncompressible, this makes moving water with low energy flow more slowly, with a tendency to accumulate under the pressure of water coming from upstream. It compensates by increasing the cross-section of its channel, creating floods above its usual banks (the major channel). Hence the importance of the study of fossil marks of sedimentation (terraces), above the usual (minor channel) and the geometry of channels, especially in sections with meanders.

Many papers and books deal with the problem of evaluation of maximum flow of palaeorivers, but the lack of universal methods of evaluation of such flows make conclusions rather qualitative. Among the existing formulas determining river flow, the Strickler–Manning formula is the most reliable to use. It gives the speed of water V for a rectilinear channel through calculations using the slope and geometric section of the river channel:

$$V = kR^{2/3}I^{0.5},$$

where I is the main slope (introducing the role of gravity), R the ratio S/P between the area of the "wet section" S and the "wetted perimeter" P (bottom profile). k is a "roughness" parameter, varying from 10 for small torrential channels, to 60 for large plain rivers. We assume in the following calculations a value of $k = 40$, the mean between "quiet rivers" and "rivers with gravel bottoms" (tables in Jauzein, 1971).

Water velocity is considerably lowered in non-linear channels by further kinetic energy losses in curves and meanders. The hydraulic concept of "tortuosity" of a channel tries to quantify the impact of curves on the speed of running water, and, therefore, on the flow. The flow loses energy when impacting the concave bank, through heat and mechanical erosion of the banks.

Turbulence is also a cause of energy loss, especially in rapids, and several sections of the Uzboy channel possess rapids (see Fig. 1). These effects slow the water flow and, therefore, give other restrictions to the maximum flow of the rivers.

For the outflow of Sary Kamysh at 58 m a.s.l. (or 53 m), the mean slope is 7.1×10^{-5}. The wetted channel may be considered a rectangle with width L and depth H, with wet section HL and wetted perimeter $L + 2P$. As P is much smaller than L, one may approximate the ratio R (S/P) as equal to L. Calculations show that a sheet of water several km wide and some centimetres deep can easily evacuate several thousands of m^3/s; and it is possible to determine a hypothetic hydrogram for this outflow (see Fig. 9).

2.2. The upper course of the Uzboy

After the summer flood season, Sary Kamysh outflow decreased towards its minimal value of 300–400 m^3/s (the 800 m^3/s of Amu during low flow, minus the losses before reaching Sary kamysh and those due to evaporation on the lake). The volume spread in the lateral solonchaks, would have represented about 10–20 km^3/year north of the Kugunek hamlet, where the Uzboy became a real river. Its banks here are modest cliffs or slopes carved in the Samartian beds of the large Kaplankir anticline on which the river superimposed itself since Pliocene times. The bottom of the riverbed reaches 50 m a.s.l. at Bala Ischem. The cross-section of the Uzboy minor bed at Kugunek near here is well known from a figure given by Kes (Fig. 4), with a cross-sectional area of 170 m^2 and a wetted perimeter of 130 m, for a possible flow of 0.36 m/s, 60 m^3/s or 2 km^3 per year. As concerns the major bed, the western part of the profile represents sand dunes of river origin amidst the termination of a south western solonchak which has, as shown on 2004 satellite images (Fig. 6), no exit towards the channel.

The major bed, representing the section for major floods, may be estimated as 300 m in perimeter and 1200 m^2 wet section, whence a possible flood of 0.76 m/s and a flow of 900 m^3/s during floods. These estimations are made for a linear channel, which are certainly too high. However, these results represent the mean and instantaneous maximal flows possible here. The dynamics of the flow varied by a factor of 15 annually, which may be compared to the ratio between the highest and lowest values for the Amu Darya (13.8): this shows the conservation of the dynamics of floods after the transmission of flow through the filled-up Sary Kamysh and its southern outlet.

Uzboy, now a well-defined channel, passes around the SE termination of Kaplankir with a series of rapids (Fig. 5), where water again loses energy, and shows traces of erosion between steep banks up to 10 m high. From Kurtysh to the Ak Yala the bed and banks are well marked and are oriented for some 25 km towards the NW to the large endoreic depression of Gokenklui solonchak (90 km × 10 km, water surface at 0 m a.s.l.; presently 2 m deep in the south and 25 m in the north). It connects with the Uzboy channel through a saddle located 10–15 m above the present bottom of Uzboy, and presently covered with dunes. This depression will be the terminal collector of the new drainage system of Turkmenistan, presently under construction, and will become a salt lake named "The golden age lake". For the Uzboy floods, this depression was a waste-weir.

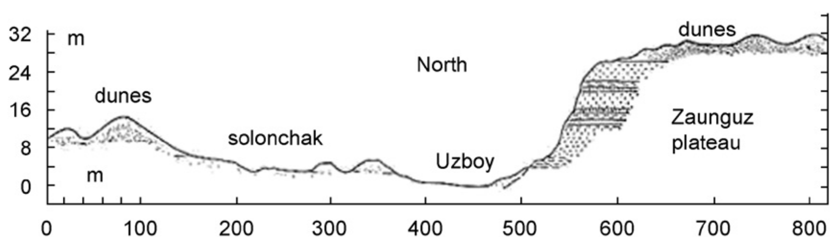

Fig. 4. Transversal profile of Uzboy at 7 Km north of Kugunek:, after Kes, 1960.

Fig. 5. Aerial photograph of Kurtysh area,taken from NW. (after Kes, 1960).

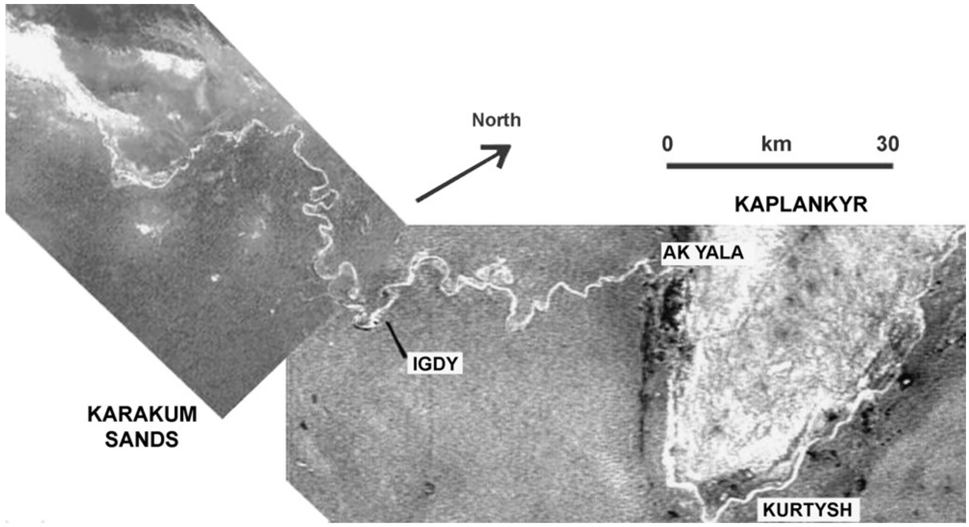

Fig. 6. XSAR satellite image of Uzboy south of Kaplankyr.

2.3. *Crossing of the Karakum desert*

The Uzboy now turns to the south and enters the Karakum sand desert (Fig. 6). For nearly 150 km it flows between two steep banks, crowned by limestones of Akchagilian age, which was the last marine intrusion from the Caspian Sea some 2–3 million years ago and which deposited these sediments in the Turkman plain to the Aral Sea. (Yurevich, 1966). These limestones form some vertical cliffs, and are capped by dunes. The morphology of this section is embanked meanders north and south of Igdy. Those were formed from the Upper Pliocene to Preglacial Quaternary. The Uzboy flowed in a plain with a low slope, conducive to formation of meanders. During slow vertical movements, rivers have a tendency to subside and keep their meander morphology. The vertical moves which formed the Kaplankyr anticline made the Uzboy sink in place (superimposition), keeping its ancient meander morphology and deepening its valley (Burbank and Anderson, 2000). This geological process lasted perhaps more than one million years.

In this section, the slope of the course is much higher (mean value: 33×10^{-5}), with dry rapids 1 to 2 m high (Fig. 7A), above and at Igdy, 60 km below Ak Yala. Between the rapids, the slope declines to a few 10^{-5}. At Igdy (Fig. 7B and C), the altitude loss is estimated as 20 m over 160 km (mean slope 1.25×10^{-4}). At the level of Igdy spur, where a Parthian fortress (according to Yusupov, 1996) was built, at 36 m above the dry minor bed which is about 60 m wide and 2 m deep. There is no trace of fluvial erosion or terraces on the slope of the bank: the perfect state of scree above the banks (Fig. 8) proves that water did not erode it. The Strickler–Manning formula applied to the cross-section at Igdy gives a possible speed of about 0.8 m/s, and a flow of 100 m^3/s. However, meanders would slow this theoretical speed. Between Ak Yala and the end of the meander section below Igdy, there are 33 curves of various convexity, with radius between 0.4 and 2 km. Supposing a mean energy loss of 5% per meander, the residual energy after 33 meanders should be $0.95^{33} = 18.4\%$ of its value at Ak Yala.

Tortuosity is applied to the characteristics of meander sections of rivers: it is defined by three parameters: number of meanders, frequency of meanders (wavelength), and convexity (radius of meanders), arranged in various formulas. Nalder (1997) related meander "length" L and water flow Q, the general form being $L = kQ^{\,0.5}$ with k between 4.6 and 9, which gives at Igdy a possible flow lower than 200 m^3/s. A formula by Charlton, quoted by Schumm and Galay (1994) uses the "wavelength" of meanders (mean distance between the apex of a series of meanders): $Lm = 65.Q^{0.5}$, which gives for the tightest series at Igdy $Q = 230\,m^3/s$. Degoutte (2002) gives a formula $V = (2g \times \text{slope} \times R)^{\,0.5}$, where R is the radius of curvature of the meander and $g = 9.81\,m/s^2$. The tightest radius in the Igdy area is 200 m and the slope is locally 2×10^{-4}, which gives a mean speed of 1 m/s. In any case, the calculated speed of water is below 2 m/s, corresponding to an annual flow of 6.4 km^3.

Some of the meanders are flat, showing a horizontal abrasion of their surface, and presenting a series of up to 8 thin terraces. Such are found above and under the Igdy spur (Fig. 7). The highest is 15 m above the bottom of Uzboy and is of Pleistocene age, following Kes, and consequently it is not relevant to discussion of the XVIth century. Such terraces correspond to an ancient deposition phase when Uzboy was digging its canyon in rather incoherent Ashkagilian deposits. A water level at 15 m above the present bottom of the channel would correspond to a maximum theoretical flow of 2400–2500 m^3/s for a wet section of 1350 m^2: this would have completely destroyed any older terrace in the meander section of the canyon. The lowest terrace below Igdy, at 4 m above the bottom of the channel, is in a perfect state of conservation. At this place,

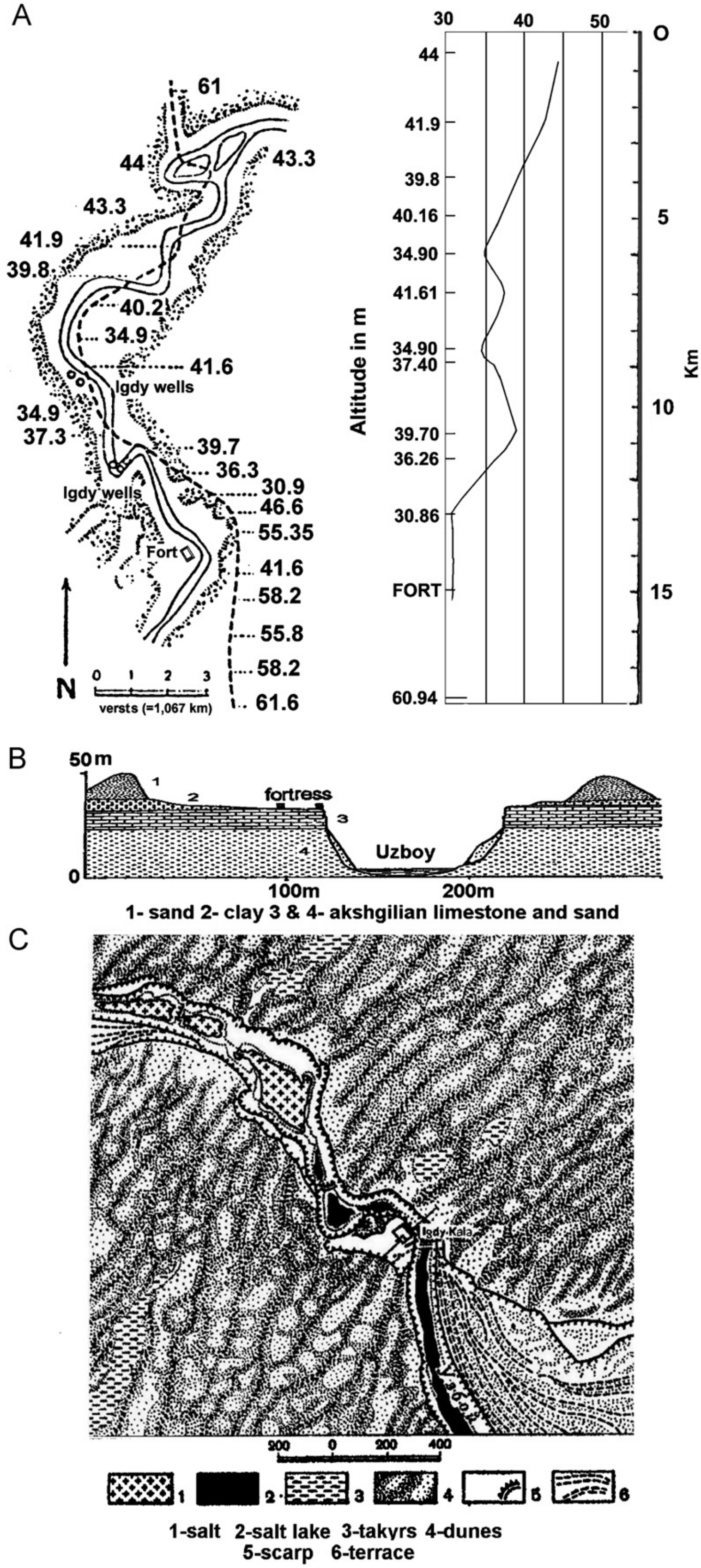

Fig. 7. Igdy characteristics: (A) longitudinal profile of the channel; (B) transversal profile (length and height at the same scale); (C) detailed map (from Létolle, 2000).

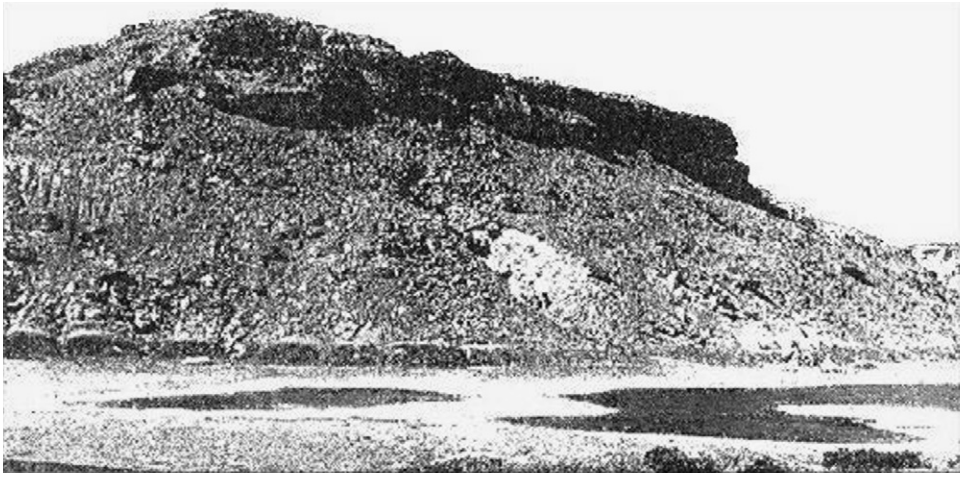

Fig. 8. The Igdy spur and fortress (after Kes).

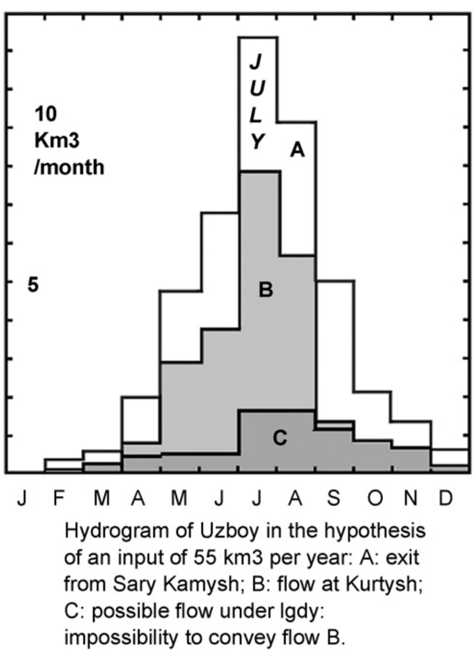

Fig. 9. Reconstitution of Uzboy annual hydrogram below Sary Kamysh, and hypothetical hydrogram below Igdy.

the bed is 130 m wide with a section of 300 m^2. Its existence is compatible with a flow of less than 130 m^3/s at the exit of the narrows.

In general, it is possible to estimate the speed of water in the Igdy section as being between 1 and 2 m/s. A hypothetic hydrogram is given in Fig. 9. At the beginning of the canyon section, as the channel has an insufficient cross-section and a reduced speed due to meanders, the water level would have risen progressively upstream. Water would accumulate creating a flood-lake in the Ak yala section, where the wet section is much larger, up to Kurtysh, then a temporary lake of a capacity of about 10 km^3 Such a lake existed earlier (Tolstov and Kes, 1960, map p. 65 for Khvalinian stage: 2–3 MA BP). This could have fed the lateral Gokenklui depression mentioned above. The Uzboy should have flooded its southern bank in this section, coming into contact with the fringe of Karakum sands, and losing water through infiltration. The ancient tombs found by archaelogists in the Kurtysh–Ak Yala section are at the limit of the sands, and not adjacent to the channel, which could have been done to prevent tomb flooding (water traces can be seen on 2004 satellite images). The formation of this lake should have begun in June, with a maximum level in August, with draining completed in autumn. The temporary accumulation of floods above narrows is a common occurrence: an example is the Ichang gorge of Yang-Tse-Kiang (Chang Yang) in China, where water accumulated during overflows (up to 80,000 m^3/s) up to 37 m above the low-water level, forming a lake 400 km long before the building of the Ichang dam. Below Igdy, the canyon section has the same characteristics for 100 km, and consequently went on slowing the current of floods.

2.4. The downstream part of the Uzboy channel

Down to the Caspian Sea, evaluation of possible flow is much easier. The thalweg is wide, generally more than 100 m, and shows a succession of sections, some with small rapids. The minor bed shows banks several metres high, alternating with sections with low banks and a wide major bed. It could easily accommodate the maximum flow estimated for the Igdy section, especially the summer flow of some km^3. To it would be added seepage from the Karakum sands, and from the Ust Urt plateau to the northwest, as exists today. Those fed a number of sections with permanent water, the celebrated ‘‘Uzboy lakes’’, of which some are salty and others fresh water. It is completely justified to think that this section of the Uzboy was used in the Middle Ages for boat traffic, in spite of the numerous meanders, functional or abandoned. Those were formed in their majority, not only by tectonic ‘‘superimposition,’’ as in the Igdy section, but also by the continual changes of the base level of the Caspian Sea, which reduced the slope during its transgressions, invading the lower course of the river for more than 200 km from the present shore.

2.5. Conclusions on the Uzboy flow capacities

Estimation of the approximate balance of Amu Darya flow to the west, for a supposed annual flow of 50–70 km^3/year, may be summarized as: 13–15 km^3 evaporating from the Sary Kamysh lake, and a maximum of 10 km^3 crossing the Igdy narrows with the difference being lost in solonchaks. The areas directly south and southeast of the Sary Kamysh could accept, on an area between 10,000 and 20,000 km^2 at maximum, an inflow of some 10 more km^3. Kvasov and Trofimets (1976) estimated the flow as 12–13 km^3/year, and Létolle (2000) as 15 km^3/year.

Recently, Trofimov (2003) briefly states from his own calculations that during the period under consideration, the Uzboy flow could have been about 30 km^3 per year. However, his paper using classical flow formulas (some incorrect) is unclear, and does not indicate if he considers the Uzboy at its origin (i.e., at the outlet of Sary Kamysh) or the total diversion of the Amu Darya, nor gives details on the geometrical data he uses for the Uzboy channel. It is also surprising that three different approaches (formulas using meander characteristics; Strictler–Manning for channels, and spillway characteristics, not used here) give very similar results. In any case, the conclusion is that an important part of the Amu annual flow was diverted elsewhere.

3. Where did Amu Darya water go?

The most evident path is diversion towards the Zaunguz desert, south of Khorezm, and not in the vicinity of the Uzboy. Ancient travellers observed that other ancient channels originating from the Khiva area existed, still well preserved under recent dunes, which cover their southern parts entirely. An important one, the Sonu Darya, clearly visible near the Saksenem hamlet, an old station between Khorezm and Kurtish, runs on the eastern side of the deep Akajata depression (bottom at 76 m below sea level, capacity 15–20 km^3). Other channels are clearly seen on the west side of this depression, losing themselves in the sand, with evident traces of flow (Fig. 10). Other possibilities of diversion of the Amu Darya exist: the relict bed of Akcha Darya, from the town of Turtkul on the river towards the NE to the plain of Dawkara east of Taktakupir, could accommodate easily 10 km^3 per year, but does not show traces of saline deposits in the interior delta. Diversions from the upstream course of the Amu, either near Chardzu or through the old dry channel of Kelif Darya, have left no traces of a diversion as recent as five centuries ago (Lyberis, pers. Commun.).

The more realistic hypothesis is that a substantial part of water during the flood seasons when the Amu flowed west went across the Zaunguz desert without transiting the Sary Kamysh. This was already admitted by Konschin (1897), Moser (1882) and Kes and Klyukanova (1999). The Sonu Darya and other channels were re-used for contemporary drainage since 1960, whose edges are presently buried in sand. It may be noted that these channels oriented to the south at an altitude slightly above the altitude of the Sary Kamysh outlets, with no connection with them, released the overflow surges of the Amu Darya. But what happened to the salts (less than 1 g/l before contemporary years), carried by Amu Darya water dissipating in sand deserts? One km^3 of Amu water contains 1 million ton dissolved salts, of which half is NaCl, the other half giving through evaporation calcium carbonate and sulphate (gypsum). Salt deposits in Zaunguz are limited to present elongated solonchaks. Approximately, a million ton of salts should have been disposed of by wind deflation. Glazovskiy (1990, pp. 20–23) estimated that anywhere from 40 to 150 million tons of salt annually may have been blowing from the dried bottom of the Aral Sea in the 1980s from an area of ranging from 17,000 to 27,000 km^2. Conversely, taking for instance a 30 km^3 volume of Amu water (with 1 g/l of salt) evaporating on 5000 km^2 of playas, which is a reasonable value for the Zaunguz water diffusion area, and with half the salt disappearing through infiltration, one finds, with a density of 2 for the deposited salts, an annual thickness of 1.5 mm, which is easily blown away.

Infiltration of water is another argument for a flow through the Zaunguz, as hydrogeological studies have shown that the movement of water in the blanket of sand surficial aquifers, above the pre-quaternary substratum, is from north to south, or NNE to SSW (Kunin and Morozov, 1963). This aquifer, used by wells for cattle breeding, is presently fed by infiltration south of the delta districts and follows the lineation of dunes on the gently sloping old sedimentary basement from northeast to the Uzboy valley. Water feeding these aquifers cannot come from another source than the Amu delta on their northern fringes. It may be observed from satellite images that most rows of dunes are fringed at their southern termination by ponds with permanent salty water (Fig. 10).

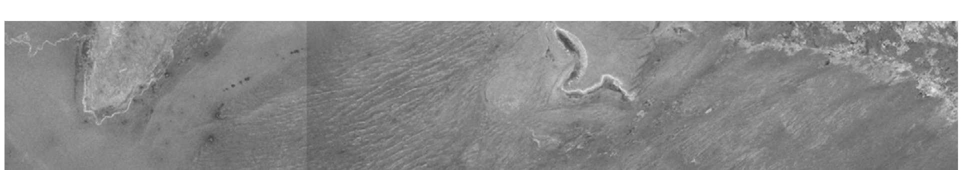

Fig. 10. XSAR radar satellite picture of past discharges SE of Sary Kamysh (Akajita depression).

The Zaunguz plateau is separated from the sandy Karakum proper by the Unguz depression, which stretches from the Chardzu area on the Amu Darya to the Darwaza area, 100 km east of Kurtysh. This has been considered as a possible relict course of the Amu Darya towards the Caspian Sea. Presently, Unguz contains solonchaks fed by springs from the Unguz southern slope, amidst dunes composed of sand from Unguz (Fig. 10). Did some water run south to the Unguz depression? Often considered to be a past channel of the Amu Darya towards the Caspian, it does not show any trace of water erosion on its bottom, nor fluviatile terraces on the shores of its numerous solonchaks. Thorough examination of satellite images, especially XSAR Radar images (Fig. 11) indicates that interdune channels of Zaunguz, oriented grossly NNW–SSE, are not continuous through this desert. Traces of past channels are not present near the north scarp of the Unguz. The festooned edge which fringes this scarp may be attributed to just a beginning regressive erosion, as its morphology shows only corries, with no stream branching characteristics. It is rather a tectonic fault cliff the erosion of which has hardly begun. Water could have flowed down to the Unguz depression on some occasions, but in too small quantities to build a real watercourse, as proved by the non-existence of traces of a river bed from Unguz at Darwaza to Uzboy near Igdy. Water would have rather infiltrated in the sand beds of the southern side of the depression, as it does today from sewage waters from southern Turkmenistan.

Apart from dispersion in the Zaunguz desert, other possibilities of diversion of the Amu Darya exist such as the Akcha Darya, an old eastern channel of the Amu Darya, which could easily accommodate 10–20 km^3/year, the banks of which, as for the Uzboy, were inhabited during millennia. Its delta in the Dawkara area, east of Takhtakupir, could have formed a lake of some 10 km^3. This volume is insufficient to account for the dispersion of some 30 km^3/year, meaning the lake should have overflowed to the south-eastern Aral, following well preserved channels. A diversion of the Amu to the northwest in the region of Chatli, or Chardzu, could also be considered. Strictly speaking, no traces of subrecent channels exist in this area of Karakum (Lyberis and Mering, 2004, and pers. Commun.).The discharge of Amu Darya in the Zaunguz desert is evidently the only way to explain the fate of tens of km^3 of water the Uzboy was unable to convey away.

4. XVIth century regression of Aral and the Uzboy problem

During Aral regressions, a small part of the Amu Darya flow went on running to the Aral. The lake dried, but kept some water. There are some indications that its level was even lower than it is in 2006 (about 30 m a.s.l.). Rubanov

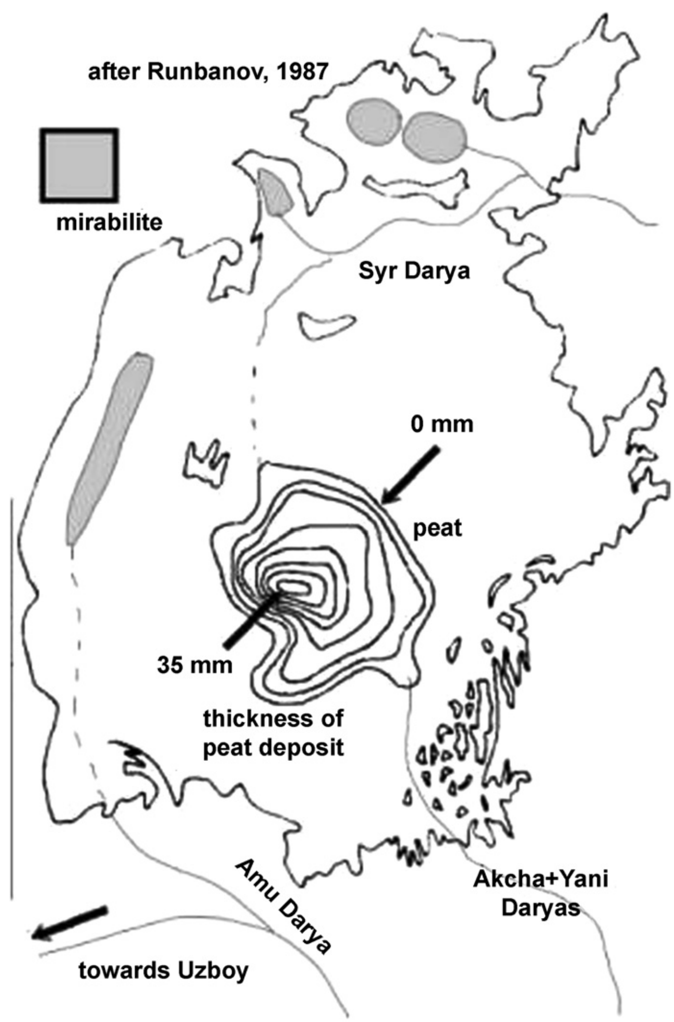

Fig. 12. State of Aral Sea during the last historical regression.

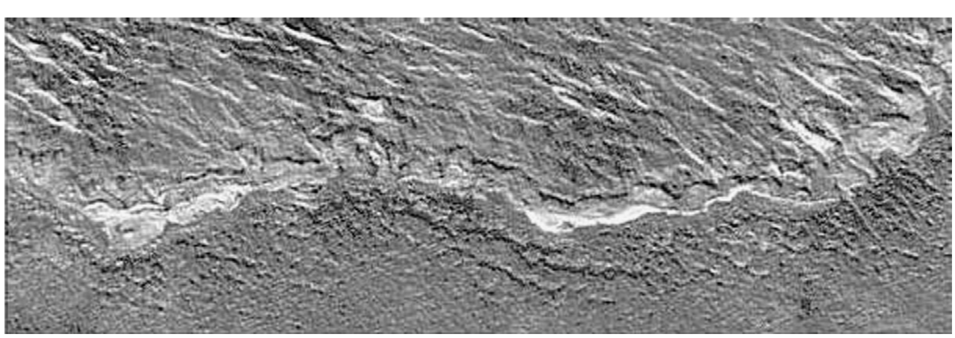

Fig. 11. XSAR photograph of a part of Unguz depression.

et al. (1987) found under recent detrital sediments a bed of mirabilite, hydrated sodium sulphate, deposition of which begins when total salinity is about 150 g/l. The Western basin, and lateral bays of the Small Sea, shows such beds, which indicate they received a very small amount of water (more should have lowered salinity, and, therefore, prevented precipitation of mirabilite and should have also re-dissolved any existing deposits. At the same time, the eastern basin contained a lagoon (Fig. 12) rich in vegetal organic matter, the age of which was estimated by radiocarbon as being about 1600 ± 100 years AD (Rubanov et al., 1987). Future studies should help determine which part of the Aral regression is due to climatic changes ("Little ice ages") and which is due to the diversion of Amu Darya and eventually Syr Darya. The numerous traces of cultivation in the Middle Ages are evidence of the development of agricultural activities in the western Karakum desert when a good part of Amu water went west (Tsvetsinskaya et al., 2002), and, therefore, not to the Aral Sea.

5. Conclusion

The hypothesis of a complete diversion of the Amu flow to the Caspian leads to some hydraulic impossibilities. It is a problem for the Sary Kamysh to convey thousands of m^3/s during the summer floods towards the present northwestern Zaunguz solonchaks without any evidence of strong mechanical erosion, and for those to absorb more than a few tens of km^3 through percolation and evaporation. It is impossible for the bed of the Uzboy east of Kaplankyr to convey more than ca. 10 km^3/year, and probably rather less, as well as problems at Igdy and surroundings, which would imply flooding to heights which show no trace of river erosion and sedimentation. It appears reasonable to consider that the Amu Darya could not carry more than 20–30 km^3 per year to the Sary Kamysh lake, due to the channel cross-section at Daryalyk and Daudan Darya, at a time when irrigation specialists estimate the total water output of Amu Darya to Aral was about 60–70 km^3/year, and eventually more. A large part of Amu water should have run through interdune channels east of the Uzboy, and dissipated in the Zaunguz desert (Fig. 13). It seems an unavoidable conclusion that a small part of the Amu flow (a few km^3/year) flowed to the southeastern basin of the Aral, feeding more or less regularly a large lagoon. The problem of the western Aral basin and of the "Small sea" shrinkage is also linked to the disappearance of Syr Darya at the same time, as is attested by Babur Sultan (1530) whose memoirs are unanimously considered as veracious "the Sayhun does not flow in any sea, but engulfs itself in sands very far downstream of the city of Turkistan".

Fig. 13. Hypothetic spread of Amu river waters in western Karakum desert.

Acknowledgements

Thanks are due to N. Lyberis and O. Marias for helpful comments and original photographs of the Uzboy valley.

References

Andrianov, V.V., 1969. Drevne orositel'nie sistem'i priaral'ia. Izdat Ak. Nauk, Inst. Ethnogr., 256p.

Babur Sultan, 1530. Babur Name; French transl. by J.L. Bacque Grammont, 1980, Pub. Orientalistes de France, p. 45.

Barthold, V.V., 1910. Nachrichten uber den Aral See und der unterlauf des Amu Darja. Leipzig, 325p.

Boomer, I., Aladin, N., Plotnikov, I., Whatley, R., 2000. The palaeolimnology of the Aral Sea: a review. Quaternary Science Reviews 19, 1259–1278.

Burbank, D.W., Anderson, R., 2000. Tectonic Geomorphology. Blackwell Publ.

Degoutte, G., 2002. Hydraulics Conferences for Advanced Students; to be published as "Traité d'hydraulique". Lavoisier, Paris, 360p.

Glazovskiy, N.F., 1990. Aral'skiy krizis: prichiny vozniknoveniya i put' vykhoda. Nauka, Moscow, USSR.

Jauzein, A., 1971. Les eaux courantes. Presses de l'ENS, Paris, 176p.

Kes, A.S. (Ed.), 1991. Ozero Sarykamish. Nauk, Moscow, 152p.

Kes, A.S., 1997. Chronicle of the Aral Sea and the sub-Aral region. Geojournal 35 (1), 7–10.

Kes, A.S., Klyukanova, I.A., 1999. Causes of Aral Sea level variations in the past. Soviet Geography 25, 602–612.

Konschin, A.M., 1897. Raziasnenie voprosa o drevnem techenii Amu Dari po sovremeni'im geologichte Sary Kamishim i fiziko-geografiche Sarykamishim dann'iu. Zap. PGO Poobctcheigeografii 33 (1), 256.

Kunin, V.N., Morozov, A.T., 1963. fresh water lenses in deserts. Izdat Akademii Nauk (in Russian).

Kvasov, D.D., Trofimets, L.N., 1976. Some questions on the Aral Sea history (in Russian). Mosk. Ispyt Priroda Bull. Geol. 51 (6), 77–92.

Létolle, R., 2000. Histoire de l'Ouzboï, cours fossile de l'Amou Daria: synthèse et éléments nouveaux. Studia Iranica 29, 195–240.

Lyberis, N., Mering, C., 2004. Evolution of the hydrographic network of the Karakum desert and environmental implications for the Aral Sea (Nikos@lgs.jussieu.fr).

Morgan, E.D., 1878. The old channels of the lower Oxus, from Russian and others sources. Journal of the Royal Society 48, 301–320.

Moser, H., 1882. Voyages en Asie Centrale, Ed.agr. et comm., Paris, 385 p.

Moser, H., 1885. A Travers l'Asie Centrale. Plon, Paris, 382p.

Nalder, G., 1997. Aspects of flow in meandering channels. IPENZ Transactions (New Zealand) 1, 41–48.

Orlovsky, N.S., 1967. Evaporation from the Jashkan lake. Probl. Ovs. Pustyn 1, 71–77 (in Russian).

Rogov, M.M., 1957. Gidrologia delt'i Amu Dar'i. Gidromet. Leningrad, 254p.

Rubanov, I.V., et al., 1987. Geologia Aralskogo More. Izdat "fan" Uzbek, Taschkent, 248p.

Saparov, Y.V., Golubchenko, V.G., 2001. Turkmenskoe Ozero b Pustinie Karakumi. Probl. Osv. Pustyn 1, 46–51 (in Russian).

Schumm, S.A., Galay, V.A., 1994. The river Nile in Egypt. In: Schumm, A., Winkley, B.R. (Eds.), Variability of Large Alluvial Rivers. Am. Soc. Civil Eng. Publ., New York, p. 91.

Tolstov, S.P., 1962. Po drevnim delt'am oksa i iaksarta. Izdat. Vostoch. Lit. Moscow, 320p.

Tolstov, S.P., Kes, A.S., 1960. Nizov'ia Amu Dar'I, Sarikamich, uzboi'. Materiali Khorezm Exped., Moscow, 348p.

Trofimov, G.N., 2003. The palaeoclimatic situation, the drain of ancient rivers and water balance of Aral in late Pleistocene and Holocene. Intas Meeting, Duchambe, pp. 51–72 and 78–82 (unpublished).

Tsvetsinskaya, E.A., Vainberg, B.I., Glushko, E.V., 2002. An integrated assessment of landscape evolution, long term climate variability and land use in the Amudarya Prisarykamysh delta. Journal of Arid Environment 51, 363–381.

Wohl, E.E., Enzel, Y., 1995. Data for palaeohydrology. In: Gregory, et al. (Eds.), ,,Global Continental Palaeohydrology''. Wiley Publ., pp. 23–59.

Wood, H., 1876. The Shores of Lake Aral. Smith, Helder & Co, London, 352p.

Yurevich, A.L., 1966. Material composition and formation conditions of Akchagilian deposits in pre-balkhan region of SW Turkmenistan. Ak. Nauk Geol. Inst. Trudy 164, 200p (in Russian).

Yusupov, K., 1996. Palaeogeography of the Uzboy as based on historical data. Probl. Desert Development 2, 29–34 (in Russian).

Yusupov, K., 2001. Geographic objects of Khorezm in antique tradition. Probl. Desert Development 1, 59.62 (in Russian).