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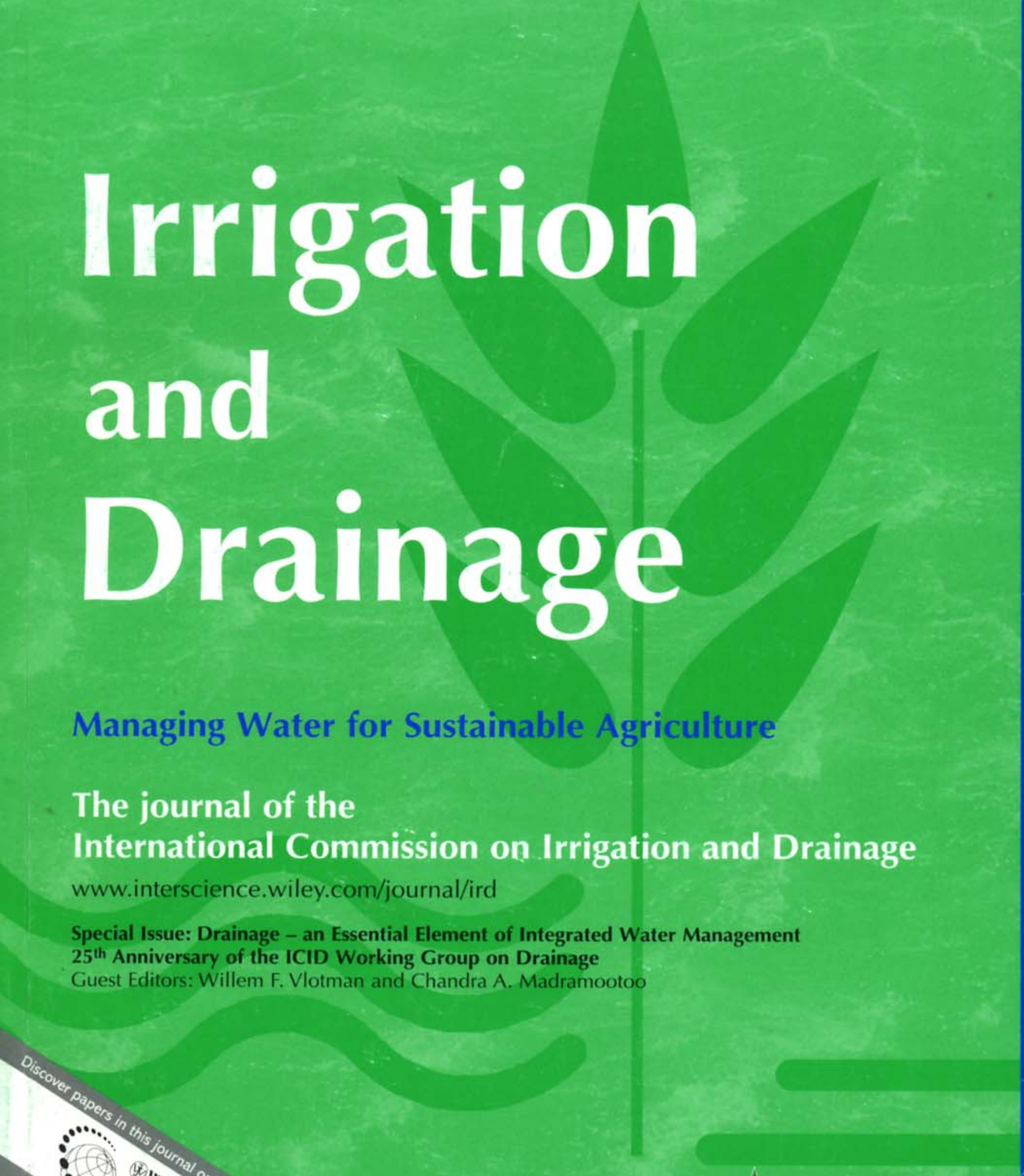

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DRAINAGE IN THE ARAL SEA BASIN[†]

VICTOR DUKHOVNY[1*], PULAT UMAROV[1],
HALDAR YAKUBOV[1] AND CHANDRA A. MADRAMOOTOO[2]

[1]*Scientific Information Centre of Interstate Commission of Water Coordination of Central Asia, Tashkent, Uzbekistan*
[2]*McGill University, Montreal, Canada*

ABSTRACT

The intensity of irrigation in Central Asia requires artificial drainage in order to control waterlogging and salinization. There are about 5.35 million ha with a combination of surface drainage, and vertical and horizontal subsurface drainage. Of the five Central Asian republics, Uzbekistan is the country with the most significant artificially drained land, of approximately 1 million ha. There have been several innovations in drainage design in the region, in order to account for seepage from irrigation canals and upstream irrigated lands, percolation from excess irrigation water, groundwater fluxes to the root zone, and the accompanying salts moving into the crop root zone. Deeper subsurface drainage depths are considered essential for the control of waterlogging and salinity.

There were significant investments in drainage in the region until the 1990s. However, with the collapse of the Soviet Union and the deterioration of economic conditions in Central Asia, investment in drainage declined. Drainage systems are no longer properly maintained and the areas suffering from salinization and waterlogging have been increasing. The drainage problems are compounded by the weakened institutional structure to successfully operate and maintain the drainage network. This paper addresses the technical and institutional improvements required to improve drainage performance, and stresses the importance of implementation of drainage with irrigation in the context of integrated water resources management. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: drainage; salinity; waterlogging; irrigation; reclamation; water management

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RÉSUMÉ

L'intensité de l'irrigation en Asie centrale exige le drainage artificiel pour contrôler l'engorgement et la salinisation des terres. Il y a environ 5,35 millions d'ha traités conjointement par drainage de surface et drainage souterrain, horizontal et vertical. Des cinq républiques d'Asie Centrale, l'Ouzbekistan est le pays le plus traité, avec environ un million d'hectares drainés. Il y a eu plusieurs innovations dans la conception du drainage dans la région, afin de prendre en compte l'infiltration à partir des canaux d'irrigation et des terres irriguées en amont, la percolation de l'irrigation excessive, les afflux d'eaux souterraines aux zones racinaires, et les sels qui les accompagnent. Un drainage plus profond est considéré comme essentiel pour maîtriser l'engorgement et la salinité.

Il y a eu des investissements significatifs de drainage dans la région jusqu'aux années 90. Cependant, avec l'effondrement de l'Union Soviétique et la détérioration des conditions économiques en Asie centrale, ces investissements ont diminué. Les systèmes de drainage souterrain ne sont plus entretenus correctement et les surfaces engorgées et salinisées augmentent. Les problèmes de drainage sont aggravés par la faiblesse des structures pour faire fonctionner et maintenir le réseau de drainage. Cet article traite des améliorations techniques et

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[*] Correspondence to: Prof. Victor Dukhovny, Director, Scientific Information Centre of the Interstate Coordination Water Commission of Central Asia (SIC-ICWC), Tashkent, Uzbekistan. E-mails: dukh@icwc-aral.uz; vdukh@yandex.ru

[†] Le drainage dans le bassin de la mer d'Aral.

organisationnelles nécessaires pour améliorer les performances de drainage, et souligne l'importance de coupler le drainage et l'irrigation dans un contexte de gestion intégrée des ressources en eau. Copyright © 2007 John Wiley & Sons, Ltd.

MOTS CLÉS: drainage; salinité; engorgement; irrigation; récupération des terres; gestion de l'eau

INTRODUCTION

The Aral Sea basin is located in the Aral–Caspian depression, which is a zone of intensive salt exchange due to arid climate, hydrological and geomorphological peculiarities formed under conditions of natural artesian water. Intensive development in the second half of the twentieth century with a twofold increase in irrigated area was accompanied by the large-scale construction of main collector drains, open and subsurface horizontal drainage systems, and especially vertical and combined (vertical and horizontal) drainage systems as most of these new irrigated lands became saline or approached salinization. As a result, almost 2.9 million ha of irrigated lands in Uzbekistan, 1.5 million in Turkmenistan, 0.4 million in Kazakhstan, 0.36 million in Tadjikistan and 0.16 million in Kyrgyzstan are artificially drained.

Drainage in arid zones such as Central Asia is necessary both for excess water disposal and control of the groundwater table. These improved soil water conditions are important for the construction of infrastructure and for good crop production. Drainage also prevents accumulation of salts in the crop root zone, which could negatively impact on crop growth and yields. The goal is to create conditions for optimal soil water management in irrigation schemes. Current irrigation and drainage practices produce millions of tonnes of salt, which create environmental concerns regarding the disposal and management of saline drainage water in rivers, lakes, wetlands and lowlands of the region.

The right choice of drainage parameters during design will allow for minimization of salt fluxes between the crop root zone and groundwater, and between drained lands and receiving water bodies. However, drainage design must also take the irrigation system and water management practices into consideration, in order to achieve the optimum water and salt balance in the crop root zone, and also to minimize the amount of salt being mobilized and entering receiving water bodies.

In the present context, drainage management in Central Asia is quite difficult because of the:

- halt to drainage development and ageing of drainage infrastructure;
- lack of financial support for drainage maintenance, repair and development;
- separation of the design and construction of drainage systems from its operation, particularly in transboundary basins and with the recent introduction of thousands of new water and land users;
- lack of technical capability for land reclamation and weakened efforts to create new drainage infrastructure.

Given the above challenges and issues, it is important that Central Asian countries put drainage and waste water management and disposal within the context of integrated water resources management (IWRM), and increase support for the upgrading and maintenance of drainage infrastructure, and also build new infrastructure. Drainage design and operational agencies will also need to be strengthened both financially and with staff trained in modern drainage, irrigation and IWRM principles.

DRAINAGE DEVELOPMENT IN THE ARAL SEA BASIN: PAST AND FUTURE

Intensive irrigation development occurred in the twentieth century, particularly in the second half, with new land development schemes in Hunger, Karshi, Dzhizak and Sherabad steppes, along the Karakum and Kyzylkum canals. In central Ferghana, the Ash district of Tajikistan made drainage a leading issue in the region. Irrigation systems became drainage–irrigation–reclamation superprojects, with joint government and farm system operation and

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management. These superprojects led to sustainable agricultural production and large tracts of fertile land. The scale of land development was phenomenal with up to 60 000 ha yr^{-1} of land improvement works.

By the beginning of the 1990s, 200 000 km of the collector-drainage network, of which 45 000 km of inter-farm and main collectors and 155 000 km of on-farm network (including 48 000 km closed drains and 7762 vertical drains in an area of 834 000 ha) were constructed. The area under horizontal drainage amounted to 4.8 million ha. However, since 1990 massive drainage developments have ceased.

The largest subsurface drained area is in Uzbekistan, with 550 000 ha of horizontal subsurface drainage, and 450 000 ha of vertical drainage wells. Kazakhstan and Tajikistan also have some subsurface drainage. However, due to its more complex hydrologeological and soil-reclamation conditions, there is very little horizontal subsurface drainage, and mostly surface drainage with an intensity of 14.7 m of open drain per ha of irrigated land. At the same time, irrigated area under vertical drainage has slightly reduced recently because of a reduction in the number of operating wells; by 2000, the area under vertical drainage was reduced to 380 000 ha, compared to 450 000 ha prior to 1990.

Until 1991, in all countries of Central Asia, the main, inter-farm collectors, vertical drainage and some of the subsurface drainage were under the control of the governments through the national Ministries of Land Reclamation and Water Management. The on-farm open collector-drainage network (CDN) and most of subsurface drains were under the control of the Oblast hydrogeological-reclamation expeditions or other specific organizations like the CDN Division of the republics, which were funded by the governments. Some of on-farm CDN, vertical drainage, and subsurface drainage systems were operated by the farms directly.

As a result of weakening economies, less investment in water projects, and the transition of agriculture to more open market conditions, drainage at the inter-farm level, being under control of government water management organizations, remained without sufficient attention and support, and the on-farm network of former collective and state farms in general was no longer properly supervised and operated institutionally. This has caused an abrupt reduction of repair and maintenance, cleaning of collectors and drains, and flushing of subsurface drains. All this catastrophically reflected on the state of drainage systems. A comparison of two resulting parameters – readiness coefficient and specific costs – shows that it mostly impacted on the subsurface drainage systems as well as on on-farm open drains (Table I). The situation was far worse for vertical drainage, which was too expensive to maintain under the new agricultural market conditions (Table II).

All of these factors have led to a sharp decline in land reclamation projects during the last decade. The area affected by groundwater tables of 2 m and less increased by 21% for the Amu-Darya basin and 65% for the Syr-Darya basin; the saline land area increased by 57 and 78%, respectively. Despite the effectiveness of horizontal subsurface drainage, vertical drainage, and a combination of both, for optimal reclamation and with minimum expenses per unit of irrigated land, these systems required high-quality rehabilitation, monitoring and water consumption control.

The collapse of the former Soviet Union and the transition to independence of the five Central Asian republics were accompanied by a destruction of all operation and repair support, weakening of the economic and institutional base in the agricultural and water sectors, and reduced financing of organizations that were responsible for the operation of drainage systems. As a result, drainage reconstruction and development rates decreased to zero, operation costs were reduced several times, with subsequent increase of salinization and waterlogging of lands and losses of soil productivity. It is surprising that with only about 30–50% of the drainage network functioning

Table I. Assessment of horizontal drainage state

Type of drainage	Parameter	Until 1990	1995	2000
Inter-farm open network	Average annual work capacity*	0.88	0.83	0.71
	Maintenance costs (US$ ha^{-1})	5.40	2.64	2.86
On-farm open network	Average annual work capacity	0.86	0.80	0.70
	Maintenance costs (US$ ha^{-1})	7.10	2.70	3.00
Subsurface horizontal drainage	Average annual work capacity	0.89	0.78	0.63
	Maintenance costs (US$ ha^{-1})	7.80	2.60	2.10

*The availability of the system to function properly expressed as a decimal fraction.

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Table II. Indicators of vertical drainage performance in Uzbekistan, 1970–2002

Indicators	Year						
	1970	1975	1980	1985	1990	1995	2002
Total quantity of vertical drainage wells (VDWs) (number)	543	939	1 952	3 137	4 239	3 908	2 700
Drained area (thousand ha)	174	199	311	407	448	448	380
Average annual work capacity	0.47	0.67	0.64	0.58	0.57	0.33	0.24
Abstracted water volume (Mm$^{3)}$	568	1 117	1 577	2 048	2 203	810	925

adequately, there is not more land salinization and waterlogging. This could be explained by the close attention paid to control the soil water–salt regime through water-saving technologies, intensive soil desalinization methods and the over-design of the open collectors' draining capacities. Furthermore, a higher drainage design intensity was implemented, in order to speed up land desalinization without taking into account future water scarcity.

As a result of some of the above explanations, it is possible that the existing drainage capacity in Central Asia is adequate for water–salt management in most cases, with normal operation and rehabilitation, except for some territories where the drainage length is unsatisfactory. However, it must be emphasized that the current technical state of drainage does not meet the requirements in most zones in Central Asia. The total economic losses connected with land salinization amount to US$354 million yr^{-1} for the Amu-Darya basin and US$254 million yr^{-1} for the Syr-Darya basin.

DRAINAGE IN INTEGRATED WATER RESOURCES MANAGEMENT

One of the IWRM characteristics of the water sector in arid zones is the integration of drainage and irrigation, i.e. consideration of their interrelated effects aimed at maintenance and effective use of water and land. In other words, integration of water and land is realized through joint management of drainage and irrigation regimes and facilities.

Irrigated land is a biologically fertile resource, destined to produce the food and fibre products for humanity. Irrigation canals and facilities, including canals and furrows, are arteries and water-feeding capillaries, while drains and collectors are diverting capillaries and veins. The upper layer of this fertile biological body, which is the soil, makes use of solar radiation and climate to support plant growth. Successful and sustainable plant growth necessitates feeding of the biological system by both water and fertilizers through the arterial (irrigation) and diverting (drainage) capillaries.

Drainage of irrigated lands therefore has the potential to increase agricultural productivity. Additional factors that improve land productivity are application of appropriate amounts of organic and inorganic fertilizers, maintaining a favourable soil water and nutrient regime in the crop root zone, good soil structure and soil aggregate composition, and intensification of photosynthesis through better agronomic practices. On the other hand, land productivity could be reduced by water and wind erosion, waterlogging, salinization, desertification and soil pollution.

By combining irrigation and drainage within the context of IWRM, the following can be successfully achieved:

- equitable, uniform, timely, stable and sustainable delivery of water in required quantity and quality;
- control of salinization and waterlogging through provision of adequate drainage and sustainable maintenance of the leaching regime;
- combating desertification through special wetting for increased soil moisture, conservation of natural moisture and precipitation, and planting of drought-tolerant trees and bushes;
- combating water and land pollution;

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- improved monitoring of water distribution;
- control of floods and their prevention.

Drainage and irrigation should be accompanied by such reclamation measures as deep tillage and subsoiling, chemical amendments and precision land levelling. The combination of drainage and irrigation is also important in that it could provide for the safe reuse of drainage water and improved methods of drainage water management. In considering the interaction between the soil, plant, downward and upward fluxes of water controlled by the irrigation and drainage systems, it is necessary to link those elements with spatial changes caused by horizontal water fluxes in the soil, depending on the location of the drains and irrigation ditches. A specific example is the irrigation of cascaded schemes that influence each other intensively. The temporal dimension should also be taken into account. This implies the need for proper operation and maintenance of the drainage system, and consequently the importance of appropriate repair and reconstruction activities.

The most complex issue of drainage management within IWRM is organization of monitoring and repair of drainage systems. During the Soviet period, all costs related to collector-drainage system maintenance were borne practically by state water-management organizations. Maintenance was performed by the state under the Provincial Hydrogeological and Reclamation Expeditions (PHREs). Since independence, virtually all Central Asian states have considerably reduced their activities for operation of drainage systems, particularly of on-farm drains and collectors. The Republic of Uzbekistan keeps up a satisfactory state of inter-farm and main collectors, though they have also reduced the intensity of work related to operation of the on-farm drainage network. In this context, the efficiency of the drainage system has been decreasing over the last 15 years. Due to shortages of water for leaching of saline lands, salinization is now on the rise. It is estimated that about 60, 70 and more than 80% of the irrigated area in Uzbekistan, southern Kazakhstan and Turkmenistan, respectively, is saline.

With the restructuring of state and collective farms, and establishment of individual farms, operation of the CDN has become more complex. For proper institutional functioning of the CDN, appropriate responsibilities are distributed among the three actors, i.e. the farmers, water user associations (WUAs) and the PHRE. A good institutional structure was proposed and developed by SIC ICWC (Scientific Information Center of the Interstate Commission for Water Coordination) within the framework of the Ferghana IWRM project under the support of the International Water Management Institute (IWMI) and the Swiss Agency for Development and Cooperation (SDC). The roles of the actors are described below:

Farmers

- responsible for supervision, maintenance and operation of the drainage effluent network;
- pay for maintenance of operation of the inter-farm CDN or participate physically in public repair and reconstruction work on a voluntary basis (*hashar* method);
- sign contracts with the WUA for repair of the on-farm network and for coverage of standard maintenance costs as part of the WUA fees;
- liable to the WUA for damaging the CDN due to poor operation;
- undertake timely leaching and crop irrigation at dates and depths as established by the WUA by avoiding the outflow of irrigation water into the CDN.

WUAs

- base their activities regarding supervision and maintenance of the CDN on interaction and contractual relations with both the farmers and PHREs;
- estimate annually the state of the CDN, and meet farmers' obligations regarding maintenance of on-farm CDN;
- conclude contracts for cleaning and repair of the CDN, and, if necessary, involve farmers in this public work;
- conclude contracts with the PHREs for diversion of water from WUA territories to the inter-farm network;
- equip inter-farm collectors and drains with water meters and measure discharge and take water samples for chemical analysis.

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PHREs

- responsible for supervision and maintenance of inter-farm CDN, ensuring good cross-section and effective depth of collectors in order to ensure required diversion of excess groundwater;
- develop pumping regime of vertical drainage wells, taking into account the use of pumped water for irrigation;
- assess collector-drainage flows in terms of its chemical composition in order to determine its suitability for irrigation and leaching;
- develop recommendations on dates and depths of leaching and control compliance;
- provide WUAs with detailed information about changes in the state of irrigated lands and of the status of the drainage systems.

SELECTION OF DRAINAGE DEPTH

Drainage of irrigated lands under arid conditions is very different from the drainage requirements of humid zones. In the latter, drainage is necessary mainly for prevention of flooding of agricultural and other lands, while in the former it has two very important obligations. One is control of salinity and creation of a framework for a leaching regime of soils. However, the other is specific only to water-scarce river basins and serves for the creation of an optimal water regime for these areas. This latter purpose was developed by Russian scientists (Dukhovny, 1984).

The underlying explanation of the Russian approach is that high evaporation in the arid zone of Central Asia creates a flux from the groundwater to the upper soil layers. This flux contributes additional water to the root zone, thus reducing the overall irrigation requirements to irrigation. However, at the same time, this flux brings salts from the groundwater to the root zone. The quantity of this salt accumulation and degree of salinization depend on mineralization of groundwater, and the flux rate, which in turn depends on capillary features of the soil layers and on the height of capillary rise. The key indicator of drainage efficiency in arid zones (as in humid zones) is the active groundwater depth. This is controlled by the drain and lateral pipe spacing. In arid zones, those features should be integrated into a combined "irrigation-drainage" system.

The depth of the groundwater is defined by the active drain depth, and the pressure of the deep groundwater. Because of the latter point, the depth of drainage installation is usually deeper than the depth of active groundwater by 0.3–1.0 m. Conditions of flooding or leaching can decrease the drain spacing by nearly twofold, depending on the discharge to the drains. Many equations for estimation of drain spacing are available in both Western (Hooghoudt) and Russian schools (Oleinic, Muraschko), with their common disadvantage of not reflecting average field conditions. For assessment of real or actual field situations, the designer should determine through intensive field observations, the average depth of groundwater spatially. However, this exercise does not take into account the impact of deeper collectors that create a depression curve along the flow direction in the drains. The optimal depth of groundwater should be estimated on the basis of the water demand for irrigation and evacuation of excess salts from the previous irrigation season. Moreover, one should consider sustainability of crop yields depending on groundwater depth and the cost of the applied water.

Maximum crop yields, without consideration of other factors, is based on the ratio of groundwater depth, average over the growing season, to the height of capillary rise, which is equal to 0.75 m. The final optimal groundwater depth depends on both those factors and groundwater mineralization (Table III).

Some of the results we have obtained, of particular interest, are:

- in the Hunger steppe high-capillary loess soils with a maximum height of capillary rise (h_k) in excess of 3.0 m, the mean groundwater depth for the growing season should be 2.7 m under groundwater mineralization of 5–8 $g\,l^{-1}$. Thus, the drainage depth should be 3.0–3.5 m;
- these results were supported by practices in the new zone of Hunger steppe, where sustainable land desalinization was achieved with gross water inputs of $9.5–10.5 \times 10^3\,m^3\,ha^{-1}$;
- in Khorezm, in stratified soil with thick sandy layer and $h_k = 1.6$ m, the mean groundwater depth for the growing season should be 1.1 m under groundwater mineralization of 3–5 $g\,l^{-1}$, and the drainage depth should be 1.5–2.0 m;

Table III. Relationship between groundwater mineralization and relative groundwater depth under optimal reclamation regime

Groundwater mineralization ($\mathrm{g\,l^{-1}}$)	$h_{\mathrm{gw}}/h_{\mathrm{k}}$	Salt removal ($\mathrm{t\,ha^{-1}}$)
1	0.5	1–2
2–3	0.6	3–7
5–7	0.9	5–10
>10–15	1.2	10–15

h_{k} = maximum height of capillary rise.
h_{gw} = groundwater level.

- for sandy soils with $h_{\mathrm{k}} = 0.5$ m, we observed that a drainage depth at 1.5 m created a specific regime when the groundwater level is located below the root zone thus forming a need for frequent irrigation.

Therefore, shallow or deep drainage is a relative definition, depending on soil properties, groundwater depth, drainage needs and groundwater mineralization.

DIFFERENCES BETWEEN DRAINAGE DESIGN AND REALITY

In order to achieve high-efficiency water use and the full potential of land productivity, the following should be ensured: uniformity of soil conditions; uniformity of water distribution and timely delivery throughout the area; proper drainage and maintenance of the water table at a level to ensure required leaching and removal of excess water, on the one hand, and uniform wetting of plants by upward flux from groundwater, on the other. The design of drainage systems, as previously mentioned, considers a certain maximum discharge that may occur in the soil because of precipitation or irrigation. Usually in the arid zone, this maximum drainage discharge also takes into account the seepage of water from upstream areas and from irrigation canals. Changes in the discharge depend on groundwater depth, time of irrigation and precipitation.

The design drainage discharge ($\mathrm{l\,s^{-1}\,ha^{-1}}$) corresponds to the maximum discharge during peak irrigation water delivery during the growing season. Though the mean design drainage discharge in the irrigation system is usually 0.15–0.25 $\mathrm{l\,s^{-1}\,ha^{-1}}$, the actual drain discharge rarely exceeds 0.07 $\mathrm{l\,s^{-1}\,ha^{-1}}$, while the maximum is around 0.15 $\mathrm{l\,s^{-1}\,ha^{-1}}$ during the growing season. However, the drainage discharge of the collectors and drains often exceeds the mean design discharge considerably, by up to 0.35 $\mathrm{l\,s^{-1}\,ha^{-1}}$. The reason for this is the considerable contribution of groundwater and secondary drainage water (through losses from the irrigation network) to the total drainage flow, as well as the additional drainage water picked up by the collectors. Placement of collectors at 1–1.5 m below the in-field drain level, and often their cutting into lower soil layers of higher permeability promote increased flows of the CDN. This also modifies the soil water regime, and causes artificial wetting and drying of the field. The impacts of this type of soil water dynamics were measured at SANIIRI's experimental farm on well-drained and levelled fields in the 1980s for cotton. The results showed that the optimal conditions of wetting and draining and accordingly, crop yields of 3.5–5 $\mathrm{t\,ha^{-1}}$, took place on 56% of the cropped area, while under-wetting and drying and resulted in crop yields of 2.5–3.5 $\mathrm{t\,ha^{-1}}$ on 23% of the cropped area. Waterlogging and salinization spots were observed on 21% of the cropped area, with yields of only 1.5–2.5 $\mathrm{t\,ha^{-1}}$.

The above experimental area was a well-levelled irrigation plot, 400 × 200 m, with the collector drain laid along its western boundary and a drain spacing of 200 m. If the required mean groundwater depth is 2.5 m along the drain mid-spacing, the drains should be installed at a depth of 3.3 m. However, even after careful setting of the drainage parameters it was found that there was insufficient groundwater control, and zones that are more distant from the drain lines remained under-drained. Results of groundwater depth calculation for the irrigated plot prove that the variation of groundwater depths under ideally designed uniform water distribution (for instance, if during leaching it is possible to irrigate the whole 8 ha at the same time, though, in fact, the size of one irrigation plot is not more than 4 ha) varied from 1.7 to 44 m. If we consider that the seepage rate from all sources is proportional to the

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drainage coefficient and the active head at a given point, the zone of insufficient leaching, and consequently of potential salt accumulation, is apparent. In order to achieve the required leaching fluxes in those zones of lower infiltration rates, the leaching period should be prolonged. This in turn leads to excessive water use.

From an engineering point of view, when designing drainage for reduction of seepage near the collector, it is advisable to lay drains without perforation and envelope within the zone of the collectors' drawdown curve. Equally important is the adequate combination of drainage with direction of irrigation furrows. It is well known that in the case of surface irrigation, a triangular shape describes the distribution of downward water fluxes, with higher water levels at the head of furrow. We studied the impact of interaction between directions of irrigation and drainage in the 1980s (Dukhovny, 1983). Under surface irrigation, which is characterized by non-uniform infiltration fluxes along the irrigation plot, depending on the influence of drainage on the groundwater depth, a significant difference of salt accumulation occurs under the combined effects of irrigation and drainage operations. This should be taken into account in the implementation of special leaching practices throughout the area.

Pereira *et al.* (2005) demonstrated from field observations the impacts of isolated irrigation and drainage as carried out using GIS (Geographical Information Systems) and remote sensing in the Fergana Valley in recent years. Periodical irrigation in 15–20 days creates uneven drainage loads and causes the dispersion of a groundwater mound (a mound-shaped groundwater body built up by seepage inflows) to a non-irrigated area. Fluctuation of this groundwater mound and groundwater level reaches a maximum in July to August, when the irrigation amount continuously increases with the average IAC (daily rate of irrigation area covered with each day of irrigation) increasing from 0.25 to 0.45, reaching a maximum of 0.8 in early August and then dropping to 0.4 in October. This is despite the duration being more than half a month in the latter case. Since the major cause of abrupt groundwater rise is seepage during irrigation, the measures undertaken to reduce inequalities in soil moisture should be dealt with by deep percolation control through an appropriate selection of irrigation techniques (furrow and tubes) and, primarily, by controlling the irrigation depths.

Based on observations, the relationship between the drainage design discharge and the degree of simultaneous irrigation between drains was obtained. Irrigation on more than 50% of the area between drain spacing increases the design drainage discharge by twice as much in the short term, while when water is applied to less than 20% of the drain spacing area, the drainage discharge decreases by 30–40% of the design discharge. This analysis shows that formation of a groundwater mound can increase the drainage discharge twofold. This is particularly visible during leaching and should be considered while designing drainage and selecting optimal irrigation regimes. Thus, the combined effects of irrigation and drainage practices on land productivity should be taken into account in drainage and irrigation system design, by selecting measures to minimize the impacts of drainage water disposal and quality. The leaching of fertilizers due to intensive draining zones is also important and ought to be considered.

MANAGEMENT OF DRAINAGE WATER DISPOSAL

Water and salt regimes of rivers and lakes in Central Asia are influenced by the interaction between land and rivers. An increase in land salinization raises river salinity when drainage water returns to the rivers, as observed in Central Asia. Because of this, river water becomes more saline (polluted) along its stream from source to mouth. Irrigation with high-salinity return flows increases irrigated land salinization, unless appropriate measures of land drainage, leaching and efficient irrigation are undertaken. On the other hand, antique soil and ground- water salinity in the middle and lower reaches of the Amu-Darya and the Syr-Darya rivers because of their state of geological development is a determinant of salt accumulation (soil secondary salinization) under irrigation.

The total volume of return waters is 14–20 km^3, of which collector-drainage water amounts to 11–16 $\mathrm{km}^3\,\mathrm{yr}^{-1}$. These waters are divided into three parts:

- return flows to the rivers – about 50% returning resource for reuse with approximately 44–55 million t of salts are brought into the rivers, thus adversely deteriorating water quality;
- direct reuse for irrigation at place of origin – 13%;
- released to natural depressions thus creating and recharging various water bodies – 36%.

Table IV. Criteria for sustainable management of drainage return flows

Type of return water distribution	Potential use	Sustainability criterion	Restrictions	Control
Release into the rivers	Water resource increase	Preventing water pollution over limit	Maximum limit for flow pollution in time	River water quality and salt accumulation in planning zones
Use for irrigation	• in place of flow origin for crop irrigation	• preventing land salinization	• water resources available	• soil salt composition as a whole and on anions
	• in desert – for salt-resistant crop irrigation	• economic and ecological stability	• land salt balance over seasons	• desalinization process
	• for leaching of saline land	• desalinizatio-n effect	• salt balance is negative, ecological expediency	
Release to water bodies and wetlands	• wetlands creation	• requirements of different branches for water salinity, discharge, oxygen exchange, etc.	• return water salinity and volume	• water speed
	• fish production		• desalinization by fresh water	• salt content
	• fur-bearing animal breeding			• oxygen content
	• forage			• biological oxygen demand
	• hunting and tourism			
	• bird migration			
	• delta restoration			

With regard to transboundary return waters, sustainable development and permanent monitoring of water quality is needed, as well as management according to criteria leading to sustainability, ecological safety and long-term productivity of ecosystems (Table IV).

CONCLUSIONS

In arid zones, drainage operations should be closely linked with performance of the irrigation network and the entire water management system to ensure optimum productivity of irrigated lands. Reliable design parameters of the drainage network, in combination with proper operation and maintenance of the system, are very important to successful IWRM, without which sustainable land fertility cannot be achieved. Along with technical and engineering decisions regarding drainage operation, attention should be paid to the following aspects:

- linkage of drainage and irrigation parameters in order to prevent waterlogging, soil salinization, and minimization of the volume of drainage water that needs to be disposed of;
- designing the drainage system and applying irrigation water in appropriate amounts and timing to reduce the impacts of the natural field and soil variability on crop growth and yields;
- sustainable operation of the integrated system of irrigation and drainage through clear institutional, financial and managerial mechanisms to provide proper maintenance of the entire water distribution and drainage disposal network;
- management and disposal of drainage effluent to avoid downstream river salinization.

LIST OF ABBREVIATIONS

CDN	Collector-drainage network
GIS	Geographical Information Systems
h_k	Maximum height of capillary rise
IAC	Daily rate of irrigation area covered with each day's irrigation
IWMI	International Water Management Institute
IWRM	Integrated water resources management
PHRE	Provincial Hydrogeological and Reclamation Expeditions
SDC	Swiss Agency for Development and Cooperation
WUA	Water user associations
$\mathrm{l\,s^{-1}\,ha^{-1}}$	Litre per second per hectare
$\mathrm{t\,ha^{-1}}$	Tonnes per hectare

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