DESERT

DESERT
Online at http://jdesert.ut.ac.ir

DESERT 12 (2008) 149-164

Decision support system (DSS) for site selection floodwater spreading schemes using remote sensing (RS) and geographical information systems (GIS)

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Received 28 March 2007; received in revised form 7 November 2007; accepted 30 December 2007

Abstract

Most aquifers of semi-arid regions in Iran suffer from over-exploitation of groundwater for irrigation purposes. It is therefore important to augment the groundwater resource by artificial recharge, using floodwaters. Generally, the recharge schemes consist of diverting part of the flood discharges of ephemeral rivers in small to medium-size catchments into infiltration basins. Apart from recharging groundwater, and supporting food production and drinking water supplies, the schemes have other benefits, such as the mitigation of flood damage. The complexity of floodwater spreading schemes using flash floods of ephemeral rivers in semi-arid regions became evident during the task of selecting, defining and structuring criteria for the selection of suitable areas and sites for a scheme. Complexity is due to a large number of factors that play a role in the selection of the most suitable sites for deciding on investment in a scheme. These factors pertain to earth science (geology, geomorphology, soils), to hydrology (runoff and sediment yield, infiltration and groundwater conditions) and to socio-economic aspects (irrigated agriculture, flood damage mitigation, environment and so on). This paper deals with developing a DSS to assist decisions as to where suitable catchments and associated infiltration areas are located. The DSS developed relies on the combined use of remotely sensed information and GIS techniques. For implementation of the related phase of the DSS, a region (Bandar Abbas) was selected as the case study for suitable zone(s) selection. The DSS shows the great ability for selection of potential zones for floodwater spreading. It can be concluded that the interpretation results could be regarded as being more than the sum of separate 'interpretation' layers: i.e. geology, geomorphology and land use. The interpreter has to have a firm footing in earth science.

Key words: Bandar Abbas; DSS; Fasa; Flood mitigation; GIS; Floodwater Spreading; RS

1. Introduction

The DSS for floodwater spreading site selection (see Figure 1) developed in this research has a scale hierarchy consisting of three levels (phases) and data contents:

- Phase 1: small scale (cartographic) for the identification and selection of potential zones (based on qualitative estimations)
- Phase 2: medium scale for area (s) suitability evaluation
- Phase 3: large scale for evaluating the suitability of site and type of design.

This paper covers the first phase (small scale) of the DSS. The main objective of this paper is to develop a method for screening zones containing feasible areas, as a component of the DSS. At the first scale (small scale), screening is done qualitatively for potentially suitable zones with the assistance of remotely sensed data, available knowledge and expert knowledge.A potential zone is a more or less

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contiguous tract of land where alluvial aquifers are found with ephemeral or perennial rivers traversing the alluvial areas, and which is not fully occupied by irrigated lands. Zone selection is a screening process and the first step in a hierarchical procedure that should lead to the identification of the most promising areas. At the zone selection scale, it is very difficult to quantify all the characteristics of the different areas within a zone. Therefore, a prior selection has to be made in qualitative terms in order to find the most promising areas in a zone. To do so, exclusionary criteria (estimated qualitatively) are used. Areas that are not feasible within potential zones will be excluded from further consideration. The result of this screening phase will be a few potential areas within a zone for floodwater spreading. The application of the exclusionary and suitability criteria by interpretation of satellite images, supplemented by other data, will be illustrated by a number of cases.

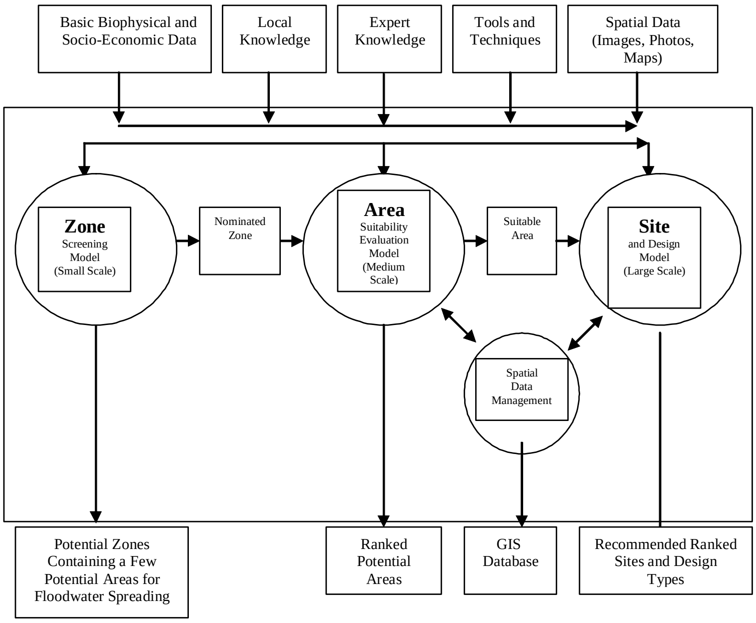


Fig. 1. DSS diagram for floodwater spreading site selection

Most potential areas for floodwater spreading schemes in Iran are the alluvial fans usually located in the intramontane depressions or as foot-slopes on the hills and mountains bordering plains along the coast or large tectonic depressions, often with playas. Other fluvial plains, not in the form of alluvial fans, could also be suitable for schemes if the deposits are coarse-grained and of sufficient thickness. Therefore, attention in this study is focused on the alluvial fans.

2. Study area

The location and an overview of the Bandar Abbas zone is shown on the TM false-colour image in Figure 2, annotated with the sub-zones and areas that are depicted at a different scale in this section. Separated by mountains or hills, there are several alluvial areas that will be discussed. In all these cases, agriculture depends almost entirely on irrigation water, because the mean annual rainfall is generally less than 300 mm while the mean annual evaporation exceeds 2000 mm, except possibly in the highest parts of the mountains.

3. Materials and methods

Obviously, the problem is to gather the information on the many aspects and what is more, one should consider these in a spatial context and on their mutual relations. It is a very lengthy process (Topcu, 1999). Moreover, most of the efforts waste because data of many areas discarded after the screening because only a few suitable areas inside a zone will remain. Therefore, the approach followed is similar to the one adopted in soil survey and land evaluation. This scale (small scale) explores to what extent interpretation of remotely sensed images supported by local field knowledge and supplemented by information from topographical maps and geological maps and by other data leads to the identification of potential areas in the zones. The image interpretation requires knowledge of (photo) geology, geomorphology and the relationships between physiographic and soils, supported by knowledge of local conditions or those having similarity.

The interpretation makes use of interrelationships between such factors as catchment geology and relief, the nature of alluvial deposits, tectonic and geomorphologic history, and the nature of the rivers and land cover. The aquifer presence and properties (depth, transmissivity and permeability) are mainly based on interpretation of the tectonic setting and geomorphologic history by applying principles of photo-geology (Miller and Miller, 1961; Drury, 1987) and information from geological and topographical maps. Geophysical and drilling data for some aquifers are used, also for extrapolation to unknown areas on the basis of similarity.

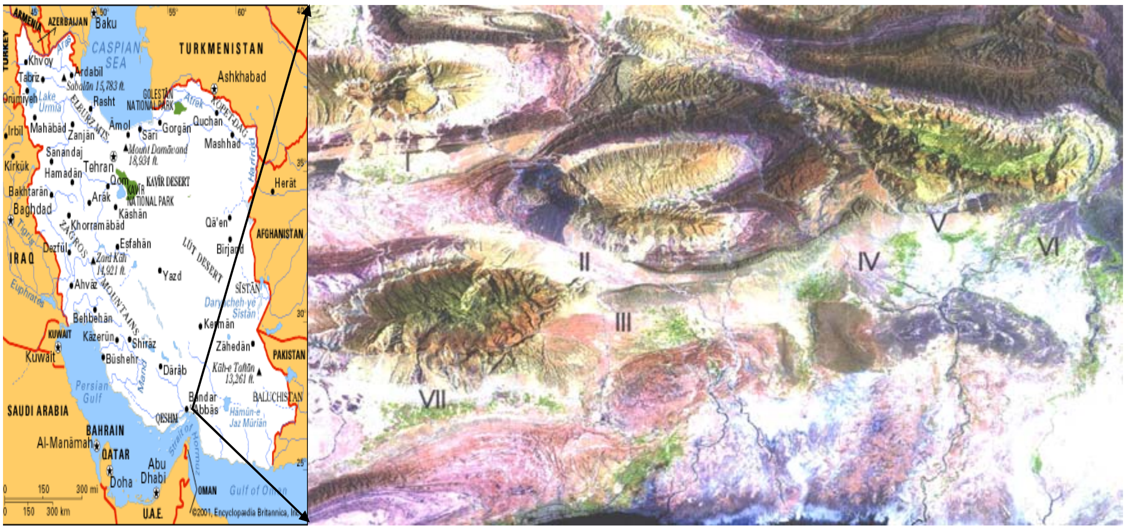


Fig. 2. Location and overview of Bandar Abbas region: location of sub-zones (false-colour TM 742)

Geomorphologic interpretation (Verstappen, 1977; Way 1978) is used to assess the nature of alluvial deposits in relation to the tectonic setting as well as to estimate relative sediment yields (qualitative). Image interpretation for groundwater is reviewed and discussed by Meijerink (1996, 1988). Transmission loss is judged (qualitatively) by variation in channel dimensions.

The land use patterns yielded information on the presence of aquifers, salinity problems and the availability of rangelands in the infiltration areas. The phreatophyte vegetation and water emergence in channels when coupled to soil salinity patterns are taken as an indication of groundwater outflow, hence shallow groundwater conditions.

The advantage of satellite images is that both catchment areas, infiltration and application areas can be viewed in a single image and that some aspects can be highlighted by using common image processing techniques. Aerial photography has the advantage of high spatial resolution and good stereo display of the terrain. The colour images used are false-colour Landsat Thematic Mapper (TM) images. Because various combinations are possible, the notation TM 742 stands for a combination whereby band 7 is coded in red, band 4 in green and band 2 in blue, etc. Since irrigated crops have a high reflectance in the near infrared band, band 4, and low reflectance in the other bands, the fields with green crops show up in green tones. TM band 4 coded in red (e.g. TM 432), so the fields would show up in red tones. Contrasts can be enhanced so as to 'sharpen' features on an image, by using appropriate histogram operations and by using Laplace type of filters. Certain features of interest, such as areas with loose sediments with high infiltration and deposited recently by active floods, can be highlighted by images resulting from orthogonal decomposition of the spectral data, such as the Principal Component method which was used in this research as will be shown in the further sections.

3.1. Decision criteria (qualitatively estimation)

The main criteria (exclusionary) for the qualitative evaluation are given below;

3.1.1. Runoff or floodwater availability

For most of the small and medium-sized catchments in Iran, there is no gauged data, therefore the initial selection procedure, or screening, has to rely on estimation methods.

Rainfall data are not considered in the screening per se because it is assumed that in all arid and semi-arid regions there is a need for augmenting the groundwater resource. Moreover, in Iran provincial and local authorities decide on the location, and the spatial distribution of rainfall generally does not vary much in the zones of the semi-arid provinces that are in need of and have potential for floodwater spreading schemes. However, in the arid tracts of Iran with less than 150 mm annual rainfall, settlements and irrigated agricultural lands are so sparse that recharge schemes are only relevant if some increase in Qanat discharge is desired.

Because of the absence of runoff regionalization studies in Iran, the relative magnitude of the ephemeral runoff in the screening is judged qualitatively on the basis of catchment size and overall catchment permeability based on the proportion of permeable rocks.

3.1.2. Sediment, amount and type

The relative volumes of sediments judged from the catchment geology, relief and dissection, bankful width of the channel and strong signs of aggradations or sedimentation. It is of interest to detect excessive sediment yields, which affect the life time of a scheme to such a degree that it may not be feasible.

Excessive width of the river-bed for the size of the catchment and the gradient is usually associated with such fast geological erosion, but it should be remembered that aggradations could have been caused by episodic events when tremors occurred during a period with much rainfall. Such catchments have been excluded from further consideration.

Because of the large temporal and spatial variation and the difficulty of estimation, the best use of local data on sedimentation should be made. In some cases, the relative sediment yield can be judged by the maintenance required in existing schemes. That information related to catchment geology and relief is of much help in making estimations in adjoining catchments. The relative magnitude of the coarse bed-load (sands and coarser) and that of the suspended/saltation load (sands and finer) can be judged from catchment geology and relief, as well as gradient of the fan, nature of the river beds and types of depositional patterns of low sediment yield. The alluvial deposition resulting from a suspended load type of river results in different patterns from those of bed-load deposition.

3.1.3. Surface area features (land use)

A trivial, but important criterion is that the potential infiltration area should be sufficiently large and the land cover should preferably consist of rangelands or bare areas, which generally belong to the government. Areas suitable for infiltration from a hydraulic point of view excluded if occupied by irrigated fields and industrial lands.

3.1.4. Presence of aquifer and its properties (transmissivity and permeability)

The presence of reflectance due to dense green crops and the absence of surface water irrigation indicates the presence of groundwater and hence an aquifer, because in hot regions with less than 350 mm annual rainfall no rain-fed agriculture is possible. The irrigation water comes from Qanats, topographical maps, and from wells, usually tube-wells fitted with diesel-fuelled pumps. It is a safe assumption to relate the extent of irrigated fields with relevant crops, as observed on satellite images, to aquifer properties, except perhaps in some remote areas, where lack of capital and poor marketing conditions could have led to under-utilization of the groundwater, or in areas where water quality is poor.

In the screening process, attention should be paid to the transmissivity of the aquifer. Most recharge by floodwater spreading takes place in mountain-front alluvial fans, where transmissivities vary much in the downstream direction. The general permeability can be interpreted by considering the catchment lithology and relief and the steepness of the alluvial fan, because of the relationship between gradient and average grain size of deposits (Pettijohn, 1957).

3.1.5. Transmission loss

The importance of transmission loss, can be so high that little floodwater of the smaller systems leaves the area, and that can be interpreted on images. When natural recharge is important, the urgency for artificial recharge may be questioned (Todd, 1980). Such high loss witnessed by a sharp reduction in the bankful width of ephemeral rivers on alluvial fans. The width to depth ratio or shape of the bankful channel does not change much in the unconsolidated coarse bed and bank materials in the downstream direction. Hence, if the width is reduced, the depth is reduced and thus the cross-sectional area, which indicates loss of discharge (transmission loss) because the gradient becomes less in the downstream direction. Strong sedimentation or aggradations can cause water to spread out over a wide surface on the alluvial fan, increasing both infiltration area and time for infiltration. In the interpretation for the screening, attention should be paid to the mountain front because most irregularities can be expected here, such as outcrops at shallow depth and the presence of impervious lime crusts. If the tectonic setting indicates rapid fill of a subsidence area along an active fault, the deposits are likely to be thick, fairly homogeneous and permeable.

3.1.6. Saturated zone

Below the infiltration area, the groundwater table should be at sufficient depth to enable an increase in head by recharge without reaching the upper zone. If so, evaporation losses will occur owing to capillary rises. However, there will be considerable time delays of recharge fluxes if the groundwater table is deep, and the probability of perched water tables and semi-confined groundwater water is higher in deep aquifers than in relatively shallow phreatic aquifers, and this complicates the evaluation of the effectiveness of the recharge scheme. For unsaturated zone thickness, some thickness classes were introduced by Kheirkhah (2005), on the strength that shallow thickness (<20 m) could cause salinization and evaporation losses, and that great thickness (>150 m) would cause substantial delay in the effect of artificial recharge, raising questions as to the short-term effectiveness of the investment in a scheme.

In the lower alluvial fan, outflow of groundwater can occur in river beds, signifying the intersection of the piesometric surface and the topographical surface. Assuming a semi-logarithmic shape of the groundwater surface and by having information of a few depths to groundwater in the middle or upper fan, a fair idea of the groundwater surface can be obtained and, in combination with estimated depth and hydro-geological parameters typical of alluvial fans, the aquifer properties can be estimated at a level that is sufficient for the screening.

In some areas, the lower part of the fan has an incised river. If groundwater from the fan flows into the river, increase in the head by artificial recharge increases the outflow, and hence loss of water. In such cases, a proper pumping scheme has to be adhered to. A groundwater or piesometric surface well below the capillary zone in the lower alluvial fan is favourable in terms of absence of salinity hazard.

3.1.7. Water demand

In this phase, the water demand estimated (qualitatively) based on the presence of areas suitable for irrigation, agricultural lands, villages, cities and industrial areas as indicators. The presence of irrigated lands on the lower to middle part of the fan indicates that soils are suitable for irrigation because textures become gradually finer in the downstream direction. The increase of clay contents accounts for increase in water holding capacity and soil fertility. It judged on images at the screening stage by how much the irrigation expanded. In addition, the presence of agricultural lands, villages, cities and industrial areas in the lower parts of the fan (water application part) will be a good indicator for water demand.

3.2. Implementation (Bandar Abbas Region)

3.2.1. Sub-zone I: Evaluation of location of small infiltration schemes

The catchments (Figure 3) are located in a large anticline, with two massive limestone units (A) separated by marls and an eroded core of the anticline (B) where marls and shales dominate. A soft and impermeable formation (shales, mudstones) is found on the southern flank of the anticline (C1-C2) and a large, eroded anticline (D) occurs in the south, consisting of impermeable rocks of Tertiary age. A depression coinciding with an a-symmetric syncline is found in between the structures. The southern flank is formed by the northwards dipping conglomerates (D1).

Quaternary deposits in the form of alluvial fan deposits have filled up the depression. The older alluvial fans E1 and E2, dissected and eroded after uplift of the northern anticlinal structure, dip below the younger deposits in the depression, indicating subsidence of the latter during late Pleistocene times. The massive limestones are karstic; hence a substantial part of the rainwater infiltrating into the limestones will be conveyed through karst conduits to springs located outside the area shown.

Irrigated fields in the depression bear witness to the presence of an aquifer that is fed mainly by transmission loss. The channels near G and H indicate that flood runoff leaves the depression, whereas the irrigation near H points to some groundwater runoff (base flow). The runoff from the western catchment, which is the largest in size and has soft marls and shales in part of the catchment, is much more than that from the eastern catchments. Transmission loss feeding the aquifer will be highest in the western parts, where wide recent river deposits occur (K), explaining some outflow of groundwater on the western side. The strong sedimentation will present a maintenance problem for a floodwater spreading scheme.

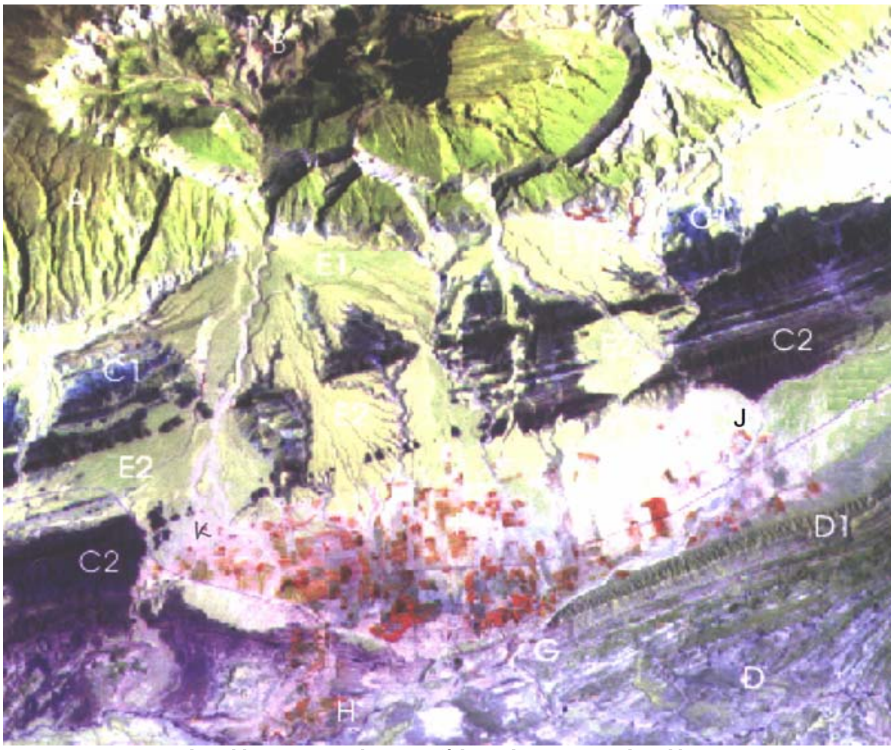


Fig. 3. Bandar Abbas region, sub-zone I (false-colour 473, produced by ILWIS 3.0)

A scheme diverting flood runoff with relative low sediment in the channel near J onto the easternmost alluvial fan could be contemplated in order to augment groundwater in the southeastern part of the depression for irrigation. However, the scheme would be of small dimension for reasons of topography and discharge, and the same could be said for the rivers reaching the central part of the alluvial depression.

3.2.2. Sub-zone II: Water quality problem

Near locality A1 in the northwest of the image in Figure 4, a dissected salt dome is present, intruded in the folded limestones and marls. As the image shows, an accumulation glacis or small bahada is found in between the salt dome and the main river (the Shuh). The deposits consist of gravel and pebbles or rock salt that extend to the main river, where they are carried further downstream. The area near A1 is therefore excluded because of high salinity (water quality exclusionary criterion), and similarly the areas where the main river feeds the groundwater in aquifer zones adjoining the river.

East of A2, bahada A3 could be regarded as a potential zone, because there are no rock salt outcrops in the catchment area and the aquifer materials are permeable. However, the catchments are small, and the rivers are unstable and lose nearly all of the water by natural recharge (exclusionary criteria). No agricultural lands are present, which indicate that there is no Qanat which skims off the layer of sweet groundwater on top of brackish or saline groundwater with greater density. Since constructing a Qanat is no longer feasible and tubewells are likely to draw up water of bad quality, area A3 has severe limitations.

Substantial infiltration takes place in the large and active fan of a river (B) with a catchment in the mountains in the southwest, maintaining the small croplands near the river in area B1, which make use of the thin layer of sweet water at shallow depths near the river. Any artificial recharge scheme should be based on increasing the layer of sweet water, for the reasons given above. As can be seen, the river is unstable and occupies a wide bed, suggesting the type of scheme to be considered in the next screening level (the middle or semi-detailed level), namely a series of small dams (gabions) across the active riverbed and fan. Incidentally, the thickness of the alluvial deposits in the main river valley can be judged because of the presence of outcrops traversing the river near B3. In fact, these outcrops mark the upthrown side of a fault that continues along the border of the mountains in the southwest.

Neotectonic movements occur in the area because older alluvial fans have been uplifted, followed by dissection. Hence the thickness of the alluvial deposits depends on the subsidence along the downthrown side of the fault. That subsidence is probably not much, a few tens of metres at maximum, because a few kilometres upstream the main river flows on bedrock.

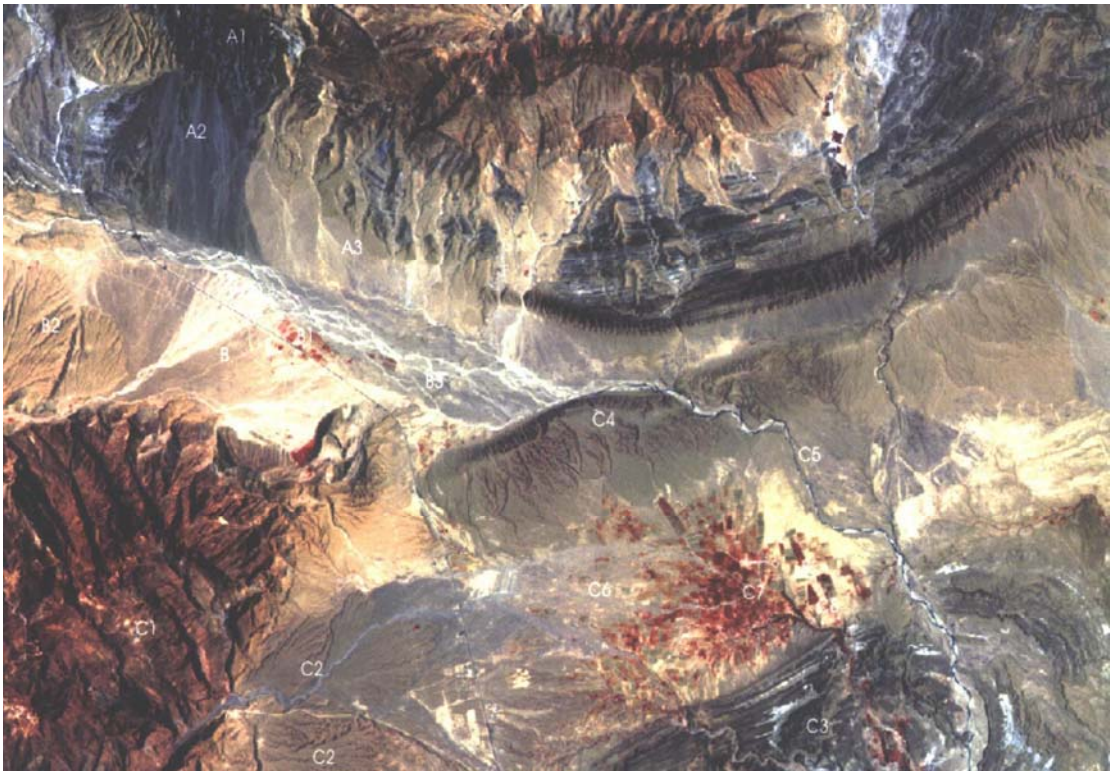


Fig. 4. Bandar Abbas region, sub-zones II and III (false-colour TM 473)

3.2.3. Sub-zone III Flood protection cum artificial recharge example

The area around C in Figure 4 shows an alluvial area that is bordered in the west by a series of uplifted and dissected fans with catchments in the adjoining mountains, where resistant rocks prevail. In the south, the alluvial aquifer is bordered by a large anticline consisting of impermeable and soft rocks (Neogene), accounting for the dissection and low relief. The northern boundary is formed by the dip slope of an a-symmetric anticline with low amplitude (cemented Bakhtiary conglomerates, Late Pliocene) and in the east by the saline Shur river. As can be noted on the image, across the Shur river to the east the thickness of the alluvial deposits is strongly reduced because outcrop patterns can be seen.

The neotectonic history of the alluvial area can be interpreted from the series of uplifted fans. After each phase of uplift in the western part, the river shifted its alluvial fan to the central part of the depression, which indicates a subsidence basin and substantial aquifer thickness (over 100 m, as proven by geophysics and drilling). In the eastern part of the alluvial areas, irrigated fields (by groundwater wells, not by Qanats) can be observed, as well as a drainage pattern with dense vegetation in the valley bottom. The observations (assisted by information from the geological map) therefore indicate a promising zone for a floodwater spreading scheme (no exclusionary criteria have been met by the area). Water and sediments from the main river spread out over a wide zone and the recent/sub-recent river deposits form good infiltration areas because of their coarse nature, due to a mountain catchment, high flow velocities, and a relatively steep gradient in the alluvial area. Although the more recent alluvial deposits can be identified and mapped on aerial photographs and various combinations of colour-coded spectral bands of the TM image, they show up on the fourth principal component (PC) images, as shown in Figure 5. It should be remembered that within a full scene, the contents of the PC images depend on the sub-window selected.

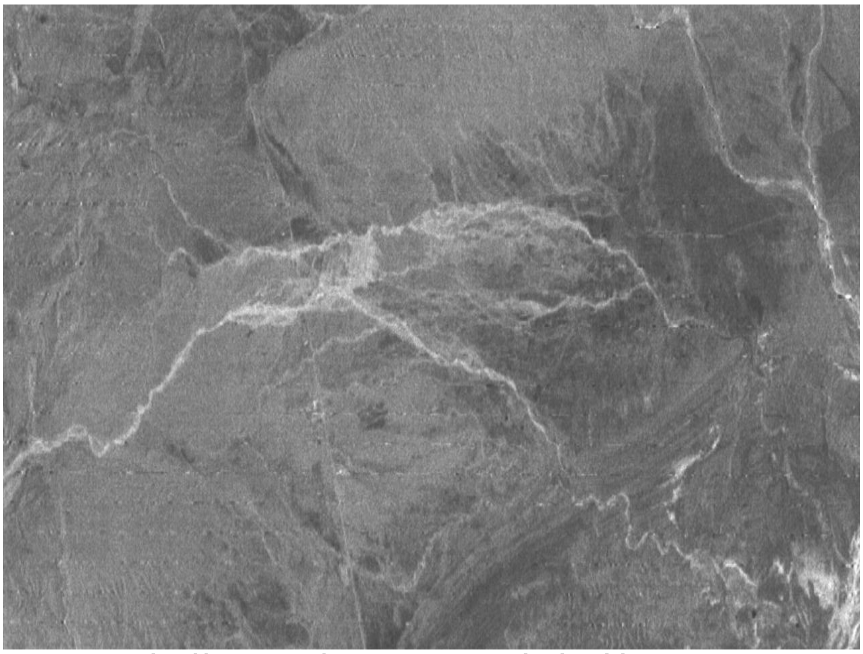


Fig. 5. Bandar Abbas region, sub-zone III: recent gravel and sand deposits on PC4 image

Occasional floodwaters reach the irrigated lands and settlements, causing damage; hence a floodwater spreading scheme serves a dual purpose: recharge and flood damage mitigation. In addition, some 40 km south of the area shown is Bandar Abbas.

The drinking water supply for this city is a problem, and this forms an additional argument for increasing the groundwater supply. Part of the flash floods are carried through the incised drainage in the eastern part out of the aquifer area, with an (very minor) outflow of groundwater, as can be noted by the presence of phreatophyte vegetation.

The above results give the interpretation aspects. In fact, a flood mitigation scheme was constructed that proved to be an important artificial recharge scheme as well. The scheme is located just upstream of observation well 5 in Figure 6a. It consists of a cascading series of basins that receive part of the flash flows of the river. The importance of the scheme and the recent gravel and sand deposits in the area where the floods have been spreading by natural causes is evident from the well hydrographs shown in Figure 6b. The hydrographs of all the wells near the recent alluvium (wells 1, 4, 5, 6, and 8) show substantial rises in the groundwater level after infiltration of flash flow water. In contrast, recharge outside the active alluvial area is small or absent, as shown by the hydrographs of the observation wells. The hydrograph of well 2 takes a special position because of the effect of the Shur river stages.

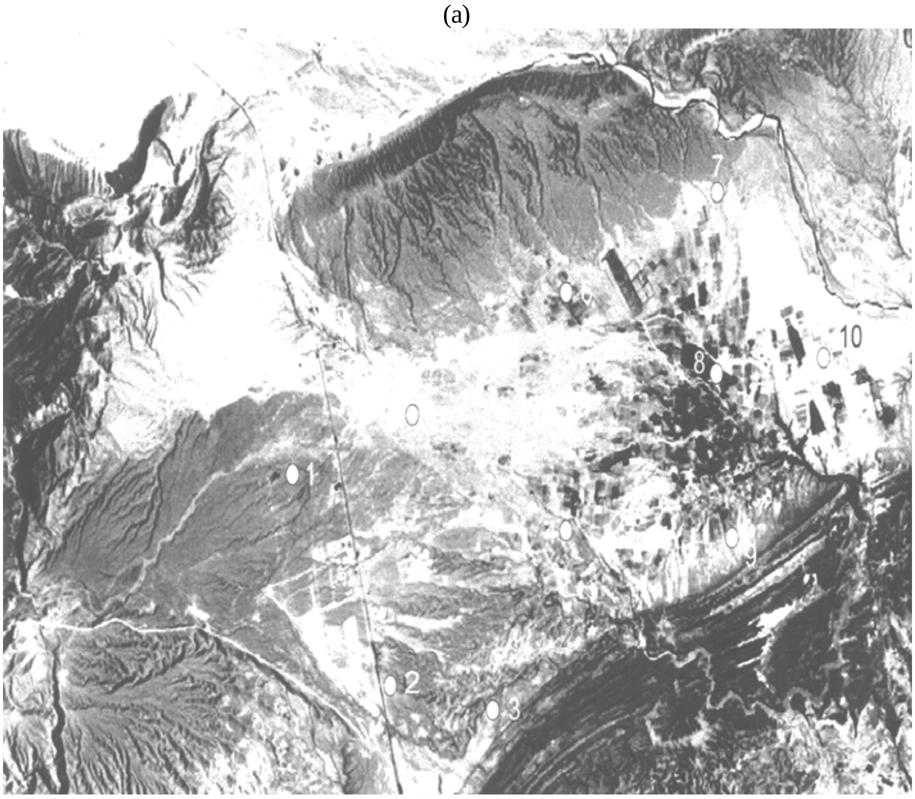
3.2.4. Sub-zone IV: Large fan, soil salinity hazard

Further eastwards in the alluvial zone, the image in Figure 7 shows folded rocks, with permeable and impermeable units, forming hills and mountains drained by larger and smaller rivers. It is important to note that the southern border is formed by a tectonic line (flexure and fault C1-C2). South of that line, impermeable rocks crop out. The presence of such rocks prohibits the flow of deeper groundwater from the higher area in the north to the lower area in the south across the flexure.

In the south are the low hills consisting of impermeable rocks of Tertiary age, the same as in sub-zone III. In between the northern and southern hills is a depression area with alluvial fans, bordered in the south by the line along E-C1-C2. North of E, the alluvial fill of the depression is likely to be of limited thickness because of uplift. The depression opens up to the east and probably the aquifer (fanglomerates) thickness increases.

The image shows that the river has base flow until a little distance below the gap (A), where it enters a large alluvial fan in a channel that is incised a little. Near B, phreatophyte vegetation indicates the presence of shallow groundwater, possibly of a perched nature. The groundwater table is close to the surface on the lower part of the fan, and groundwater drains out in the rivers near C1, C2 and C3. The irrigated fields (red tones) derive their water from wells and Qanats and are found in a fringe along the lower part of the fans, where the soils are suitable for agriculture because of their water holding capacity due to fine textures. The textures on the upper-middle part of the fan are coarser.

(a)



(b)

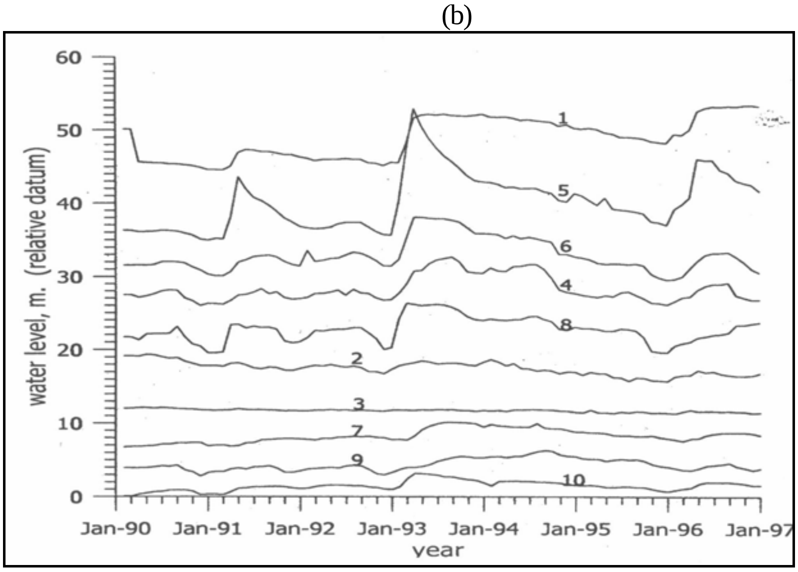


Fig. 6. Sarkhon aquifer, Bandar Abbas region, zone III: (a) location of observation wells, (b) groundwater levels in observation wells

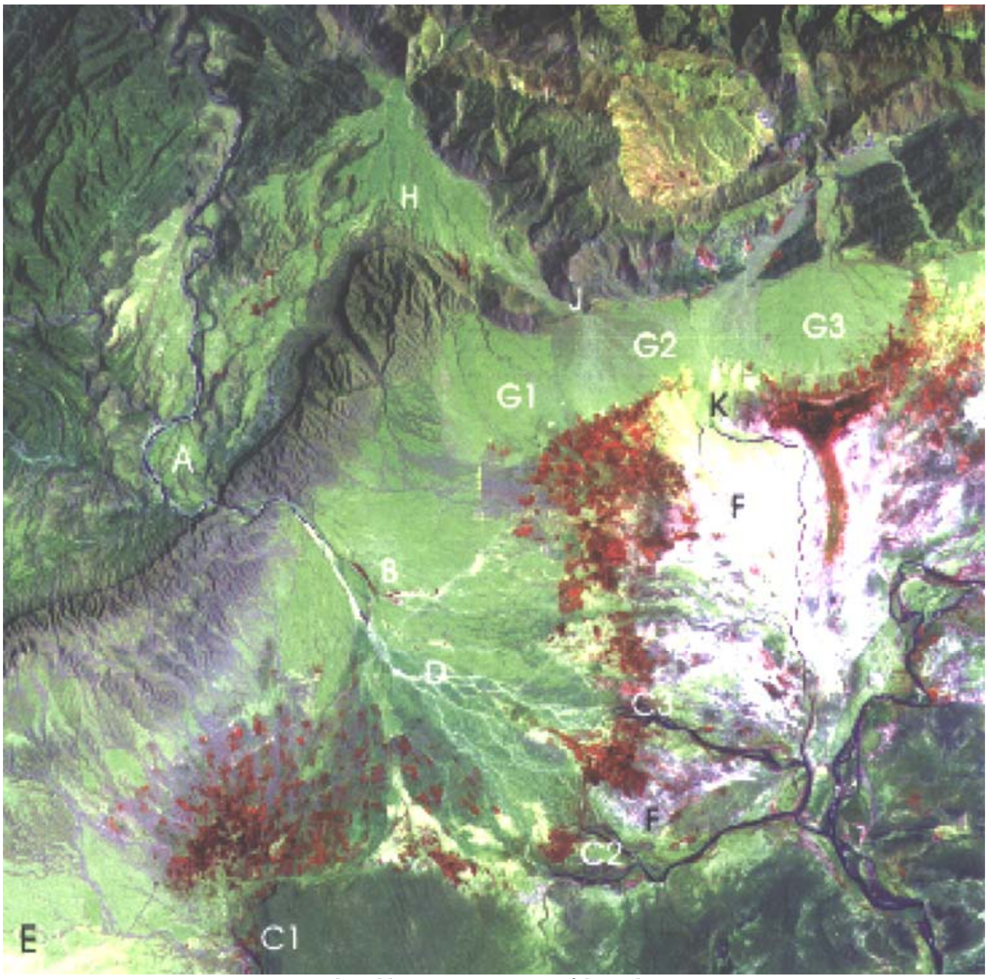


Fig. 7. Bandar Abbas region, zone IV (false-colour TM 472)

If a scheme is considered, the intake(s) should be upstream of D to avoid the unstable section of the river. No irrigated fields are found in the area with the many (shifting) river channels. Because of the size of the catchment, the flood discharges are substantial and only a small part of the floodwaters are retained on the fan by transmission loss, considering the total widths of the active channels in the lower part of the fan.

The typical sequence of textures associated with an alluvial fan of a large river with a coarse bedload, large discharge, and the presence of irrigable lands is in favour of a floodwater spreading scheme. However, starting south of C3 in the direction of F and beyond, saline soils are found belonging to the large saline coastal plain (see overview image, Figure 2). Since the groundwater table in large parts of the fan is shallow, increasing the groundwater level by artificial recharge could lead to salinization of the fields in the lower part of the fan because of capillary rises. Therefore, a recharge scheme should be accompanied by well fields withdrawing water at the same average rate as the recharge.

3.2.5. Sub-zone V: Aggradations and transmission loss by sheet-wash

The areas of interest are the alluvial fans G1, G2 and G3 in Figure 7. Fan G1 has developed in a synclinal depression whose axis is perpendicular to the main tectonic line that separates the hills and mountains in the north and the alluvial fans and coastal plain deposits in the south. The fan deposits of G3 are older than those of G2. They were laid down at the time when the river formed a fan around H, which after uplift was dissected, and the present, active river shifted to the eastern margin. Since runoff from the dissected fan deposits around H is very low, little water will reach fan G1, and that water will infiltrate fully on the fan itself (low amount of floodwater and transmission loss exclusionary criteria). The small quantity of recharge water is reflected in the disappearance of irrigated fields in the southwestern part of fan G3. Hence there is no scope for a scheme.

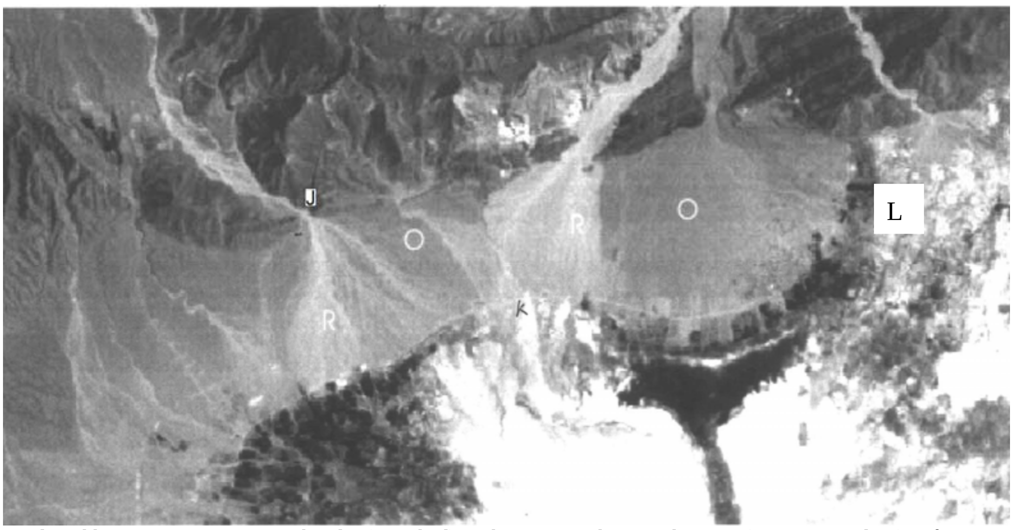


Fig. 8. Bandar Abbas region, zone V: TM band 1 (stretched) to show active sheet wash traces (transmission loss) in fans G1, G2 and G3 of Figure 7

The active alluvial fan G2 has a sizeable catchment, while the overview in Figure 4 shows relatively dense vegetation on the mountains forming the northeastern part of the catchment, indicating higher rainfall. However, the fast surface runoff is subdued because a large part of the catchment consists of karstic limestones. The high infiltration causes dry season flow at the place where the river leaves the mountain, but that flow infiltrates the fanglomerates around H. The subsurface gradient of the older fan deposits is likely to be steeper to the southwest than to the southeast because of the deep incision of the river near A and the narrow gap in the rocks near J. Little groundwater will flow through the gap (J) and the recharge supporting the irrigated areas northwest of F must take place by infiltration of flash flows over the fan itself. It is interesting to note that the water spreads out over a wide area downstream of J, as illustrated in Figure 8. This figure shows TM band 1, with appropriate 'stretching' of grey tones to highlight the difference between the older, non-active fan parts (O) and the active parts (R) where floodwaters spread out, accompanied by the deposition of sediment consisting of sands, pebbles and boulders near the apex and sand mixtures in the remaining part of the fan. The sharp transition between the fan and the coastal plain deposits is also a topographical break in slope. The area near K has few or no irrigated fields because of the concavity in between two fans, forming a low topography with saline coastal sediments close to the surface, and the occurrence of episodic flood runoff from the catchment of fan G3. The strong aggradations of the valley upstream of the fan can be noted. The base flow from the mountains infiltrates the coarse alluvial fill deposits but flows below the surface over the contact with the impermeable shales of the dark toned rocks (L). Part of that water emerges as perennial flow at the surface near K (Figure 8). Along the southern fringe of alluvial fan G3, there is a waterlogged area that is of ecological value.

The arguments for giving a lower priority to fans G2 and G3 for a scheme are the strong transmission losses and the fact that Qanat systems are in operation that do not pose a threat of salinity hazard, as would be the case if well irrigation were introduced.

3.2. Sub-zone VI: Area with large fine-grained sediment load, salinity hazard, unstable rivers

The image in Figure 9 shows a narrow tectonic depression that is bordered by faults in the north and northeast and by a large anticlinal structure in the south. The image is a false-colour composite of TM 473, and green vegetation is depicted in red tones. Much of the catchment geology is dominated by argillaceous suites of rocks, partly shown in the overview image in Figure 2.

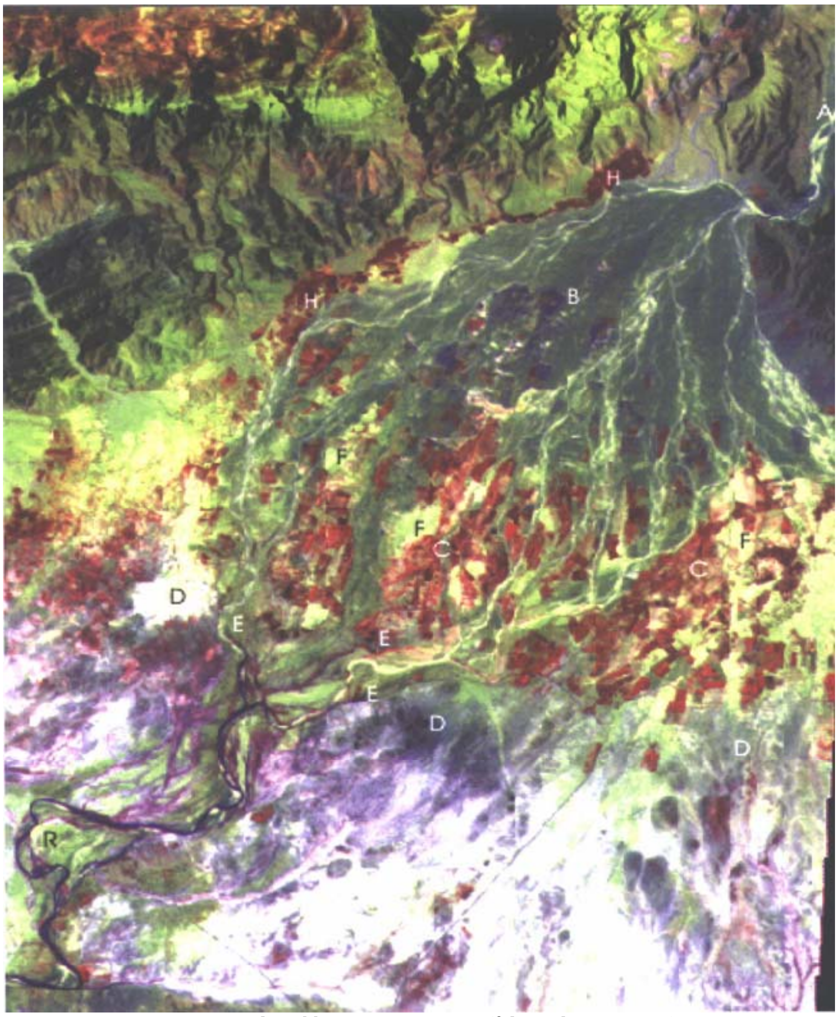


Fig. 9. Bandar Abbas region, zone VI (false-colour TM 472)

For this reason, the sediment load of the river has a much higher proportion of clay and silt than those of the rivers discussed earlier. The bedload consists of a mixture of sands and coarser fractions, but has a high proportion of shale fragments. The general fine-grained nature of the fanglomerates is reflected in the gentle gradient of the fan. Aggradation still takes place, starting at the floodplain upstream of the fan and continuing till the downstream part (R), causing instability in plan.

The depth of the alluvial deposits is considerable, but the overall permeability of the aquifer is much less than in the previous cases on account of the richness in clay. Transmission losses on the alluvial fan are relatively low, which explains why the rivers on the fan do not decrease much in width. Sandy lenses do occur throughout the fan deposit, and the groundwater table is not deep in the middle and lower parts of the fan. For this reason, a considerable amount of groundwater emerges in the lower part of the aquifer in the southwest (E) and in the southeast (shown in the overview image, Figure 2), caused by the gradual decrease in permeability towards the lower fan. The shallow groundwater table in the lower part has caused waterlogging and salinization in various stages (D).

The upper part of the fan has under rangeland vegetation cover. Along the contact with folded rocks in the north is a narrow fringe with irrigated fields (H) that derive their water from springs and base flow of the rivers in the mountains, where limestone is present. In the middle part of the fan, fields are irrigated by groundwater (C). The fields with a good crop response are not contiguous, as they are separated by fields with poor crop responses and bare patches that point to either salinity or poor groundwater conditions, or both.

Some of the criteria in favour of a scheme are met: the presence of a large river, much water leaving the area, rangelands in the upper part of the alluvial fan, the presence of groundwater-irrigated agriculture. However, the instability of the rivers; the high sediment load, both bedload and suspended load; poor aquifer properties because of deposits rich in clay in the upper part of the fan; and a salinity hazard in the lower part of the fan; these are matters of concern. Because of the large catchment of the river, hydraulic measures to control flows at the apex of the fan are a major investment because of the very large floods.

3.3.7. Sub-zone VII: Variation in sediment load

This sub-zone (Figure 10) has great similarity as regards geological and geomorphological setting to sub-zone I. The mountains in the north (A), with hard sandstones, conglomerates, limestone and interbedded rocks or less resistance and permeability, are in steep contact with the steeply dipping impermeable rocks of formation B. In the south is a large anticline of the impermeable Tertiary rocks (C1) that dip gently (C2) below the younger alluvial deposits. Alluvial fans overlying B have been uplifted along the east-west fault D1-D2, and continue in the direction of D4 after an offset by fault D2-D5.

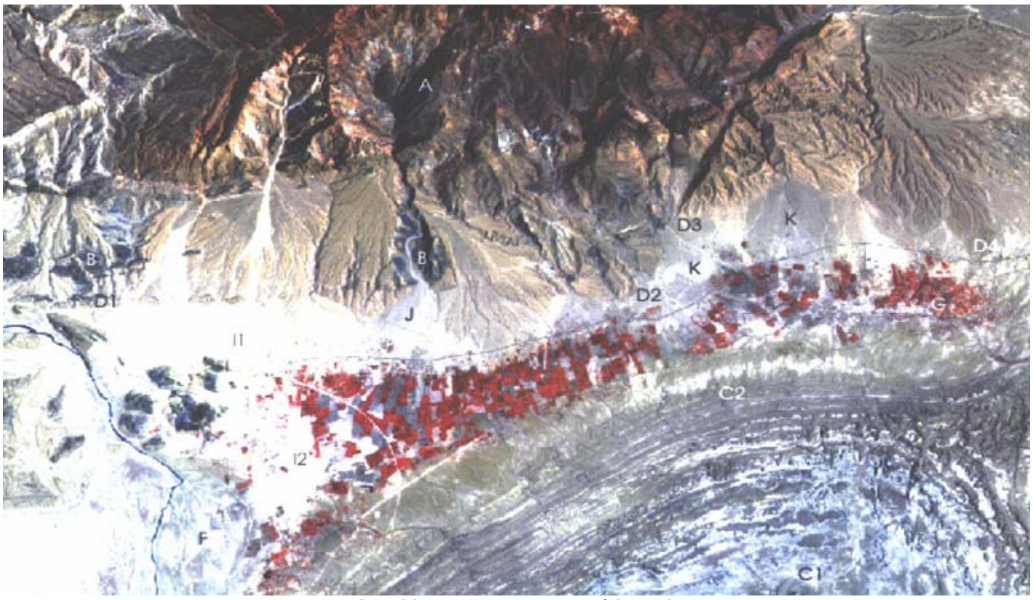


Fig. 10. Bandar Abbas region, zone VII (false-colour TM 472)

The alluvial depression and aquifer is bordered in the west by outcrops (E) and the deposits of a river (F) with brackish water, and in the east by outcrops of formation C. The aquifer of the depression is recharged by transmission losses of the active fans of the northern catchments and to a lesser extent by the runoff from the low hills in the south. In the east, the phreatophyte vegetation in the small river (G) bears witness to the outflow of groundwater from the eastern part of the depression and indicates shallow groundwater in the lowest part of the depression. The aquifer drains out to the west to the saline fluvial deposits (F), and a broad groundwater divide is located near H. Fields irrigated by groundwater (red tones) occupy a large part of the lower alluvial depression, but there is some scope for expansion of irrigation in some fields that are fallow.

The westernmost part of the alluvial area suffers from much deposition of sands (I1 and I2) from the northern catchments, owing to the occurrence of mass wasting and gulling. The large bedload and the large transmission loss (exclusionary criteria) make that area less attractive for a scheme. Fan J could be considered for a scheme because of the size of the catchment, permeable conditions in the rangelands of the fan, flooding by sheetwash, and sediment deposition in the irrigated area. The same is valid for the area around K, where the sedimentation problem is less, and the amount of water, because catchments are smaller. However, field data on soils, hydrochemistry and irrigation potential are needed for a proper evaluation of the western part of the zone.

3.3. Evaluation

For large schemes sub-zone III is the best. Apart from a relatively large volume of runoff and good infiltration properties for an exploited aquifer (irrigation and drinking water supply), an additional argument is the mitigation of the flood hazard. Sub-zone IV has much inflow and is well watered considering the base flow leaving the area. Expansion of irrigation by wells in the future may require artificial recharge by floodwater spreading, considering the salinity hazard.

For small schemes the areas I-J and II-B are the most suitable, with area I-K as a second-best option. The general results of the evaluation for all the discussed areas in Bandar Abbas zone and the exclusionary criterion/criteria for each excluded area are shown in Table1.

4. Discussion and Conclusions

The objective of this paper was to develop a method for screening zones containing feasible or potentially suitable areas, as a component of the DSS. The screening was done at a small scale. It was based on the interpretation of remotely sensed images supplemented by generally available additional sources of information, such as geological and topographical maps.

It was concluded that the interpretation results could be regarded as being more than the sum of separate interpretation layers, i.e. geology, geomorphology and land use. The study has shown that image interpretation facilitated by field visits and by the presence of hydro-geological data allows empirical knowledge to be accumulated for understanding interrelationships of features on the images and for extrapolation purposes. This enables potentially suitable areas to be identified and areas with little or no promise to be excluded by using criteria such as catchment size, presence of aquifer, water quality, excessive sediment yield, high transmission losses and lack of space for schemes in suitable infiltration areas, and so on. The end product of the screening was the identification of possible suitable areas within a zone, grouped according to a relative qualification.

The screening for zones with potential was based on qualitative results achieved using the interpretation of remotely sensed images, supplemented by generally available additional sources of information, such as geological and topographical maps. By interpreting these data and using criteria such as catchment size, presence of aquifer, water quality, excessive sediment yield, high transmission losses, lack of space for schemes in suitable infiltration areas, and so on, it was possible to obtain sufficient evidence to exclude areas that seemed potentially suitable at first glance. It was found that zones with potentially suitable areas to be retained for further scrutiny consisted of catchments of medium size (a few tens to hundreds of square kilometres in size) with rivers that formed alluvial fans. The interpretation of the collected data also resulted, before ending the screening, in specifying the nature of the field data required and in giving specific points of attention for the next stage of evaluation, such as the presence of a salinity hazard. By coupling groundwater-level fluctuations in wells close to active rivers or active sedimentation on alluvial fans, the importance of river recharge or transmission loss could be demonstrated. The type of image processing technique to highlight such areas was mentioned.

To arrive at results, the interpretation required a holistic approach, supported by field knowledge of various regions of Iran. The geological setting and dynamic geomorphology had to be assessed first to estimate relative runoff and sediment yield, as well as probable gross nature and depth of aquifers. In many parts of Iran, it was found that neotectonics played a role in the erosion and deposition. Using images to study details of the fluvial geomorphology gave information on the general feasibility of a scheme, considering transmission losses and the main type of scheme possible in view of suitable sites for intakes for a diversion scheme. Because of the age-old use of groundwater in Iran, interpreted land cover information allowed conclusions to be drawn on the presence of aquifers, the suitability of soils for irrigation and possible increase in acreage using artificially recharged water, saline water, and space for floodwater spreading schemes (also in relation to land acquisition). Because of the interrelationships that, owing to cause-and-effect relationships, often exist between the terrain features of relevance for the selection of areas for floodwater spreading schemes, it can be concluded that the interpretation results could be regarded as being more than the sum of separate ‘interpretation’ layers: i.e. geology, geomorphology, land use. The interpreter has to have a firm footing in earth science. The end product of the screening was the identification of potentially suitable areas within a zone, grouped according to a relative qualification, leaving options open for the selection of the most suitable areas when considering the size of possible scheme.

Table 1. Evaluation results for the studied areas, Bandar Abbas region

Zone or Sub Zone	Areas					
I	J		K			
	Excluded area	Potential area	Excluded area	Potential area		
	Exclusionary criteria	+	Exclusionary criteria	+		
II	A1		A3 (Bahada)			
	Excluded area	Potential area	Excluded area	Potential area	Excluded area	Potential area
	Exclusionary criteria	-	Exclusionary criteria	-	Exclusionary criteria	+
	Water quality		Runoff or flood water availability & transmission loss & water demand			
III	Area around C					
	Excluded area	Potential area				
	Exclusionary criteria	+				
IV	D					
	Excluded area	Potential area				
	Exclusionary criteria	+ The recharge scheme should be accompanied by well fields withdrawing water at the same average rate as the recharge				
V	G1		G2		G3	
	Excluded area	Potential area	Excluded area	Potential area	Excluded area	Potential area
	Exclusionary criteria	-	Exclusionary criteria		Exclusionary criteria	
	Transmission loss & runoff or flood water availability		Transmission loss & soil salinity		Transmission loss & soil salinity	
VI	Alluvial fan area					
	Excluded area	Potential area				
	Exclusionary criteria	-				
	Sediment, amount and type & presence of aquifer and its properties (transmissivity and permeability) & soil salinity					
VII	I1, I2		J		K	
	Excluded area	Potential area	Excluded area	Potential area	Excluded area	Potential area
	Exclusionary criteria		Exclusionary criteria	+ Field data on soils, hydrochemistry and irrigation potential is needed	Exclusionary criteria	+
	Sediment, amount and type & transmission loss					

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