Characteristics of direct human impacts on the rivers Karun and Dez in lowland south-west Iran and their interactions with earth surface movements

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Abstract

Two of the primary external factors influencing the variability of major river systems, over river reach scales, are human activities and tectonics. Based on the rivers Karun and Dez in south-west Iran, this paper presents an analysis of the geomorphological responses of these major rivers to ancient human modifications and tectonics. Direct human modifications can be distinguished by both modern constructions and ancient remnants of former constructions that can leave a subtle legacy in a suite of river characteristics. For example, the ruins of major dams are characterised by a legacy of channel widening to 100's up to c. 1000 m within upstream zones that can stretch to channel distances of many kilometres upstream of former dam sites, whilst the legacy of major, ancient, anthropogenic river channel straightening can also be distinguished by very low channel sinuosities over long lengths of the river course. Tectonic movements in the region are mainly associated with young and emerging folds with NW–SE and N–S trends and with a long structural lineament oriented E–W. These earth surface movements can be shown to interact with both modern and ancient human impacts over similar timescales, with the types of modification and earth surface motion being distinguishable. This paper examines the geomorphological evidence and outlines the processes involved in the evolution of these interactions through time. The analysis shows how interactions between earth surface movements and major dams are slight, especially after ancient dam collapse. By contrast, interactions between earth surface movements and major anthropogenic river channel straightening are shown to be a key factor in the persistence of long, near-straight river courses. Additionally, it is suggested that artificial river development, with very limited river channel lateral migration, may promote incision across an active fold at unusually long distances from the fold "core" and may promote markedly increased sinuosity across a structural lineament.

Keywords

- Earth surface movement;
- River channel;
- Fold;
- Human impact;

- Iran

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1. Introduction

Variability of major rivers is an inherent property and applies over a wide range of spatial scales from river reaches to river basins (Leopold and Wolman, 1957, Howard, 1967,Schumm, 1991 and Schumm, 2005). Such variability includes, for example, variations in channel pattern and major avulsions, with these autogenic changes influenced by factors that include topography, river hydrology, and river sedimentology (Lang et al., 2003 and Downs and Gregory, 2004). Some variability of major rivers may be driven by allogenic factors that include climate, relative sea-level (or base level) changes, human activities, and tectonics (Jones et al., 1999b, Blum and Törnqvist, 2000, Schumm et al., 2000, Dollar, 2004, Brierley and Fryirs, 2005, Schumm, 2005 and Burbank and Anderson, 2012). Of these external factors, human activities and tectonics are especially influential at the river reach scale. Human activities influencing major rivers can be sub-divided into indirect human impacts due to land use changes (such as woodland clearance and agriculture) and direct human impacts on river channels by river regulation and channel modifications (such as dam construction and channel straightening) (Brookes, 1994, Brierley and Fryirs, 2005, Heyvaert and Baeteman, 2008, Walstra et al., 2010b and Heyvaert et al., 2012). Though there are considerable overlaps, indirect human impacts mainly relate to river catchment and river basin scales, whereas direct human impacts mainly relate to river reach scales.

Earth surface movements by active tectonics can be sub-divided into forms of faulting, folding, and tilting (Schumm et al., 2000). Folding has a variety of impacts on river reaches, particularly with major transverse rivers encountering folds. Where rates of fold uplift are less than rates of river aggradation, a transverse river will flow without impedance across the fold, with little or no topographic relief developing (Burbank et al., 1996). Where a fold does develop a surface topographic expression, a river may flow across the fold by developing incising reaches across the fold, and by developing aggrading reaches immediately upstream and downstream of the fold (Holbrook and Schumm, 1999 and Douglass and Schmeeckle, 2007). Alternatively, a river may be diverted around the fold by channel migrations and avulsions, or it may be “ponded” in a basin behind the fold, depending on the balance between river aggradation and incision and fold growth (Burbank et al., 1996, Amos and Burbank, 2007 and Burbank and Anderson, 2012).

The variety of river response to perturbation can make it difficult to disentangle the influences of direct human impacts from the influences of active folds on major rivers at river reach scales. The aims of this paper are to determine the distinguishing characteristics of direct human impacts on major rivers and to determine the nature of the interactions between earth surface movements and these human impacts. Critically, at locations where direct human modifications to river channels and active folds coincide, there will be interactions between these two external factors, notably if they have significant influences over similar timescales (Schumm, 1991). Such interactions are only very poorly known from previous work; with, for instance, changes to the River Indus in Pakistan from an aggrading, anastomosing river into an incising, meandering river associated with the Jacobabad-Khairpur zone of uplift, being considered to have been enhanced by the Sukkur Barrage which was constructed in 1932 AD (Harbor et al., 1994).

This paper uses a single major river system (the River Karun and its main tributary, the River Dez, in lowland south-west Iran) within a single foreland basin (the Mesopotamian-Persian Gulf Foreland Basin) with similar types and orientations of folds in various stages of development, to delineate and disentangle these complex human–tectonic interactions. The focus is on horizontal spatial scales extending to the reach scale (river channel dimensions to fold dimensions), and temporal scales of mainly decades to millennia (river channel migrations to fold uplift). By having a focus on a single major river at these scales, the various other factors influencing major river responses over similar timescales, such as climate, will be fairly similar over the drainage basin (Potts, 1999 and Badripour et al., 2006). As such, the rates of sediment supply from the basin hinterland are likely to be similar at the scale of the river reach (Peng et al., 2010) and relative sea-level changes will be largely controlled, since most of the river reaches are upstream of sea-level influences; that is, upstream of a distance of about 150 km from the shoreline (Shanley and McCabe, 1993) and upstream of the extent of the river backwater length (the distance over which the scoured channel base is at or below sea-level) (Li et al., 2006 and Blum et al., 2013). This paper examines a range of reach lengths where human modifications and tectonic folds can be identified and attempts to disentangle their complex histories using the geomorphological evidence available.

2. Study area

The River Karun and River Dez are major rivers in south-west Iran (average water discharges c. 575 m^3 s^{-1} and 230 m^3 s^{-1}, respectively) which flow from the Zagros orogen in the N and NE across the Upper and Lower Khuzestan Plains into the Mesopotamian-Persian Gulf Foreland Basin to the S and SW (Fig. 1). Their basins extend over a few climate zones with mean annual precipitation decreasing from c. 400 mm–1000 mm in the Central Zagros Zone to less than 200 mm in the Arid Zone of the Lower Khuzestan Plains (Frey and Probst, 1986, Potts, 1999, Badripour et al., 2006,Alijani, 2008 and Woodbridge, 2013).

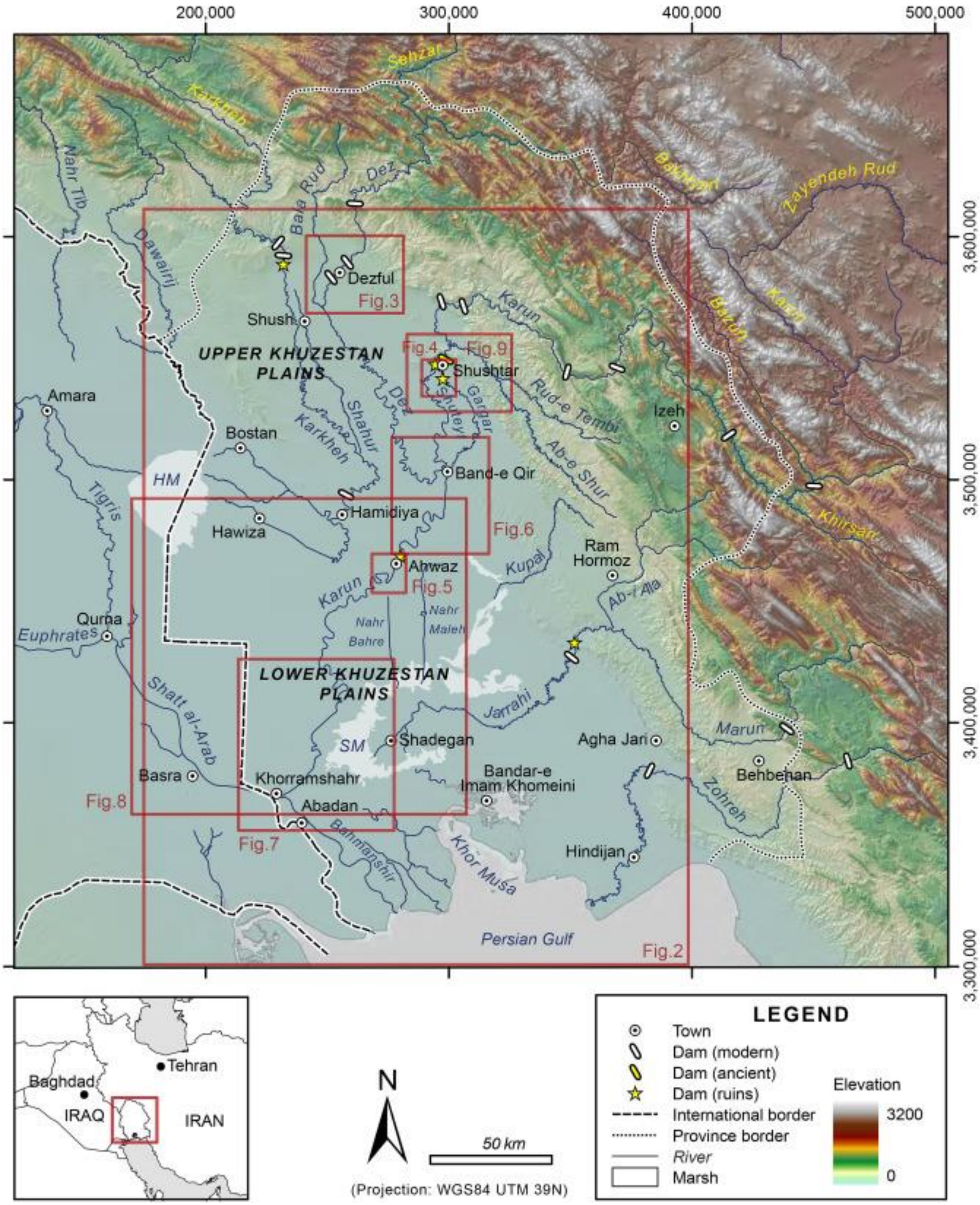

Fig. 1.

Relief map and main river courses of the province of Khuzestan and its environs (modified from Heyvaert et al., 2013). Rectangles indicate the location of Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6, Fig. 7, Fig. 8 and Fig. 9.

2.1. Tectonics and earth surface movements in south-west Iran

Throughout the Zagros region, the main geological structures are NW–SE trending thrust faults and folds produced by the convergence of the Arabian Plate towards the Eurasian Plate, which is continuing in an approximately N–S direction at rates of c. 16–22 mm yr^{-1}(Sella et al., 2002). Within the Khuzestan Plains and the Zagros region in general, earthquakes have only accounted for a small part (c. 10%–20% at most) of the deformation required by the convergence of the Arabian and Eurasian plates. Most of the earth surface movements (probably c. 95%) on faults and folds are by aseismic folding, faulting, and stable creep (probably due to lubricated décollements on evaporite layers) (Jackson et al., 1995, Masson et al., 2005 and Hatzfeld et al., 2010).

Mainly from the Pliocene (c. 5 Ma) onwards, there has been a migration of the deformation away from the orogen towards areas of thinner crust, to produce successions of mainly NW–SE oriented thrust faults and associated detachment folds and fault bend folds (Allen et al., 2004). Typically, these folds are asymmetric anticlines at or near the ground surface, with a more steeply dipping fore-limb to the south-west and a more gently dipping back-limb to the north-east (Blanc et al., 2003). Though there are slight variations between individual folds, river erosion in lowland south-west Iran typically exposes the following fold lithostratigraphy: Quaternary deposits (c. 1 Ma – Present; generally unconsolidated alluvial sands, muds, gravels, and marls) – Middle Pliocene to Pleistocene Bakhtyari Formation (c. 3 Ma – 1 Ma; well-consolidated conglomerates, sandstones, and mudstones) – Middle Miocene to Middle Pliocene Agha Jari Formation (c. 10 Ma – 3 Ma; sandstones, marls, and mudstones) (James and Wynd, 1965, Hamzepour et al., 1999 and Abdollahie Fard et al., 2006). The NW–SE oriented folds are generally younger and less developed towards the south-west away from the orogen (Alavi, 1994) and die out in the vicinity of the Zagros Deformation Front (ZDF) (Haynes and McQuillan, 1974 and Hatzfeld et al., 2010), a NW–SE oriented line c. 30 km south-west of the demarcation between the Upper and Lower Khuzestan Plains (Fig. 1 and Fig. 2).

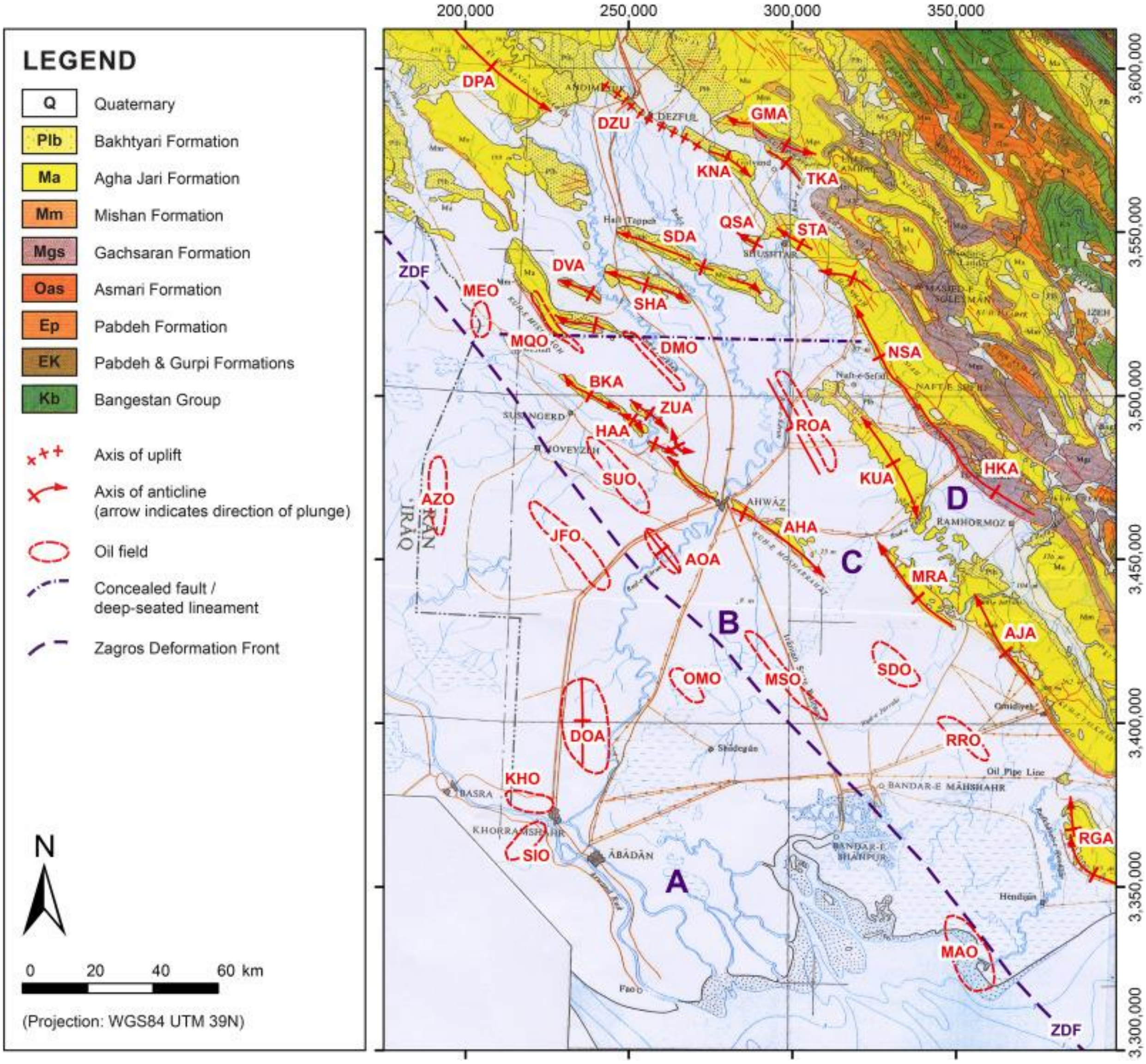

Fig. 2.

Geological map of south-west Iran showing selected anticlines, oilfields and oilfield anticlines in the lowlands (modified from NIOC, 1973 using various sources). AGA = Abu ul-Gharib Anticline, AHA = Ahvaz Anticline, AJA = Agha Jari Anticline, AOA = Ab-e Teymur Oilfield Anticline, AZO = Azadegan Oilfield, BKA = Band-e Karkheh Anticline, DMO = Dasht-e Mishan Oilfield, DOA = Dorquain Oilfield Anticline, DPA = Dal Parri Anticline, DVA = Darreh-ye Viza Anticline, DZU = Dezful Uplift, GMA = Gach-e Moh Anticline, HAA = Hamidiyyeh Anticline, HKA = Haft Kel Anticline, JFO = Jufeyr Oilfield, KHO = Khorramshahr Oilfield, KNA = Kuhanak Anticline, KUA = Kupal Anticline, MAO = Mahshahr Oilfield, MEO = Mehr Oilfield, MQO = Mushtaq Oilfield, MRA = Marun Anticline, MSO = Mansuri Oilfield, NSA Naft-e Safid Anticline, OMO = Omid Oilfield, QSA = Qal'eh Surkheh Anticline, RGA = Rag-e Safid Anticline, ROA = Ramin Oilfield Anticline, RRO = Ramshir Oilfield, SDA = Sardarabad Anticline, SDO = Shadegan Oilfield, SHA = Shahur Anticline, SIO = Siba Oilfield, STA = Shushtar Anticline, SUO = Susangerd Oilfield, TKA = Turkalaki Anticline, ZDF = Zagros Deformation Front, ZUA = Zeyn ul-Abbas Anticline. **Key to geology** (James and Wynd, 1965, Hamzepour et al., 1999 and Abdollahie Fard et al., 2006).

Q = Quaternary (c. 1 Ma – Present; generally unconsolidated alluvial sands, muds, gravels, and marls). Plb = Bakhtyari Formation (Middle Pliocene to Pleistocene, c. 3 Ma – 1 Ma; well-consolidated conglomerates, sandstones, and mudstones). Ma = Agha Jari Formation (Middle Miocene to Middle Pliocene, c. 10 Ma – 3 Ma; sandstones, marls, and mudstones). Mm = Mishan Formation (Middle Miocene, c. 16 Ma – 10 Ma; marls, limestones and sandstones). Mgs = Gachsaran Formation (Early Miocene, c. 23 Ma – 16 Ma; anhydrite and salt, limestones, marls and shales). Oas = Asmari Formation (Oligocene – Early Miocene; mainly limestones). Ep = Pabdeh Formation (Palaeocene – Oligocene; mainly marls and shales). EK = Pabdeh & Gurpi Formations (Santonian – Oligocene; mainly marls and shales). Kb = Bangestan Group (Late Cretaceous (Albian – Campanian); mainly limestones). **Key to approximate zones of earth surface movements** (Woodbridge, 2013 and Woodbridge and Frostick, 2014). A = Subsidence. B = Minimal vertical earth surface movements. C = Uplift at rates of approximately 0.1–0.8 mm yr^{-1}. D = Uplift at rates of approximately 0.2–2.3 mm yr^{-1}.

Within the wedge-top of the foreland basin to the north-east of the ZDF (the Dezful Embayment in lowland SW Iran) there is regional uplift, whereas within the foredeep of the foreland basin to the south-west of the ZDF (the Mesopotamian foredeep in lowland SW Iran) there is regional subsidence (Falcon, 1974, DeCelles and Giles, 1996 and Abdollahie Fard et al., 2006). Within the Mesopotamian foredeep there are some mainly N–S oriented folds with very low rates of uplift (Edgell, 1996, Soleimany and Sàbat, 2010 and Soleimany et al., 2011).

In addition to these folds, there are a number of structural lineaments in lowland south-west Iran, with a particularly prominent c. 110 km long "concealed fault/deep-seated lineament" oriented E–W at about 31°47′N (Fig. 2; NIOC, 1977).

2.2. Interactions of the rivers Karun and Dez with growing folds

The rivers Karun and Dez encounter the NW–SE and N–S oriented folds as a succession of "obstacles" to their courses as major transverse rivers, and respond to each fold either by incising across the fold or by diverting around the "nose" of the fold.

As may frequently be the case in other fold-thrust belts (such as the Apennines of central Italy; Alvarez, 1999), the rivers Karun and Dez exhibit a paradoxical tendency to transect these anticlines at or near locations of their greatest structural and topographic relief (Oberlander, 1965). Within the Zagros Mountains and foothills with well-developed folds, the courses of the rivers Karun and Dez are generally "fixed" as "water gaps" in deeply incised valleys, and here the tendency may be due to the drainage network having been superimposed from above by a structurally conformable more easily eroded horizon (Oberlander, 1985) or by other mechanisms which apply after the initial stages of fold development (Simpson, 2004, Montgomery and Stolar, 2006 and Babault et al., 2012). Within the Khuzestan Plains with young and emerging folds, the courses of the rivers Karun and Dez are generally free to move by migrations and avulsions across the plains, and here the tendency is produced by mechanisms associated with the initial emergence of the folds (Woodbridge, 2013).

Where a major river initially encounters a fold as an emerging fold “core”, the river flows across the uplifting fold for sufficient time (at least several decades; Lahiri and Sinha, 2012) for the development of a narrow channel-belt, thus producing an incising river course (or “water gap”) across the fold in the vicinity of the fold “core” and the subsequent structural culmination. However, where a major river initially encounters a fold as a larger, emerged fold, the river does not flow across the uplifting fold for sufficient time, due to repeated channel migration in response to lateral fold growth, thus producing a river course diverting around the fold “nose”. Hence, river reaches across the fold axis for river incision are characterised by narrow channel-belts, low channel sinuosities, high specific stream powers, with river crossing locations relatively near to the fold “core” (generally less than 16 km). By contrast, river reaches across the fold axis projection for river diversion are characterised by average channel-belt widths and channel sinuosities with fairly wide ranging values, fairly low specific stream powers, and river crossing locations relatively far from the fold “core” (greater than 22 km) (Woodbridge, 2013).

2.3. Direct human impacts on the rivers Karun and Dez

In lowland south-west Iran, there are four main categories of direct human modifications to the river channels of the River Karun and River Dez: major dams, ruins of major dams, major anthropogenic river channel straightening, and artificial river development.

There are three major modern dam complexes in the Khuzestan Plains: the Gotvand Regulating Dam about 4 km north of Gotvand on the River Karun across the Turkalaki Anticline (KWPA, 2010); the Dez Regulating Dam in northern Dezful and the Dez Diversion Dam in southern Dezful on the River Dez across the Dezful Uplift (Fig. 3;KWPA, 2010); and the Band-e Mizan weir, Pol-e Boleiti dam-bridge and water mills in Shushtar on the River Gargar on the forelimb of the Shushtar Anticline (Fig. 4; Selby, 1844, Torfi et al., 2007, Verkinderen, 2009 and Moghaddam, 2012). The Gotvand Regulating Dam and the dams in Dezful are modern constructions and their use dates from about 1977 AD and 1963–1965 AD onwards, respectively (KWPA, 2010). The Band-e Mizan weir and Pol-e Boleiti dam-bridge in Shushtar are ancient constructions and their use dates from about the Early Sassanian Period (c. 224 – 379 AD) onwards (Alizadeh et al., 2004 and Verkinderen, 2009).

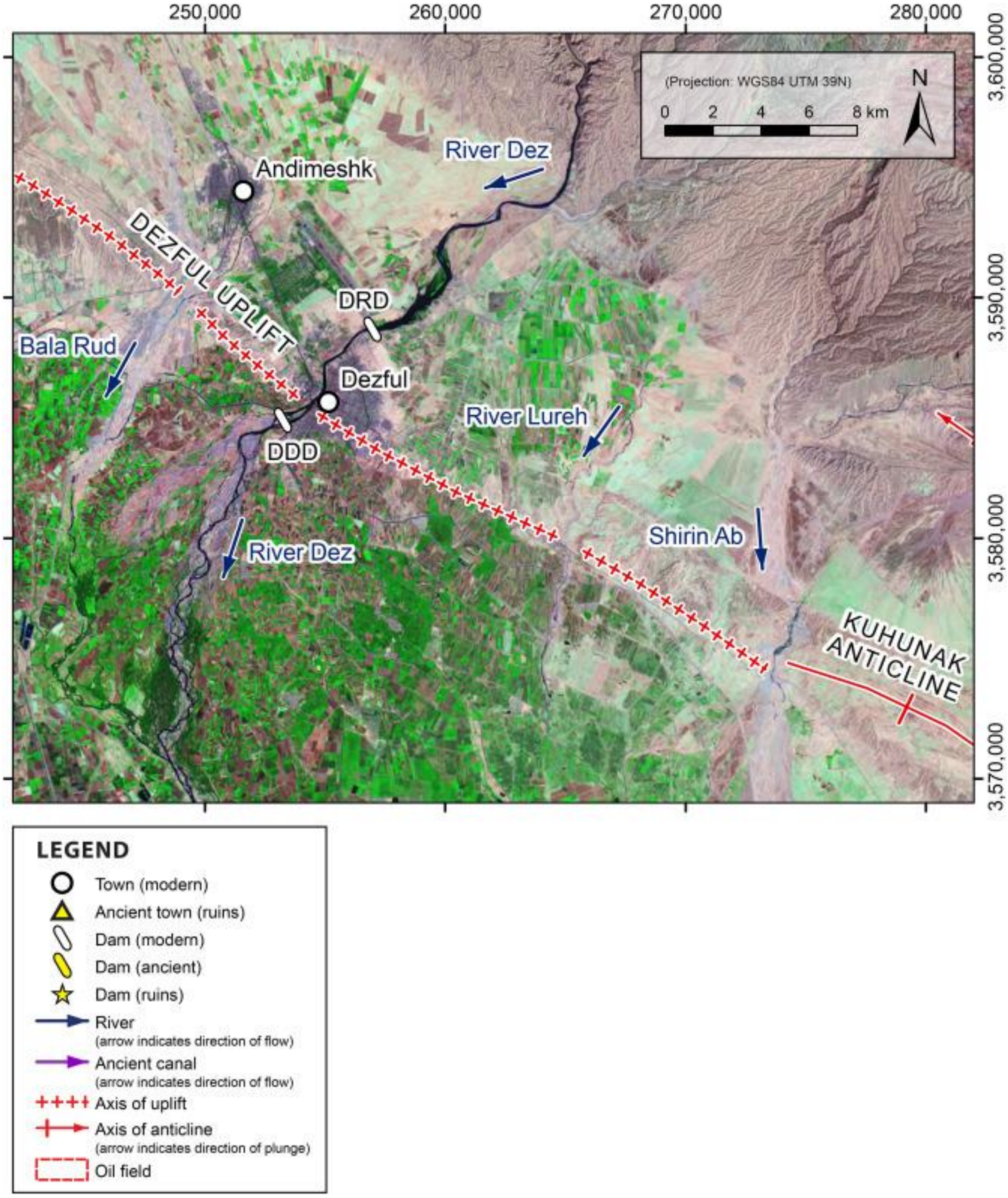

Fig. 3.

False-colour Landsat image (2000) of the vicinity of Dezful showing the Dezful Uplift extending to the NW off image and to the SE to the Shirin Ab. DRD = Dez Regulating Dam, DDD = Dez Diversion Dam.

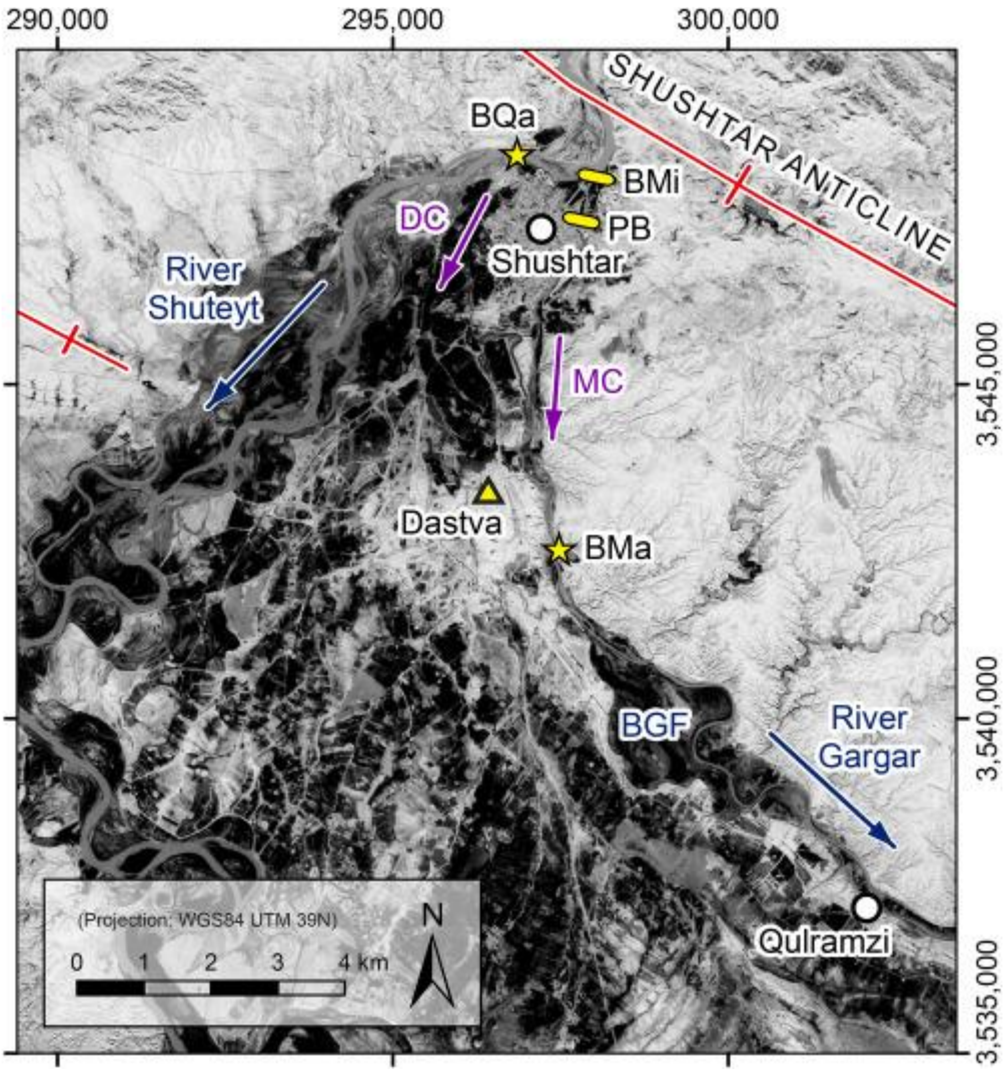

Fig. 4.

CORONA image (1968) of the vicinity of Shushtar showing the location of ancient dams and canals associated with the River Shuteyt and River Gargar. BQa = Band-e Qaisar, BMi = Band-e Mizan, PB = Pol-e Boleiti, BMa = Band-e Mahibazan, DC = former course of the Darian Canal, MC = former course of the Masrukan Canal, BGF = Broadened River Gargar floodplain. For a key to the symbols see legend of Fig. 3.

There are the ruins of three ancient major dams (or bunds) in the Khuzestan Plains: the "Band of Ahvaz" in Ahvaz on the River Karun across the Ahvaz Anticline (Fig. 5; Graadt van Roggen, 1905, GBNID, 1945, Aleyasin, 2001 and Walstra et al., 2010b); the Band-e Mahibazan on the River Gargar on a linear sandstone outcrop (Fig. 4; Moghaddam et al., 2005, Verkinderen, 2009 and Moghaddam, 2012); and the Band-e Qaisar in Shushtar on the River Shuteyt on the fore-limb of the Shushtar Anticline (Fig. 4; Torfi et al., 2007 and Verkinderen, 2009). The "Band of Ahvaz" collapsed at an unknown time in antiquity; though during the 19th Century AD a rebuilt dam was present (Ainsworth, 1838) and in the early 20th Century only the wall bases of the "Band of Ahvaz" dam and traces of mills on the end walls of the dam remained (Graadt van Roggen, 1905). The Band-e Mahibazan collapsed at an unknown time in antiquity, possibly during the 10th – 14th Centuries AD (Le Strange, 1905). The Band-e Qaisar ultimately collapsed in about 1885 AD (Modi, 1905 and Verkinderen, 2009). As ruins, these dams have limited impacts on the major rivers, though they may leave a prominent legacy. For instance, the past raising of river water levels by the Band-e Qaisar which fed into the Masrukan and Darian ancient monumental canal systems, ultimately resulted in the development of the Gargar branch of the River Karun (Woodbridge, 2013).

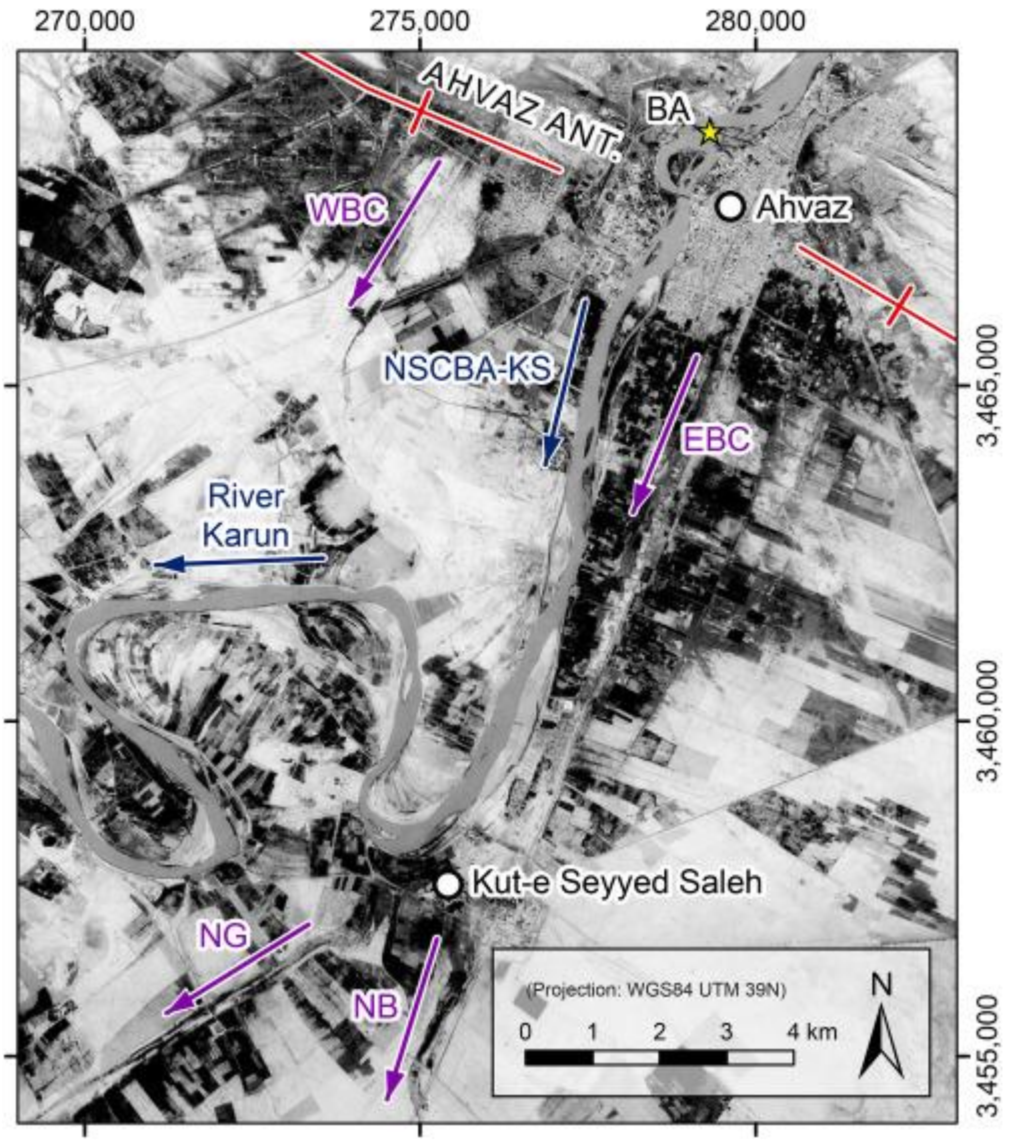

Fig. 5.

CORONA image (1968) of the vicinity of Ahvaz showing the near-straight river course of the Karun and the location of associated ancient canals. BA = Band of Ahvaz, NSCBA-KS = near-straight river course between the Band of Ahvaz and Kut-e Seyyed Saleh, EBC = East Bank Canal, WBC = West Bank Canal, NG = Nahr Gumalq, NB = Nahr Bahreh. For a key to the symbols see legend of Fig. 3.

There are four major near-straight river courses of the River Karun in the Khuzestan Plains: the c. 19 km long near-straight N–S course between Band-e Qir and Veys (NSCBQ-V) (Fig. 6; Layard, 1846, Le Strange, 1905, Bakker, 1956 and Alizadeh et al., 2004); the c. 11 km long near-straight NNE–SSW course between the “Band of Ahvaz” and Kut-e Seyyed Saleh (NSCBA-KS) (Fig. 5; Graadt van Roggen, 1905, Verkinderen, 2009 and Walstra et al., 2010b); the c. 13 km long near-straight NE–SW course between Dorquain and Masudi (NSCD-M) (Fig. 7 and Fig. 8; Chesney, 1850, Baeteman et al., 2005 and Verkinderen, 2009); and the c. 18 km long near-straight NE–SW course of the Haffar cut (HC) upstream of Khorramshahr (Fig. 7 and Fig. 8; Curzon, 1890, Potts, 2004,Walstra et al., 2010b and Heyvaert et al., 2013). The histories of these four major anthropogenic river channel straightenings are only poorly known, though it is possible to determine the likely minimum length of time that each of the long near-straight river courses has been in existence with only limited human maintenance. The NSCBQ-V probably developed by avulsion or diversion into the ancient Masrukan canal during the 10th – 14th Centuries AD, with very limited human impacts over about the last 600 years (Fig. 6; Le Strange, 1905, Bosworth, 1987 and Alizadeh et al., 2004). The NSCBA-KS probably developed from channelization procedures employed by the Sassanians and subsequent peoples, with only limited human impacts, such as rebuilding a dam at the location of the “Band of Ahvaz” and maintenance of the large East Bank Canal over about the last 700 years (Fig. 5 and Fig. 8; Ainsworth, 1838 and Verkinderen, 2009). The NSCD-M may have developed from a branch of the Mubaraki Canal, with very limited human impacts for maybe the last 200–700 years (Fig. 7 and Fig. 8; Chesney, 1850 and Bosworth et al., 1984). The HC was originally dug in about the 10th Century AD, with some human maintenance over the subsequent 1000 years, particularly from the mid-18th Century onwards when the course of the Haffar cut to the Bahmanshir River and the Shatt al–Arab became the main outlet of the Karun (Fig. 7 and Fig. 8; Curzon, 1890, Le Strange, 1905, Potts, 2004, Verkinderen, 2009, Walstra et al., 2010b and Heyvaert et al., 2013).

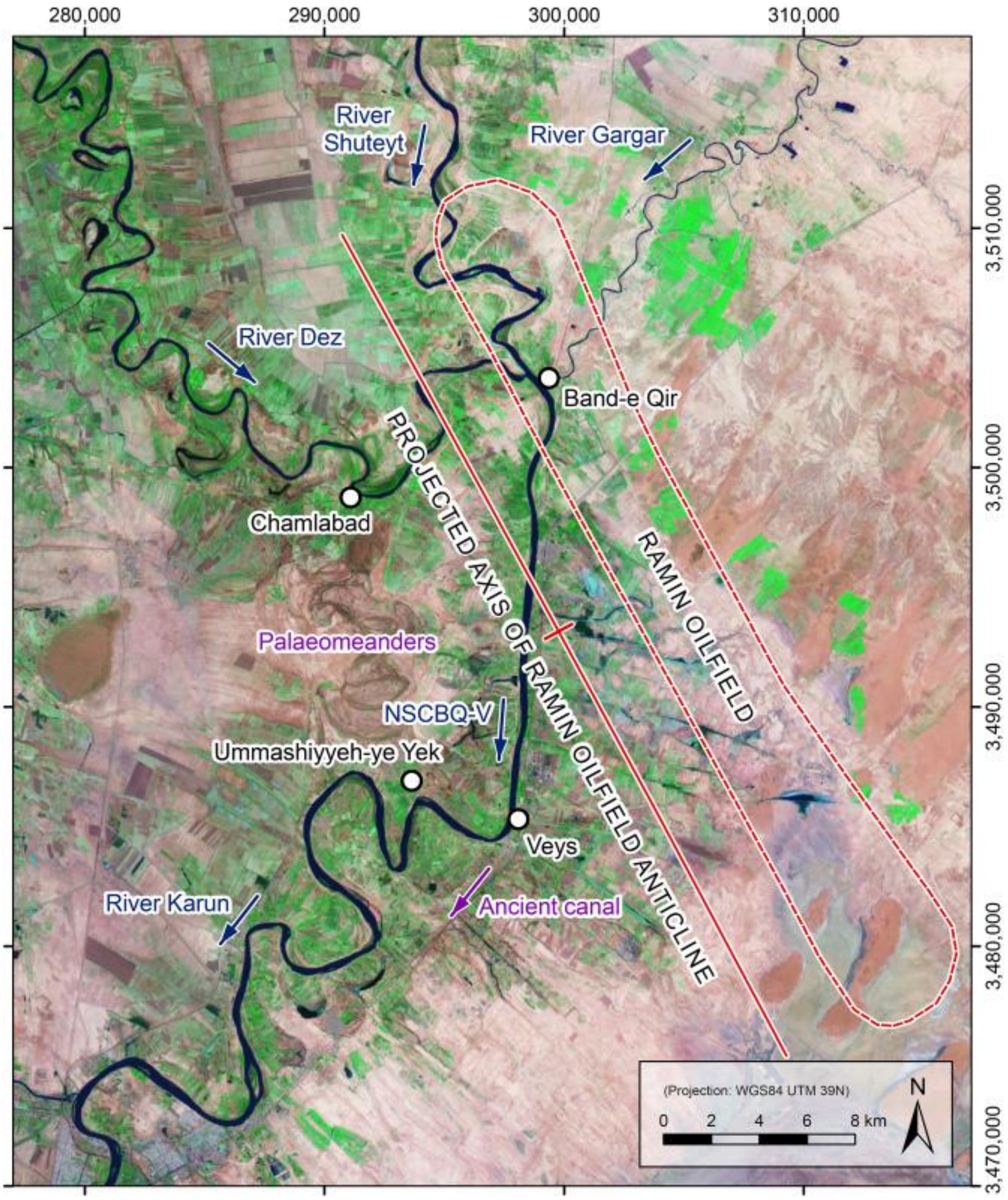

Fig. 6.

False-colour Landsat image (2000) of the vicinity of Veys showing the main river courses and location of the Ramin Oilfield Anticline. NSCBQ-V = near-straight river course between Band-e Qir and Veys. For a key to the symbols see legend of Fig. 3.

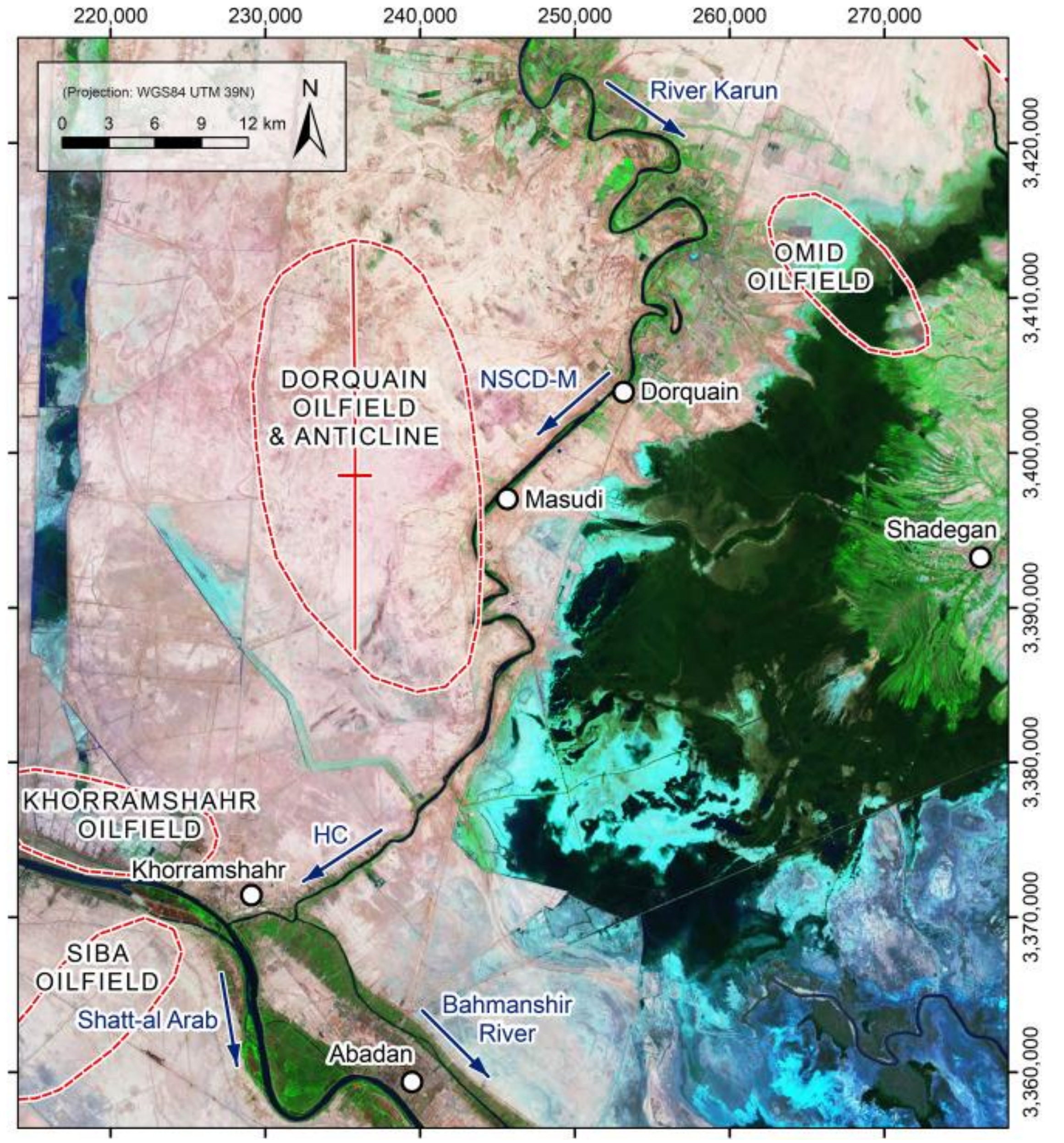

Fig. 7.

False-colour Landsat image (2000) of the lower reaches of the River Karun showing the main river courses, anticlines and oilfields. NSCD-M = near-straight river course between Dorquain and Masudi, HC = Haffar Cut. For a key to the symbols see legend of Fig. 3.

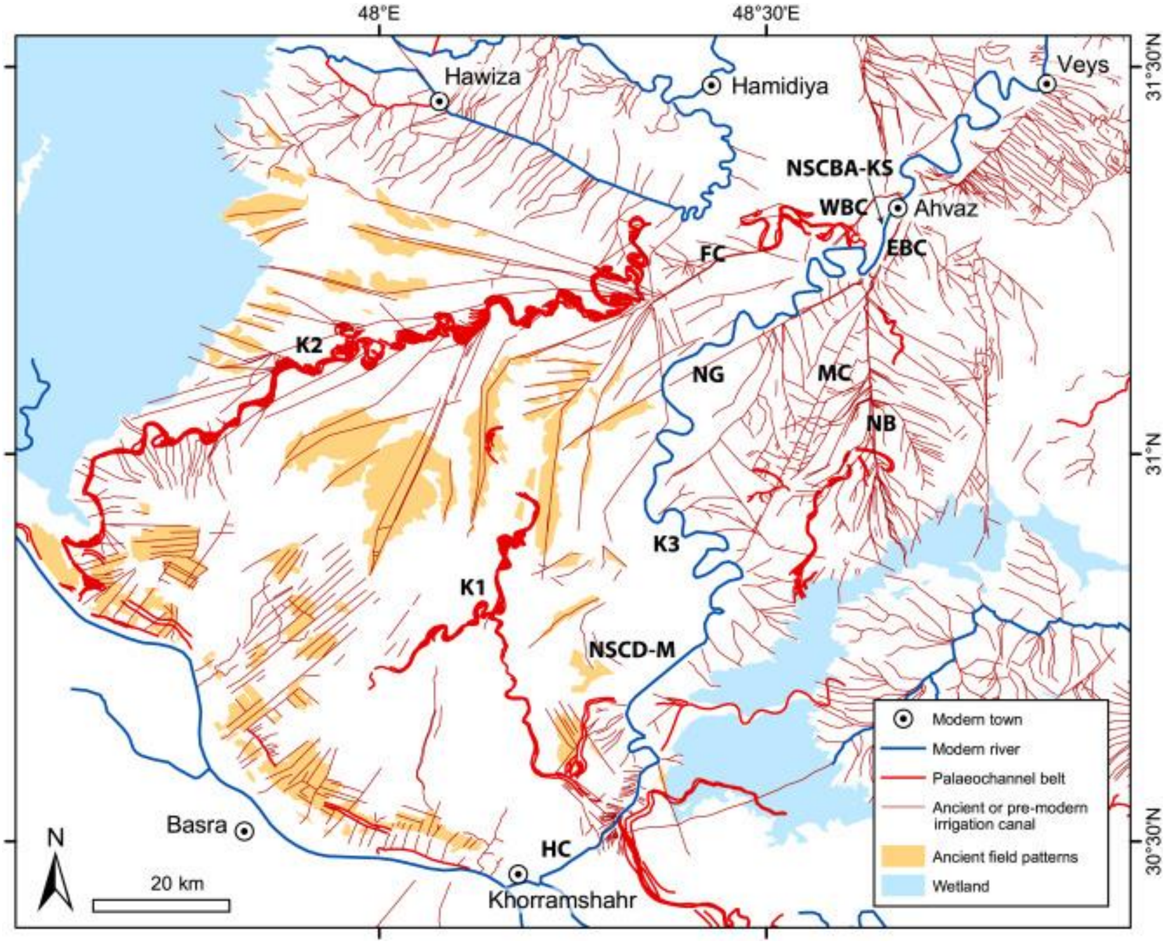

Fig. 8.

Large ancient irrigation systems of the Lower Khuzestan Plains, as mapped from CORONA satellite images. The East Bank large Canal (EBC) serving Nahr Gumalq (NG), Mubaraki Canal (MC) and Nahr Bahreh (NB) and the West Bank large Canal (WBC) serving a large Feeder Canal (FC) and numerous "feather canals" (depicted by ancient field patterns). Active straight river sections include the Band of Ahvaz to Kut-e Seyyed Saleh near-straight river course (NSCBA-KS), the Dorquain to Masudi near-straight river course (NSCD-M) and the Haffar Cut (HC). K1 and K2 represent palaeochannel belts of the River Karun, while K3 represents its currently active channel belt.

The only artificial river development of the Karun river system in the Khuzestan Plains is the River Gargar between Shushtar and Band-e Qir, a major branch of the River Karun (Fig. 1, Fig. 4 and Fig. 6). This artificial river development is distinct from anthropogenic river channel straightening in that it probably developed from an entire monumental irrigation system (the ancient Masrukan canal system mainly constructed in the Early Sassanian Period, c. 224 – 379 AD) when this large canal system fell into disuse, probably during the 10th – 14th Centuries AD (Le Strange, 1905, Bosworth, 1987,Moghaddam and Miri, 2003, Moghaddam and Miri, 2007, Alizadeh et al., 2004 and Moghaddam, 2012). It is a large feature with a valley length of c. 55 km and a mean annual discharge of c. 46 $m^3 s^{-1}$, with considerably greater discharges in the past (in the 14th – 15th Centuries AD the River Gargar was known as the “Du Danikah” or “two sixths” of the River Karun (Layard, 1846 and Modi, 1905), implying that its water discharges were roughly three times that of today). It has a number of natural characteristics including river incision, limited meandering, capture of wadis, and avulsions (Alizadeh et al., 2004).

2.4. Timescales of interactions between direct human impacts and earth surface movements

There is a relatively long history of prominent direct human impacts on the major rivers Karun and Dez in the Khuzestan Plains. These human impacts may interact with the gradual, mainly aseismic earth surface movements of faults and folds at locations where they coincide in the Khuzestan Plains, provided they have influences over the generally longer timescales of tectonics. Hence, influences on the reaches of major rivers can be sub-divided into three broad timescales:

i) Short timescales (less than 100 years) for which the influences of direct human impacts predominate (Downs and Gregory, 2004)

ii) Intermediate timescales (about 100 – 2000 years) for which there may be significant interactions between direct human impacts and earth surface movements

iii) Long timescales (more than about 2000 years) for which the influences of earth surface movements predominate, especially prior to the commencement of the monumental irrigation systems of the Sassanian Period (prior to c. 224 AD) (Alizadeh et al., 2004 and Burbank and Anderson, 2012)

3. Methods

To investigate the Karun and Dez in the Khuzestan Plains, the entire main river courses between Gotvand/Dezful and the Persian Gulf were sub-divided into a succession of river reaches (average length 8.0 km; extreme range of lengths 0.8 km–50.5 km). A reach was defined as a length of channel with homogeneous morphology and discharge (Hogan and Luzi, 2010) and significant changes in general river course direction and morphology were used to demarcate the end of one reach and the start of the next. A variety of methods were applied, including field survey (Kavanagh, 2009), geomorphological and sedimentological fieldwork (Goudie et al., 1990 and Jones et al., 1999a), and analysis of topographical information, geological maps, and remote sensing images. This included the use of a unified LandsatTM and CORONA database of processed and geo-referenced imagery using ERDAS IMAGINE and ArcGIS® software (Walstra et al., 2010a and Walstra et al., 2011). All of the data was compiled and used with data from previous work in the region to demarcate areas of human activities, structural geology, and river characteristics which included river hydrology, sedimentology, morphology, migration, and longitudinal profiles. The data was analysed to determine the key characteristics associated with human and tectonically induced controls on river geomorphology (Woodbridge, 2013).

Also, because earth surface movement rates in south-west Iran were only very poorly known, radiocarbon dating and Optically Stimulated Luminescence (OSL) dating of carefully selected samples to derive dated indicators of vertical earth surface movements was undertaken in the environs of the study area. Along the north-east coast of the Persian Gulf, two marine terraces were recognised. Radiocarbon dating was undertaken on marine mollusc shell samples from marine terrace sediments, using standard procedures for sampling (Gillespie, 1984, Aitken, 1990 and Pilcher, 1991). Radiocarbon laboratory procedures were undertaken by the Centre for Isotope Research, University of Groningen, the Netherlands, with conventional (beta-radioactivity) radiocarbon dating being used for larger shell samples (greater than 15 g mass) and Accelerator Mass Spectrometry (AMS) radiocarbon dating for smaller shell samples (Mook and Streurman, 1983, Van der Plicht and Lanting, 1994 and Van der Plicht et al., 2000). Details of the methods are given in Woodbridge (2013).

In the Upper Khuzestan Plains, six river terraces of the Karun river system were recognised. Optically Stimulated Luminescence (OSL) dating was undertaken on well-cemented block sediment samples from relatively homogeneous river terrace deposits containing fine and very fine sand and no gravels, using standard procedures for sampling and targeting sands at least several decimetres above bedload coarse sands and gravels (Aitken, 1998 and Colls et al., 2001). OSL laboratory procedures (Aitken, 1998) were undertaken by the Sheffield Centre for International Drylands Research (SCIDR), U.K. on quartz grains in the size range 90–180/250 μm using the single aliquot regenerative (SAR) approach of Murray and Wintle, 2000 and Murray and Wintle, 2003, as described in two Quartz Optical Dating Reports (Bateman and Fattahi, 2008 and Bateman and Fattahi, 2010). Details of the methods are given in Woodbridge (2013) and Woodbridge and Frostick (2014).

4. Results

The results for key river characteristics which help to differentiate between river incision across a fold, river diversion around a fold, and the four main categories of direct human impacts are summarised in Table 1a, Table 1b and Table 1c. In these tables, useful discriminating characteristics are highlighted in *italics* and especially useful discriminating characteristics are highlighted in ***bold and italics***.

Table 1a

Table 1a.

Key characteristics (human constructions and river geomorphology) which help to differentiate between the influences of active folds and direct human				
Type of external factor influencing river reaches	Characteristic of river (human constructions and river geomorphology)			
	Human constructions (and their traces) associated with river reaches	General river course direction (compass bearing in degrees)	Channel sinuosity	Vertical river incision (m)
River incision across a fold	No consistent changes of note	Reaches across fold axis: Generally approx. orthogonal (70° – 90°) to fold axis	Reaches across fold axis: Generally less than 1.4 (for reaches with no major direct human impacts<comma> lowest value is 1.12) and reduced (by mean 0.368) compared to upstream and downstream	Reaches across fold axis: Generally prominent vertical river incision<comma> c. 2 m – c. 7 m to 20 m or more below surrounding plains
River diversion around a fold	No consistent changes of note	Approx. parallel (0° – 20°) to fold axis upstream of fold nose<comma> changing by approx. 20° – 70° to flow around fold nose	Reaches across fold axis projection: Fairly wide range of values (for reaches with no major direct human impacts<comma> range is c. 1.27–1.79) and reduced (by mean 0.117) compared to upstream and downstream	No consistent changes of note
Major dams	Major dam and reservoir (dam c. 4 m – 27 m high<comma> reservoir up to c. 8.3 km long × 0.7 km wide)	No consistent changes of note	Compared with prior to major dam: Slight decrease by c. 0.017–0.046 upstream of dam (associated with reservoir)	Within 2.5 km channel distance downstream of major dam: Prominent vertical river incision<comma> c. 3 m – c. 8 m to 20 m or more below surrounding plains
Ruins of major dams	Ruins of major dam and reservoir remnant	No consistent changes of note	No consistent changes of note	No consistent changes of note
Major river channel straightening	Channel straightening	No consistent changes of note	Generally less than 1.1 over a greater than 10 km long river course	No consistent changes of note
Artificial river development	Many human constructions (including major structures<comma> canal traces and remnants<comma> and large ancient settlements)	No consistent changes of note	Wide range of values (c. 1.07–3.20)	Prominent vertical river incision<comma> c. 2 m – c. 8.5 m to 10 m or more below surrounding plains

Table 1b.

Key characteristics (channel geomorphology and river hydrology) which help to differentiate between the influences of active folds and direct human impacts.

	Characteristic of river (channel geomorphology and river hydrology)			
Type of external factor influencing river reaches	Channel width (m)	Channel width:depth ratio (and channel cross-sectional shape)	Channel water surface slope (m m−1)	Specific stream power (W m−2)
River incision across a fold	No consistent changes of note	Reaches across fold axis: Less than 70 (variety of cross-sectional forms)	Reaches across fold axis: Generally greater than 1.5 × 10−4 m m−1	Reaches across fold axis: Generally greater than 1.6 W m−2 and generally increased (by mean 8.285) compared with upstream and downstream
River diversion around a fold	No consistent changes of note	Reaches across fold axis projection: Less than 70 (variety of cross-sectional forms)	Reaches across fold axis projection: Less than 1.3 × 10−4 m m−1 and generally reduced (by mean 1.11 × 10−4 m m−1) compared to upstream and downstream	Reaches across fold axis projection: Wide range of values<comma> all less than 2.5 W m−2
Major dams	Within 2.5 km channel distance downstream of dam: Less than about 160 m (range c. 62 m – 154 m; c. 20 m – 57 m for R. Gargar)	Within 2.5 km channel distance downstream of major dam: Less than 50<comma> with range of values c. 3–50 (mainly triangular cross-sections)	Large drop of c. 2 m – 15 m in river water levels across major dam	Within 6.0 km channel distance downstream of major dam: Greater than about 16.0 W m−2 (range of values c. 16.3–67.3 W m−2)
Ruins of major dams	Within about 1.5 km channel distance upstream: Widening to c. 101 m – 850 m associated with the reservoir remnant	No consistent changes of note	Very slight drop in river water levels across the dam ruins of c. 0–1 m	No consistent changes of note
Major river channel straightening	Mean channel width of greater than about 180 m (range c. 140 m – 500 m)	Mean channel width:depth ratio greater than about 20<comma> with range of values c. 7–150 (trapezoidal or rectangular cross-sections along more than 70% of its length)	No consistent changes of note	No consistent changes of note
Artificial river development	Less than about 80 m	Generally less than 20 (mainly triangular & other cross-sections)	No consistent changes of note	No consistent changes of note

Table 1c.				
Key characteristics (river migration and river sedimentology) which help to differentiate between the influences of active folds and direct human impacts.				
Type of external factor influencing river reaches	Characteristic of river (river migration and river sedimentology)			
	Average channel-belt width (km)	Average channel migration rate 1966/68–2001 (m yr−1)	Average grain size of channel bed surface sediments	Average grain size of channel bank sediments
River incision across a fold	Reaches across fold axis: Less than 2.7 km (generally less than 1.5 km) and reduced (by mean 1.2 km) compared to upstream and downstream	Reaches across fold axis: Generally less than 1.8 m yr−1	No consistent changes/slightly increased across fold axis compared to upstream and downstream (21% of cases)/slightly decreased just upstream of fold compared with reaches further upstream (37% of cases)	No consistent changes/slightly increased across fold axis compared to upstream and downstream (31% of cases)/slightly decreased just upstream of fold compared with reaches further upstream (37% of cases)
River diversion around a fold	Reaches across fold axis projection: Wide range of values<comma> mostly greater than 2.7 km	Reaches across fold axis projection: Wide range of values<comma> mostly greater than 1.8 m yr−1	No consistent changes of note	No consistent changes of note
Major dams	No consistent changes of note	Within 6.0 km channel distance of major dam: Low rates of less than c. 1.1 m yr−1 (range c. 0.53 m yr−1 – 1.10 m yr−1; c. 0.08 m yr−1 for R. Gargar)	Not known	Not known
Ruins of major dams	No consistent changes of note	No consistent changes of note	No consistent changes of note	No consistent changes of note
Major river channel straightening	Less than 1.1 km (range of values c. 0.22 km – 1.09 km)	Less than c. 3.5 m yr−1(and generally less than c. 1.0 m yr−1)	No consistent changes of note/slightly decreased along near-straight reach compared to upstream and downstream	No consistent changes of note/slightly decreased along near-straight reach compared to upstream and downstream
Artificial river development	Less than 2.0 km (mostly less than 0.6 km)	Very low rates of less than 0.5 m yr−1throughout (and mostly less than 0.2 m yr−1)	No consistent changes of note	No consistent changes of note

The results for the fieldwork relating to earth surface movement rates, including the radiometric dating, are described in detail in Woodbridge (2013) and Woodbridge and Frostick (2014). Only a very short summary of the results is given here.

Along the north-east coast of the Persian Gulf of Iran two marine terraces were found: Marine terrace A, a moderately continuous ridge or berm of surface elevation of about +0.7 m to +3 m above Mean High Water, and Marine terrace B, a planar surface preserved as a capping on high rock outcrops at surface elevations of about +10 m to +30 m above Mean High Water (Woodbridge, 2006 and Woodbridge, 2013).

In the Upper Khuzestan Plains of south-west Iran, six river terraces of the Karun river system were found associated with active folds, and the terraces were assigned names in accordance with recommended stratigraphic practice (Salvador, 1994). As shown inFig. 9, four river terraces were associated with the Naft-e Safid Anticline: the ‘Dar Khazineh terrace’, the ‘Batvand terrace’, the ‘Naft-e Safid terrace’ and the ‘Abgah terrace’, on the fold fore-limb and back-limb. One river terrace was associated with the Sardarabad Anticline: the ‘Kabutarkhan-e Sufla terrace’, and one river terrace was associated with the Shushtar Anticline: the ‘Kushkak terrace’; both on the fold back-limb (Woodbridge, 2013 and Woodbridge and Frostick, 2014).

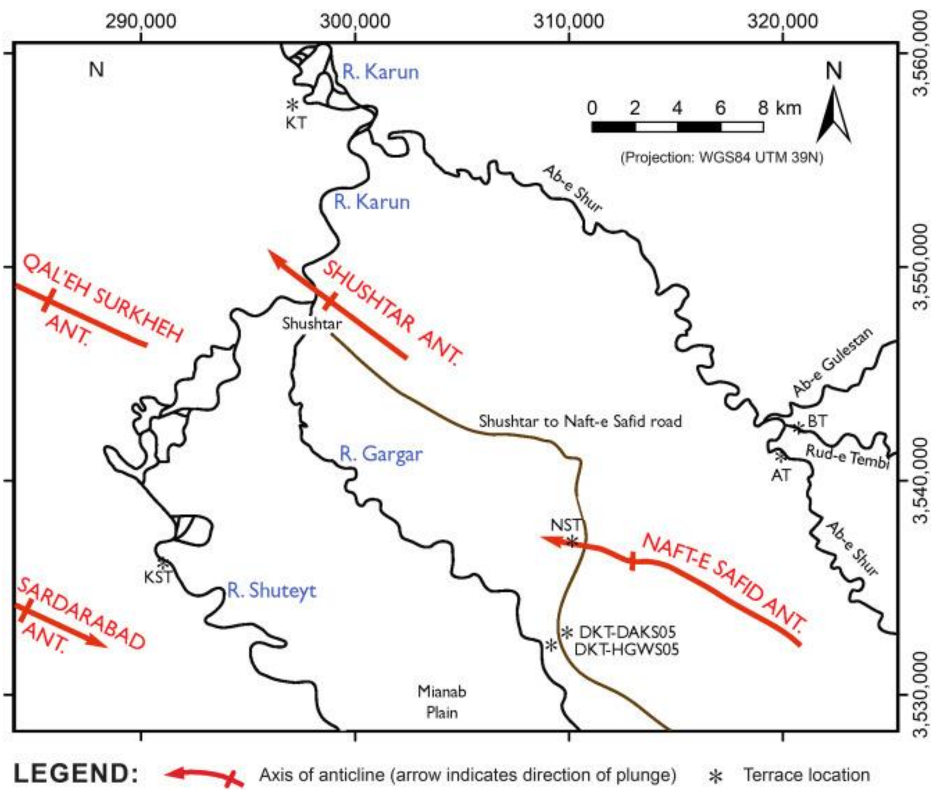

Fig. 9.

River terraces of the Karun river system in the Upper Khuzestan Plains (from Woodbridge, 2013). AT = Abgah terrace, BT = Batvand terrace, DKT-DAKS05 = Dar Khazineh terrace location DAKS05 (on east side of road), DKT-HGWS05 = Dar Khazineh terrace location HGWS05 (on west side of road), KST = Kabutarkhan-e Sufla terrace, KT = Kushkak terrace, NST = Naft-e Safid terrace.

The results of radiometric dating undertaken on samples from the marine terraces and the river terraces are summarised in Table 2.

Table 2.

Summary of radiometric dating results for the marine and river terraces.

Sample location (Terrace name, location code, and bed number)	Latitude and longitude	Elevation above MHW (Mean high water), NCC datum or rwl (river water level)	Sample type	Method of radiometric dating and laboratory code	Age (years BC or years cal.BC with error ± one σ)
Marine terraces					
Marine terrace ABANDN1 Bed 2	30°06′47″N50°07′44″E	+2.51 m above MHW	Marine mollusc shell	AMS14C datingGrA-15580	815 ± 87 cal.BC
Marine terrace ABINAK3 Bed 1	29°43′18″N50°20′44″E	+1.62 m above MHW	Marine mollusc shell	Conventional14C datingGrN-25106	1390 ± 91 cal.BC
Marine terrace BBINAK 4 Bed 6	29°43′39″N50°20′28″E	Approx. +18 m above MHW	Marine mollusc shell	AMS14C datingGrA-21606	>43,000 BC (infinite 14C age)
River terraces					
'Dar Khazineh terrace'DAKS05 Bed 2	31°54′47″N48°59′29″E	+29.89 m NCC+8.09 m rwl	Sediment (90 – 180/250 μm)	OSL datingFMMShfd08206	480 ± 190 BC
'Dar Khazineh terrace'DKLTFH Bed 10	31°54′46″N48°59′23″E	+30.52 m NCC+8.72 m rwl	Sediment(90 – 180/250 μm)	OSL datingFMMShfd08202	820 ± 220 BC
'Dar Khazineh terrace'HGWS05 Bed 7hgw	31°54′35″N48°59′09″E	+28.37 m NCC+6.57 m rwl	Sediment (90 – 180/250 μm)	OSL datingFMMShfd08207	3670 ± 360 BC
'Kabutarkhan-e Suflaterrace'KBS4OS Bed 2	31°56′28″N48°47′21″E	+29.90 m NCC+4.57 m rwl	Sediment (90 – 180/250 μm)	OSL datingCAM/FMMShfd08021	15,590 ± 2100 BC
'Batvand terrace'BFLS05 Bed 5	32°00′08″N49°06′06″E	+99.85 m NCC+6.69 m rwl	Sediment (90 – 180/250 μm)	OSL datingFMMShfd08024	8480 ± 830 BC
'Batvand terrace'BFLS05 Bed 2	32°00′08″N49°06′06″E	+98.49 m NCC+5.33 m rwl	Sediment (90 – 180/250 μm)	OSL datingFMMShfd08205	23,860 ± 1750 BC
'Kushkak terrace'KUHKL3 Bed 2	32°08′07″N48°50′34″E	Approx.+58.98 m NCC+9.18 m rwl	Sediment (90 – 180/250 μm)	OSL datingFMMShfd08210	17,970 ± 2000 BC
'Naft-e Safid terrace'DKITEB Bed 2	31°57′15″N48°59′32″E	+49.67 m NCC+27.61 m rwl	Sediment (90 – 180/250 μm)	OSL datingCAMShfd08019	20,490 ± 1100 BC
'Abgah terrace'BAF2BR Bed 4	31°59′32″N49°05′43″E	Approx.+114.82 m NCC+6.90 m rwl	Sediment (90 – 180/250 μm)	OSL datingFMMShfd08209	18,590 ± 3130 BC

5. Discussion

5.1. Earth surface movement rates

Rigorous analysis of the results of the OSL dating and archaeological dating of river terrace deposits and the geomorphological changes associated with ancient canals and ancient hydraulic structures cut across anticlines was applied to determine average rates of river incision subsequent to the deposition of river terrace deposits and the disuse of ancient canals and hydraulic structures (Woodbridge, 2013). River incision after terrace formation and after canal disuse depends on a number of factors including subsequent changes in sediment supply due to changes in climate, vegetation and land use, and subsequent changes in human activities (Woodbridge and Frostick, 2014). Nevertheless, average rates of river incision can be a guide to average rates of tectonic uplift, particularly over periods of thousands of years, since over these longer timescales the influences of changes in aggradation and incision due to changes in sediment supply tend to be evened out (Bull, 1991 and Burbank and Anderson, 2012). With these caveats, careful analysis of all of the data indicated average rates of uplift of c. 0.19–1.53 mm $yr^{-1}$for the Naft-e Safid Anticline, c. 0.23–0.29 mm yr^{-1} for the Sardarabad Anticline, c. 1.94–2.13 mm yr^{-1} for the Shahur Anticline, and c. 0–2.26 mm yr^{-1} for the Shushtar Anticline (Fig. 2 and Fig. 9; Woodbridge, 2013).

In addition, evidence for approximate rates of tectonic uplift was compiled using interpreted data for the river terraces, marine terraces (using the results of the radiocarbon dating of marine mollusc shells and a correction for $^{+}$0.7 m of hydro-isostasy), ancient canals and ancient hydraulic structures (Woodbridge, 2013), and interpolation of rates of GPS-detected horizontal surface motion of the Zagros relative to Arabia (Hatzfeld et al., 2010). This indicated that earth surface movements in lowland south-west Iran can be considered in four broad groupings, or four NW–SE trending zones, relative to the Zagros Deformation Front (ZDF) (Fig. 2; Woodbridge, 2013 and Woodbridge and Frostick, 2014):

A.

South-west of the ZDF: subsidence

B.

Vicinity of the Zagros Deformation Front (approximately 0–20 km to the SW and NE of the ZDF): Minimal vertical earth surface movements

C.

Approximately 20–60 km to the NE of the ZDF: Uplift at rates of approximately 0.1–0.8 mm yr^{-1}

D.

Approximately 60–130 km to the NE of the ZDF: Uplift at rates of approximately 0.2–2.3 mm yr^{-1}

These are approximate zones with some degree of overlap, due to errors involved with the data and due to the natural variation of tectonic movements, especially variations between individual folds (Woodbridge, 2013 and Woodbridge and Frostick, 2014). Nevertheless, the general trends of subsidence to the SW of the ZDF, minimal vertical movements in the vicinity of the ZDF, and increasing uplift with distance NE of the ZDF, are broadly consistent with what is known of the structural geology of the region (Berberian, 1995, Abdollahie Fard et al., 2006 and Nissen et al., 2011).

5.2. Interactions between major modern dams and earth surface movements

The three major modern dam complexes associated with the Karun river system in the Khuzestan Plains are readily distinguishable due to the large size of the dams (c. 4 m – 27 m high) and their associated reservoirs (up to c. 8.3 km long × 0.7 km wide). Also, there are prominent associated river characteristics in the vicinity of the dam (such as a large drop of c. 2 m – 15 m in river water levels across the dam) and for several kilometres upstream and downstream of the dam (such as channel widths of less than c. 160 m within 2.5 km channel distance downstream of the dam) (Table 1a and Table 1b). The main challenge is interpreting which characteristics were present before the dam was constructed (mainly related to fold–river interactions) and which characteristics developed after the dam was constructed (mainly related to human activities). Major dams are often constructed where a river incises across a moderately or well-developed fold, due to features such as low channel sinuosities, low braiding indices, narrow valleys and channel-belts, and outcrops of firm bedrock which make these locations good sites for dams (Weaver and Bruce, 2007).

There are three major modern dams located near to the fold axis of the Turkalaki Anticline and the Dezful Uplift on the rivers Karun and Dez (Fig. 3) and one ancient dam still in use located on the fore-limb of the Shushtar Anticline on the River Gargar (Fig. 4). Though there are no detailed survey data available prior to their time of construction (c. 1963 – 1977 AD and c. 224 – 379 AD), it is clear that some of their characteristics, such as a large drop in river water levels across the dam and a reservoir upstream of the dam, are due to human activities. What is less clear is which proportion of the river incision just downstream of these dams (with high specific stream powers of 16.3–67.3 W m^{-2} within 6.0 km downstream, Table 1b) is attributable to clearer, "hungry" water emerging from the dam (Kondolf, 1997), and which proportion was present prior to dam construction and thus attributable to uplift of the fold. In this respect, the characteristic of average channel-belt width is a useful discriminator. For river reaches across the fold axis of the Turkalaki Anticline, Dezful Uplift and Shushtar Anticline, there are narrow channel-belts with average channel-belt widths of 1.214 km, 2.579 km and 0.533 km, respectively, which have probably taken centuries to develop and which are very similar on remote sensing images from before and after the construction of the three modern dams. Hence, it is likely that the river incision associated with limited channel migration in the vicinity of the fold axis is mostly influenced by fold uplift and exposure of erosion-resistant fold rocks. The river incision associated with increased channel water surface slopes and increased specific stream powers just downstream of the dam is probably mostly influenced by the construction and use of the dam.

The three modern major dams in the study area have only been in use over about the last 50 years. Over this relatively short time interval with uplift at rates of c. 0.1–2.3 mm yr^{-1}, total vertical earth surface movements will have been very small, of the order of c. 0.01 m – 0.12 m. Hence, to date, ***there have been no significant interactions between earth surface movements and direct human impacts associated with the modern dams***. With time, uplift of the Turkalaki Anticline should increase sediment aggradation upstream of the Gotvand

Regulating Dam located very near the fold axis, and enhance river incision immediately downstream of this dam. With time, uplift of the Dezful Uplift should enhance river incision between the two dams located near the edges of the limbs of the Dezful Uplift. These changes would be undesirable since they would promote undermining of the Gotvand Regulating Dam and the Dez Regulating Dam (Komura and Simons, 1967 and Downs and Gregory, 2004), especially in the case of an earthquake.

The Pol-e Boleiti dam-bridge in Shushtar on the River Gargar is a much older major dam. Its original construction probably dates to the Early Sassanian Period (c. 224 – 379 AD) and, with various repairs and constructions through history, it is likely that some dam or structure holding back the River Gargar has been present at the locality for more than 1700 years from the time of the Sassanians to the present (Alizadeh et al., 2004 and Verkinderen, 2009). Over this relatively long time interval there will have been some notable vertical earth surface movements associated with uplift of the fore-limb of the Shushtar Anticline. If these vertical movements were uplift at rates of c. 0–2.26 mm yr^{-1} (Woodbridge, 2013), then total vertical movements over this time span would have been of the order of c. 0 m – 3.8 m. It is difficult to determine the influences that this structural uplift has had on the characteristics of the River Gargar, due to the other large changes which have occurred through history, particularly the change from the Masrukan canal to the River Gargar in the c. 10th −14th Centuries AD, and the collapse of the Band-e Qaisar dam-bridge in c. 1885 AD, which changed the River Gargar into a much smaller river (Le Strange, 1905, Modi, 1905 and Verkinderen, 2009). It may be that the deep, narrow gorge downstream of the Pol-e Boleiti dam-bridge in Shushtar is partly natural, due to river incision in response to long-term uplift of the fore-limb of the Shushtar Anticline (Woodbridge, 2006), and that incision through this gorge since the construction of the Masrukan canal has been enhanced by continued anticlinal uplift.

5.3. Interactions between ruins of major dams and earth surface movements

The ruins of the three major ancient dam ruins associated with the Karun river system in the Khuzestan Plains are readily distinguishable from the prominence of the dam ruins (Fig. 4 and Fig. 5) and the associated slight increases in channel widths immediately upstream of the ruins due to the reservoir remnant (Table 1b). These ancient dams would have had considerable impacts on river characteristics whilst in use and, since their collapse, the modified river characteristics have become progressively muted with time.

The major dam ruins are associated with the relatively small changes of channel broadening to about 101 m–850 m within about 1.5 km channel distance upstream of the ruins associated and very slight drops in river water levels of about 0 m–1 m across the ruins (Table 1b). The original dams and their ruins have had influences over intermediate timescales of 100 years to 1000 years or more (Curzon, 1892, Bosworth et al., 1984,Hodge, 1992, Moghaddam and Miri, 2007, Verkinderen, 2009, Walstra et al., 2010b and Moghaddam, 2012). These timescales are sufficiently long for interactions with earth surface movements to have taken place. For the Ahvaz Anticline with probable uplift rates of c. 0.1–0.8 mm yr^{-1}, total vertical movements have probably been c. 0.07 m – 0.56 m for the “Band of Ahvaz” on the River Karun. For the Shushtar Anticline with uplift rates of c. 0–2.26 mm yr^{-1}, total vertical movements have probably been c. 0 m – 1.35 m for the Band-e Mahibazan on the River Gargar and c. 0 m – 0.26 m for the Band-e Qaisar on the River Karun (Shuteyt) (Woodbridge, 2013). Also, these vertical earth surface movements may have promoted river incision and narrowing of the reservoir remnant upstream of the dam ruins. In short, ***there have been probable interactions between earth surface movements associated with active folds and major dam ruins, though with only slight and localised effects on major rivers***.

5.4. Interactions between major anthropogenic river channel straightening and earth surface movements

There are four major anthropogenic river channel straightenings of the River Karun in the Khuzestan Plains. It is important to distinguish these from the influences of earth surface movements, since some co-workers informally considered that they may be primarily related to faulting or sedimentology, and for one case (the c. 13 km long NSCD-M) there are no historical records linking the near-straight course to human activities.

The main discriminative characteristic is the very low channel sinuosity of generally less than 1.1 over a greater than 10 km length. Such long, near-straight alluvial river courses are very rare in nature and, generally, are associated with braided channel belts rather than single-thread meandering river systems (Frenette and Harvey, 1973, Rosgen, 1994, Orfeo and Stevaux, 2002 and Wang and Ni, 2002). The longest presumed natural near-straight river course in the Khuzestan Plains (a River Dez reach across Sardarabad Anticline of channel sinuosity 1.120) has a channel length of only 6.535 km. Also, natural near-straight river channels are generally narrow and deep, frequently with channel width:depth ratios of less than 12 (Rosgen, 1994). By contrast, human-influenced near-straight river channels are broad and shallow, with mean channel widths of greater than about 180 m and mean channel width:depth ratios of greater than about 20 in the Khuzestan Plains (Table 1b). Hence, where long, near-straight river courses also have broad, shallow channels with mainly trapezoidal and rectangular channel cross-sections and low rates of river migration, it is reasonable to conclude that they were predominantly due to direct human impacts.

The four cases of major anthropogenic river channel straightening of the River Karun in the Khuzestan Plains have probably been present over intermediate timescales of about 200 – 1000 years (Alizadeh et al., 2004 and Verkinderen, 2009); sufficiently long for interactions with earth surface movements to have taken place. Uplift rates for the anticlines associated with the four cases are approximately 0.1–0.8 mm yr^{-1}, so total vertical movements will have been c. 0.02 m – 0.80 m over about 200 – 1000 years.

It is unexpected that these long, near-straight river courses should have persisted over hundreds of years with only limited subsequent direct human modifications. It is particularly unexpected when it is considered that some features (such as the canal traces) indicate that ancient canals originally extended beyond the preserved near-straight courses, and that when the ancient Masrukan canal fell into disuse across the Mianab Plain it did not retain its original near-straight course but developed into the meandering River Gargar (Fig. 4 and Fig. 6). Three out of four cases of major anthropogenic river channel straightening have river courses across the axis of an anticline and the fourth (the NSCD-M) has a river course immediately upstream of an emerging anticline. Hence, ***it is likely that earth surface movements associated with active folds are key factors in the persistence of the long, near-straight river courses***.

There are details of the near-straight river courses which support this interpretation. The c. 19 km long NSCBQ-V and a c. 4 km long River Dez short near-straight SW–NE reach upstream of Band-e Qir both coincide with the approximate projected surface location of axis of the emerging Ramin Oilfield Anticline (Fig. 6). Along these very low sinuosity reaches (1.038 and 1.062, respectively), average channel-belt widths are narrow (about 0.718 km and 1.944 km, respectively) and specific stream powers are moderate (about 1.663 W m^{-2} and 2.849 W m^{-2}, respectively). By contrast, immediately upstream and downstream of these near-straight reaches, the average channel-belt widths are broader (about 2.494–4.920 km) and the specific stream powers are slightly less (about 1.485–2.488 W m^{-2}) (Woodbridge, 2013). This indicates that the human-influenced near-straight reaches are being preferentially maintained in response to the structural uplift of the Ramin Oilfield Anticline, even though the rates of uplift of this anticline are not known. The mechanism whereby this takes place is that across the axis and crest of the anticline where uplift rates are greatest, very low channel sinuosities, narrow channel-belts and relatively high specific stream powers are promoted to maximise river erosion and incision in response to fold uplift (Brocklehurst, 2010 and Burbank and Anderson, 2012). Upstream and downstream of this area of higher structural uplift rates, any promotion of river incision is much less and the river is “free” to migrate away from the confines of the human-influenced near-straight reaches and to have a natural, meandering course.

The c. 11 km long NSCBA-KS coincides with the axis of Ahvaz Anticline. Along this very low sinuosity reach (1.063), average channel-belt width is narrow (about 0.787 km) and specific stream power is high (about 10.777 W m^{-2}) along the initial c. 3 km of the near-straight reach. By contrast, immediately upstream and downstream of the near-straight reach, the average channel-belt widths are broader (about 2.060–5.002 km) and the specific stream powers are less (about 0.663–0.978 W m^{-2}) (Woodbridge, 2013). This pattern is similar to that for the River Karun and River Dez across the Ramin Oilfield Anticline and similarly indicates that the human-influenced c. 11 km long near-straight reach is being preferentially maintained in response to structural uplift of the Ahvaz Anticline. However, there are differences between the initial c. 3 km of the near-straight reach coincident with the axis and outcrops of the Ahvaz Anticline (which includes the Ahvaz rapids and high specific stream powers of c. 10.777 W m^{-2}) and the final c. 8 km of the near-straight reach beyond the outcrops of the Ahvaz Anticline (which includes alternating point bars accumulating on a previously very straight course and low specific stream powers of c. 0.631 W m^{-2}; Fig. 5) (Woodbridge, 2013). Hence, it appears that structural uplift and greater rock erosion resistance associated with the Ahvaz Anticline greatly influences the initial c. 3 km of the near-straight reach, whereas the influences of the Ahvaz Anticline on the final c. 8 km of the near-straight reach are only slight. It is likely that the diversion away from the near-straight course at Kut-e Seyyed Saleh towards the west is influenced by other factors in addition to tectonics, such as diversion away from the slightly elevated "Karun canal lobe" to the south. This canal lobe probably developed from sedimentation associated with disuse of channels and canals (such as the Mubaraki Canal, Nahr Bahreh and Nahr Gumalq shown on Fig. 8) from about the Early Islamic Period (c. 633 – 750 AD) onwards (Baeteman et al., 2004, Verkinderen, 2009 and Heyvaert et al., 2013).

The c. 13 km long NSCD-M does not coincide with any anticlines or oilfield anticlines known from geological maps or published articles (Fig. 2 and Fig. 7). If this NE–SW near-straight channel was originally an extension of Mubaraki Canal to the north-east (Fig. 8) which was retained as a course of the River Karun when the canal fell into disuse, then its NE end near Dorquain is expected due to the slightly elevated "Karun canal lobe" which the course of the River Karun diverts around (Fig. 7 and Fig. 8; Baeteman et al., 2004,Verkinderen, 2009 and Heyvaert et al., 2013). The reasons for it not having a downstream extent further SW than Masudi are unclear, though tectonic uplift associated with the Dorquain Oilfield Anticline may be an influence. The course of the River Karun diverts to the south on encountering the margin of the Dorquain Oilfield Anticline at Masudi (Fig. 7) and has a reduction in channel water surface slopes (from 7.70×10^{-5} to 1.32×10^{-5} m m^{-1}) and specific stream powers (from 1.646 to 0.427 W m^{-2}) with distance along the near-straight course (Woodbridge, 2013). These could be features associated with tectonic uplift of the Dorquain Oilfield Anticline, though there does not appear to be a topographic high at the mapped location of the Dorquain Oilfield and it is probable that rates of uplift associated with its anticline are slight at around 0.1 mm yr^{-1}(Abdollahie Fard et al., 2006 and Soleimany and Sàbat, 2010). In summary, earth surface movements probably have had an influence on the Dorquain to Masudi near-straight reach, though the influence is fairly slight and it is associated with the south-west extent of the near-straight reach. Other factors, such the constraining influence of the River Jarrahi delta to the east (Fig. 7), may have been more influential in the persistence of this near-straight river course (Walstra et al., 2010a and Heyvaert et al., 2013).

For the c. 18 km long River Karun near-straight NE–SW course of the Haffar cut (HC) there are associations with tectonics in that the HC flows across the southern projection of the

Dorquain Oilfield Anticline (Fig. 7). Since this anticline probably extends beyond the mapped extent of the oilfield and there is a N–S structural trend in its vicinity (Edgell, 1996, Abdollahie Fard et al., 2006 and Maleki et al., 2006), it is probable that the river reaches immediately upstream of the HC and along the initial c. 14 km of the HC, flow across an area of uplift. Along this stretch across the projection of the anticlinal axis, values of channel sinuosity (1.050) and average channel-belt width (c. 0.374 km) are low, and slightly less than values for reaches immediately upstream and downstream (channel sinuosity c. 1.125–1.675 and average channel-belt width c. 0.321–1.208 km). This suggests that uplift associated with the Dorquain Oilfield Anticline is promoting the persistence of the straightness of the HC, by promoting river incision and inhibiting meandering. However, across the projection of the Dorquain Oilfield Anticline values for channel water surface slopes (c. 3.31×10^{-5}) and specific stream powers ($1.015 Wm^{-2}$) are rather low and certainly are not greater than for reaches slightly further downstream (Woodbridge, 2013). Also, as stated above, rates of uplift associated with the Dorquain Oilfield Anticline are probably slight at around $0.1 mmyr^{-1}$(Abdollahie Fard et al., 2006 and Soleimany and Sàbat, 2010), which over the c. 1000 years since the HC was initially dug (Potts, 2004) would only entail total vertical movements of the order of about 0.10 m. Such vertical movements might be sufficient to influence a major river on the very gently sloping Abadan Plain, but would be a fairly small influence compared with other factors like the mid-18th Century AD channel widening and recent dredging programs (Potts, 2004 and Verkinderen, 2009). In summary, earth surface movements probably have exerted an influence on the persistence of the near-straight river course of the Haffar cut, but other human impacts may have exerted a greater influence.

5.5. Interactions between artificial river development and earth surface movements

The River Gargar artificial river development is readily distinguishable by the many human constructions associated with its c. 55 km valley length and by its lack of features of mature meandering channels (Alizadeh et al., 2004, Moghaddam and Miri, 2007 and Moghaddam, 2012). It is characterised by a narrow channel-belt (average channel-belt widths less than 2.0 km), low average channel migration rates (less than $0.5 myr^{-1}$ for the period 1966/1968–2001), and prominent vertical river incision (about 2 m–10 m or more below the surrounding plains) (Table 1a and Table 1c). Many of the features of the River Gargar are partly natural, such as its gently meandering course, its capture of tributary wadis from the east, and its incision across folds (Verkinderen, 2009), but findings like straight canal traces, no meander cut-offs, and stream confluences at unnatural angles show that these features have developed after disuse of a human cut canal (Alizadeh et al., 2004).

Along its length, the artificial River Gargar encounters the projections of two anticlines, the Qal'eh Surkheh Anticline and the Kupal Anticline. The River Gargar incises across the fold axis projections of the Qal'eh Surkheh Anticline and Kupal Anticline with little change in average channel-belt widths (an increase from c. 0.068 km–0.193 km, and a decrease from c.

0.433 km–0.205 km, respectively) and ***the River Gargar incises at a long distance of 43.0 km from the fold "core" of the Kupal Anticline***. These fold–river interactions for the artificial River Gargar are significantly different to the fold–river interactions for the comparatively natural River Karun (Shuteyt) and River Dez, which incise across the axis of folds at distances from the fold "core" of less than 16 km (Woodbridge, 2013).

The different response of the artificial River Gargar to these folds compared with the natural River Karun and River Dez is related to the very limited lateral channel migration of the River Gargar. Throughout its history of about 600 – 1000 years it has produced no meander cut-offs or oxbow lakes and so probably has had channel-belts of average width similar to the 2.0 km or less of the present-day (Le Strange, 1905, Alizadeh et al., 2004 and Verkinderen, 2009). With such limited lateral migration, the River Gargar will only respond to encountering an active fold by incising across the fold or by being "defeated" by the fold, and in both cases the river was not "defeated". For the Qal'eh Surkheh Anticline, the river incision is not unexpected since the extent of the ESE influence of the fold is unclear. For the Kupal Anticline, the river incision across the fold near the fold "nose" is somewhat unexpected, especially since the course across the fold axis has developed into a meandering channel (albeit of fairly low channel sinuosities of c. 1.259–1.301), rather than retaining the original near-straight channel of the ancient Masrukan canal which would have maximised incision across the fold. It may be that with possibly rapid breaches or collapse of the Band-e Mahibazan, there was a short period of rapid incision, flooding (especially in the broadened River Gargar floodplain shown inFig. 4), and gentle meander formation, which acted at a rate that was too rapid (perhaps a few decades) to be influenced by the earth surface movements of the order of c. 1.0 mm yr^{-1}. Subsequently, when rates of incision and other changes had slowed as the artificial River Gargar trended towards an equilibrium, the River Gargar may have responded to tectonic uplift associated with the Kupal Anticline by slight decreases in channel sinuosity and average channel-belt width, in a manner similar to that found for natural rivers incising across active folds (Brocklehurst, 2010 and Burbank and Anderson, 2012). More research on the development of the artificial River Gargar is needed to fully interpret its interactions with active folds.

The River Gargar also encounters the c. 110 km long "concealed fault/deep-seated lineament" oriented E–W at about 31°47′N (NIOC, 1977) and is influenced by it. As shown in Fig. 2, ***the location of the E–W lineament corresponds closely with a highly sinuous reach of the River Gargar which has prominent E–W oriented meanders***. Whilst the details of the movements associated with this deep-seated lineament are not known, the majority of extensive lineaments with lengths of tens of kilometres are associated with fault zones or shear zones bounding structural blocks in the Pre-Cambrian basement, which produce joints and small vertical displacements that may be of the order of one or two metres (Mason, 1992 and Gay, 2012). Such a vertical displacement appears to be manifest as fairly steep valley slopes (6.121×10^{-4} m m^{-1}) for this reach of the River Gargar, with the high channel sinuosity (3.195) developing to maintain fairly typical Gargar channel water surface slopes (5.65×10^{-5} m m^{-1}) across the slight vertical displacement of the lineament (Woodbridge, 2013). The E–W meander orientation for this reach most probably is related to the approximate E–W orientation of the lineament and associated joints, especially since they may act as hydraulic conduits or barriers (Park, 1997, Gleeson and Novakowski, 2009 and Gay, 2012). The River Karun (Shuteyt) and the River Dez flow across this extensive structural lineament with no notable geomorphological modifications (Fig. 2), probably due to their greater water and sediment discharges and greater stream powers.

5.6. Interactions between direct human impacts and earth surface movements at valley and basin scales

These direct human impacts and their interactions with earth surface movements at river reach scales may also have influences at valley and basin scales, due to their influences on the development of river courses.

The most significant influences on the drainage network and drainage basin are associated with the locations where rivers incise across emerged folds. Once a river has developed and maintained a narrow channel-belt across a fold for several millennia, the river course effectively becomes “fixed” at that location. The river course may change from this “fixed” or “captured” river course if the river is subsequently “defeated” by the active fold, though this is rare with major rivers due to their relatively high discharges and stream powers (Woodbridge, 2013).

Major dams may have influences on these “fixed” river course locations, though their influences are slight. Major dams may enhance river incision across the fold where they are constructed on a river near to where it is incising across a fold axis, as is the case with the Gotvand Regulating Dam on the River Karun across the Turkalaki Anticline and the two major dams on the River Dez across the Dezful Uplift (Fig. 3). However, the River Karun across the Turkalaki Anticline near Gotvand and the River Dez across the Dezful Uplift at Dezful may have originally developed these “fixed” locations many centuries or millennia ago. The major dams will only significantly influence their future development if they are maintained for centuries to come. The ruins of major dams in the Khuzestan Plains demonstrate that a dam may have significant influences on river characteristics and development, but that these influences reduce rapidly if the dam should collapse and not be restored. The Band-e Qaisar, which was probably constructed in the 3rd Century AD, created the monumental Masrukan canal/River Gargar and the Darian canal, but with its disuse and collapse in the 19th Century AD, the River Gargar and the Darian canal became considerably reduced in size and water flows (Modi, 1905 and Verkinderen, 2009). Thus, the influences of a major dam on river courses are dependent on human activities in the future.

Major anthropogenic river channel straightening and artificial river development have more prominent influences on these “fixed” river course locations. In the Upper Khuzestan Plains, the development of the disused ancient Masrukan canal into the River Gargar has greatly altered the course of the River Karun on the Mianab Plain. At Shushtar, the river divides into two main branches, with the artificial Gargar branch having a course through a gorge just south of Shushtar and across the Kupal Anticline near its fold “nose”. ***If conditions and human impacts are similar for centuries to come, the “new” River Gargar will become a “fixed” branch of the River Karun, and the N–S river course on the limb of the Shushtar Anticline near the water mills and the NE–SW river course across the Kupal Anticline upstream of Band-e Qir will both become “fixed”*** (Fig. 2, Fig. 4 and Fig. 6).

Further south, the influence of the Masrukan canal has altered the courses of the River Karun and River Dez so that they now have a confluence at Band-e Qir rather than at Chamlabad, and a near-straight course further east between Band-e Qir and Veys (the former course of the Masrukan canal) rather than between Chamlabad and Ummashiyyeh-ye Yek (Fig. 6). ***If the near-straight course between Band-e Qir and Veys is maintained for many centuries to come, then a “fixed” river course will develop N–S across the Ramin Oilfield Anticline***. Thus, the influences of major anthropogenic river channel straightening and artificial river development on river courses are dependent on human activities in the future. It is interesting to consider that a length of the ancient Masrukan canal (the c. 19 km NSCBQ-V) may persist for millennia to come as a result of structural uplift of the Ramin Oilfield Anticline.

The major anthropogenic river channel straightening between the “Band of Ahvaz” and Kut-e Seyyed Saleh is likely to be maintained, even with minimal future human impacts, since the narrow channel-belt course of the River Karun across the Ahvaz Anticline has been established for many millennia with an incised valley that is tens of metres deep.***The human-straightened channel increases stream powers and erosion across the Ahvaz Anticline and thus promotes the maintenance of this “fixed” NNE–SSW river course across the fold***. The straightened course has merely developed alternating point bars and very gentle meandering over about the last 700 years since its general disuse (Fig. 5), indicating that this near-straight river course is likely to be maintained for millennia to come.

6. Conclusions

Direct human impacts on the major rivers Karun and Dez in lowland south-west Iran can be distinguished by the human constructions and their remnants associated with the river channels, and by suites of river characteristics. Major dams are readily identified by a large drop in river water levels and river incision immediately downstream of the dam. With ruins of major dams, only a remnant of the reservoir immediately upstream of the dam ruins may remain (with channel widening to c. 101 m – 850 m within upstream channel distances of 1.5 km). For major anthropogenic river channel straightening, river reaches are characterised by very low channel sinuosities (generally < 1.1) over a greater than 10 km long river course, by relatively broad, shallow channels, and very narrow channel-belts. Artificial river development is characterised by many associated human constructions, very low rates of river migration (<0.5 m yr^{-1}), and prominent vertical river incision. Since direct human modifications to rivers are distinct entities, it is likely that the range of river characteristics for each of these categories of human impacts will be extended with more cases.

The external factors of earth surface movements and human activities on the rivers Karun and Dez may have notable interactions where they coincide, mainly over the intermediate timescales of about 100 – 2000 years and spatial scales of river reaches for which both factors can have significant influences. Interactions between earth surface movements and major dams and their ruins are slight, since modern major dams only date to about the last 50 years and ruins of major dams only have slight influences on overall river characteristics. Interactions between earth surface movements and major anthropogenic river channel straightening are key factors in the persistence of long, near-straight river courses. Three out of four cases of major anthropogenic channel straightening on the River Karun have river courses across the axis of an anticline, and the fourth has a river course immediately upstream of an emerging anticline. Artificial river development with very limited river channel lateral migration may promote incision across an active fold at unusually long distances from the fold "core" and may promote markedly increased sinuosity across a structural lineament. Where direct human impacts on river reaches promote river incision across a fold at a location, over subsequent centuries and millennia these may develop into "fixed" locations of the rivers Karun and Dez which shape the subsequent development of their drainage networks and river basins.

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