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ORIGINAL PAPER

Step Wells of Jodhpur, Western Rajasthan, India: Implication for Hydro-geosites and Hydro-geotourism

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Abstract
Geodiversity is defined as the variety of geological, geomorphological, pedological and hydrogeological phenomena (IUCN 2022). Step wells in India are magnificent groundwater bodies characterized by their greater values of hydrogeological geodiversity. Step wells of Jodhpur situated in the Thar Desert of western India are locally known as Jhalra and Baori which are good practices of ground water harvesting, conservation and management system of medieval period. Furthermore, these are magnificent artefacts showcasing historical-cultural (archeological), Architectural and civil engineering geo-monumental heritage of India. In absence of any methodology and guidelines, the hydrological heritage aspects of step wells are least understood and were not adequately explored for their geoheritage values. The present study explores in light of their potential to characterize and recognize them as hydro-geosites of hydro-geoheritage values to promote hydro-geotourism in India. Thus, based on the proposed methodology, out of 134 inventoried step wells of Jodhpur, eight are selected as hydro-geosites for their characterization to be utilized them for educational and hydro-geotourism purposes. Very less number of qualified hydro-geosites clearly reveals that most of them are in pathetic stage due to their negligence since long time that needs urgent conservation. For their conservation, these hydro-geosites should be protected as an important geoheritage sites similar to National Geological Monument (NGM) and Monument of National Interest (MNI) in India. Further, the self-sustainable economic development through awareness and hydro-geotourism would be the best tools for their conservation, promotion and for socioeconomic developments of the region.

Keywords Jodhpur · Step wells · Hydrogeological diversity · Water conservation · Hydro-geosites and Hydro-geotourism

Introduction

The official content of the standardized descriptions of the UNESCO global Geoparks was recently been analysed by Ruban (2019). UNESCO issued a resolution in 1972 to conserve the world's cultural and natural heritage and defines natural heritage as a diverse set of bio-ecological and geomorphological/geological characteristics of nature that are well-intentioned for preservation. In recent years, the appraisal and importance of Earth's heritage and management have grown in the shape of geodiversity and biodiversity concepts (Brilha 2002; Zouros 2004, 2005; Staces and Larwood 2006; Carcavilla et al. 2007; Panizza 2009; Zouros 2007; Zouros et al. 2009; Zouros and McKeever 2009; Page 2018. The urbanization in last couple of decades in nineteenth century has degraded many sites of cultural and geological importance, however in the middle of twentieth century substantial awareness for the conservation of such sites is emerged (Page and Wimbledon 2009). The management of the environment and an assessment of the geoheritage's long-term viability, potential hazards, and geodiversity are all included in the geoconservation of geoheritage. Geodiversity implies the combined geological, geomorphological, pedological, and hydrological properties (Sheth et al. 2017). As the trees, habitats, and wildlife are natural treasures that need to be preserved, on the other hand the geological and hydro-geological landforms on which they are dependent and record the history and evolution of the planet if destroyed cannot be recreated. Such heritage monuments are natural value for the country where they occur and must be safeguarded from activities of human harm. A

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classified system for geo-conservation, geo-education, and geo-tourism consists of a hydro-geosite at the lowest scale, geotope confines at greater scales, and a geopark at the biggest scale (Eder 2008; Ieleniz 2009; Joyce 2010; Moufti and Németh 2016).

Geoparks can boost the local economy through geotourism. In several nations, hydro-geological and geomorphological features are protected by identifying and documenting "geosites" (Panizza and Piacente 1993; Wimbledon et al. 1995; Wimbledon 1996; Panizza 2001; Reynard 2004; Carobene and Firpo 2005). India has great potential for geopark and geoheritage sites. Some of the heritage stones (e.g., Deccan traps, Vindhyan sandstone, Jaisalmer Golden limestone, Jodhpur sandstone) (Kaur et al. 2019a, b, 2020a, b) and geoheritage locations e.g., Slates, are from Chamba and Kangra, Elephanta caves, Deccan traps, Cenozoic successions of Western Kachchh, Tertiary succession (Shekhar et al 2019), and Mehrangarh ridge, Jodhpur (Mathur et al. 2021a, b). Chauhan et al. (2021) proposed the Kachchh Basin as a unique geoheritage and national geoparks potential. Bhosle et al. (2021) identified Jurassic fossil geotop sites in Wagad (E. Kachchh) with its cultural and historical significance. Terrestrial Martian analogues in Kachchh area also identified as potential geoheritage sites (Chavan et al. 2022). Mathur et al. (2023) propose geodiversity of Fatehgarh Formation of proliferous Barmer basin as a potential geopark, while Thakkar et al (2023) gave merits of the Zanskar range of Kashmir Himalaya as a field geological museum. Chauhan and Desai (2023) present evidences of Mesozoic life and its evolutionary fingerprints in Kachchh using ichnosites, sedimentary structures, and dual-porosity petrophysical characteristics. Thakkar et al. (2022) describes Harappan sites in Kachchh can be potential locations for geoarcheological tourism and can serve as a great avenue for boosting the economy of the local communities. It is found that almost all of the work relates the geologically important sections, landforms, and archeological monuments as potential geoheritage sites while none describes any natural and anthropological hydro-geological structure as hydro-geosites of geoheritage value in India.

It was found in analysis of descriptions of the water objects (seas/oceans and rivers) in UNESCO global Geoparks is mentioned with 55% and 47% respectively bear their photos (Ruban 2019). Further, in UNESCO global Geoparks, water bodies are generally strongly related to geological heritage (in 80% of cases) representing hydro-geodiversity on natural landscapes (IUCN 2022) and can be potential geotourism sites (Perotti et al. 2019). The interaction of water with rocks in subsurface provide significant underground water resources and features represent various hydrogeological phenomena. These phenomena are best representing in step-wells of India which are traditional underground water bodies displaying significant hydro-geodiversity and monumental heritage of additional cultural values. Step wells are large subterranean stone structures consisting of water-well and a downward stony stairway leading from ground level to the underground water table where water laid ten to hundreds of meters beneath. These were primarily constructed in India to provide water for drinking and agriculture purposes (Lautman 2013; Singh and Mathur 2014; Rathore et al. 2016). These are outstanding examples of ground water harvesting, conservation and management system of medieval period of India. These stony structures are variously known as "Jhalra," "Baori," "Bawdy," "Baoli," "Vav," "Vavdi," "Vai," "Kalyani," or "Pushkarni" "Vapi" or "Vapika" in different part of India (Jain-Neubauer 1999, Lautman 2013, Mathur et al. 2021b and Singh 2022).

Remarkably, ancient Jodhpur city in Rajasthan of western India is endowed with large number of step wells. The history of step wells of Jodhpur date back to the 4th millennium BC when rock cut *Sumanohar* Baori was constructed at Mandore (old capital of Marwar state) in Jodhpur. Uninterrupted tradition of construction of step wells went on for centuries, attaining the peak of their glory in the sixteenth centuries overlapping the peak of traditional architecture of Kingdome of Rajput's (Rathore and Mathur 2014). This was the time, when King Rao Jodha shifted the capital of Marwar state from Mandore to Jodhpur in 1659 AD (Tillotson 1987). Jodhpur city situated in the Thar Desert has survived in extreme water scarcity thus; old kings and local communities consistently have vision to build step wells to fetch ground water. As a result of which since foundation of Jodhpur, the city has developed more than hundred step wells which are locally known as *Jhalra* and *Baories*. Step wells are not only representing ancient patronage of Jodhpur but significantly have great archeological (historical, cultural and religious) values and are magnificent hydro-geological objects. Step wells primarily combines a utilitarian (being a source of underground water) and social functions (meeting, resting, religious and ritual place for community people) places. Step wells are also showcase of water engineering (harvesting, conservation, and management of water) with significant architectural and civil engineering (monumental structures) concepts (Singh and Mathur 2014). Moreover, step wells are constructed by heritage stone resources (HSR) locally known as Jodhpur sandstone thus, considered as heritage monuments of India (Singh 2022). Because of these characters, step wells of Jodhpur are designated as outstanding traditional ground water bodies of India which are developed in extreme dry climatic conditions of the Thar Desert (Singh 2013; Singh and Mathur 2014; Rathore et al. 2021 and Singh 2022). Thus, the step wells are rare and unique type of geological sites and have great potential to promote them as hydro-geoheritage sites of educational and hydro-geotourism values in India. Earlier, all types of water bodies (seas, oceans, rivers, and Lakes) internationally were designated as geomorphosites (Pereira and Pereira 2010). Later on, Simić et al. (2010) coined the term hydro-geosites based on hydrogeological diversity of the water body. However, many other types especially unique traditional ground water bodies occur in some countries including prominently in India are rare and unique in the world. Hence, the term hydro-geosites coined by Rathore and Mathur (2014) for traditional step wells of India is very appropriate to be used in the Indian context similar to the concept utilize internationally (Simić et al. 2010). Thus, considering step well, as a "hydro-geosite" in Indian context would be the potential sites to promote education and tourism through hydro-geotourism as an additional tool, similarly established in many countries (Simić et al. 2010; Poltnig 2015; Perotti et al. 2019; Ruban 2019, IUCN 2022 and Julia et al. 2022). In this paper, we have discussed an overview of the geology with hydrogeological attributes of the Jodhpur and proposed qualitative methodology to select and assess the hydro-geosites. This paper also highlights the importance of eight hydro-geosites to establish their hydro-geoheritage significance for education and geotourism values.

Geological Setting

The geology of Jodhpur has been studied by many workers (Pareek 1984; Chauhan 1999; Roy and Jakhar 2002; Maheshwari et al. 2004 and Singh 2013 and Mathur et al. 2019a and b; 2021a and b) in great detail with various aspects. These aspects reveal that Jodhpur is endowed with four prominent NNE-SSW trending ridges of the rocks of Malani Igneous Suite (MIS) of Cryogenian and Jodhpur Group (JG) of Ediacaran age Marwar Supergroup of great geoheritage values (Mathur 2021 and Mathur et al. 2021a). The Jodhpur city is developing in the linear valleys in which most of the hydro-geosites are situated dominantly on the aquifers of Quaternary alluvium made from the Jodhpur Formation (Fig. 1; Mathur et al. 2021b).

Malani Igneous Suite

Malani Igneous Suite (MIS) in Jodhpur is mainly represented by two stages of volcanism: (1) lava phase (rhyolites and rhyolite porphyry) and (2) younger Pyroclastic phase (agglomerates welded tuff, ignimbrite and minor ash beds). All these phases constituting an "igneous cycle" of Bhushan (1975) and are reflection of the Pan-African Event of Cryogenian age (Bhushan 2000; Pandit 2001; Sharma

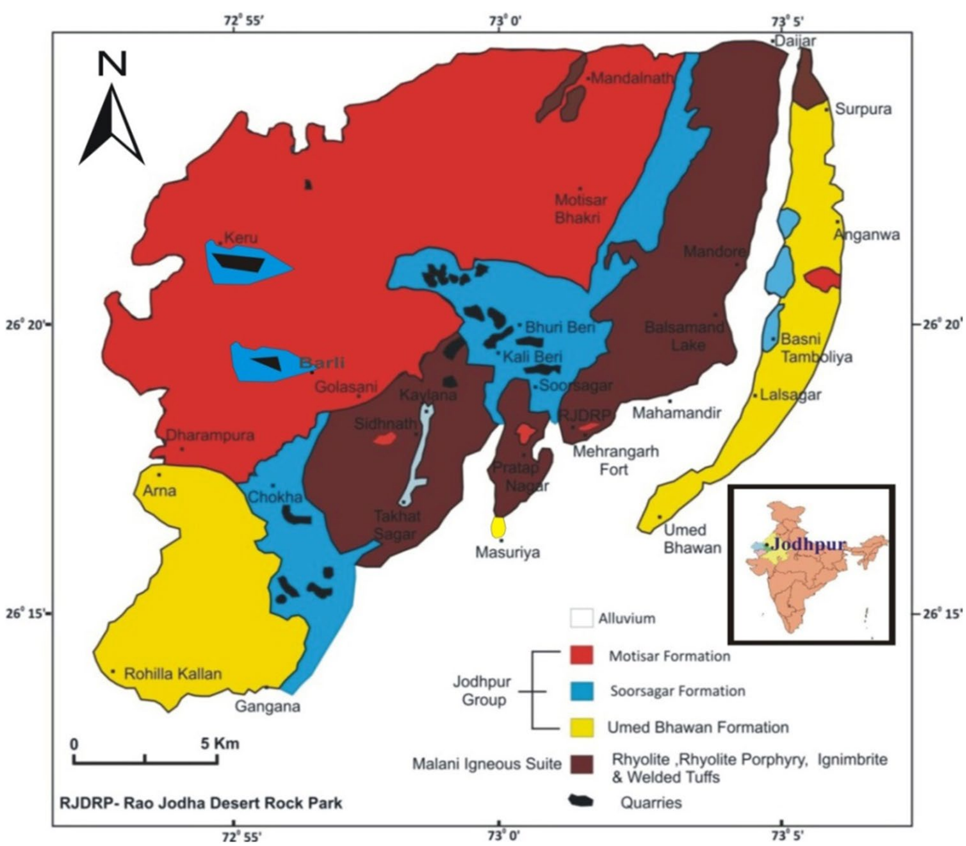

Fig. 1 Geological map of Jodhpur showing outcrops of MIS and Jodhpur Group (JG) of Marwar Super Group (MSG) exposed in Jodhpur (Mathur et al. 2021a)

2005; Gregory et al. 2009; Pradhan et al. 2010 and Mathur et al. 2021a). The Malani rocks are underlying the Pre-Malani rocks of Delhi Supergroup and overlain by Jodhpur Group of rocks of the Marwar Supergroup at and around Jodhpur (Chauhan 1999; Bhushan 2002; Roy and Jakhar 2002; Maheshwari et al. 2009; Mathur 2021 and Mathur et al. 2019a and b; Mathur et al. 2021a and b). The pyroclastic rocks of MIS, their unique features and interface with sandstone of Jodhpur Group of MSG have been declared as National Geological Monument (NGM) of India (GSI 2001a and b) are the significant geoheritage elements of the India (Mathur 2021 and Mathur et al. 2021a and b). In Jodhpur, fractured rhyolite and welded tuffs of MIS formed aquifers.

Jodhpur Group

Jodhpur Group (JG) of Jodhpur is represented by the lower sequences of the Marwar Super Group (MSG). JG is divided into three distinct successions viz: Umed Bhawan Formation (UBF), Soorsagar Formation (SSF) and Motisar Hill Formation (MSF) in chronostratigraphic order (Fig. 2; Chauhan; 1999; Mathur et al. 2019a and b) formed bold ridges and hillocks in the study area. The sequences of UBF comprises of excellent outcrops represented by gradational coarsening upward deltaic sequences with shale at the base followed by siltstone, shaly sandstone, fine to the coarse grained sandstones and pebbly sandstone at the top (Mathur et al. 2019a). The overlying near coastal beach sediments of SSF of JG comprises dominantly fine to medium grained sandstones. These sandstones preserve treasure of sedimentary structures (Chauhan et al. 2004; Mathur et al. 2019a and b) and diverse species of Ediacaran fossils (Raghav et al. 2005; Kumar and Ahmad 2012; Sharma and Mathur 2014; Srivastava 2012; 2014 and Parihar et al. 2019) of great sedimentary and paleontological type geoheritage values (Mathur et al. 2019a and b and 2021a). The upper most fluvial Motisar Hill Formation is represented by fining upward sequences represented by conglomerate at the base followed by pebbly sandstone, coarse grained sandstones, medium to fine grained sandstones and silt stone at the top (Fig. 2; Mathur 2021). In Jodhpur, mainly shale and sandstones of Jodhpur Group formed aquifers.

Alluvial Formation

A sheet of 4- to 76-m-thick Quaternary to Recent alluvium and wind-blown sand deposits are spread in valley areas covering all the formations of JG in and around Jodhpur city. This formation is mainly composed of course to fine silt, sand with clay along with wind-blown sand at the top. Most of the step wells were developed on the alluvial formation which formed principle aquifers.

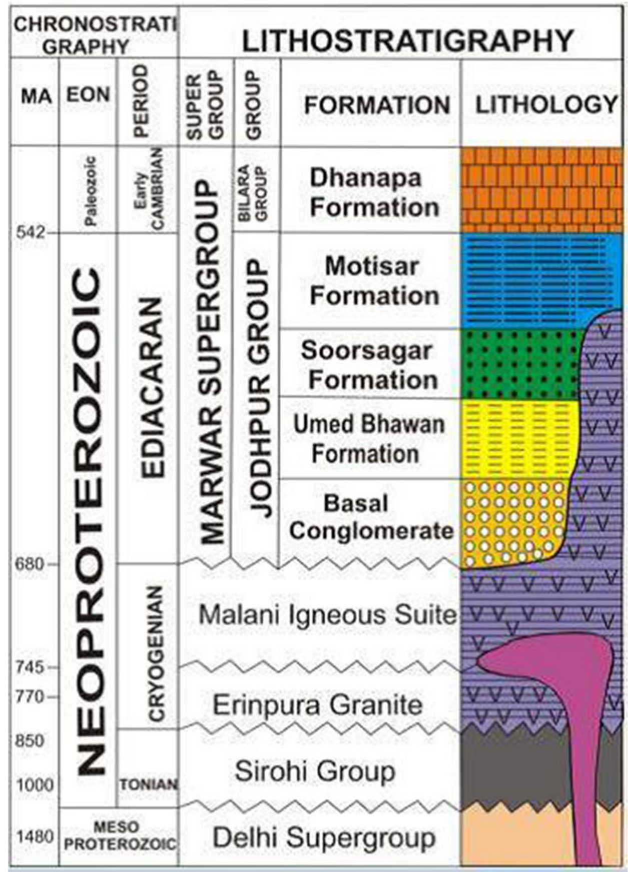

Fig. 2 Lithostratigraphy of the Jodhpur Group of the Marwar Supergroup (Mathur et al. 2022)

Hydrogeology of Jodhpur

The geological scenario discussed above indicates that, the Jodhpur city has mainly three hydrogeological conditions of aquifers. The deep aquifers are of weathered rhyolite – rhyolite porphyry and inter-bedded pyroclastic rocks of MIS, the intermediate one are of inter-beds of shale, sandy shale, sandstone of JG and Quaternary alluvium forming shallow aquifers (Fig. 3). All aquifers have different hydrogeological properties and cannot be considered as a single hydro-geological system. Deep aquifers have about 300-m thickness (mainly, rhyolite), intermediate one has 50-150m (shale and sandstones) and shallow aquifers (alluvium) have 2.25- to 78-m thickness of unconfined nature. Groundwater occurs under the unconfined to the confined conditions and major water level of the Jodhpur city is controlled by structural features and thickness of geological formation. The depth of the groundwater in the alluvium to the south of the Jodhpur city varies from 2.25 m (at Binakiya) to 36.05 m (at Pal) and 78m (at Basni) area. In shale and sandy shale, it ranges between 1.60 (at Boori) to 17.31 m (at Sodhon ki Dhani). Sandy shale formation exists in the north and the

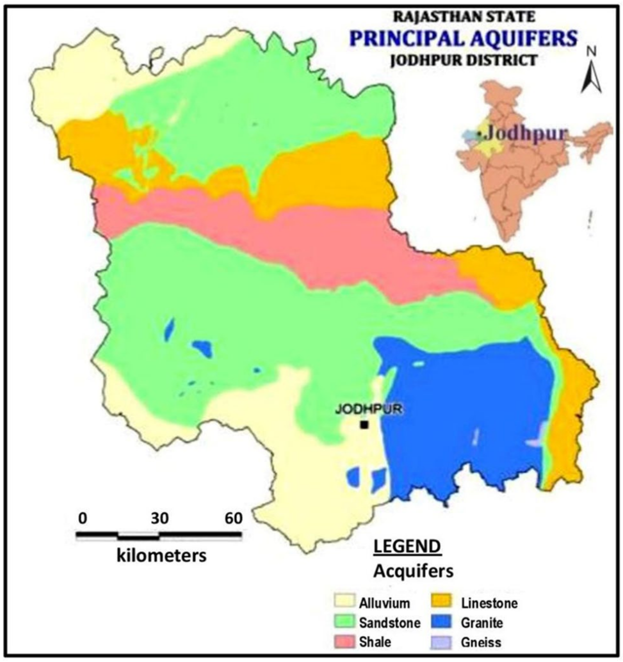

Fig. 3 Map of Jodhpur district showing principle aquifers in Jodhpur city (CGWB Report 2021)

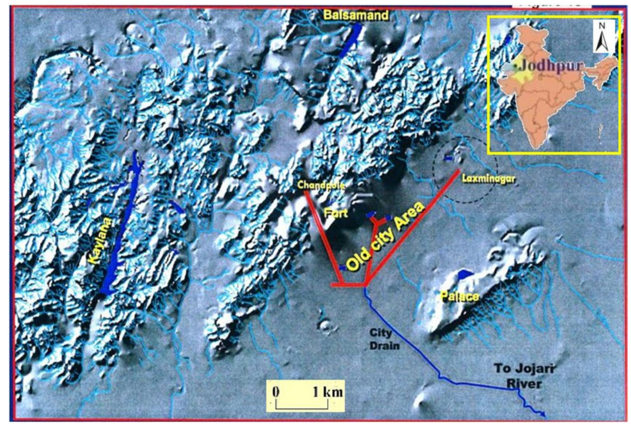

Fig. 4 Landsat imagery showing drainage pattern in Jodhpur flowing to the Jojri River (Mathur et al. 2021a and b)

middle part of the city showing raising water table which is intercalated with shale. Shale serving as impervious layer in some troubled area underlies the alluvium formation in the city. Rhyolite existing in the west part of the city, showing water level variation of 2.28 m (at Koyaj) to 21m (Magra Punjla). The yield of the aquifer varies widely from place to place depending on the porosity permeability and availability of weathered and fracture zone (CGWB Report 2021; Singh 2013; Singh and Mathur 2014). The ground water flow direction in Jodhpur city is towards south and south east which follows the geomorphic gradient and finally joins the Jojri River. Remarkably, there is no major drainage system developed from the vast hilly tract of Jodhpur but an ephemeral stream as Jojri River is passing through the city in its southern direction clearly indicates that most of the water is recharging the three aquifers of the city without being fully drained to Jojri River (Fig. 4).

Methodology

Under the present investigation during rigorous field work, the author inventoried and surveyed 134 step wells to be recognize them as hydro-geosites. To characterize and assess them, various physiographic, geological, geomorphological, and hydrogeological characters are taken to establish their hydro-geoheritage significance with their historical, cultural, and esthetic values. Under the survey programme authors utilize various geological and remote sensing techniques to collect various data. These are mainly, geographic location, size, and type of water body, aquifer nature, yield, water level, water quality, siltation and pollution status along with geology, morphometric, and hydrogeological conditions of individual site on local scale.

Step wells of India represent interesting scientific values but have not yet been highlighted and explored for education and tourism purposes obviously in absence of any methodology. Thus a comprehensive qualitative methodology to select hydro-geosites is proposed (Table 1). Based on proposed methodology, eight hydro-geosites are qualified which are further characterized and assessed to establish their hydro-geoheritage values in Indian context (Table 2) with educational and hydro-geotourism significance (Table 3).

These methods also fit well in view of highlighting the intrinsic and the additional values, uses and management characteristics of hydro-geosites of the study area. Accordingly, the primary issue for the development of methodologies for selection of hydro-geosites and assessment of hydro-geoheritage are mainly focus on the evaluation of the different scientific aspects of the water bodies. Obviously, in particular natural environment, the scientific significance is the fundamental parameter along with ecological and/or esthetic, traditional, and archeological (historical and cultural) values (Brilha 2018).

In the Indian context, archeological heritage and its values are often associated with surrounding environment of hydro-geosites which impart additional values in the criterion to establish present methodologies. Accordingly, the Indian hydro-geosites can be defined, based on one of the essential factors of scope with its five sub-criterions particularly giving a name to hydro-geosites, utilizing geological, geographical, historical, cultural, and or religious references with their GPS locations. Accessibility of the hydro-geosites can be defined by the transport infrastructures, i.e., types of

Table 1 Criteria and indicators for the selection and assessment of hydro-geosites (Modified from Brilha, 2016 and Mathur et al. 2021a)

Main criteria	Sub-criteria	Indicators
	Name of hydro-geosites	Name for easy identification, should utilize geological, geographical, historical, cultural, and or religious reference and should have GPS location
A. Scope	Accessibility	Transport infrastructures, types of roads, distance from city center/ rail bus stand and airport
	Visibility	Perceiving conditions of the hydro-geological elements regarding the distance, the presence of vegetation, human structures, and need of electrical lights etc
	Safety	Assessment of potential danger for the visitors/ tourists considering slope, slippery floor, and availability of safety measures from dangers of water and mass movements
B. Scientific Values	Hydro-geological and Geological framework characterization	Hydro-geological and geological status, description of hydro- geosites/ surrounding landscape, spectacular, unique and rare features, and characters of local/regional/ national and international significance
C. Utilization	Indications	Road guide marks, descriptive signboards on nearby roads, and within hydro-geosites
	Use of hydro- geological /geological and geo-monumental heritage values	Promotion of the hydro-geosites through internet social media, advertisement, cartography & illustrations guide books, leaflets brochures, interpretative and visitor centers. Description of monuments at and near the hydro-geosite and their heritage significance
	Use of other values	Existence of other natural, traditional, historical, cultural, and religious values and their promotion and present use
	Land status	Ownership of the land having hydro-site, Possibility to visit the hydro-geosites, existence of boundary/fences, accessing fees, and functioning hours etc
D. Coordination and organization	Cleanness	Status of cleanness, sanitary facilities and conditions of the site, existence of dirt and garbage, and consideration of other hygienic parameters
	Toilets	Availability of public toilets even in restaurants and cafes in the surroundings, considering their distance from the site
	Food	Good and hygienic existence of restaurants and cafes in the nearby areas

Table 2 Major criteria for qualitative assessment of hydro-geoheritage of hydro-geosites of educational values (Modified from Brilha, 2016 and Mathur et al. 2021a)

Scientific value	Additional value	Management
Rarity	Natural, traditional, aesthetics, and archeological values	Accessibility
Representativeness	Spectacular-sculptures and landscape	Visibility
Integrity	Vulnerability	Conservation and
Diversity	Ecological and paleogeographical value	Protection status

roads, distance from city centre, railway station, bus stand, and airport.

The perceiving conditions of the hydro-geological elements regarding distance of particular object to watch, the presence of vegetation and human structures, and need of electrical lights decide the visibility of the hydro-geosites. Safety for the visitors/tourists is very important factor, which is defined by the assessment of potential danger considering steps, slippery floor, and availability of safety measures from the dangers of water and mass movements at a particular hydro-geosites.

Scientific values of hydro-geological and geological documentation and description should be available for the visitors. It includes the objective criterion like geological, geomorphological, and hydro-geological framework with their description indicate scientific values of the hydro-geosites. Additionally, description of spectacular, unique and rare features with particular object/ geological/

Table 3 Criteria for the assessment of hydro-geosites for hydro-tourism value (modified from Pereira and Pereira, 2012 and Mathur et al. 2021a)

Main criteria	Sub-criteria	Indicators
A. Availability	Accessibility	Accessing the site considering the types of roads, possible means of transportation, distances, and if difficult need of special equipment
	Visibility	Preserving conditions of the geological feature vision distance, presence of obstacles of vegetation, and human structures and need of artificial light
	Safety	Potential danger for the visitors considering steep slope, slippery floor, presence of water and mass movements, and danger due to presence of wild life animals
B. Uses	Indications	Display of signage on roads and nearby hydro-site referring it as a geosites with some specific features to attract tourists
	Use of geological values	Promotion of the hydro-geosites through the Internet with attractive photographs and short description in guidebooks, brochures, leaflets, and existence of panels and interpretative centers on the site
	Use of esthetic values	Existence of other natural, religious, historical, cultural, and archeological values and their promotion and present use
	Land status	Possibility to visit the hydro-geosites regarding property of the land, existence of gate boundary or fences, accessing fees, and functioning hours etc
C. Logistics	Cleanness	Cleaning and sanitary conditions of the site and existence of garbage, recipients considering the possibility of picnics or bathes
	Toilets	Existence of public restrooms or availability of toilets nearby hydro-geosites near or considering their distance from the hydro-geosites
	Food	Existence of restaurants and cafes, considering their distance from the site
	Accommodation	Existence of guest houses, hotels and camping sites from considering their distance the geosites

archeological/ architectural and civil engineering and monumental heritage characters to utilize and to decide the local/ regional/ national and international significance. Among subjective criterion, utilization of the hydro-geosites is assessed through information, advertisement, and potential use and protection requirements. Coordination and organization define the facilities which are available for visitors around the hydro-geosites. Further, intrinsic value of the hydro-geosites can be assessed through determination of scientific, ecological, archeological, and other esthetic features.

Further, after identification and characterization, major criteria of scientific values, additional values, and management indicators are adopted with some modifications (Table 1). Accordingly, the qualitative assessment of hydro-geosites for their educational significance is based mainly on the scientific values. These are rarity with natural, traditional, esthetics, archeological, accessibility, and utilization of subordinate additional values with management criterion. The rare features, processes and events, representativeness of a certain period or a significant event of hydro-geological history of Earth enhance the scientific values of the hydro-geosites. Integrity defines the present protection and conservation status of hydro-geosites. The diversity defines the number of various unique geological, hydro-geological, and ecological features and/or hydro-geological processes which are present at the hydro-geosites (Table 2). To establish significant hydro-geoheritage of the hydro-geotourism values, various criteria modified from Pereira and Pereira (2010) and Mathur et al. (2021a) are adopted (Table 3).

Accordingly, the major criteria are availability, uses, logistics, and perceptiveness that are utilized for establishing hydro-geoheritage values for their hydro-geotourism significance. Availability is the main criteria can be defined by safety, visibility and accessibility of the hydro-geosites. Similarly, uses can be defined by various indicators of indications, land status, and use of esthetic, geological, and hydrogeological values. Further, logistics facilities can be decided by the indicators like status of cleanness, facilities of toilet, availability of food, and range of accommodation in and nearby areas of the hydro-geosites for visitors (Table 3).

After establishing hydro-geoheritage significance, authors marked them on maps as discussed above, including surrounding infrastructures and roads etc. utilizing Google Earth satellite data and Google images taken from USGS website of respective areas using GIS, Arch-GIS, and Corel Draw software. Present maps with published geological maps were utilized with literature and present work to get geological and hydro-geological information of hydro-geosites after necessary authentications. To know the history, cultural, and religious aspects of hydro-geosites, old record and cartographic material were also utilized by personal interview with old persons knowing details of water bodies of the study area. Additionally, photographs of selected hydro-geosites and surrounding significant geological and hydro-geological characters are taken to illustrate them. Further, archeological (historical, cultural, and religious) with water engineering, monumental architect, and civil engineering aspects are taken to characterize hydro-geosites which impart additional values to them. The present system and methodology applied on the study area is more or less similar to Karkonosze National Park of Poland (Knapik et al. 2009) where these aspects already been applied successfully.

Common Characters of Hydro-geosites of the Jodhpur

Hydro-geosites (step wells) of Jodhpur are magnificent small to large stony structures built on the principle of community sharing. Scientifically, these are originated through natural processes of ground water geology representing favourable hydrogeological conditions and their human interaction. These are distinctively built in rectangular, square, L or I shaped with a series of levels (three to five) in one direction (Baories) or in all directions (Jhalra). These are conventional sources of underground fresh water and played an important role in sustaining human and animal life for ages especially during drought periods. These were built by the Kings or leaders of communities and tribes with the help of local people. Almost every residential colony in old Jodhpur city had one or more step wells built by indigenous technologies. These were developed to fetch water from confined or artesian aquifers occur at the depth up to 10 to 100m. These were magnificently built in lower and mid-slope positions utilizing best hydrological conditions (suitable aquifers, lineaments, fractures, joints, and favorable natural slopes of hilly terrain) where they can capture maximum runoff and seepage through Monsoon rains.

Most of the hydro-geosites of Jodhpur are lying on lineament or within lineament zones to receive maximum seepage (Singh 2013; Singh and Mathur 2014). Beautifully carved mouth of cow made up of Jodhpur sandstone is connected through paleo-conduit system and water is continuously flowing from them (cow mouth, similar to tap) throughout the year even in summer seasons is possibly an evidence of lineament passing through these water bodies. Apart from science and technology, their magnificent architectural design and civil engineering structures constructed by the local Jodhpur sandstone (HSR) makes them unique heritage monuments of old time. They were constructed with strong boundary walls having one or two arched gates with pavilions, corridors, having statues of deities and symmetrical steps in one, three or in all sides to reach to the water table. In order to prevent structure from breakage a, spillways were built at a certain height so that water can be stored up to an optimum limit for the use during the rest of the year. Thus, step wells are meticulous water harvesting and conservation system endowed with monumental heritage features showcasing rich scientific and engineering knowledge of our ancestors (Singh and Mathur 2014; Singh 2022).

Due to rapid urbanization, lack of maintenance with prolonged negligence, most of these step wells are polluted, deteriorating, damaged, and many are nearing to extinction. They have become unusable and many of them are converted into dustbins and garbage bins. The situation become alarming as after 1997, plenty of water is being supplied from Indira Gandhi Canal Project (IGNP) and these were no longer part of the water supply system of Jodhpur. Under the present scenario, rebuilding of such magnificent and unique heritage water monuments is a difficult task, while many are under great threat of being damaged needs scientific study for their proper geo-conservation. For which, on the basis of scientific study, their hydro-geoheritage values will be established, which could be utilized for education and tourism not only for their conservation but for socioeconomic development of the region. Based on the published literature, present proposed methodologies, and intrinsic study, the step wells of the Jodhpur can be categorized into two types: (1) Jhalra Type hydro-geosites, (2) Baori Type hydro-geosites (Fig. 5).

1. Jhalra Type Hydro-geosites

Jhalra are large (more than 20m in length) and single storied human-made ground water bodies dominantly found in Jodhpur in Rajasthan state of India. These are essentially meant for various community uses and for religious and ritual purposes. These are often rectangular in design, have steps on three or four sides on a series of levels. Jhalra are magnificently built to ensure easy and regular supply of water to the surrounding resident communities. Jhalra has number of wells at their base up to the depth of more than tens of metre. Water filled by run off (through canals) and also by the subsurface subterranean seepage. These hydro-geosites are old buildings of magnificent architectural designs constructed by local Jodhpur sandstone (HSR). These includes beautiful pavilions, corridors, domes, balconies with intricate carvings developed by human activities thus, are significant monumental heritage of India (Figs. 6, 7, 8, 9, 10).

2. Baori Type Hydro-geosites

Baories are small (less than 20 m in length) human multiple storied ground water bodies found in Rajasthan essentially meant for community use and for religious rites. These are significantly built to ensure easy and regular supply of water to the surrounding resident communities. These are rectangle: I or L shaped ground water bodies with symmetrically built steps on a series of levels in each flight. A single well is situated at the base with the depth of more than tens of metre mostly filled by the subsurface seepage. These are also magnificent monumental buildings constructed by the locally available Jodhpur sandstone (HSR). These have magnificently constructed verandas, pavilions, corridors, balconies with intricate carvings and pavements in one or all side provide community spaces also for rituals to the local people in old time (Figs. 11, 12, 13). Based on published literature,

Fig. 5 Google image showing locations of hydro-geosites of the Jodhpur

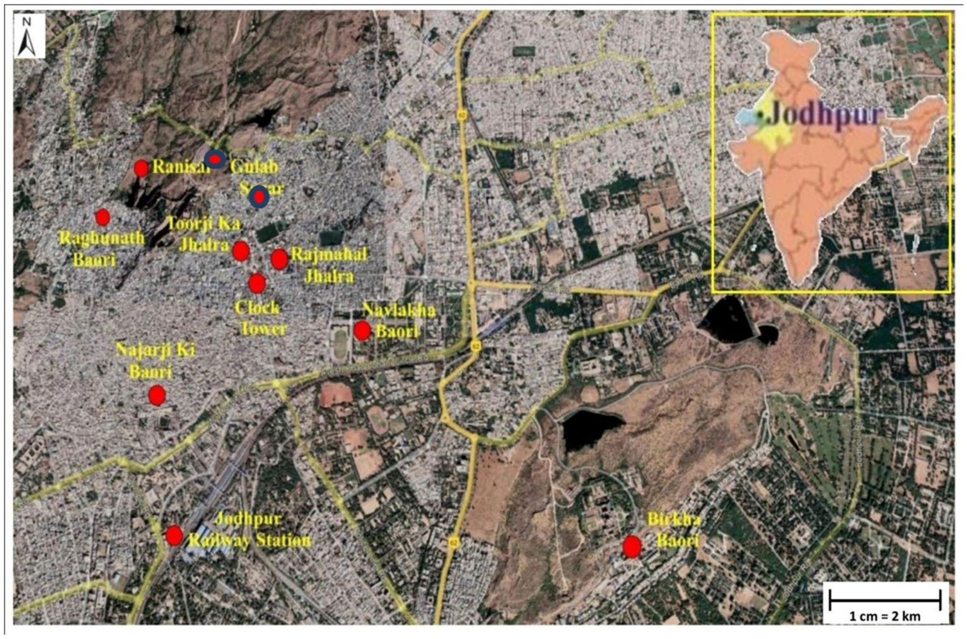

Fig. 6 Toorji ka Jhalra hydro-geosite

Fig. 7 Rajmahal Jhalra hydro-geosite

Fig. 8 Gulab Sagar hydro-geosite and imposing Mehrangarh fort in the background

Fig. 9 Bijolai palace hydro-geosite with rhyolite hills and Kayalana Lake in background

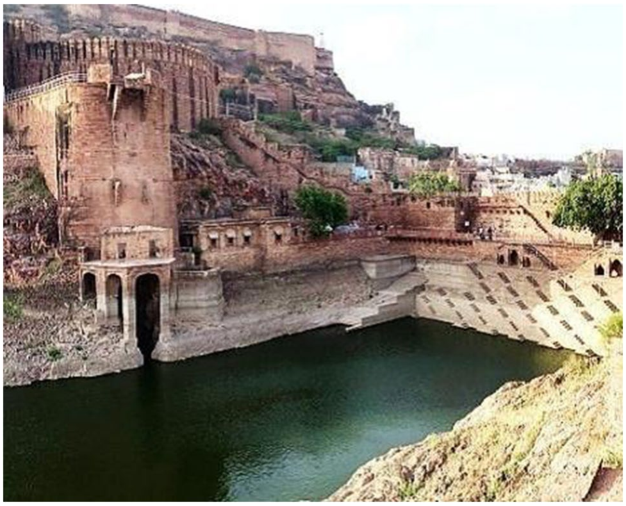

Fig. 10 Ranisar hydro-geosite

Fig. 11 Ragunath Baori hydro-geosite

Fig. 12 **a** Damaged Navlakha Baori, **b** renovation work going on at Navlakha Baori hydro-geosite

present work, and proposed methodology, eight hydro-geosites of Jodhpur are qualified and selected for study (Fig. 5) are of national and international Significance.

Fig. 13 A front view of Najarji ki Baori

These hydro-geosites showcasing important features of geology, geomorphology, and hydrogeological with archeological values of more than 550 years old patronage of India developed in the great Thar Desert. These values will certainly help to promote hydro-geotourism and also justify the necessity with their role in proposal of Geopark in Jodhpur (Mathur et al. 2021a and b) as an additional value.

Jhalra Type Hydro-geosites

(1) Tunwarji ka Jhalra Hydro-geosite It is located about 3 km north of the Jodhpur railway station inside the old Jodhpur city near historical clock tower (Fig. 5). This hydro-geosite is a single storied magnificently built rectangular monumental building. It was built by Tanwar Kanwar queen of HH Abhay Singh in *Vikram Samvat* 1740 CE (1805 AD). Geologically, it is situated at the foot hills of the Mehrangarh Ridge. It has two confined wells situated in alluvial aquifers overlying shale of Umed Bhawan Formation of JG. Water table is situated at the depth of about 80 f. This is the most beautiful hydro-geosite of Jodhpur because of its architectural designed and symmetrically arranged steps on three sides at various levels. It has *gaumukh* (Cow Mouth of sandstone) from which water is flowing throughout the year showing knowledge of our ancestors in identifying the paleo-conduit system indicating rich knowledge of subsurface structures, geology and hydro-geology of the area (Fig. 6).

The spectacular verandas (pavilions) supported by intricately carved pillars with beautiful arched *Jarokha* (windows) with carved icons having statues of gods and goddesses make it an outstanding monumental site of the Jodhpur. Recently, this and Rajmahal Jhalra hydro-geosites were cleaned by Mr. Caron, a 70-year-old Irish, with our research group and local residents. Now, both have become the center of attraction for tourists, as many guest houses and restaurants with roof top bars have been opened at and near these hydro-geosites can contribute to tourism and socioeconomic developments.

(2) Rajmahal Jhalra (Mahila Bagh) Hydro-geosite It is located about 2.5 km north of the Jodhpur railway station inside the old Jodhpur city near historical clock tower (Fig. 5). This magnificent hydro-geosite was built by Gulab Rai, second queen of HH Maharaja Vijay Singh as a gift to the public in the year 1775 CE. It has a remarkable design with steps at various levels from all sides with spectacular *varandas*, (pavilions) dome-carved pillars, and arches represent rich architect and civil engineering of old time (Fig. 7).

Hydro-geologically, it is developed on alluvial aquifer which receives seepage from the hilly terrain of Mehrangarh Ridge. It is a colossal step well of about 24m, 26m wide and having 22 m of depth with symmetrical stairs in all sides to reach up to the water table.

HH Vijay Singh has also constructed magnificent palace as residence of Queen Gulab Rai adjacent to this hydro-geosite impart additional values to this hydro-geosite. Later on, it was converted into a big hospital for females under the leadership of Dr. Haward and senior compounder of English time Mr. Banshi Lal Mathur. This hydro-geosite is the main source of water for hospital and surrounding residential colony since old time thus its importance is still prevailed for promotion of tourism in Jodhpur.

(3) Gulab Sagar Hydro-geosite It is located about 2.5 km north of the Jodhpur railway station inside the old Jodhpur city near the historical clock tower. Gulab Sagar was built by Gulab Rai, a concubine of HH Vijay Singh during the year 1780 to 1788 AD. Geologically, it is situated at the foot hill zone of Mehrangarh Ridge (Fig. 5). It is connected with canal that drains water from Balsamand Lake that received drain water from vast catchment area situated around Ghoda Ghati to Mandore area (Mathur et al. 2021b). It has six confined wells situated in the alluvial aquifer. These wells receive seepage from the hilly terrain of Mehrangarh Ridge on which imposing Mehrangarh Fort is situated, imparting additional values to this hydro-geosite (Fig. 8). Hydro-geologically, it is a large hydro-geosite having length of 120m, 60m width with depth of maximum about 10m. In each three step sides, beautiful arched open and closed pavilions are constructed by Jodhpur sandstone. Each has statues of deities placed in the centre of the arches make them a very famous ritual place of the Jodhpur. It is well protected by a strong wall having steps in three sides to fetch water and one side has a bridge that separate *Gulab Sagar ka Bachha*.

Another, adjacent water body (Gulab Sagar ka Bachha) is built to commemorate the birth of the son of concubine Gulab Rai were built just adjacent to Gulab Sagar hydro-geosite is separated by a beautiful bridge. On the eastern bank, an architecturally beautiful palace (now used as girl's school) is construed having with steps that were earlier used by royal family. To beautify this hydro-geosite recently, fountains, heritage lights, pillars, and benches were placed. Both spectacular hydro-geosites were earlier used for various rituals, swimming, and bathing purposes and are also an attractive tourist places with recreational and boating facilities. Hence, large number of tourists visits both hydro-geosite as these are situated near the famous clock tower, and Rajmahal Jhalra. Because of these characters, both well-maintained hydro-geosites are attractive tourist place of the Jodhpur city.

(4) Bijolai Palace Hydro-geosite It is located about 9 km from Jodhpur Railway Station near Kayalana Lake (Fig. 5). Bijolai hydro-geosite, Bijolai palaces, Machia Fort, and Bhim Bhadak cave temple were constructed during 1859 to 1862 by Maharaja Takhat Singh for resting and hunting place for royal families. It is surrounded by rhyolite hills of MIS from two sides and at another sides a beautiful palace and boundary wall is situated having symmetrical steps (Fig. 9). Recently, due to natural beauty, magnificent palace on bank of this hydro-geosite, it is declared as a heritage resort of India by INTACH (Indian National Trust of Cultural Heritage). This hydro-geosite receives water from vast catchment area of rhyolite hills of MIS. It is said that this hydro-geosite has three wells situated in aquifer of fractured rhyolite received seepage water from surrounding hilly terrain The Beautiful palace constructed by Jodhpur sandstone is converted into hotel in 2004 and was handed over to Jal Bhagirathi Foundation (JBF). The income from the hotel is utilised to provide drinking water from this hydro-geosite to the local communities.

Many species of migratory birds used to have camps on this hydro-geosite in winter including Demoiselle Cranes, flamingo and local birds make it a popular place for bird watchers. The spectacular outcrops of rhyolite, Panoramic view of Kaylana Lake, Mahadev Temple, and Bijolai palace impart additional cultural and esthetic values to this hydro-geosite.

(5) Ranisar Hydro-geosite Ranisar hydro-geosites is located about 4 km north of the Jodhpur railway station at the back yard of Mehrangarh Fort (Fig. 5). The oldest and magnificently built Ranisar hydro-geosite was built in the year 1459 by Jasmade Hada queen of Rao Jodha. Geologically, this hydro-geosite is surrounded by rhyolite hills of MIS. Dominantly, it receives drain water through a rock cut *Hati* (elephant) canal. Its depth is of 6.7m, having five wells at the bottom to receive subsurface ground water from fractured rhyolite. There is a water outlet towards Padamsar hydro-geosite to drain excess water. In a 78-m-long fort wall on hills of rhyolite its symmetrical steps, *verandas* (pavilions) with a temple in its northern and eastern sides impart esthetic and scenic beauty to this hydro-geosite (Fig. 10). Water of this hydro-geosite was used by the inhabitants of Mehrangarh Fort. For water supply to the palaces and houses of Mehrangarh Fort various types of devices have been used in the past. From 1840 AD, the water was lifted from Ranisar by Arhat technique (Chain of buckets). Subsequently, it was replaced by a powerful motor which was operated by coal. In 1889, a powerful electrical engine of 12 HP was used to supply water in the Mehrangarh fort.

Baori Type Hydro-geosites

(6) Raghunath ki Baori It is located in Chand pole area about 2.5 km north of the Jodhpur railway station (Fig. 5). Its construction was carried out by Deewan Bhandari at the time of H.H. Ajit Singh around 1720 AD. Hydro-geologically, it is situated on alluvial aquifer which receives seepage from the hilly terrain of rhyolite of Mehrangarh ridge. The magnificent and beautiful structure of this hydro-geosite is about 60 ft long, 15 ft wide and total height is about 45 ft with four floors constructed by Jodhpur sandstone (HSR). Architecturally, each floor is magnificently constructed with number of carved pillars, arches, veranda (pavilion) having intricate carvings. Wall has icons and statues of god and goddess, make it an outstanding monumental and religious site of Jodhpur (Fig. 11).

(7) Navlakha Baori, Hydro-geosite (Public Park) This Baori is located in public park (Umed Garden) on the High Court Road; about 2 km north of the Jodhpur railway station (Fig. 5). It is situated in the lush green Umed garden spread in 82 acres area having 5 separate gates around it. This hydro-geosite was constructed by Maharaja Abhay Singh during his reign from 1724 to 1749 AD. Hydro-geologically, it is developed on alluvial aquifer which receives seepage from the hilly terrain of Mehrangarh ridge situated in northern side. Due to the consistent negligence, many parts of this magnificent hydro-geosite are damaged. Presently, its renovation work to return its glory is in progress by *Mehrangarh* Museum Trust and *Hinduja* foundation (Fig. 12a, b) with our scientific association to provide its original heritage look and structure.

It has three floors; each floor is spectacularly built with carved pillars, arches, and verandas constructed by Jodhpur sandstone. The water of this hydro-geosite is supplied to Umed Garden. It comprises, within its boundaries, lush green garden, esthetically designed water fountains, a library with a range of ancient and modern books, and a zoo. The Sardar museum was constructed under the reign of his son, Maharaja Umed Singh. It was built by Henry Vaughan Lanchester in 1909. The museum contains an arresting collection of 397 stone sculptures, more than 1900 miniature paintings, weaponry, coins and other arts and crafts belonging to different time periods impart additional values to this hydro-geosite.

(8) Najarji ki Baori It is located between Jalori Gate and Baiji ka Talab about 2.5 km from Jodhpur railway station on the road which leads from Jalori Gate to Kabutaron ka Chowk (Fig. 5). It was constructed in the reign of HH Takhat Singh in the year 1859 by Nazir Altmas (Almaas). Two more Baories were constructed by Nazir Altmas, one was in the Sardarpura Mosque, and another is called as Julahon ki Baori. Najarji ki Baori has four floors with verandas supported by beautifully carved pillars and arches (Fig. 13).

It has symmetrical steps goes to about 60 ft to reach to the water table. This hydro-geosite receives water from vast catchment area of rhyolite hills of MIS situated in the north direction of this Baori. Earlier, much of the part of this hydro-geosite was damaged but looking to its beautiful structure it was renovated in 1992–1993 under a scheme called 'thirty districts and thirty development works' of state Government of Rajasthan. An iron net was put over it to protect its water from litters as its water is still being used for the locals and surrounding inhabitants. This hydro-geosite is famous because it is important ritual centre of Jodhpur.

Hydro-geoheritage Attributes

Hydro-geologically, water is considered as an important Georesource and water bodies as hydro-geosites of hydrological heritage values (Simić et al. 2010). Thus, water bodies can be utilized in the same perspective as geoheritage sites of geotourism values (Brilha 2005 and Mathur et al. 2021a). Further, Ruban (2019) clearly manifested that water bodies (geomorphosites) like seas/oceans, rivers, Lakes and ponds (Pereira and Pereira 2010) are mentioned with 55% of descriptions in UNESCO Global Geopark proved the scientific significance and geotourism values of hydro-geosites (Fig. 14). These findings imply a significant attention and importance to hydro-diversity on the earth. Despite of varied water bodies (oceans, lakes, rivers ponds, Jhalra and Baori), the aspects of hydro-geodiversity of hydro-geosites were not adequately explored in India particularly for their geoheritage values. Significantly, these hydro-geosites are endowed with rich hydro-geoheritage values and have great potential to be utilized as hydro-geotourism sites to promote tourism as an additional tool for socio-economic developments as utilized successfully in Geoparks (Simić et al. 2010).

In addition to various types of geomorphosites (Pereira and Pereira 2010), Jodhpur is endowed with unique and rare types of hydro-geosites (step wells) designated as traditional hydro-monumental heritage of India (ASI 2014). Based on previous and present work, 134 step wells inventoried (Singh 2013; Singh and Mathur 2014) of which 117 Baories and 14 Jhalra type hydro-geosites are found in Jodhpur. The presence of large numbers of step wells with natural water bodies clearly manifested higher percentage of description of water phenomena in the study area showing their significance similar to studies of hydro-geosites in Geoparks (Ruban 2019). Thus, the ground water bodies (step well hydro-geosites) are unique in the world, additionally endowed with archeological (cultural and historical), scientific, and water engineering values that also represent old patronage of India.

The common characters of hydro-geosites (step wells) of the study area clearly manifested that the intrinsic geoheritage values are inherent in them. Both types (Jhalra and Baori) of hydro-geosites witnessed (a) significant geological and hydro-geological characters of scientific values, (b) development through significant geological, geomorphological, and hydrogeological processes thus showing observation science of educational and esthetic values, (c) important aquatic micro-ecosystem of climatic, and ecological values, (d) elements integrated by society with hydrogeology and archeological

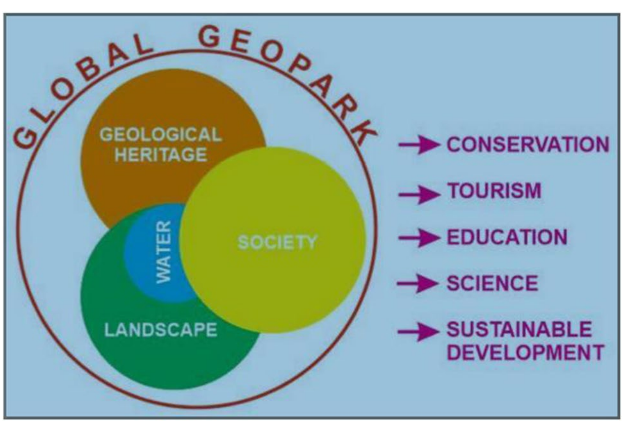

Fig. 14 Various segments including the water in "Global Geopark elements utilized for the sustainable socio-economic development" through geotourism (Ruban 2019)

(history, culture, and religions) values, and (e) elements integrated with hydrogeology and use of HSR in construction of geo-monumental heritage of additional engineering values.

In ancient greater India, the step wells were built in different types, style and are located where suitable geological and hydrogeological conditions are available. The characterization of hydro-geosites clearly witness outstanding knowledge of water harvesting, conservation and management system of ancient communities as exemplify from the study area (Fig. 15) represent outstanding scientific heritage of India. Thus, hydro-geosites can be the significant segments of future Geopark in India to promote tourism for sustainable developments.

It is clearly depicted in Fig. 15 that from rhyolite hills of MIS, water drain to feed Ranisar hydro-geosite through a canal constructed in 1873 AD (Singh 2022). Overflow of Ranisar hydro-geosite first goes to Padamsar hydro-geosite, simultaneously, continuous seepage of water from both hydro-geosites goes to fractured rhyolite and alluvium aquifer. Further, the seepage water in alluvium aquifer percolates and recharge water significantly to various hydro-geosites in downward side of old Jodhpur city. Magnificently, each Jhalra type hydro-geosite has an outlet (carved as cow mouth) from which water is flowing throughout the year by paleo-conduit system and or lineament showing deep knowledge of subsurface geology and hydrogeology of the ancient communities. Such meticulous water harvesting and conservation system of the study area shows more than 500 years old rich scientific knowledge of great geoheritage values.

Hydro-geosites of the study area are small, multispecies systems, consisting of a subset of the biotic community and abiotic properties of an ecosystem. These micro-ecosystems are small terrestrial aquatic environmental zone that have the common features such as food chains, production–consumption cycles, and hierarchies. The microbial communities are naturally found in hydro-geosites includes microorganisms like bacteria, fungi, viruses, and protozoa (Nama and Raj 2018). Water of hydro-geosites is clean and due to availability of wide variety of food hence, fishes and other aquatic species can easily grow which represents biodiversity in these micro-ecosystems of scientific values.

The hydro-geosites of the study area are generally endowed with elements integrated by society with hydrogeology and archeological (history, culture, and religions) significance. These generally combine a utilitarian (being a source of water) and social function (being a meeting and resting places for local communities and for women (while drawing water). Many hydro-geosites premises are closely associated with temples or worship places and are very important ancient spiritual sites. By constructing them, local communities felt pride and realised to have actually the potential of achieving the powers. The construction of such hydro-geosites was considered as of higher merit than even

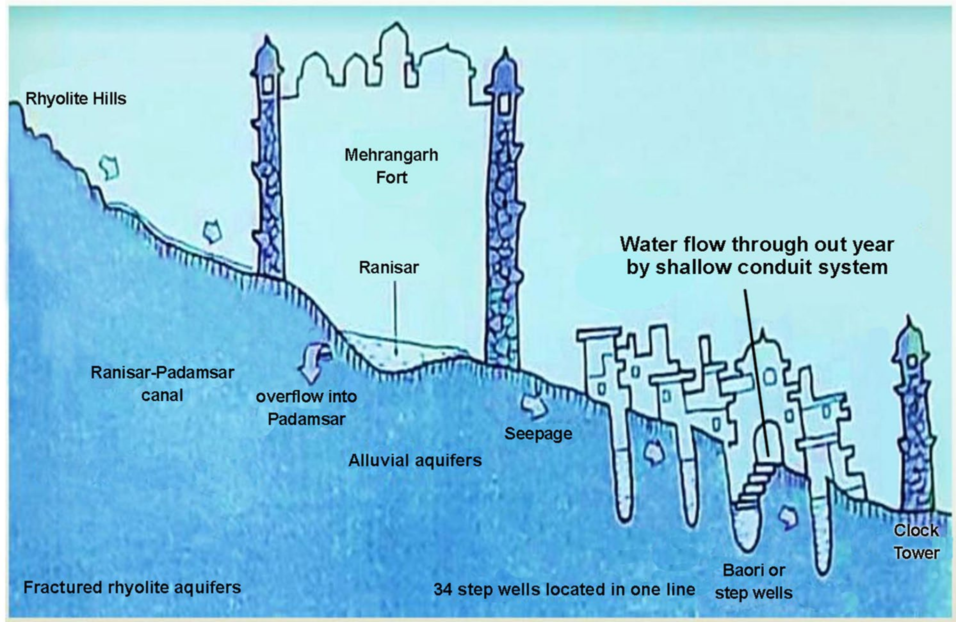

Fig. 15 Schematic diagram showing water harvesting, conservation and management system of Jodhpur (Mathur et al. 2021b)

the performance of a sacrifice as mentioned in Vedic and post-Vedic prescriptions (Amirthalingam 2015).

The structure of step wells are mainly constructed in two parts, one is used as water reservoir-storage purpose and second as the galleries, courtyards and chambers to provide as cool and calm retreat to the local communities and travellers during hot days. The structures are showing culture of particular era and dynasty which are reflected by intricate carvings, arched pillars, symmetrical steps, statues of Gods, Goddesses, and animals. Additionally, the structure of hydro-geosites are more than 200 years old and are constructed with architectural and civil engineering marvels of medieval period of India. These are often associated with palaces, temples, cenotaphs, parks and recreational places (Jain-Neubauer 1999 and ASI 2014) impart additional cultural values to them. Thus, step well hydro-geosites of the study area can be considered as hydro-geoheritage monuments as these were constructed by HSR (Kaur et al. 2020a) influenced and change with different dynasties, culture, and regions. Hence, they are different in their pattern, style and designs provide versatility and are unique in the world showcasing old patronage of India.

Such hydro-geoheritage monuments are generally structured with several stories let down steps to the bottom to reach water table. The common architectural features and types made them a typical step pond, with a large open upper part and gradually sides become narrow meeting relatively at higher depth. They usually incorporate a narrow shaft, which protected them from direct sunlight normally by roof, ending in a deeper, rounded or square or rectangular well-end. The structure of these hydro-geosites mainly consist of two parts, one is used as ground water storage purpose and the second one has galleries, pavilions, chambers and temples built in upper part with beautiful intricate carvings in their walls, pillars, and *Jharokhas* (windows). Sometimes the complex design and engineering of Hindu and Islamic architecture made them stylish and unique. Mostly, the Islamic version offers the arched side-niches while the Hindu architecture is full of decorative columns, and pillars with statues of God and Goddess. Some of the step wells are the fusion of Indo-Islamic culture (Pandey 2016a, b; Singh and Mishra 2019). Thus, beside hydro-geoheritage values, hydro-geosites of the study area also represent ancient geoheritage-monumental structures of national interest (ASI 2014) with additional archeological, civil, and architectural values.

Discussions

Recently, the work of Perotti et al. (2019) aims to systematize knowledge related to geodiversity assessment of water resources and how it is influenced by geological and hydrological processes and to recognize them as geotourism sites. Similarly, Ruban (2019) examines the role of water bodies in UNESCO Global Geoparks and found that water is an important landscaping element with its significant touristic values. Water provides esthetic values in attracting visitors that also highlights the need for a sustainable scientific, educational, and touristic development of water resources and their conservation. Ruban (2019) also argued that focusing only on geological features might not bring enough visitors to the region on the long run. Thus, water bodies should thoroughly consider in advance how far they bring the resource water to the fore without displacing the importance of geology. In this regard, hydro-geosites of Karavanke Geopark is the best example which is characterized by a rich geological diversity and significant transboundary groundwater and surface water bodies (Poltnig 2015). Further, to focus on these aspects an international workshop on the topic of valorisation and protection of water geo-resources in UNESCO Global Geoparks was held in February 2022. Its recommendations clearly manifested that the water is an important element of geodiversity shaping landscapes esthetically thus, offers attractive linkages to the hydro-geoheritage of the area. As per international practices, the varied water objects (surface and or ground water) can also be promoted in the form of geo-points (hydro-geosites) in India to establish their hydro-geodiversity and hydro-geoheritage values. Further, popularization of these aspects can be performed through guided tours, workshops and other communication methods for educational and awareness rising as well as research activities to be utilized to promote hydro-geotourism.

The hydro- geodiversity and hydro-geoheritage concepts in India are least understood and are not adequately explored in terms of hydro-geotourism development for sustainable economic developments. It is obvious that the developing nation like India is facing tough challenges and hindrances against such development due to their higher dependency on primary resources. It is also due to lack of public awareness and importance given to sustainable development of heritage water objects. Though, India is endowed with varied types of hydro-geosites (both surface and ground water) having national and international significance. Similar to the development at international level (Simić et al. 2010; 2010; Pereira and Pereira 2010; Poltnig 2015; Ruban 2019 and Perotti et al. 2019) importance of water bodies as hydro-geosites and their geoheritage values has grown steadily over the years in India (Jain-Neubauer 1999; Tegel et al. 2012; Singh 2013 and 2022; Amirthalingam 2015; Singh and Mathur 2014; Victoria and Gupta 2017; Nawre 2018; Singh and Mishra 2019; Marathe 2021 and Mathur et al. 2021b).

The hydro-geosites of the study area are geoheritage-monuments showcasing unique characteristics of geological, geomorphological, hydrogeological and archeological values. These hydro-geosites are magnificent artefacts constructed by local HSR showcasing civil and architect engineering representing various types, designs and style which are unique in the world (Pandey 2016a, b; Singh and Mishra 2019). Thus, hydro-geosites of the study area are not only showcase of scientific and peerless engineering aspects but are also magnificent ancient monumental heritage structures representing ancient history and culture of medieval India. The creation and construction of such ancient artefacts is difficult to develop in present time. Thus, these unique structures should be conserved having significant hydro-geodiversity of geoheritage values of educational and geotourism significance.

Additionally, designs and architect are very popular internationally as at many famous places, their structures and stone veneer for inside or outside decorative walls and steps were constructed are influenced by designs of hydro-geosites of the study area. Among them, the design and steps pattern of Rajmahal hydro-geosite is utilized magnificently at world fame site of compact at Gandia, Spain and famous Vessel, located at Manhattan, USA (Konstantinos 2019 and Marathe 2021), endorsing their importance in the present time.

Significantly, these hydro-geosites are primarily geological objects showcasing scientific heritage with respect to their representation as spectacular groundwater harvesting conservation and management system of mediaeval period of India. Beside geological significance, additionally these are endowed with archeological (historical, cultural, and religious), architectural, and civil engineering values. Thus are very important and potential candidates for National Geological Monuments (NGM) and Monument of National Importance (MNI) of India. Among 32 NGM sites declared by Geological Survey of India (GSI 2001a and b), surprisingly, not a single hydrogeological site is included despite of their significant geological and hydrogeological values. Based on present investigation, we propose Ranisar hydro-geosite as the potential candidate to be recognized as NGM of India to be utilized for education and the promotion of hydro-geotourism.

Further, under Indian Archaeological Policy, 1915, the ancient heritage geo-monuments are protected and conserved as Archaeological Sites and Remains by Archaeological Survey of India. The Policy, also deals with topical aspects like the management of tourism and development within and around geo-monuments. Based on IAP, 2015, three hydro-geosites, viz., Chand Baori (Jaipur), Ranijiki Baori (Bundi), and Neemrana Baori of Alwar hydro-geosites of Rajasthan, India, have been declared in 2018 as Monuments of National Importance (MNI) by ASI. Present investigation clearly reveals that four hydro-geosites of the study area are potential candidates to satisfy the Indian IAP, 1915 regulation. Accordingly, we propose Ranisar, Gulabsagar, Toor ji Ka Jhalra and Rajmahal Jhalra hydro-geosite as potential sites to be declared as MNI's to promote tourism for socioeconomic development of the region. Significantly, these hydro-geosites performed an array of functions with great cultural, religious, social and utilitarian significance and are hydro-geological heritage of India. Thus, these hydro-geosites are representation of socio-cultural approaches to understand how ideas, beliefs and concepts display the knowledge of local communities since mediaeval time significantly represent old patronage of India (Singh and Mathur 2014; Pandey 2016a).

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Declarations

Conflict of Interest The authors declare no competing interests.

References

Amirthalingam M (2015) Ecological traditions of India. C.P.R. Environmental Education Centre, Tamilnadu, India, pp 88–98

ASI report (2014) National policy for the conservation of the ancient monuments, archaeological sites and remains. Archaeological Survey of India, Ministry of Culture Government of India Janpath, New Delhi, p 24

Bhosle S, Chaskar K, Pandey DK, Lakhote A, Thakkar A, Chauhan G, Bhandari S, Thakkar MG (2021) Jurassic geodiversity and geomorphosite of Kanthkot area, Wagad, Kachchh Western India. Int J Geoheritage Parks 9(1):51–68. https://doi.org/10.1016/j.ijgeop.2020.12.008

Bhushan SK (1975) The Malani rhyolite; Indian Minerals. Geol Survey of India 30:99–100

Bhushan SK (2000) Malani Rhyolite a review. Gondwana Res 3:65–77

Bhushan SK (2002) Geology and geochemistry of the magmatic rocks of the Malani Igneous Suite and tertiary alkaline province of Western Rajasthan. Geological Survey of India p 181

Brilha J (2002) Geoconservation and protected areas. Environ Conserv 29:273–276

Brilha J (2005) Patrimônio geológico e geoconservação: a conservação da natureza na sua vertente geológica. São Paulo: Palimage editora, Portugal p 173

Brilha J (2018) Geoheritage: inventories and evaluation. In: Emmanuel Reynard and José Brilha (ed) Geoheritage 67–86

Carcavilla L, López-Martínez J, Durán J (2007) Patrimonio geológico y geodiversidad: investigación, conservación, gestión y relación con lo espacios naturals protegidos. Istituto Geológico y Minero de España, Madrid

Carobene L, Firpo M (2005) Conservazione e valorizzazione dei geositi costieri in Liguria: l'esempio del tratto di costa tra Varazze e Cogoleto. In: La valorizzazione dello spazio fisico come via alla salvaguardia ambientale (eds) R

CGWB Report, Western Region (2021) Ground water flow modelling of Jaisalmer district and parts of Jodhpur, District, Rajasthan, p 58

Chauhan DS (1999) Tectonic and sedimentary evolution of the Marwar-basin: a Neoproterozoic - early Cambrian sag- basin. In: Kataria, P. (ed), Proceedings of Seminar on Geology of Rajasthan: Status and Perspective, MLS University, Udaipur 111–125

Chauhan S, Desai B (2023) Geosites of the Early Cretaceous (Bhuj Formation) Based on their ichnological values: insights from the Kachchh Basin Western India. Geoheritage 15:9. https://doi.org/10.1007/s12371-022-00772-y

Chauhan DS, Ram B, Ram N (2004) Jodhpur Sandstone: a gift of ancient beaches to western Rajasthan. J Geol Soc India 64:265–276

Chauhan G, Biswas SK, Thakkar MG, Page KN (2021) The unique geoheritage of the Kachchh (Kutch) Basin, Western India, and its conservation. Geoheritage 13(1):1–34

Chavan A, Sarkar S, Thakkar A, Solanki J, Jani C, Bhandari S, Bhattacharya S, Desai BG, Ray D, Shukla AD, Sajinkumar KS, Mitra S, Gupta S, Chauhan G, Thakkar MG (2022) Terrestrial Martian Analog Heritage of Kachchh Basin Western India. Geoheritage 14:33. https://doi.org/10.1007/s12371-022-00666-z

Eder W (2008) Geoparks–promotion of earth sciences through geoheritage conservation, education and tourism. J Geol Soc India 72(2):149–154

Gregory LC, Meert JG, Bingen B, Pandit M, Torsvik TH (2009) Paleomagnetism and geochronology of the Malani Igneous Suite, Northwest India: implications for the configuration of Rodinia and the assembly of Gondwana. Precambrian Res 170:13–26

GSI (2001a) National Geological Monuments, Jodhpur Group-Malani Igneous Suite Contact. Memmo. Geoll Surv India 27:65–67

GSI (2001b) Monuments of Stratigraphic Significance, Malani volcanism overlain by Jodhpur sandstone. Memmo. Geol Surv India 27:68–69

Ieleniz HM (2009) Geotope, geosite, geomorphosite. Ann Valahia Univ Târgovişte Geogr Ser 9:7–22

IUCN World Commission on Protected Areas annual report (2022) Geoheritage and protected areas. IUCN, Gland, Switzerland, p 73. https://www.iucn.org/theme/world

Jain-Neubauer J (1999) The step-wells of Delhi'. India Int Centre Quarterly 26(2):75–80

Joyce EB (2010) Australia's geoheritage: history of study, a new inventory of geosites and applications to geotourism and geoparks. Geoheritage 2(1–2):39–56

Julia Z, Lilia S, Gerald H, Michael J (2022) Water as a significant resource in UNESCO Global Geoparks: Results of an international survey. Int J Geoheritage Parks 11(2):286–297

Kaur G, Makki MF, Avasia RK, Bhusari B, Duraiswami RA, Pandit MK, Baskar R, Kad S (2019a) The late cretaceous-paleogene deccan traps: a potential global heritage stone province from India. Geoheritage 11(3):973–989

Kaur G, Singh S, Kaur P, Garg S, Pandit MK, Agrawal P, Acharya K, Ahuja A (2019b) Vindhyan Sandstone: a crowning glory of architectonic heritage from India. Geoheritage 11(4):1771–1783

Kaur G, Ahuja A, Thakur SN, Pandit M, Duraiswami R, Singh A, Kaur P, Saini J, Goswami RG, Prakash J, Acharya K (2020a) Jodhpur sandstone: an architectonic heritage stone from India. Geoheritage 12(1):1–7

Kaur G, Bhargava ON, de Argandona VG, Thakur SN, Singh A, Saini J, Kaur P, Sharma U, Garg S, Singh JJ, Cardenes V (2020b) Proterozoic slates from Chamba and Kangra: a heritage stone resource from Himachal Pradesh. India Geoheritage 12(4):1–20

Knapik R, Jała Z, Sobczyk A, Migoń P, Aleksandrowski P, Szuszkiewicz A, Krąpiec M, Madej S, Krakowski K (2009) Inwentary zacjai walory zacja geostanowisk Karkonoskiego Parku Narodowegoi jegootulin yorazwykonani emapy geologicznejtegoobszaru. Jelenia Góra 5–8

Konstantinos V (2019) Evolution of water wells focusing on Balkan and Asian Civilizations. Water Supply, IWA Publishing, pp 347–364
Kumar S, Ahmad S (2012) Discovery of Thalassinoides burrows in the Ediacaran Jodhpur sandstone (Pokaran sandstone), Marwar Supergroup, Pokaran area, western Rajasthan. J Palaeontol Soc India 57(2):159–162
Lautman V (2013) India's forgotten step-wells. Available at: http://www.archdaily.com/395363/india-sforgottenstep-wells. Accessed 23 Apr 2017
Maheshwari A, Sial AN, Mathur SC, Tripathi RP (2004) Stable carbon v ariation in Late Jurassic Carbonates, Jaisalmer Formation, Western India. Gondwana Res Japan 6:931–934
Maheshwari A, Coltorti M, Rajput SK, Verma M (2009) Geochemical characteristics, discrimination and petrogenesis of Neoproterozoic peralkaline granites, Barmer District, SW Rajasthan, India. Int Geol Rev 51:12–19
Mathur S (2021) Geological and remote sensing investigation of significant igneous and sedimentary type georesources of Jodhpur, Western Rajasthan, India: implication for Fossil Park and Geopark for socioeconomic development through Geotourism. Unpublished Ph. D Thesis. Suresh Gyan Vihar University, Jaipur: p 171
Mathur S, Sudhanshu, Singh SK, Mathur SC (2019a) Ediacaran Fauna of the Jodhpur Group (Marwar Supergroup) in Jodhpur city, Western Rajasthan, India: implication for potential Geoheritage Sites, Estudios Geologicos, Spain. e-105 75(2): 1–4
Mathur S, Tripathi RP, Mathur SC, Mathur S, Gaur SD (2019b) Implication from chemical study of magnetic spherules from a thin ferruginous layer located in Fatehgarh Formation of Barmer Basin, India. J Geol Soc India 93:56–60
Mathur S, Sudhanshu S, Singh SK, Mathur SC (2021a) Qualitative assessment of geoheritage for geotourism promotion: a case study from Mehrangarh Ridge in Jodhpur city, Western Rajasthan. India Geoheritage 13(80):1–20
Mathur S, Rathore SS, Mathur SC (2021b) Jodhpur, Rajasthan - a potential Geopark of India. INTACH, volume on potential Geopark of India 129–148
Mathur S, Sudhanshu SK, Singh SK, Khichi CP, Mathur SC, Nathawat MS, Rathore SS (2022) Landslide in rocks of Jodhpur Group at Masuria hill in Jodhpur, western Rajasthan, India: its causes and threat to significant Geoheritage. Annals Nagi 42(1):1–15
Mathur S, Sharma S, Singh SK, Rathore SS, Mathur SC (2023) Late Cretaceous-Early Paleocene Geodiversity of Fatehgarh Formation of Petroliferous Barmer Basin, Western Rajasthan, India: A Potential Geopark Site. Geoheritage 15:54. https://doi.org/10.1007/s12371-023-00817-w
Moufti MR, Németh K (2016) Geoheritage of Volcanic Harrats in Saudi Arabia. Springer International Publishing
Nama P, Raj D (2018) Water quality assessment using physico-chemical parameters of ponds Jodhpur district, Rajasthan. Int J Res Anal Rev India 5(3):935–938
Nawre A (2018) Between community and culture: the criticality of landscape infrastructure reuse in India. J Landsc Arch 13(3):54–63
Page KN (2018) Chapter 6 - Fossils, heritage and conservation: managing demands on a precious resource. In: Reynard E, Brilha J (eds) Geoheritage assessment, protection, and management. Elsevier, pp 107–128
Page KN, Wimbledon WA (2009) The conservation of Jurassic heritage in the UK -a critical review of current practice and effectiveness. Volumina Jurassica 6:163–173
Pandey A (2016a) Bawdi: the eloquent example of hydrolic engineering and ornamental architecture. Int J Res Granthaalayah 4(1):217–222
Pandey A (2016b) Society and environment in ancient India (Study of Hydrology). Int J Human Soc Sci Invent 5(2):26–31
Pandit MK (2001) Neoproterozoic acid magmatism in western India. An Acad Bras Ciênc 73(3):461–474
Panizza M (2001) Geomorphosites: concepts, methods and example of geomorphological survey. Chin Sci Bull 46:4–6
Panizza M (2009) The geomorphodiversity of the dolomites (Italy): a key of geoheritage assessment. Geoheritage 1:33–42
Panizza M, Piacente S (1993) Geomorphological Asset Evaluation. Z Geomorph NF 87:13–18
Pareek HS (1984) The Quaternary geology and mineral resources of North-western Rajasthan Memoir. Geol Surv India 115:p99
Parihar VS, Ram H, Nama SL & Mathur S.C. (2019) Aspidella: the Ediacaran body fossil from the Jodhpur Sandstone of the Marwar Supergroup, Sursagar area, Jodhpur, western Rajasthan, India Estudios Geologicos, Spain, e-109: 75(2):1–4
Pereira P, Pereira D (2010) Methodological guidelines for geomorphosite assessment. Géomorphol Relief, Processus, Environ 2:215–222
Perotti L, Carraro G, Giardino M, De Luca DA, Lasagna M (2019) Geodiversity evaluation and water resources in the Sesia Val Grande UNESCO Geopark (Italy). Water (switzerland) 11(10):1–12. https://doi.org/10.3390/w11102102
Poltnig W (2015) Die Mineralquellen der Karawanken / MineralniIzviriKaravank. January 2004KaraWAT - Strategy for the sustainable management of water resources in the Karavanke/Karawanken UNESCO Global Geopark: www.geopark-karawankeen.com
Pradhan VR, Meert JG, Pandit MK, Kamenov G, Gregory LC, Malone S (2010) India's changing place in global Proterozoic reconstructions: new geochronologic constraints on key paleomagnetic poles from the Dharwar Aravalli/Bundelkhand Cratons. J Geodyn 4:1–19
Raghav KS, De C, Jain RL (2005) The first record of Vendian Medusoid and trace fossil-bearing algal mat-ground from the basal part of the Marwar Supergroup of Rajasthan. Indian Minerals 59:23–30
Rathore SS, Mathur SC (2014) Journey of the Jodhpur city through water bodies and heritage sites. 84th Annual Session of The National Academy of Science (NASI), JNV University, Jodhpur: p 36–51
Rathore SS, Saurabh M, Mathur SC (2016) Hydrogeological investigation of natural water impounding structures of the Jodhpur city, western Rajasthan, India Implication for hydro-geotourism sites. Proceeding volume of Workshop of Ministry of water resources on groundwater sustainability in paleo-channels. CGWB publication, Jodhpur: p 74–94
Rathore SS, Saurabh M, Shruti K, Mathur SC (2021) Ajmer, Rajasthan - a potential national geopark of India. INTACH volume on potential Geopark of India: p 211–231
Reynard E (2004) Geosite. In: Goudie A (ed) Encyclopedia of geomorphology. Routledge, London, p 440
Roy AB, Jakhar SR (2002) Geology of Rajasthan (NW India) – precambrian to recent. Sci Publishers (India): p 421
Ruban DA (2019) Water in descriptions of global geoparks: not less important than geology? Water (switzerland) 11(9):1–12. https://doi.org/10.3390/w11091866
Sharma KK (2005) Malani magmatism: an extensional lithospheric tectonic origin. In: Foulger GR, Natland JH, Presnall DC, Anderson DL (Eds.), Plates, Plumes, and Paradigms. Geological Society of America Special Paper 388:463-476
Sharma M, Mathur SC (2014) Paleontological note on Arumberia –like Mat of Ediacaran age of the Jodhpur Group of the Marwar Supergroup, Western Rajasthan, India. In: Shrivastava KL and Arun Kumar (Eds.). Georesources. Indian Science congress volume, Scient. Pub. Jodhpur: p 167–175
Shekhar S, Kumar P, Chauhan G, Thakkar MG (2019) Conservation and sustainable development of geoheritage, geopark, and

geotourism: a case study of Cenozoic successions of Western Kutch, India. Geoheritage 11:1475–1488. https://doi.org/10.1007/s12371-019-00362-5
Sheth H, Samant H, Patel V, D'Souza J (2017) The volcanic geoheritage of the Elephanta caves, Deccan traps, Western India. Geoheritage 9:359–372
Simić S, Gavrilović LJ, Belij S (2010) Hydrological Heritage - a New Direction in Hydrology and Geoheritage. Bullet Serbian Geogr Soc 90(4):83–102
Singh S (2013) Geological investigation of natural and traditional water structures and their relationship with rising ground water problem of the Jodhpur city, Western Rajasthan. India. J.NV. University, (Unpublished Ph.D. thesis): p 120
Singh S (2022) Investigation of hydrogeological aspects of important ancient natural and traditional water impounding structures of the Rajasthan, India : implication for Hydrogeotourism and as potential World Heritage Sites (unpublished D.Sc. Thesis): p 393
Singh S, Mathur SC (2014) Journey of Jodhpur city since its foundation through water impounding structures. In: Shrivastava KL, Srivastva PK (eds) Frontiers of Earth Science. Scientific Publisher, India, pp 527–550
Singh A, Mishra S (2019) Study of ancient step wells in India. Int J Res Eng Sci Manag 2(10):632–634
Srivastava P (2012) Treptichnuspedum: an ichnofossil representing Ediacaran-Cambrian boundary in the Nagaur Group, the Marwar Supergroup Rajasthan. India Proc Indian Natl Sci Acad 78(2):161–169
Srivastava P (2014) Largest Ediacaran discs from the Jodhpur Sandstone, Marwar Super-group, India: their palaeobiological significance. Geosci Front 5:183–191
Staces H, Larwood JG (2006) Natural foundations: geodiversity for people, places and nature. English Nature, Peterborough
Tegel W, Elburg R, Hakelberg D, Stäuble H, Büntgen U (2012) Early Neolithic water wells reveal the world's oldest wood architecture. PLoS ONE 7(12):46–58
Thakkar A, Jadeja JM, Rajesh SV (2022) Geoarchaeological Heritage of Kachchh Region, Gujarat Western India: Geotourism Potentials. Geoheritage 14:128. https://doi.org/10.1007/s12371-022-00748-y
Thakkar MG, Chauhan G, Padder AH, Sharma S, Parcha SK, Thakur VC, Dorjay CP (2023) Geoheritage merits of the Zanskar Range of the Kashmir Himalaya: a Field Geology Museum from Precambrian to Present. Geoheritage 15:75. https://doi.org/10.1007/s12371-023-00842-9
Tillotson GHR (1987) The Rajput Palaces: the development of an architectural 1450–1750. Yale University Press, Nand, p 224
Victoria L, Gupta D (2017) The vanishing step wells of India. Merrell Publishers, p 224
Wimbledon WAP (1996) GEOSITES, a new IUGS initiative to compile a global comparative site inventory, an aid to international and national conservation activity. Episodes 19:87–88
Wimbledon WAP, Benton MJ, Bevins RE, Black GP, Bridgland DR, Cleal CJ, Cooper RG, May VJ (1995) The development of a methodology for the selection of British sites for conservation. Part 1. Mod Geol 20:159–202
Zouros N (2004) The European Geoparks Network Geological heritage protection and local development. Episodes 27(3):165–171
Zouros N (2005) Assessment, protection and promotion of geomorphological and geological sites in the Aegean area, Greece. Géomorphol Relief Processus Environ 3:227–234
Zouros N (2007) Geomorphosite assessment and management in protected areas of Greece. The case of the Lesvos island coastal geomorphosites. Geogr Helv 62(3):169–180
Zouros N, McKeever PJ (2009) European Geoparks Network and geotourism. In Neto de Carvalho C, Rodrigues J (eds) New challenges with geotourism. Proceedings of the VIII European Geoparks Conference, Idanha-a-Nova 14–16 September (2009), Portugal: 19–23
Zouros N, Ramsey T, McKeever P, Patzak M (eds) (2009) European Geoparks. EGN, Sigri Lesvos