Hydrogeology Journal (2014) 22: 1493–1506
DOI 10.1007/s10040-014-1151-z

Review: Carbonate aquifers and future perspectives of karst hydrogeology in India

Farooq Ahmad Dar · Jerome Perrin · Shakeel Ahmed · Allu China Narayana

Abstract About 3 % of India's total land surface is occupied by carbonate rocks which are mostly karstified and constitute a significant source of groundwater. The groundwater drawn from these aquifers matches the water demand of ~35 million people living in 106 districts of the country and also the water needs of livestock, irrigation and industry. The studies on karst in India carried out so far have mostly addressed geology, hydrology and groundwater contamination. A literature survey suggests that there is a need for detailed research, applying new approaches and techniques for proper carbonate aquifer identification, characterization and management. Such specific approaches will improve modeling, exploitation and protection of karst groundwater. An overview of the research carried out on groundwater resources of karst formations in India is presented, which also throws light on the protection of karst aquifers from existing anthropogenic activities such as mining and groundwater over-exploitation.

Keywords Carbonate rocks · Karst · Water resources · Literature survey · India · Review

Introduction

The karst (*krs* or *kras*, a Slavic term meaning 'stony ground') is a near-surface landscape developed mostly in carbonate lithology due to the dissolution processes associated with groundwater flow. The term was coined by the father of karst geomorphology, Jovan Cvijic, in 1893 in the publication *Das Karstphanomen* (Ford 2006). The landscape with exo- and endo-karst features (karren and karrenfield, sinkholes, swallow holes, dry valleys, poljes, ouvalas, blind valleys, dolines, underground drainage system, caves, springs and a number of beautiful depositional speleothems) is called a karst landscape (Ford and Williams 2007; Andreo et al. 2010). Dissolution of carbonate rocks (i.e., limestones and dolomites), gypsum and halite leads to the formation of true karst (Bakalowicz 2005). Sometimes sandstones/quartzites are also prone to karstification (pseudo-karst) under favorable hydrogeochemical conditions (Wray 2003; Ford and Williams 2007).

Carbonate rocks cover 20 % of the world's continents and are home for nearly 17 % of the world's population. Karst is developed in these rocks globally (Fig. 1) and presents unique characteristics which have specific consequences for land and water-resources management (e.g. White et al. 1997; Ford and Williams 2007). Karst areas have also been known for their valuable water resources for millennia, as nearly 25 % of the human population utilizes groundwater derived from karst aquifer systems, either directly or indirectly (Ford and Williams 2007).

Specific characteristics in terms of karst morphology and hydraulic/hydrodynamic processes, developed by dissolution, make karst aquifers different and more complex than other aquifers (Bakalowicz 2005). These aquifers are characterized by dual recharge (focused recharge through swallow-holes and diffuse recharge), dual flow properties (high in conduits and low in the rock matrix), and dual storage properties (high in the rock matrix and low in the conduits; Hobbs and Smart 1986). They are characterised by a triple porosity system consisting of dissolution-enlarged conduits, fractures and primary pores (White 2002; Ford and Williams 2007). The nature of flow is laminar (i.e., Darcian) in fractures and pores and usually turbulent in conduits. Readers are encouraged to refer to Legrand and Stringfield (1973); Ford and Williams (2007); Andreo et al. (2010); Ghasemizadeh et al. (2012) for further information about these aquifers. The objective of this paper is to review the work carried out on carbonate formations and aquifer systems in India and highlight their importance in terms of groundwater and other resources (construction material,

Received: 29 October 2013 / Accepted: 28 April 2014
Published online: 14 June 2014

F. A. Dar (✉) · S. Ahmed
Indo-French Centre for Groundwater Research,
CSIR-National Geophysical Research Institute, Hyderabad, India
e-mail: farooq.dar1@gmail.com

J. Perrin
BRGM, Avenue Claude Guillemin, BP 36009,
45060 Orleans Cedex 02, France

F. A. Dar · A. C. Narayana
Center for Earth and Space Sciences,
University of Hyderabad, Hyderabad, 500046, India

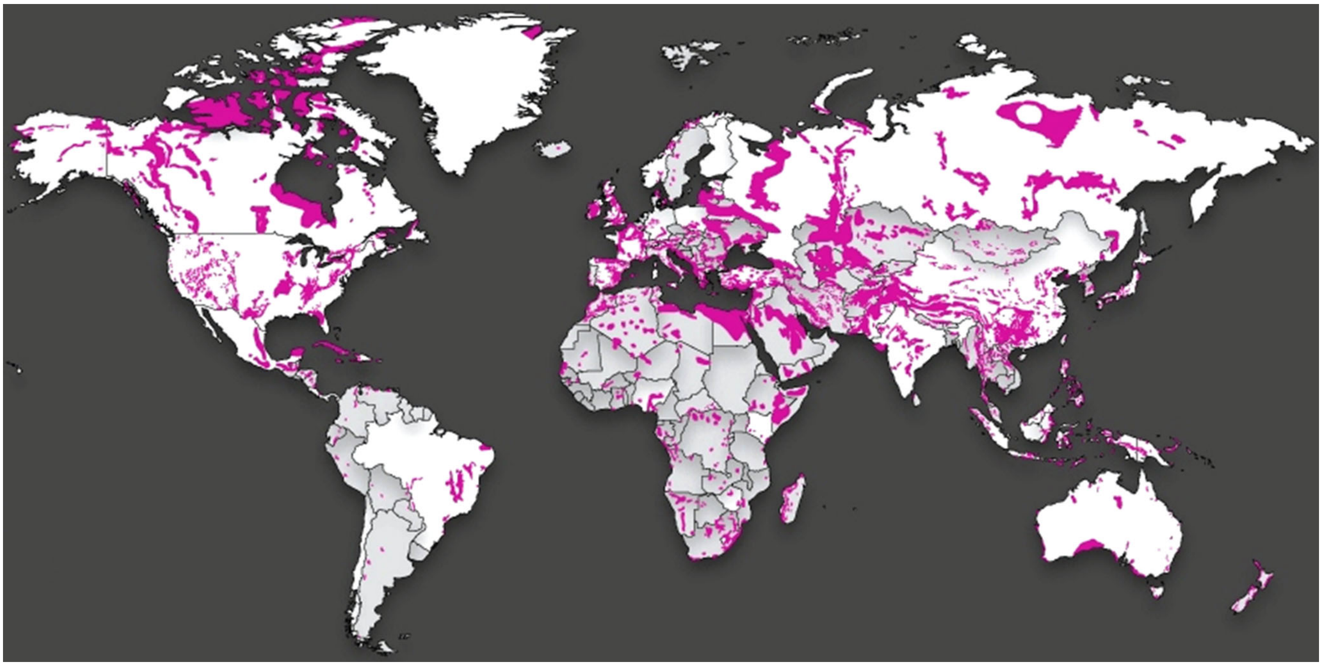

Fig. 1 Major carbonate rock outcrops (*red areas*), which provide a close global-scale estimate of karst regions (Ford and Williams 2007). Map downloaded from Circle of Blue (2010)

cement production, touristic potential). The scope of this paper outlines the management of groundwater in limestone terrains using karst-specific studies (e.g., Goldscheider and Drew 2007). The paper also addresses the assessment of suitable methods for exploitation and management of groundwater in karst aquifers.

Karst hydrogeology: practical issues

Typical karst areas are represented by a general lack of soil cover, absent or a low density of surface streams, presence of disappearing (sinking) streams and highly variable groundwater flow velocities (high in channels and low in matrix), groundwater flow through solution channels, presence of large caves and springs as major outlet of groundwater flow with a highly variable discharge, and water chemistry. However karst can also exist with its specificities under non-karstic rock cover and, therefore, without presence of typical karst features at the surface; this context is described as mantled karst or covered karst. Given such highly complex nature of karst aquifer systems, their hydraulic characterization and modeling can be extremely challenging. Watershed delineation in karst may be challenging: the total watershed may be comprised of the karst outcrops where diffuse recharge occurs and surface watershed of streams that infiltrates in the karst by swallow-holes; also, the presence of inter-basin groundwater flow through solution channels is common, meaning that two aquifer systems may share partly common watersheds. Interpolation and extrapolation methods give unsatisfactory results due to the presence of usually irregular and discontinuous groundwater levels. The rate and direction of groundwater flow is usually undetermined which may cause poor predictability of their water resources. The estimation of representative hydraulic conductivity is difficult because it is highly scale-dependent with a strong increase from local-scale measurements (e.g., on limestone core) to basin-scale estimates (e.g., modeling; Kiraly 1975).

In general, karst areas are not suitable for waste disposal sites due to thin soils and the possibility of rapid groundwater infiltration through high permeability zones. Thus, karst aquifers are highly prone to contamination and pollution. Progressive dissolution weakens the overlying rock mass above the caves causing subsidence and engineering-related problems (e.g., collapse sinkholes, suffosion sinkholes, subsidence sinkholes). Construction of dams and reservoirs is challenging in karst because of likely water leakage through high permeability zones. The degree of karstification varies depending on the geo-climatic context and the nature of the carbonate rocks (degree of primary fissuration, bedding planes frequency, primary porosity, etc.).

Indian scenario

Carbonate rocks are widely present in India, either directly exposed at the surface or as buried geologic layers. The Indian stratigraphic record reveals the presence of carbonate rocks from Precambrian to Tertiary periods mostly consisting of limestones and dolomites (Fig. 2). Highly karstified carbonate rocks are well developed in certain areas of the country in different geomorphological and climatic zones particularly within different sedimentary basins (e.g., Cuddapah, Vindhyan and Chattisgarh) and Himalayan regions. A detailed map of carbonate and

 DOI 10.1007/s10040-014-1151-z

Age		Rock Unit	Formation	Description
Cenozoic	Pleistocene		Miliolitic Ls. (Gujarat)	Oolitic limestone
	Miocene-Oligocene		Nari & Gaj Fm. (Kutch)	Buff limestone
			Baripada beds (Orissa)	Limestone
	Eocene		Subathu series	Nummulitic limestone and shales
			Ranikot & Chharat Ls.	Limestones
			Kopili & Sylhet Ls.	Limestone
			Kirthar Ls.	Formaniferal limestone
			Ranikot Ls.	Nummulitic Ls.
	Palaeocene		Limestone (Pondichery)	Nummulitic limestone
Mesozoic	Cretaceous		Chikkim Ls. (Spiti)	Fossiliferous Limestone
			Kiogar Ls.	Limestone
			Landpar stage	Sandy limestone
			Bagh beds	Coral limestone
			Turuvai & Kalakadu Ls.	Fossiliferous limestone
			Niniyur stage	Oolitic limestone
			Trichinopoly stage	Shelly limestone
			Uttatur stage	Limestone and coral
	Jurassic		Mount Everest Ls.	Fossiliferous Limestone
			Kalhan Ls.	Limestone
			Lilang Gr. Daonella	Limestones
			Jasalmer Ls.	Dolomite
			Kioto Ls.	Unfossiliferous limestone
	Triassic		Patcham Fm.	Shelly limestone
Palaeozoic	Permian		Other Himalayan Ls.	Limestone and dolomites
			Zewan Fm.	Limestone, shale
			Productus Ls.	Fossiliferous limestone
	Carboniferous		Lipak beds	Limestone
			Syringothyris Ls.	Grey limestone
	Silurian		Hapathnar Gr.	Limestone, shale
	Ordovician		Dhaulagiri& Nilgiri Ls.	Limestone
Proterozoic	Upper Purana	Upper Vindhyan	Rewa & Bhandar Ls.	Micritic oolitic stromatolitic Ls.
		Kurnool Gr.	Koilkuntla Ls.	Massive and flaggy limestones
			Narji Ls.	Massive and flaggy limestones
		Bhima Gr.	Shahabad Ls.	Limestone
			Katamdevari Ls.	Stromatolitic Ls.
		Indravati Gr.	Kanger Ls.	Flaggy dolomitic limestone
			Jagdalpur Ls.	Dolomite
		Chhattisgarh SG.	Hiri Do.	Dolomite
			Chandi Ls.	Stromatolitic limestone
			Charmuria Ls.	Limestone with dolomite bands
			Chatrela Fm.	Limestone and other rocks
		Dongargarh SG.	Sausar sereis	Dolomite and marbles
	Lower Purana	Lower Vindhyan	Nimbahara Ls.	Limestone
			Kuteshwar Ls.	Limestone
			Fawn and Rohtas Ls.	Stromatolitic dolomitic Ls.
			Kajrahat Ls.	Limestone and shale
		Cuddapah SG.	Vempalle Fm.	Dolomite
			Chanda Ls.	Dolomitic limestone

Fig. 2 Stratigraphic record of geology showing the major carbonate units in India (compiled from Wadia 1939; Adyalkar 1977; Murty 1988; GSI 1997; Kumar 1985a, b). Abbreviations: *SG* super group; *Gr* group; *Fm* formation; *Ls* limestone; *Do* dolomite

 DOI 10.1007/s10040-014-1151-z

		Pakhal Gr.	Rajaram Ls.	Limestone and dolomite
			Pandikunta Ls.	Stromatolitic dolomitic limestone
		Kaladgi Gr.	Katagari Ls.	Limestone.
			Arlikatti Do.	Dolomite
			Chikshellikeri Ls.	Limestone
			Muddapur Do.	Dolomite
			Manikgarh Ls.	Limestones
		Gangpur Gr.	Birmitrapur Fm.	Limestone, dolomite, quartzite
			Jammu & Riassi Ls.	Limestone
			Bijawar & Raiola Ls.	Limestone and dolomite
			Gangpur series	Limestone and dolomite
ARCHAEAN				

Fig. 2 (continued)

karstified rocks of India was prepared using a wide range of information (Fig. 3) which will help to update the world karst data base (Fig. 1) and the International Association of Hydrogeologists (IAH) World Karst Aquifer Mapping Project (IAH 2013).

As seen in Fig. 3, carbonate rocks include rocks that are clearly karstified and rocks for which the degree of karstification is poorly known. Non-karstified rocks have not been subjected to geological processes such as dissolution and have remained as homogenous formations. The karstified rocks are strongly subjected to dissolution processes and were karstified during the past humid conditions, with some of them showing relict karst features which are sometimes hidden (paleo-karst). Many karstified massifs possess spectacular surface and sub-surface features including the longest and deepest caves (Fig. 4) of India.

From the available data, it is estimated that karst and carbonate rocks, which have potential for karstification, cover about 3 % of the country's total area. The karstified rocks are also concealed beneath the soils or buried deep under the surface geology in many areas of India; for example karst in the Borunda area of Rajasthan is covered under a thick blanket of sand (Meijerink 2007). These deep karstified rocks may also serve as good aquifers in areas where groundwater overexploitation or contamination problems occur in other aquifers.

Literature survey

The first study of karst formations of India was concerned with the geological aspects and was carried out by William King (King 1872, 1882) of the Geological Survey of India. Although the geology of various carbonate rocks, limestone, dolomites, etc. of this region were discussed by later researchers, the studies about karstification, aquifer systems and hydrogeological characteristics are very limited, which is evident from the very few scientific publications related to karst hydrology and karstification in India. A significant study on the karstic nature of limestone formations of India was first reported by Adyalkar (1977) but no further work on the characterization and nature of karst aquifers is recorded. Murty (1988) outlined the major carbonate formations and karstic horizons in the Indian stratigraphy. The occurrence of karst aquifers in India and the groundwater potential has also been assessed by a few individuals and organizations. Using similar methodology applied in other porous groundwater media, the Groundwater Estimation Committee (GEC 2009) has estimated the specific yield of carbonate aquifers of India at 0.03 and of karstified rocks at 0.08. Although in 2011 the Central Groundwater Board (CGWB) brought out a detailed report on the groundwater scenario of major cities of India and highlighted the general groundwater conditions in the country, there was no emphasis (in the report) on the study of karst aquifers. Details furnished about the karst-related keywords in the GEC and CGWB groundwater reports (Table 1) throw light on this shortcoming. The following sections provide an overview of the literature available about the carbonate aquifers of India.

Carbonate rock hydrogeological properties

Proterozoic sedimentary basins in mainland India

Singh (1985a, b) discussed the nature of karstified formations of the Proterozoic Period in the Vindhyan System, particularly extending in the Rewa region of Madhya Pradesh, Central India. The paper defined surface karst features, such as karren, sinkholes, fluvio-karst, sinking streams, springs, etc. He also highlighted the nature of karst formations and porosity and groundwater flow properties in karst aquifers. It was calculated that the primary porosity of such karst formations is only 7 %, but no quantitative information about the conduit porosity was provided. CGWB (2009) published an overview of groundwater resources in Chhatarpur district (Madhya Pradesh), but no information was provided on the karst aquifers of this area. Saifuddin (2000) suggested that more humid conditions existed in the past and this culminated in the karstification of marbles in the Vindhyan basin which is demonstrated by the presence of paleo-karst

 DOI 10.1007/s10040-014-1151-z

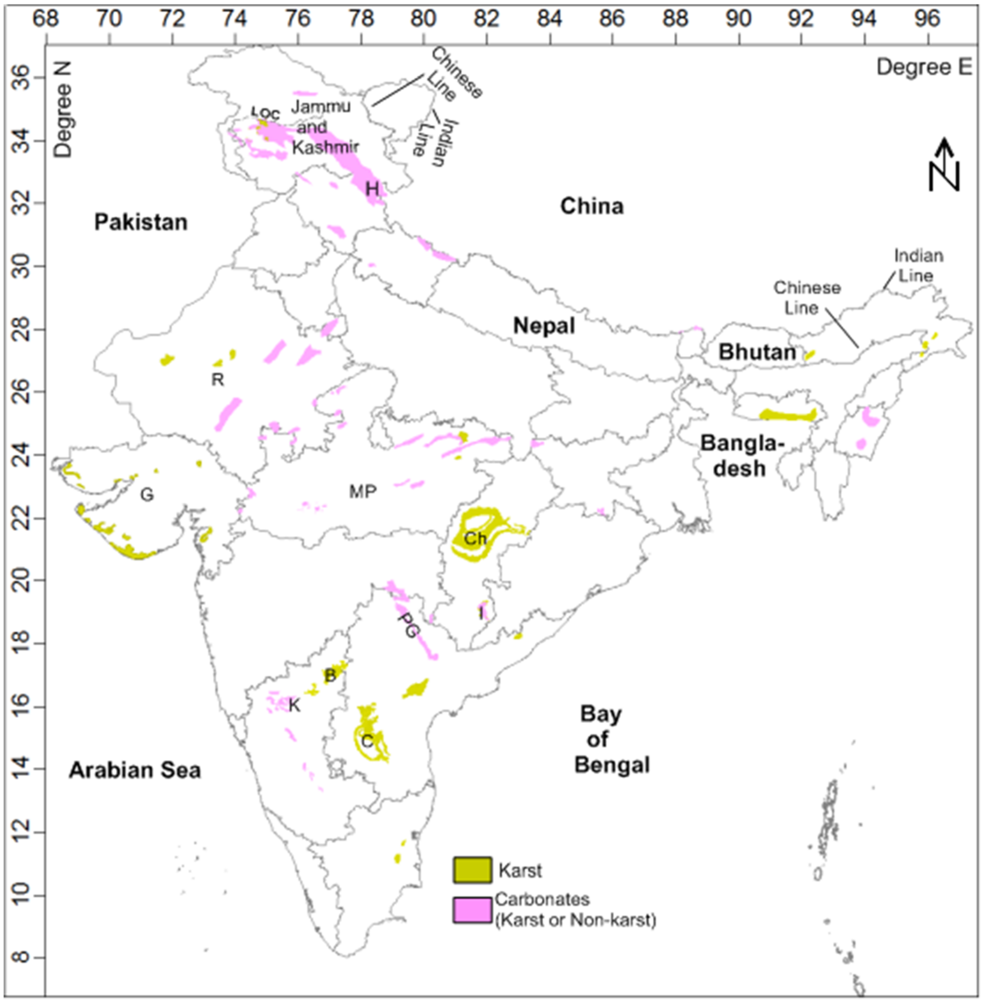

Fig. 3 Map of India showing karstified and potential karst (carbonate) aquifers of India. The maap is compiled from different sources which are referenced in the paper. *Thin lines* in the map represent state boundaries. Boundaries of the map are marked as per UNO Map No. 3953 and 4140, Rev. 4, 2011. *C* Cuddapah basin; *K* Kaladgi basin; *B* Bhima basin; *PG* Pranhita-Godavari basin; *I* Indravati basin; *Ch* Chattisgarh basin; *MP* Madhya Pradesh; *G* Gujarat; *R* Rajasthan; *H* Himalayan region

features, which can be used as indicators to locate aquifer zones. Using geological and hydrogeological information, Venkatanarayana et al. (1999), who observed that the flow in the aquifer is mostly of conduit type, gave a conceptual model of the Kuteshwar limestone aquifer of Madhya Pradesh, which is highly karstified. Earlier, Singh (1985a, b) also developed a hydrogeological model of the karstified Kuteshwar aquifer. The study reveals the presence of three porosities (matrix, fracture and conduit) and the abundance of sub-surface karst features (i.e., fractures, crevices and solution voids). He further inferred from the packer test data that the hydraulic conductivity of limestone aquifer decreased from ~1.03 m/day near the Chhoti Mahanadi River to $\sim 3\times 10^{-4}$ m/day away from the river and the conduit porosity varies from 12.5 to 43 %.

Singh (1985a, b) also discussed the protection of the Kuteshwar limestone aquifer from the possible effects of dam and reservoir construction. According to him, the construction of a dam on the limestone will not have any major consequences on the hydrogeological regime of the area. Although the rocks are karstic in nature, Singh (1985a, b) did not mention the possible activation of the dissolution processes by the enhanced infiltration of surface water, which is more aggressive than the stored groundwater. In the future, this may enlarge the already present cavities and could lead to many engineering problems, like subsidence, failure of dam, reservoir water loss, etc.

Evaluating the pollution susceptibility of karst aquifers through a DRASTIC approach, Dubey et al. (2006) suggested that the shallower parts of the Bhander limestone aquifer (Madhya Pradesh, India) are more prone to pollution than the deeper parts. Without taking the heterogeneity of the aquifer characteristics into account, the authors recommended some measures for evaluating the future pollution of the groundwater.

Karst aquifers constitute a large source of groundwater in Chattisgarh (CGWB 2012), which is also indicated by a large number of wells used for groundwater withdrawal. The CGWB study reveals that more than 50 % of all the wells existing in the area are located in limestone aquifers. The aquifers in this area have a specific yield of 1–2 %

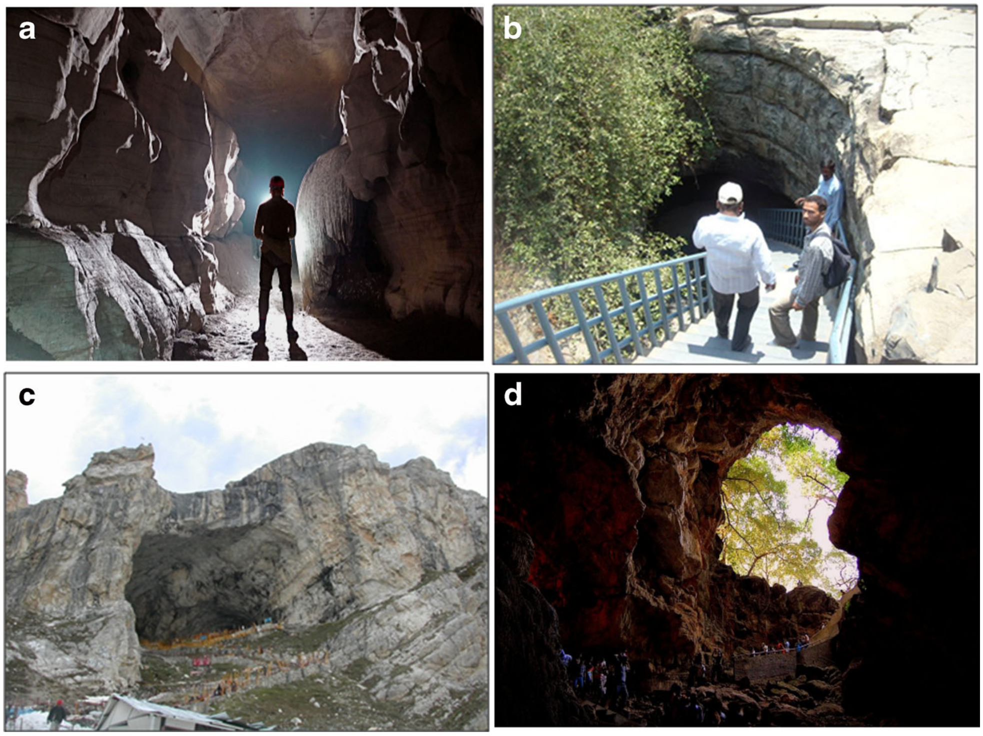

Fig. 4 A window to the underground. **a** Munagamanu cave in the Cuddapah basin (Andhra Pradesh); **b** Belum cave, Cuddapah basin; **c** Amarnath Cave, Kashmir; **d** Borra Cave, Vishakhapatnam (Andhra Pradesh)

and transmissivity values ranging between 4 and 140 m^2/day. From the water-table fluctuation method, annual recharge of 60–220 mm/year was estimated. Using stable oxygen and hydrogen isotopes and water chemistry, Sinha et al. (2002) assessed the contamination problems in the Chandi limestone formation of Raipur city of Chattisgarh. According to them, the aquifer is prone to contamination and pollution from landfills, waste disposal sites and other anthropogenic sources; however, their work fails to consider the aquifer as karstified.

The paper by Ruggieri and Biswas (2011) is about the geometric setup of the karst system of the Python Cave area of Chattisgarh. They surveyed and mapped the subsurface karst conduits and concluded that the cave system is controlled by the tectonic structural pattern of the area. The area is also an example of well-developed karst terrains located in a complex geological system of Precambrian age.

Table 1 Representation of karst-specific terminology in four selected reports on groundwater (i.e. the number of times that keywords were mentioned in the text) published by the Groundwater Estimation Committee (GEC) and Central Groundwater Board (CGWB)

Keyword	Number of times keyword mentioned in the text			
	GEC (2009)	CGWB (2010)	CGWB (2011)	CGWB (2012)
Carbonate	10	7	20	0
Karst	2	0	2	1
Limestone/dolomite	19	2	34	6
Cave	1	0	0	0
Spring	1	0	106	3
Cavities	1	2	3	0
Solution/dissolution	1	2	5	0
Epikarst	0	0	0	0
Conduit	0	0	0	0
Sinkhole	0	0	0	0
Speleothems	0	0	0	0

Shibasaki et al. (1985) investigated the karst formations of the Cuddapah basin of southern India. The study was based on the geological field information collected from many karstified areas. The results provided an encouraging preliminary picture about the regional karstification in the Cuddapah basin, while a broader speleological view of the caves of different parts of India was given in other studies (Gebauer and Abele 1983; Gebauer 1985, 1997; H. D. Gebauer, Mandhip-Khol., “Resources on the speleology of Chhattisgarh State, India”, unpublished report, 2007). These surveys have led to the discovery of many significant caves which currently constitute the backbone of a growing tourist activity.

Dar et al. (2010, 2011a, b and 2012) highlighted the significance of karst aquifers of India and focused on the need to include karst-specific methodologies for their characterizing and management. Detailed karst hydrogeological studies were carried out in the Cuddapah sedimentary basin (Dar et al. 2011a, b). The three karstified geological units (Vempalle dolomite, Narji and Koilkuntla limestones) possess prominent surface and sub-surface karst features in this semi-arid region. The paper discussed the groundwater occurrence, flow and transport and the role of karst geomorphology on different groundwater processes in these highly karstified rocks. A model of karstification was proposed by Dar et al. (2011a,

 DOI 10.1007/s10040-014-1151-z

b; Fig. 5) to provide information related to the past climatic changes as well as other changes responsible for the karstification in southern India. These aquifers are highly exploited for water and other resources (building stones, lime for cement factories), which have large impacts on the environment and ecology of the area. Dar (2013) carried this work forward by incorporating results from multiple approaches (geology, geomorphology, hydrology, hydrochemistry, isotopes, tracers, speleology) in the semi-arid Cuddapah basin where karst groundwater is the sole perennial water source. The results were discussed in terms of the hydrogeological characterization of the karstified rocks and recharge mechanisms, using the hydrogeochemistry of groundwater taken from springs, bore-wells, cave streams, etc. (F. A. Dar, CSIR-NGRI, unpublished paper, 2014) discussed the possible geochemical processes that lead to the evolution of karst water chemistry in the Narji limestone of the Cuddapah basin.

Himalaya range and foothills

From the available hydrogeological data, it is evident that the Kashmir Valley of the Himalayan region has significant karst aquifers. The stratigraphic record reveals that the carbonate rocks exposed in the Himalayan region are mostly Palaeozoic to Cenozoic in age. Some of these carbonate rocks are a source of many permanent springs (Fig. 6), the water of which is used for drinking, irrigation and other purposes. Verinag spring in the Anantnag district serves as an originating source for the River Jhelum, a major river flowing through the Kashmir Valley. During an expedition, British karst researchers explored many Himalayan areas, particularly the Valley of Kashmir, and provided an overview of the karst features found in the carbonate rocks of this area (Waltham 1972). Chadha (1975) discussed the nature of karst features along with the occurrence and mode of formation of phytokarst in the Great Limestone formations of Udhampur district of Jammu and Kashmir, India. According to them, these carbonate rocks were subjected to the action of blue green algae which enhanced the mode of normal karstification and formed phytokarst features. Earlier, few authors provided a detailed study of the dolostones of this area without discussing the phytokarst features (Chadha 1975). From the field and tracer test data, Coward et al. (1972) gave an explanation about the hydrogeological configuration of the major karst areas of Kashmir. Based on tracing test results, they concluded that some springs flow with

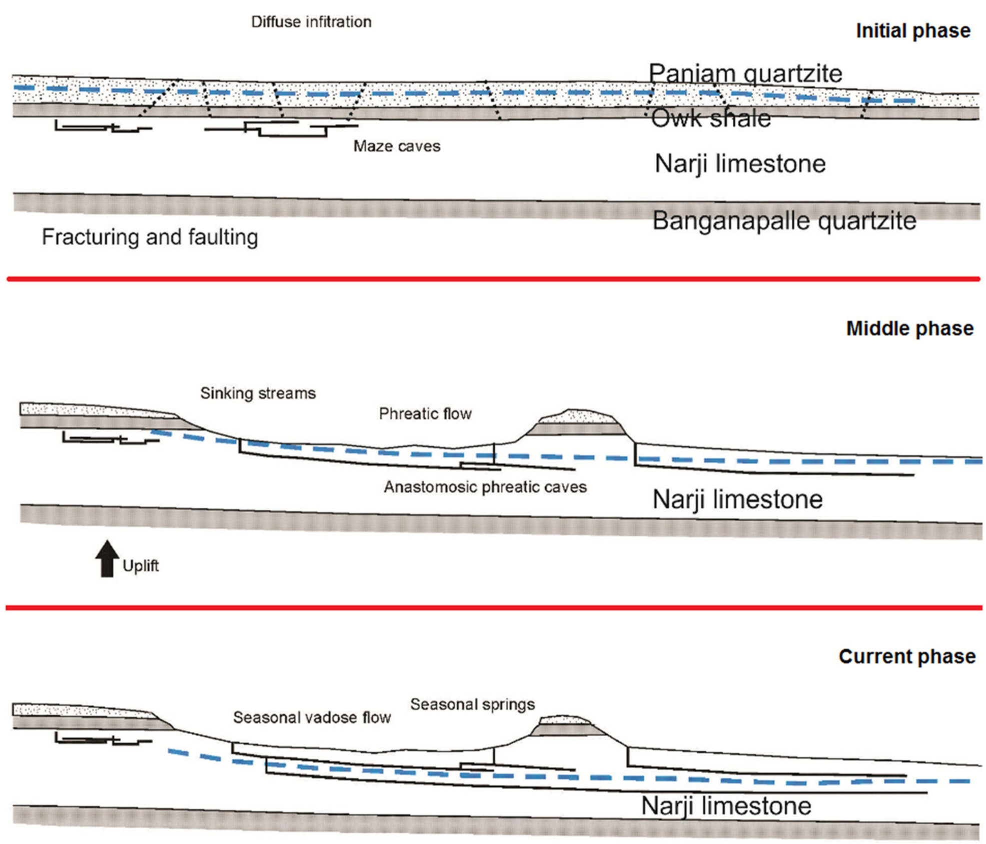

Fig. 5 A conceptual model of karstification in the Cuddapah basin, India. Three stages of karst development are explained (Dar et al. 2011a, b). *Initial phase*: Development of maze cave systems in a confined setting during more humid conditions prior to the onset of monsoonal conditions and Western Ghats uplifting at ~8 Ma when sea level was ~100 m higher than present level. *Middle phase*: Following tectonic uplift, a positive relief favoured surface runoff and progressive erosion of overlying layers exposed Narji limestone, and anastomosic phreatic cave systems develop. Western Ghats uplift lead to semi-arid conditions. *Current phase:* Water table progressively deepens, maze cave systems became inactive (relict caves) and the aquifer became unconfined, inducing a deeper level of karstification (present state) forming phreatic caves. Fast infiltration favours more dissolution through sinkholes, etc.

 DOI 10.1007/s10040-014-1151-z

Fig. 6 Some of the karst springs in India: **a** Verinag Spring, Kashmir **b** Yaganti Spring, Kurnool (Andhra Pradesh)

large discharge and are recharged both by diffuse infiltration and point infiltration in upgradient streams. The spring water is utilized for many uses and this exploitation of spring water is increasing day by day. Jeelani (2005, 2010) measured the water quality of some karst springs of the Kashmir Valley and discussed various related health and environmental issues resulting from the polluted waters. Based on the hydrochemistry of the springs of the valley, a conceptual model was also proposed by Jeelani (2004), while in another publication, Jeelani (2008) discussed the impacts of climate change on the karst springs of Kashmir and concluded that these springs are highly vulnerable to climate changes. The study by Jeelani et al. (2010) analyzed the nature of recharge in karst springs of the Lidder Valley of the Kashmir Himalayas using isotopic data of water from springs, streams and precipitation. According to them, the altitudinal effect on groundwater recharge is observed from the isotopic signature of the waters; additionally, they also concluded that the recharge to the karst aquifers is dominated by snowmelt in the area. In a similar study (Bhat and Jeelani 2012), water chemistry and isotope data were used to delineate the recharge zones in these karst springs. These karst springs are also under threat from human activities and their water resources must be conserved for sustainable use (e.g., Jeelani et al. 2012).

It is also observed from the literature that north eastern India is famous for karst landscapes. Karst is well developed in the Kopili River Basin of Assam with well-developed karst landforms (Kumar 1985a, b). Brooks (1995) carried out speleological studies in the caves of Meghalaya and explored largest cave systems, while in the same area, Arbenz and Weidmann (2003) described several large cave systems with active underground rivers including Krem Liat Prah with over 30 km of explored conduits, which is likely the longest cave system of India. Many karst springs drain out in the form of conduits from these karst aquifers at many locations but no accessible documentation is yet available.

Limestone mining activities

Limestone areas of India are extensively exploited for use in cement factories, which are operated at large scale, serving as the economic backbone in many areas. Groundwater around cement factories also causes serious environmental problems. The mining activity has large and negative impacts on the sustainability of water resources (Limaye 2003), which are also due to elevated concentration of major ions (Ca^{2+}, Mg^{2+}, etc.) that may easily get released from the mining waste. A study by Soni (2007) has argued that the operation of limestone mines will not adversely affect the karst aquifers of the Chandrapur area of Madhya Pradesh. Without taking advantage of any proper scientific methodology, the author recommended that the diversion of surface drainage will be feasible to carry out the mining operation without having any impact on the local hydrological or environmental setup of the area. This contradicts the position, when considering the impacts of mining on karst aquifers, as discussed by many authors all over the world (LaMoreaux et al. 1997; Milanovic 2002; Coxon 2011; Urich 2002; Bonacci and Rubinic 2009). Limestone mining can have local environmental as well as social impacts in many areas of Western India (Ranade 2007). The remotely sensed data used by Rande (2007) to detect the land-use changes on the surface gave no mention of how this will affect the groundwater and surface-water regime of the area. Water-balance studies were undertaken for a limestone mining area of Tamil Nadu (Chaulya 2009) without considering limestone as a specific media where conventional groundwater estimation methodology is not valid due to the karstic nature of these rocks.

Saline intrusion in coastal carbonate aquifers

In the case of coastal carbonate aquifers, saline intrusion may reach a given aquifer very easily through solution channels, which has not been discussed in detail so far with respect to India, except in limited studies (Limaye 1988 and 2003; Pujari and Soni 2009). Small-scale karst features are present in the 50-m thick coastal Milionitic limestone of Gujarat (Limaye 1988); the aquifer is under threat due to saline intrusion. Using geophysical methods, potential groundwater bearing zones were located in Gujarat, but no detailed studies were undertaken. Seawater intrusion is the main problem for groundwater resources in many coastal areas of Gujarat and the situation can worsen with more pumping and mismanaged limestone mining activities (Pujari and Soni 2009). According to Pujari and Soni (2009), electrical resistivity tomography studies have shown that mining pits are

 DOI 10.1007/s10040-014-1151-z

particularly prone to seawater intrusion; although the limestone is also karstified to some extent, karstic properties of the aquifer were not considered in their results. Seawater intrusion problems in karstified carbonate aquifers of western Rajasthan have been discussed by Rushton and Raghava Rao (1988); seawater intrusion has contaminated the aquifer to a large extent due to irrigation causing drawdown in certain areas. The aquifer recharge was estimated by utilizing the daily soil-moisture-balance technique. The specific yield varies from 0.12 for the karstified limestone to 0.04 for the less permeable limestone of Rajasthan.

Geophysical approaches in karst regions

Geophysics is an important tool in detecting underground solution channels in limestone aquifers (Dutta et al. 1970; Limaye 1988; Singh and Chauhan 2002; Pujari and Soni 2009). The results help to determine the depth to fractures and solution channels along with quantification of the water resources. Singh and Chauhan (2002) also highlighted the importance of ground penetrating radar (GPR) in assessing the impact of limestone mining on groundwater exploration and management in India; based on the geophysical results, they suggested that limestone mining should be limited to a certain depth so that solution channels and enlarged fractures may not become exposed. Geophysical methods were also used in the Kurnool area of southern India to test the reliability of these methods in delineating karst related features (Chandra et al. 1987); their results showed that different electrical geophysical methods can help to delineate the lateral extent and orientation of the solution cavities in karst aquifers in the Kurnool district. These methods have not been extended to other karst areas. Using geological and geophysical investigations as a tool, Venkatanarayana and Rao (1989) delineated the karst structures in some areas of the Cuddapah basin.

Other scientific studies regarding karst

Karst areas of India have been studied for the nature of diversity of living organisms dwelling inside many caves of the Himalayan region, in terms of their physiological, metabolic and behavioral characteristics in space and time, a concept called biospeleology (Biswas and Biswas 2014; Rajput and Biswas 2012a, b; Ruedi et al. 2012; Biswas and Shrotriya 2011). Biswas and Shrotriya (2011) discussed the factors (darkness, high humidity and constant geophysical factors) responsible for making harsh sub-surface cave ecosystems unique, where life is possible. Cave environments were certainly utilized by pre-historic people for their habitation. Such environments are deteriorating constantly due to a number of factors which degrade these pre-historic dwellings (Biswas 2009; Biswas et al. 2013; Rajput and Biswas 2012a, b).

Speleothems deposited in the caves are a reliable source of record for paleo-climatic reconstruction. Many researchers used data from caves as proxies for paleo-climate reconstruction in India (Kotlia et al. 2012; Sanwal et al. 2013; Laskar et al. 2011, 2013; Yadava and Ramesh 2001, 2005, 2006; Yadava et al. 2004; Lone et al. 2014; Sinha et al. 2005, 2007). $\delta^{18}O$ data generated from stalagmites of Valmiki cave of Cuddapah Basin suggested an increase in moisture content in Indian Summer Monsoon during the last deglaciation at ~14,800 years BP in southern India, which lead to the deposition of speleothems in these caves (Lone et al. 2014). They concluded that aragonite is the major component of stalagmites because of the dolomitic nature of the host rock favored by degassing of CO_2. These studies focused on the climatic variability but lack in correlating this moisture variability with karstification processes.

Caves were used as favorable locations by Paleolithic and Neolithic people in southern India for their habitation, where they developed industries in the caves and valley floors of the carbonate rocks some 74,000 years ago (Petraglia et al. 2009); however, these types of studies have not extended further to the other karst areas of India.

Significance of carbonate terrains in India

Carbonate rocks and their intrinsic resources, particularly water, are becoming economically more and more important due to the relatively good quality and quantity of these waters. In certain parts of the Indian subcontinent, karst aquifer systems are of vital importance as they serve as the primary sources for drinking-water supply and are extensively exploited for irrigation purposes, particularly in semi-arid and arid regions. For example, in southern India, karstified rocks yield a large quantity of water and supply many drought prone areas of the Cuddapah basin (Dar et al. 2011a, b). Karst springs also supply the large population of the Kashmir Valley and are a source of large rivers such as the River Jhelum (Fig. 6a). A number of karst springs and caves of India also have religious importance as well (Fig. 6b), and many caves additionally possess various beautiful architectural secondary calcite depositional features which may serve as proxies for paleo-climatic reconstruction studies.

Carbonate-rock areas are exploited at a rising rate for their mineral resources (limestone, Fig. 7) in India, and a wide variety of natural and cultural habitats, like soils, forests, caves, etc. are highly vulnerable to impacts from such human activities (Fig. 7). A general limestone-mining map of India is given in the website of Maps of India (2007). The limestone is used for a number of societal applications (detailed uses of limestone can be found in the website of Longclifee Quarries Limited (2014).

Future perspectives on karst hydrogeology in India

Karst aquifers have received much attention from the worldwide scientific community over the past two decades due to increasing importance of their resources (e.g.,

DOI 10.1007/s10040-014-1151-z

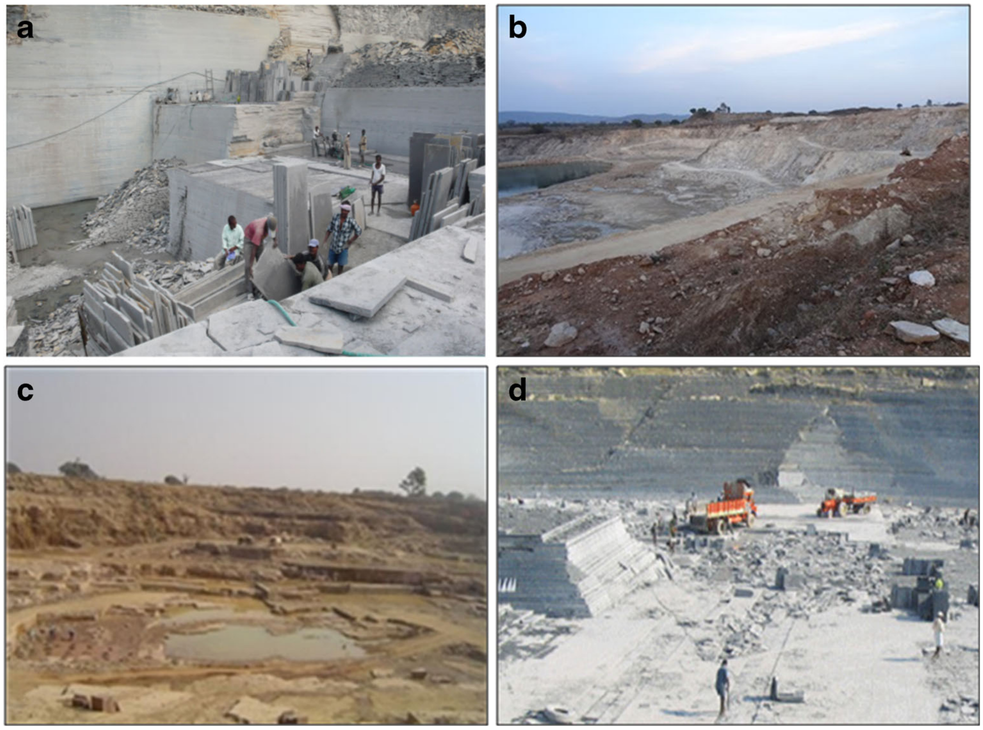

Fig. 7 A view of limestone exploitation in India: **a** limestone quarrying in Kolimigundla mandal of Kurnool district, Andhra Pradesh; **b** Birmitrapur mine, Jharkhand; **c** largest limestone mine Dhaneshwar, Rajasthan; **d** limestone mining, Satna MP

Andreo et al. 2010). However, karst aquifers and the discussion related to the karstification processes have been somewhat neglected by the hydrogeological community in India. The literature review suggests that the very limited studies about groundwater characteristics in karst terrains of India have not taken the specificities of karst into consideration (Dar et al. 2011a, b). This is also evident from Table 1, which shows that the reports and publications from major groundwater research organizations lack proper definition, explanation and treatment of karst aquifers.

Since carbonate areas are also widely used for their resources (e.g., limestone mining) in India, the need arises to fully characterize them in order to understand their system behaviour, geometry, fluxes, etc. The karstic or dissolved nature of these rocks must be considered for careful planning and future research and development programmes in karst areas of the country. Adequate management programs will help to prevent future depletion of karst resource quantity and quality. The future studies should focus on understanding the aquifers' hydrodynamic behavior, their hydraulic heterogeneity, adequate groundwater modeling flow and transport, speleogenesis and its relation to tectonics, etc.

Further, accessibility to safe drinking water is threatened by rapid contamination, overexploitation, saltwater intrusion and inappropriate irrigation practices (Fig. 8a) in such areas. Water-quality assessment in karstified aquifers is important as the recharging water carries contaminants and a large amount of eroded material (sediments/soil) concentrates into fractures and dissolution channels very rapidly, making the aquifers highly vulnerable to contamination. The sediments can clog pores, fractures and even underground channels, thereby reducing the pore space and limiting the quantity of stored water; thus, it is important to understand the contamination and pollution problems and to study the interactions between water and rock material in detail. Studying artificial recharge (managed aquifer recharge) is needed because groundwater is being exploited at a rising rate. The potential to store recharging water in limestone aquifers in order to replenish the exploitation loses and for reclamation and reuse is of growing interest to meet the increasing demands for water.

Exploitation of carbonate areas, whether for groundwater exploitation or quarrying, has created a number of irreversible environmental problems. Water-table depletion may lead to the sudden appearance of sinkhole collapses as observed in the Nossam area (Fig. 8c) of the Kurnool district (Dar et al. 2011a, b). Possible potential impacts resulting from climate change could add further problems (LaMoreaux et al. 1997; Milanovic 2002; Ford and Williams 2007). In the Kolimigundla mandal of the Kurnool district, an existing limestone quarry area is increasing in areal extent at a rate of 0.6 km^2/year (Dar et al. 2011a, b). More elaborate research on the impact of limestone mining on groundwater is necessary. A few carbonate terrains of the country are sites of dams and reservoirs developed to store surface water for future uses (Fig. 8b). Unexpected collapses, reservoir leaks and inaccurate groundwater budgeting, etc. may occur in such

Fig. 8 Carbonate areas used for other purposes which can have land- and water-management-related problems. **a** Extensive paddy agriculture in Kurnool; **b** Owk reservoir on Narji limestone, Kurnool (Andhra Pradesh); **c** development of sinkholes in agricultural lands due to extensive exploitation of groundwater in the Nossam area of the Kurnool district

areas. It is therefore, necessary for the public and for planners to avoid any possible catastrophic events that are likely to occur due to karstic nature of the rocks.

The proper study of karst resources will strengthen further research and will improve techniques of groundwater monitoring, assessment methods and management practices in these highly complex geological systems. It will help in protecting important karst eco-systems from possible anthropogenic impacts. A broader communication between scientists from multi-disciplinary research fields (geology, geochemistry, biology, ecology and geography, etc.) can fertilize new scientific findings and will encourage new students to carry out their research in this challenging field. Paleo-karst study using cave sediments, speleothems, etc. is a developing concept which helps to reconstruct the past historical records of changing climate. Geophysical applications in karst areas provide new opportunities for hydro-geophysical investigations. Carbonate dissolution is also a contributor of the global carbon cycle (Liu et al. 2010); hence, the studies focusing on present dissolutional processes will add to further knowledge for environmental and climatic studies.

Conclusion

Scientific studies devoted to carbonate aquifers are much needed in India, as these aquifers are highly heterogeneous and anisotropic and groundwater management is not easy. Preliminary estimates have shown that ~3 % of the India's total area is occupied by carbonate rocks in various geo-climatic settings. These rocks form potential groundwater resources for a significant portion of the country's population. It is estimated that ~35 million people in India are utilizing groundwater of karst aquifers for human consumption, livestock, irrigation practices and industrial uses. These aquifers are still treated with indifference in India where karst-specific methodology has not been utilized to characterize them. The existing scientific literature has shown that karst-related information is lacking in most of the publications. There is a lot of scope to test and develop karst-related methodologies in India, especially when considering that karst groundwater resources may be threatened by large-scale mining (quarries), industrial contamination, urban spreading, irrigation practices and climate change effects. Therefore, these aquifers need adequate characterization involving state-of-the-art methodologies and by taking the specific heterogeneity of the aquifer into account.

Acknowledgements The authors are thankful to the Director, CSIR-National Geophysical Research Institute for permission to publish this work. The first author would like to thank the University Grants Commission for providing the JRF and SRF fellowship and the French Embassy for providing 4 months traineeship at BRGM France. The authors also acknowledge Dr. Jiu Jimmy Jiao, editor, and two anonymous reviewers for constructively reviewing the manuscript.

References

Adyalkar PG (1977) Hydrogeology of karstic terrains (limestone areas). In: Exploration techniques for groundwater. COSTED, Chennai, India, pp 128–142

Andreo B, Carrasco F, Durán JJ, LaMoreaux JW (2010) Advances in research in karst media. Springer, Heidelberg

Arbenz T, Weidmann Y (2003) Meghalaya (Indien) Höhlenforschen in der Wolkenstube [Meghalaya (India) cave exploration in the clouds]. Stalactite (Swiss Speleol Soc Bull) 1:4–13

Bakalowicz M (2005) Karst groundwater: a challenge for new resources. Hydrogeol J 13(1):148–160

Bhat NA, Jeelani G (2012) Delineation of recharge areas of some karst springs using hydrogeochemistry and stable isotopes of hydrogen and oxygen. MSc Thesis, University of Kashmir, India. http://www.dspaces.uok.edu.in/jspui/handle/1/1197. Accessed August 2013

Biswas J (2009) The biodiversity of Krem Mawkhyrdop of Meghalaya, India, on the verge of extinction. Curr Sci 96:7

Biswas J, Biswas S (2014) *Heteropoda fischeri* Jäger, 2005: a huntsman spider hunting on fellow cavernicoles in the caves of Meghalaya, India. J Bomaby Nat Hist Soc 110(1):25–26

Biswas J, Shrotriya S (2011) Dandak: a mammalian dominated cave ecosystem of India. Subterranean Biol 8:1–8

Biswas J, Sharma K, Harris KK, Rajput Y (2013) Biodeterioration agents: bacterial and fungal diversity dwelling in or on the prehistoric rock-paints of Kabra-pahad, India. Iran J Microbiol 5(3):309–314

Bonacci O, Rubinic J (2009) Water losses from a reservoir built in karst: the example of the Boljunčica reservoir (Istria, Croatia). Environ Geol 58(2):339–345

Brooks S, Smart S (1995) Caving in the abode of the clouds: caves and karst of Meghalaya, North East India. Meghalaya 94, Bradford on Avon, UK, 68 pp

CGWB (2009) District groundwater information of Chhatarpur district, MP. Central Ground Water Board, Madhya Pradesh, India

CGWB (2010) Ground water scenario of India 2009–10. Central Ground Water Board, Faridabad, India

CGWB (2011) Groundwater scenario in major cities of India. Central Groundwater Board, Lucknow, India

CGWB (2012) Aquifer systems of Chhattisgarh. Central Groundwater Board, Chhattisgarh Region, Anupam Nagar, India

Chadha SK (1975) Note on the evolution of phytokarst topography in the great limestone formation of Jammu province, J and K state, India. Curr Sci 44:665

Chandra PC, Satyanarayana T, Raju KCB (1987) Geoelectrical response of cavities in limestones: an experimental field study from Kurnool District, Andhra Pradesh, India. Geoexploration 24(6):483–502

Chaulya S K (2009) Water resource development study for a limestone mining area. J Soil Water Sci 2(2):75–134

Circle of Blue (2010) Karst regions of the world. Map source: Williams and Fong, world map of carbonate rock outcrops V 3.0. Map downloaded from http://www.circleofblue.org/waternews/2010/world/chinas-karst-region-infographics. Accessed May 2014

Coward JMH, Waltham AC, Bowser RJ (1972) Karst springs in the Vale of Kashmir. J Hydrol 16:213–233

Coxon C (2011) Agriculture and karst. In: van Beynen PE (ed) Karst management. Springer, Dordrecht, The Netherlands, pp 103–138

Dar FA (2013) Hydrogeological characteristics of carbonate formations of the Cuddapah Basin, India. PhD Thesis, University of Hyderabad, India

Dar FA, Perrin J, Ahmed S (2010) Geomorphology and hydrogeology of the Belum Karst Aquifer, southern Andhra Pradesh, India. 7th AOGS conference, Hyderabad, India, 5–9 July 2010

Dar FA, Perrin J, Ahmed S, Narayana AC (2011a) Karst aquifers: a promising groundwater resource in scarcity context: discovering their hydrogeological potential in semi-arid southern India. Vth WAC (Exhibition and Conference), New Delhi, 16–18 Nov. 2011

Dar FA, Perrin J, Riotte J, Gebauer HD, Narayana AC, Ahmed S (2011b) Karstification in the Cuddapah Sedimentary Basin, southern India: implications for groundwater resources. Acta Carsolog 40(3)457–472

Dar FA, Ahmed S, Perrin J, Narayana AC (2012) Development of hydrogeological thoughts in disregarded karst lithologies: a case study from southern Andhra Pradesh, India. Fifth International Groundwater Conference (IGWC-2012), Aurangabad, Maharashtra, India, 18–21 December 2012

Dubey DP, Tiwari RN, Dwivedi U (2006) Evaluation of pollution susceptibility of karst aquifers of Rewa Town (Madhya Pradesh) using DRASTIC Approach. J Environ Sci Eng 48(2):113–118

Dutta NP, Bose RN, Saikia BC (1970) Detection of solution channels in limestone by electrical resistivity method. Geophys Prospect 18(3):405–414

Ford D (2006) Jovan Cvijic and the founding of karst geomorphology. Environ Geol 51:675–684

Ford DC, Williams PW (2007) Karst geomorphology and hydrology. Wiley, Chichester, UK, 562 pp

Gebauer HD (1985) Kurnool 1984: report of the speleological expedition to the district of Kurnool, Andhra Pradesh, India. Abh Karst Höhlenkunde 21:77

Gebauer HD (1997) Indien 1996/97: Kurnool, Jaypur-Jagdulpur und Meghalaya [India 1996/97: Kurnool, Jaypur-Jagdulpur und Meghalaya]. Mitteil Verband Höhlen Karstforsch 43(4):104–111

Gebauer HD, Abele A (1983) Höhlen von Indien und Nepal [Caves of India and Nepal], vol 6. Self published, Schwäbisch Gmünd, Germany, 166 pp

GEC (2009) Report of the Groundwater Resource Estimation Committee: groundwater resource estimation methodology. Ministry of Water Resources, Government of India, New Delhi

Ghasemizadeh R, Hellweger F, Butscher C, Padilla I, Vesper D, Field M, Alshawabkeh A (2012) Review: Groundwater flow and transport modelling of karst aquifers, with particular reference to the North Coast Limestone aquifer system of Puerto Rico. Hydrogeol J 20:1441–1461

Goldscheider N, Drew D (2007) Methods in karst hydrogeology. Taylor and Francis, London

GSI (1997) Geological map series of carbonate areas of India, Geological survey of India, Calcutta, India

Hobbs SL, Smart PL (1986) Characterisation of carbonate aquifers: a conceptual base. 9th International Congress of Speleology, Barcelona, Spain, August 1986

IAH (2013) World Karst Aquifer Mapping Project (WOKAM). International Association of Hydrogeologists, Goring, UK. Source: http://www.agw.kit.edu/english/wokam.php. Accessed March 2014

Jeelani G (2004) Effect of subsurface lithology on hydrochemistry of springs of a part of Kashmir Himalaya. Himal Geol 25(2):145–151

Jeelani G (2005) Chemical quality of the spring waters of Anantnag, Kashmir. J Geol Soc Ind 66(4):453–462

Jeelani G (2008) Aquifer response to regional climate variability in part of Kashmir Himalaya in India. Hydrogeol J 16:1625–1633

Jeelani G (2010) Chemical and microbial contamination of Anantnag springs. Kashmir Val Him Ecol Sust Dev 5:1–10

Jeelani G, Bhat NA, Shivanna K (2010) Use of δ18O tracer to identify stream and spring origins of a mountainous catchment: a case study from Liddar watershed, Western Himalaya, India. J Hydrol 393:257–264

Jeelani G, Ahmed S, Absar A (2012) Essential and toxic elements in karst spring of Kashmir. Curr Sci 103(9):10

King W (1872) Kadapah and Kurnool formations in the Madras presidency. Geological Survey of India Mem 8, GSI, Calcutta, India

King W (1882) Geological sketch of Vizagapatam district, vol 19. Records of the Geological Survey of India, Gov. of India, Calcutta, 143–157 pp

Kiraly L (1975) Rapport sur l'état actuel des connaissances dans le domaine des caractères physiques des roches karstiques [Report on the current state of knowledge in the field of physical characteristics of karstic rocks]. In: Burger A, Dubertret L (eds)

 DOI 10.1007/s10040-014-1151-z

Hydrogeology of karstic terrains. Int Union Geol Sci Ser B 3, IUGS, Paris, pp 53–67
Kotlia BS, Ahmad SM, Zhao JX, Raza W, Collerson KD, Joshi LM, Sanwal J (2012) Climatic fluctuations during the LIA and post-LIA in the Kumaun Lesser Himalaya, India: evidence from a 400 yr. old stalagmite record. Quat Int 263:129–138. doi:10.1016/j.quaint.2012.01.025
Kumar A (1985) Karst landform of Upper Kapili River, Assam. Facets of geomorphology. Thinker's Library, Anil Kumar, India, 212 pp
Kumar R (1985b) Fundamentals of historical geology and stratigraphy of India. Wiley, New Delhi, 254 pp
LaMoreaux PE, Powell WJ, LeGrand HE (1997) Environmental and legal aspects of karst areas. Environ Geol 29:1–2
Laskar AH, RaghavS, Yadava MG, Jani RA, Narayana AC, Ramesh R (2011) Potential of stable carbon and oxygen isotope variations of speleothems from Andaman Islands, India, for paleomonsoon reconstruction. J Geol Res 2011:272971, 7 pp. doi: 10.1155/2011/272971
Laskar AH, Yadava MG, Ramesh R, Polyak VJ, Asmerom Y (2013) A 4 kyr stalagmite oxygen isotopic record of the past Indian summer monsoon in the Andaman Islands. Geochem Geophys Geosyst 14(9):3555–3566. doi: 10.1002/ggge.20203
Legrand HE, Stringfield VT (1973) Karst hydrology: a review. J Hydrol 20:97–120
Limaye SD (1988) Groundwater for small scale irrigation in mini-karstic limestone terrain in Saurashtra area in Western India. IAH, 21st Congress, Karst Hydrogeology and Karst Environment Protection, Guilin, China, 10–15 October 1988
Limaye SD (2003) Groundwater and cement industry: the Indian experience. RMZ Mater Geoenviron 50(1):189–191
Liu Z, Dreybrodt W, Wang H (2010) A new direction in effective accounting for the atmospheric CO2 budget: considering the combined action of carbonate dissolution, the global water cycle and photosynthetic uptake of DIC by aquatic organisms. Earth Sci Rev 99(3–4):162–172
Lone MA, Ahmad SM, Dung NC, Shen CC, Raza W, Kumar A (2014) Speleothem based 1,000-year high resolution record of Indian monsoon variability during the last deglaciation. Palaeogeogr Palaeoclimatol Palaeoecol 395:1–8
Longcliffe Quarries Ltd (2014) Processing and major uses of limestone. http://www.longcliffe.co.uk/limestone/limestone-uses.asp. Accessed February 2014
Maps of India (2007) Lime stone mines in India. Compare Infobase Limited, New Delhi. http://www.mapsofindia.com/maps/minerals/lime-stone-mines-map.html. Assessed July 2013
Meijerink AMJ (2007) Covered karst: example of Borunda, Rajasthan, India. Remote sensing applications to groundwater. UNESCO, Paris
Milanovic P (2002) The environmental impacts of human activities and engineering constructions in karst regions. Episodes 25(1):13–21
Murty KS (1988) Karst hydrogeology: India. In: Proc. 21st IAH Congress, Karst Hydrogeology and Karst Environment Protection, Guilin, China 10–15 October 1988, pp 446–450
Petraglia M, Korisettar R et al (2009) Human occupation, adaptation and behavioral change in the Pleistocene and Holocene of South India: recent investigations in the Kurnool district, Andhra Pradesh. Eurasian Pre Hist 6(1–2):119–166
Pujari PR, Soni AK (2009) Sea water intrusion studies near Kovaya limestone mine, Saurashtra coast. India Environ Monit Assess 154(1–4):93–109
Rajput Y, Biswas J (2012a) Subterranean depth dependent protein constitutions of the *Micrococcus* sp., isolated from the Kotumsar Cave, India. Asian J Biochem 7(2):90
Rajput Y, Biswas J (2012b) The role of heterotrophic bacteria in bio-deterioration of our cultural heritage: a case study of Udayagiri caves of Odisha, India. J Eco Biotechnol 4(2):112–115
Ranade P (2007) Environmental impact assessment of land use planning around the lease limestone mine using RS technique. Iran J Environ Health Sci Eng 4(1):61–65
Ruedi M, Biswas J, Csorba G (2012) Bats from the wet: two new species of tube-nosed bats (Chiroptera: Vespertilionidae) from Meghalaya, India. Swiss Rev Zool 119(1):111–135
Ruggieri R, Biswas J (2011) The karst Mandhip Khol-Python cave complex in the lenticular limestone intercalations of the metamorphic Chhatrela formation (Chhattisgarh, India). Acta Carsolog 40(1):7–15
Rushton KR, Raghava Rao SV (1988) Groundwater flow through a Miliolite limestone aquifer. Hydrol Sci J 33(5):449–464
Saifuddin I (2000) Quaternary signatures of paleo-humidity in arid zone, Rajasthan, India. J Arid Environ 45:151–158
Sanwal J, Kotlia BS, Rajendran C, Ahmad SM, Rajendran K, Sandiford M (2013) Climatic variability in Central Indian Himalaya during the last 1,800 years: evidence from a high resolution speleothem record. Quat Int 304:183–192
Shibasaki T, Balakrishna S, Yoshimura T, Venkatanarayana B, Furukama H, Venkateswara RT, Chuman N, Ramanohan RY, Venkateswaralu K (1985) Karstification process of carbonate rocks in the Cuddapah sedimentary Basin, Indian Peninsular Shield. J Fac Mar Sci Technol Tokai Univ 21:31–45
Singh KKK, Chauhan RKS (2002) Exploration of subsurface strata conditions for a limestone mining area in India with ground penetrating radar. Environ Geol 41:966–971
Singh TN (1985a) Kuteswar limestone deposit studies for protection against Bansagar dam. Karst water resources, Proc. of the Ankara-Antalya Symposium, July 1985, IAHS Publ. 161, IAHS, Wallingford, UK
Singh Y (1985b) Hydrogeology of the karstic area around Rewa, MP, India. In: Karst water resources, Proc. of the Ankara-Antalya Symposium, July 1985, IAHS Publ. No. 161, IAHS, Wallingford, UK
Sinha UK, Kulkarni KM, Sharmaa S, Rayb A, Bodhankar N (2002) Assessment of aquifer system using isotope techniques in urban centers Raipur, Calcutta and Jodhpur, India. http://www-pub.iaea.org/MTCD/publications/PDF/te_1298_web/t1298_part2.pdf. Accessed on 10 November 2013
Sinha A, Cannariato KG, Stott LD, Li HC, You CF, Cheng H, Edwards RL, Singh IB (2005) Variability of southwest Indian summer monsoon precipitation during the Bølling-Ållerød. Geology 33:813–816. doi:10.1130/G21498.1
Sinha A, Cannariato KG, Stott LD, Cheng H, Edwards RL, Yadava MG, Ramesh R, Singh IB (2007) A 900-year (600 to 1500 A.D.) record of the Indian summer monsoon precipitation from the core monsoon zone of India. Geophys Res Lett 34:L16707. doi:10.1029/2007GL030431
Soni AK (2007) Evaluation of hydrogeological parameters associated with limestone mining: a case study from Chandrapur, India. Mine Water Environ 26:110–118
Urich PB (2002) Land use in karst terrain: review of impacts of primary activities on temperate karst ecosystems. Science for Conservation, Dept. of Conservation, Wellington, New Zealand
Venkatanarayana B, Rao TV (1989) Geological and geophysical investigations for delineating karstic structures of the south-western portion of Cuddapah basin, Andhra Pradesh, India. In: Berry BF (ed) Proc. of 3rd Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Oct. 1989, USA, Balkema, Dordrecht, The Netherlands, pp 59–64
Venkatanarayana B, Ahmed S, Agnihotri V (1999) The hydrogeology of the Kuteshwar limestone deposits. Madhya Pradesh, India. J Environ Hydrol 7, 5 pp
Wadia DN (1939) Geology of India. Macmillan, London
Waltham AC (1972) Caving in the Himalaya. Himalayan J 31 (9). http://www.himalayanclub.org/hj/31/9/caving-in-the-himalaya. Accessed November 2013
White WB (2002) Karst hydrology: recent developments and open questions. Eng Geol 65:85–105
White WB, Culver DC, Herman JS, Kane TC, Mylroie JE (1997) Karst lands: the dissolution of carbonate rock produces unique landscapes and poses significant hydrological and environmental concerns. Am Sci 83(5):450–459

Wray RAL (2003) Quartzite dissolution: karst or pseudokarst? Speleogenesis Evol Karst Aquifers 2:2

Yadava MG, Ramesh R (2001) Past rainfall and trace element variations in a tropical speleothem from India. Mausam 52:307–316

Yadava MG, Ramesh R (2005) Monsoon reconstruction from radiocarbon dated tropical Indian speleothems. The Holocene 15(1):48–59. doi:10.1191/0959683605h1783rp

Yadava MG, Ramesh R (2006) Stable oxygen and carbon isotope variations as monsoon proxies: a comparative study of speleothems from four different locations in India. J Geol Soc India 68(3):461–475

Yadava MG, Ramesh R, Pant GB (2004) Past monsoon rainfall variations in peninsular India recorded in a 331-year-old speleothem. The Holocene 14:517–524

 DOI 10.1007/s10040-014-1151-z