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1 Hydrology and Water Resources Management in Ancient 2 India

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10

11 **Abstract.** Hydrologic knowledge in India has a historical footprint extending over several millennia through
12 the Harappan Civilisation (~ 3000 BC – 1500 BC) and the Vedic period (~1500-500 BC). As in other ancient
13 civilisations across the world, the need to manage water propelled the growth of hydrologic science in ancient
14 India also. Most of the ancient hydrologic knowledge, however, has remained hidden and unexplored to the world
15 at large till the recent times. In this paper, we provide some fascinating glimpses into the hydrological, hydraulic
16 and related engineering knowledge that existed in ancient India, as discussed in contemporary literature and in the
17 recent explorations and findings. The Vedas, particularly, the *Rigveda*, *Yajurveda* and *Atharvaveda* have many
18 references to water cycle and associated processes, including water quality, hydraulic machines and other
19 structures and nature-based solutions (NBS) for water management. The Harappan Civilization epitomizes the
20 level of development of water sciences in ancient India that includes construction of sophisticated hydraulic
21 structures, wastewater disposal systems based on centralized and decentralized concepts as well as methods for
22 wastewater treatments. The Mauryan empire (~ 322 BC – 185 BC) is credited as the first “hydraulic civilization”
23 characterised by construction of dams with spillways, reservoirs, channels equipped with spillways, pynes and
24 *Ahars*, understanding of water balance, development of water pricing systems, measurement of rainfall and
25 knowledge of the various hydrological processes. As we investigate deeper into hydrologic references in ancient
26 literature, including the Indian mythology, many fascinating dimensions of the early scientific endeavours of
27 Indians emerge.

28 1 Introduction

29 Water is intimately linked to human existence and is the source of societal and cultural development, traditions,
30 rituals and religious beliefs. The humans created permanent settlements about 10,000 years ago when they adopted
31 an agrarian way of life and started developing different socio-cultural societies and settlements, largely dependent
32 on water in one way or other (Vuorinen et al., 2007). These developments established a unique relationship
33 between humans and water. Most of the ancient civilizations, e.g., the Indus Valley, Egyptian, Mesopotamian,
34 and Chinese civilizations were developed at places where water required for agricultural and human needs was
35 readily available, i.e., in the vicinity of springs, lakes, rivers and low sea levels (Yannopoulos et al., 2015). As



36 water was the prime mover of the ancient civilizations, a clear understanding of the hydrologic cycle, nature and
37 pattern of its various components along with water uses for different purposes led these civilizations to flourish
38 for thousands of years.

39

40 The Harappan (or Indus Valley) civilization (3000 BC – 1500 BC), one of the earliest and most advanced
41 civilizations, was also the world's largest in spatial extent and epitomises the level of development of science and
42 society in proto-historic Indian sub-continent. Jansen (1989) states that the citizens of Harappan civilization were
43 known for their obsession with water; they prayed to the rivers every day and accorded the rivers a divine status.
44 The urban centres were developed with state-of-the art civil and architectural designs with provisions of
45 sophisticated drainage and waste water management systems. Agriculture was the main economic activity of the
46 society and an extensive network of reservoirs, wells, canals along with low cost water harvesting techniques were
47 developed throughout the region at that time (Nair, 2004). The Mohenjo-Daro and Dholavira, major cities of Indus
48 Valley are the best examples having the state-of-the art water management and drainage systems. The Great Bath
49 of Mohenjo-Daro of Indus Valley is considered as the "earliest public water tank of the ancient world". The
50 "Arthashastra" attributed to Kautilya "who reportedly was the chief minister to the emperor Chandragupta (300
51 BC), the founder of the Mauryan dynasty" (Encyclopaedia Britannica, <https://www.britannica.com/topic/Arthashastra>)
52 deals with several issues of governance, including water governance. It mentions about a manually
53 operated cooling device "Variyantra" (revolving water spray for cooling the air). It also gives an extensive
54 account of hydraulic structures built for irrigation and other purposes during the period of the Mauryan empire
55 (Shamasastri, 1961).

56

57 The Pynes and Ahars (combined irrigation and water management system), reservoir (Sudarshan lake) at Girnar
58 and many other structures were also built during the Mauryan empire (322-185 BC). McClellan III and Dorn,
59 (2015) noted that '... the Mauryan empire was first and foremost a great hydraulic civilization ...'. This reflects
60 that the technology of the construction of the dams, reservoirs, channels, measurement of rainfall and knowledge
61 of the various hydrological process was well known to the ancient Indian society. The water pricing was also an
62 important component of the water management system in Mauryan empire. There are also adequate archaeological
63 evidences to testify that the Harappans of the Indus Valley were well aware of the seasonal rainfall and flooding
64 of the river Indus during the period between 2500 and 1700 B.C., which is corroborated by modern meteorological
65 investigations (Srinivasan, 1976).

66

67 The Vedic texts, which were composed probably between 1500 and 1200 BC (1700–1100 BC according to some
68 scholars), contain valuable references to 'hydrological cycle'. It was known during Vedic and later times
69 (Rigveda, VIII, 6.19, VIII, 6.20; and VIII, 12.3) (Sarasvati, 2009) that water is not lost in the various processes of
70 hydrological cycle namely evaporation, condensation, rainfall, streamflow, etc., but gets converted from one form
71 to another. Indians were, at that time, acquainted with cyclonic and orographic effects on rainfall (*Vayu Purana*)
72 and radiation, and convectional heating of earth and evapotranspiration. The Vedic texts and other Mauryan period
73 texts such as 'Arthashastra' mention about other hydrologic processes such as infiltration, interception, streamflow
74 and geomorphology, including the erosion process. Reference to the hydrologic cycle and artesian wells is
75 available in *Ramayana* (200 B.C.) (Vālmīki and Goswami, 1973). Ground water development and water quality



76 considerations also received sufficient attention in ancient India, as evident from the *Brihat Samhita* (550 A.D.)
77 (Jha, 1988). Topics such as water uptake by plants, evaporation, clouds and their characteristics along with rainfall
78 prediction by observing the natural phenomena of previous years, had been discussed in *Brihat Samhita* (550
79 A.D.), *Meghamala* (900 A.D.) and other literature from ancient India.

80

81 Historical development of hydro-science has been dealt by many researchers (Baker and Horton, 1936; Biswas,
82 1969; Chow, 1964). However, not many references to the hydrological contributions in ancient India are found.
83 Chow (1974) rightly mentions that "... the history of hydrology in Asia is fragmentary at best and much insight
84 could be obtained by further study". According to Mujumdar and Jain (2018), there is rigorous discussion in
85 ancient Indian literature on several aspects of hydrologic processes and water resources development and
86 management practices as we understand them today.

87

88 Evidences from ancient water history provide an insight into the hydrological knowledge generated by Indians
89 more than 3000 years ago. This paper explores the many facets of ancient Indian knowledge on hydrology and
90 water resources with focus on various hydrological processes, water management and technology, and wastewater
91 management, based on earlier reviews of Indian scriptures such as the Vedas, the *Arthashastra* (Shamasastri,
92 1961), *Astadhyayi* (Jigyasu, 1979), *Ramayana* (Vālmīki and Goswami, 1973), *Mahabharata*, *Puranas*, *Brihat
93 Samhita* (Jha, 1988), *Meghmala*, *Mayurchitraka*, Jain and Buddhist texts and other ancient texts.

94 **2 Knowledge of Hydrological Processes in Ancient India**

95 Hydrologic cycle is the most fundamental concept in hydrology that involves the total earth system comprising
96 the atmosphere (the gaseous envelop), the hydrosphere (surface and subsurface water), lithosphere (soils and
97 rocks), the biosphere (plants and animals), and the Oceans. Water passes through these five spheres of the earth
98 system in one or more of the three phases: solid (ice), liquid and vapour. The *Rigveda*, which is an ancient religious
99 scripture, contains many references to hydrologic cycle and associated processes (Sarasvati, 2009). The *Rigveda*
100 mentions that 'the God has created Sun and placed it in such a position that it illuminates the whole universe and
101 extracts water continuously (in the form of vapour) and then converts it to cloud and ultimately discharges as rain'
102 (Verse, I, 7.3). Many other verses of the *Rigveda* (I, 19.7; I, 23.17; I, 32.9) further explain the transfer of water
103 from earth to the atmosphere by the Sun and wind; breaking up of water into small particles and evaporation due
104 to Sun rays and subsequent rain; formation of cloud due to evaporation of water from the mother Earth and
105 returning in the form of rain. The verse I, 32.10 of the *Rigveda* further mentions that the water is never stationary
106 but it continuously gets evaporated and due to smallness of particles we cannot see the evaporated water particles.
107 According to *Atharvaveda* also (1200-1000 B.C.), the Sun rays are the main cause of rain and evaporation (Verse,
108 I, 5.2, in Sanskrit language):

109

110 amurya up surye yabhirg suryah sah| ta no hinvantvadhavaram||

111

112 The *Yajurveda* (1200 – 1000 BC) explains the process of water movement from clouds to Earth and its flow
113 through channels and storage into oceans and further evaporation (Verse, X, 19). During the time of *Atharvaveda*,
114 the concept of water evaporation, condensation, rainfall, river flow and storage and again repetition of cycle was



115 also well known as in the earlier Vedas. Therefore, it can be inferred that during the Vedic and earlier periods in
116 India, the concepts of infiltration, water movement, storage and evaporation as the part of hydrologic cycle were
117 well known to the contemporary Indian scholars.

118

119 The epic *Mahabharata* (Verse, XII,184.15-16) explains the water uptake process by plants and mentions that
120 rainfall occurs in four months (the Indian summer monsoon, ISM) (Verse, XII,362.4-5) and in the next eight
121 months (non-monsoon months), the same water is extracted by the Sun rays through the process of evaporation.
122 Likewise, in other Indian mythological scriptures such as *Puranas* (which are dated probably between 600 B.C.
123 to 700 A.D.), numerous references exist to hydrological cycle (NIH, 2018). The *Matsya Purana* (Verse, I, 54.29-
124 34) and *Vayu Purana* (Verse, 51.23-26) mention about the evaporation process which burns water by Sun rays
125 and is converted to smoke (i.e., process of evaporation) which ascend to atmosphere with the help of air and again
126 rains in next rainy season for the goodness of the living beings (NIH, 2018). The *Vayu Purana* and the *Matsya*
127 *Purana* also mention the rainfall potential of clouds and the formation of clouds by cyclonic, convective and
128 orographic effects (Nair, 2004). Similarly, the *Linga Purana* (Verse, I, 36.67) clearly explains the various
129 processes of hydrologic cycle such as evaporation, condensation and mentions that water can't be destroyed; it
130 gets changed from one form to the other (NIH, 2018; Sharma and Shruthi, 2017) as:

131

132 jalasya nasho vridwirva natatyevasya vichartah| ghravenashrishttho vayuvrishti sanhrte punah||

133

134 The *Brahmanda Purana* (Verse, II, 9.138-139; 167-168) explains that Sun has rays of seven colors which extracts
135 water from all sources through heating (evaporation) and it gives to the formation of clouds of different colors
136 and shapes and finally these clouds rain with high intensity and great noise (NIH, 2018). The *Vayu Purana* also
137 refers to the various underground structures and topography such as lakes, barren tracts, dales, rocky rift valley
138 between mountains (Verse, 38.36).

139

140 The *Kishkindha sarga* (Chapter 28; Verses: 03, 07, 22, 27, 46) of the epic *Ramayana* discusses various aspects of
141 hydrological cycle. The verse 3 mentions about the formation of clouds by Sun and wind (through process of
142 evaporation from sea) and raining the elixir of life (water) and verse 46 mentions the overflowing of the rivers
143 due to heavy rains in rainy season. The verse 22 explains the process of cloud transportation laden with water and
144 elevational effects of the mountains on the whole processes. Based on these verses (and many more, not mentioned
145 here) a depiction on the various stages of the hydrologic cycle may also be established similar to Horton (1931).
146 Malik (2016) also compared the various concepts of modern hydrologic cycle with those presented in the
147 *Ramayana* and found that a corollary may be established between them.

148

149 The *Brihat Samhita* (literally meaning *big collection*) (550 A.D.) by Varahamihira, contains many scientific
150 discourses on the various aspects of meteorology, e.g., pregnancy of clouds, pregnancy of air,
151 winds, cloud formations, earthquakes, rainbows, dust storms and thunder bolts among other things such as colours
152 of the sky, shapes of clouds, the growth of vegetation, behaviour of animals, the nature of lightning and thunder
153 and associated rainfall patterns (Jha, 1988). The water falling from sky assumes various colours and tastes from
154 differences in the nature of Earth. Out of 33 chapters in the *Brihat Samhita*, 10 chapters are specifically devoted



155 to the meteorology. This highlights the depth of the meteorological knowledge prevalent during the period of
156 Varahmihira and his predecessors in the ancient India.

157

158 The verse 54.104 of *Brihat Samhita* explains the relation between soil and water. It is mentioned that pebbly and
159 sandy soil of copper color makes water astringent. Brown-colored soil gives rise to alkaline water, yellowish soil
160 makes water briny and in blue soil, underground water becomes pure and fresh. *Brihat Samhita* also discusses
161 about the geographical pointers such as plants, reptiles, insects as well as soil markers to gauge the groundwater
162 resources (occurrence and distribution) (Chapter 55, Dakargalam). It explains the groundwater recharge as "...
163 the water veins beneath the earth are like vein's in the human body, some higher and some lower..." as given in
164 the following verses (NIH, 2018):

165

Dharmyam yashashyam va vadabhaytoham dakargalam yen jaloplabdhiha
Punsam yathagdeshu shirastathaiva chhitavapi pronnatnimnasanstha.

168

Ekayna vardayna rasayna chambhyashchutam namasto vasudha vishayshanta
Nana rastvam bahuvarnatam cha gatam pareekshyam chhititulyamayva.

170

171
172 The 'Dakargalam' (*Brihat Samhita*, Chapter 55) deals with ground water exploration and exploitation with various
173 surface features, that are used as bio indicators to locate sources of ground water, at depths varying from 2.29 m
174 to as much as 171.45 m (Prasad, 1980). The bio indicators, described in this ancient Sanskrit work, include various
175 plant species, their morphologic and physiographic features, termite mounds, geophysical characteristics, soils
176 and rocks (Prasad, 1986). All these indicators are nothing but the conspicuous responses to biological and
177 geological materials in a microenvironment, consequential to high relative humidity in a ground water ecosystem,
178 developed in an arid or semi-arid region. Variation in the height of water table with place, hot and cold springs,
179 groundwater utilization by means of wells, well construction methods and equipment are fully described in the
180 Dakargalam (Jain et al. 2007). It also means that the water which falls from the sky originally has the same colour
181 and same taste, but assumes different colour and taste after falling on the surface of Earth and after percolation.

182

183 Glucklich, (2008) opines about the *Brihat Samhita*: "... as the name of the work itself indicates, its data came
184 from numerous sources, some of them probably quite old. However, the prestige and systematic nature of the
185 *Brihat Samhita* gave its material the authority of prescriptions". Further, it is also appropriate to quote
186 Varahmihira (Chapter 1, Verse, II, *Brihat Samhita*) that '... having correctly examined the substance of the
187 voluminous works of the sages of the past, I attempt to write a clear treatise neither too long nor too short ...'
188 (Iyer, 1884).

189

190 An interesting fact covered in details by Varahmihira is the role of termite knolls as indicator of underground
191 water. Apart from the underground water exploration, some of the verses of the chapter deal with topics such as
192 digging of wells, their alignment with reference to the prevailing winds, dealing with hard refractory stony strata,
193 sharpening and tempering of stone-breaking chisels and their heat treatment, treating with herbs of water with



194 objectionable taste, smell, protection of banks with timbering and stoning and planting with trees, and such other
195 related matters.

196

197 The Jain literature also made considerable contribution in the field of meteorology. The ‘*Prajanapana*’ and
198 ‘*Avasyaka Curnis*’ provide outstanding references to the various types of winds (Tripathi, 1969). The *Avasyaka*
199 *Curnis* furnishes a list of fifteen types of winds and the ‘*Prajanapana*’ also mentions the snowfall and hailstorm
200 as form of the precipitation. The Buddhist literature also throws significant light on meteorology. In the narrative
201 of the first Jataka, named ‘*Apannaka*’, several climatological facts are described therein. The Buddhist literature
202 refers to two general classes of clouds as: monsoon cloud and storm clouds or accidental ones (Tripathi, 1969).
203 The *Samyutta Nikaya* classifies clouds into five categories as (i) cool clouds, (ii) hot clouds, (iii) thunder clouds,
204 (iv) wind clouds –formed due to the activity of convection current in the atmosphere, and (v) rain clouds – most
205 probably cumulonimbus which brings copious downpour of rain.

206 3 Measurement of Precipitation

207 The “*Arthashastra*” and “*Astadhyayi*” of Panini (700 B.C.) mention about the rain gauges (Nair, 2004), which
208 was introduced by the Mauryan rulers in the *Magadha* country (south Bihar) in the fourth or third century B.C.
209 They are also credited with the establishment of first observatory. The system continued to be used by the
210 succeeding rulers until the end of the sixth century A.D. (Srinivasan, 1976). During the Mauryan period, the
211 rain gauge was known as “*Varshamaan*”. In the *Arthshastra*, the construction of the rain gauge is described as “...
212 in front of the store house, a bowl (Kunda) with its mouth as wide as an aratni (24 *angulas* = 18” nearly) shall
213 be set up as rain gauge”. However, the ‘*Arthshastra*’ does not have any information about the height of the
214 rain gauge (Srinivasan, 1976). This rain gauge continued to be employed effectively by the succeeding rulers until
215 the end of the 600 A.D (Srinivasan, 1976; Murty, 1987). A schematic of the modern rain gauge is shown in Figure
216 1. By comparing the dimensions of the ancient Indian and Symon’s rain gauge, one can infer about the advanced
217 level of knowledge possessed during that period.

218 The distribution of rainfall in various regions was well known during the Mauryan period. The ‘*Arthshastra*’
219 mentions as: “The quantity of rain that falls in the country of *jangiila* (desert regions or regions full of jungles) is
220 16 *dronas*; half as much more in *anupanam* (moist regions); as the regions which are fit for agriculture
221 (*desavapanam*); 13.5 *dronas* in the regions of *asmakas* (Maharashtra); 23 *dronas* in Avanti (probably Malwa);
222 and an immense quantity in *aparantanam* (western regions, the area of Konkan); the borders of Himalayas and
223 the countries where water-channels are made use of in agriculture”. Kautilya’s method of classification of rainfall
224 areas in relation to the annual average quantity is indeed remarkable and he is the only classical author who treats
225 this aspect in a nutshell covering almost the whole of the Indian subcontinent (Srinivasan, 1976). From this, it is
226 evident that the methodology of measurement of rainfall given in *Arthshastra* is same as we have today, the only
227 difference is that rain was expressed in weight units. Discussing on the further geographical details of rainfall
228 variation, it is mentioned therein that “...when one third of the requisite quantity of the rainfalls, both during the
229 commencement and closing months of the rainy season, and two third in the middle, then the rainfall is considered
230 very even...”.



231 The science of forecasting the rains had also come into existence as and must have been developing empirically.
232 It is further mentioned in the 'Arthshastra' that "the rainfall forecasting can be made by observing the position,
233 motion and pregnancy (garbhadhan) of Jupiter, the rising, setting and motion of Venus, and the natural or
234 unnatural aspects of the Sun. From the movement of Venus, rainfall can be inferred". Detailed descriptions on
235 classification of clouds and their water holding capacity (equivalent to the concept of atmospheric rivers) and
236 interrelationship of rainfall patterns and agriculture can also be found in the 'Arthshastra'.

237 Therefore, it can be concluded that during the Vedic era and afterwards in the age of epics and Puranas, (i.e.,
238 from 3000 B.C. to 500 A.D.), the knowledge of hydrologic cycle, ground water and water quality was highly
239 advanced, although the people of those times were solely dependent upon their experience of nature, without
240 sophisticated instruments of modern times. In the Vedic age, Indians had developed the concept that water gets
241 divided into minute particles due to the effect of Sun rays and wind, which ascends to the atmosphere by the
242 capillary of air and there, it gets condensed and subsequently falls as rainfall (Vayu Purana, 51. 14-15-16). The
243 Linga Purana also details on the various aspects of hydrological cycle (Sharma and Shruthi, 2017). Month wise
244 change in the facets of hydrological cycle was also known. Water uptake by plants which gets facilitated by the
245 conjunction of air along with the knowledge of infiltration is revealed in the ancient literature. In Brihat Samhita,
246 a separate chapter is devoted to the formation of clouds (Garbhalakshanam). A detail discussion has been given
247 on the properties of rainy seasons and their relationship with the movement of the planet and cloud formations
248 (Murthy, 1987). The Brihat Samhita also details on the measurement of rainfall and the dimensions of the
249 raingauge (Murty, 1987).

250 During the Mauryan period, it was possible to describe the distribution of rainfall in different areas of India.
251 Mauryans are credited with the installation of first observatory worldwide (Srinivasan, 1976). Modern
252 meteorological facts like arid region of Tibetan rain shadow area and no rainfall due to polar winds are fully
253 covered in Puranas. The Jain and Buddhist works guessed the actual height of clouds. Knowledge of monsoon
254 winds (Tripathi, 1969) and their effects as conceived by ancient Indians (Brihat Samhita) is in accordance to
255 modern hydro-science. These facts show that there was enriched knowledge of water science and associated
256 processes, including meteorology during ancient times in India, which is at par to the modern water science.

257 Well before many centuries of Christ, ancient Indians were aware of underground water bearing structures, change
258 in the direction of flow of ground water, high and low water tables at different places, hot and cold springs, ground
259 water utilization by means of wells, well construction methods and equipment, underground water quality and
260 even the artesian well schemes. This shows that well developed concepts of hydrological cycle, groundwater and
261 water quality were known to the ancient Indians in those ancient times while the contemporary world was relying
262 on the wild theories of origin and distribution of water.

263 **4 Water Management Technology in Ancient India**

264 The development of socio-cultural societies, agricultural establishments and permanent settlements led to the
265 establishment of a unique relationship between humans and water (Vuorinen et al., 2007; Lofrano and Brown,
266 2010). Scarborough (2003) and Ortloff (2009) discussed the impacts of water management practices on ancient
267 social structures and organizations with examples of the Eastern and Western hemispheres. Lofrano and Brown,



268 (2010) presented an in-depth review of wastewater management in the history of mankind. In this review work
269 they have categorically discussed about the evolution of sanitation through different civilizations of the world,
270 including the ancient Indus civilization).

271 During the Vedic age, the principle of collecting water from hilly areas of undulating surface and carrying it
272 through canals to distant areas was known (Bhattacharya, 2012). In the *Rigveda*, many verses indicate that the
273 agriculture can be progressed by use of water from wells, ponds (Verse, I, 23.18 and Verse, V, 32.2). Verse (VIII,
274 3.10) mentions construction of artificial canals by (Ribhus/Engineer) to irrigate desert areas. Verses (VIII, 49.6
275 and X, 64.9) emphasizes for efficient use of water, i.e., the water obtained from different sources such as wells,
276 rivers, rain and from any other sources on the earth should be used efficiently, as it is a gift of nature, for well-
277 being of all. There are also references of irrigation by wells (Verse, X, 25), canals (word '*kulya*' in *Rigveda*)
278 (Verse, X.99), and digging of the canal (Verse, X75) in the *Rigveda*. In *Mahābhāṣya* of Patañjali (150 B.C.) the
279 word '*kulya*' is also used.

280 Interestingly, the *Rigveda* (Verses, X 93.12; X 101.7) has a mention of '*asmacakra*' (a wheel made of stones) and
281 water was raised with help of wheel in a pail using a leather strap. There is also a mention of '*Ghatayantra*' or
282 '*Udghatana*' (a drum-shaped wheel) round which a pair of endless ropes with ghata (i.e. earthen pots) tied at equal
283 distances. In Arabic literature, the water lifting wheel is also known as '*Noria*'. Yannopoulos et al., (2015) also
284 mentioned that the ancient Indians had already developed water lifting and transportation devices. Further,
285 according to Joseph Needham (<https://www.machinerylubrication.com/Read/1294/noria-history>), due to evidence
286 documented in Indian texts dating from around 350 B.C., the '*Noria*' was developed in India around the fifth or
287 fourth century B.C and transmitted to the west by the first century B.C. and to the China by the second century
288 A.D.

289 Similar to *Rigveda*, *Yajurveda* also contains references on water management. Verses VI, 100.2 and VII,11.1
290 mention "...that the learned men bring water to desert areas by means of well, pond, canals etc....and the man
291 should think about the drought, flood and like natural calamities in advance and take preventive measures
292 accordingly. Verse (XII,1.3) of *Atharvaveda* mentions that those who use rainwater by means of rivers, wells,
293 canals for navigation, recreation, agriculture etc., prosper all the time. Similarly, verse (XX, 77.8) of the
294 *Atharvaveda* directs the king to construct suitable canals across mountains to provide water for his 'subject' for
295 agriculture other purposes. The *Yajurveda* also has references, directing the man to use rain and river water by
296 means of wells, ponds, dams and distribute it to various places having need of water for agriculture and other
297 purposes. The *Atharvaveda* talks about the drought management through efficient use of available water resources
298 and emphasizes, these waters are used efficiently, will reduce the intensity of droughts. Verse (2.3.1) of the
299 *Atharvaveda* instructs for proper management of various water bodies such as brooks, wells, pools and an efficient
300 use of their waters resources for reducing the droughts intensity and water scarcity (Sharma and Shruthi, 2017).

301

302 As in many other parts of the World, civilization in India also flourished around rivers and deltas. Rivers remain
303 an enduring symbol of national culture (Nair, 2004). The Harappan (or Indus Valley) Civilization (Figure 2)
304 which prospered during 2600–1900 B.C. (Chase et al., 2014) or about 5000 years ago (Dixit et al., 2018) had well



305 planned cities equipped with the public and private baths, well planned network of sewerage systems through
306 underground drains built with precisely laid bricks, and an efficient water management system with numerous
307 reservoirs and wells (Sharma and Shruthi, 2017). Evidences show that the Indus people developed one of the
308 smartest urban centres in those old times with exemplary fusion of civil, architectural and material sciences
309 (Possehl, 2002; Kenoyer, 1998; Wright, 2010). According to Shaw et al., (2007), the development of advanced
310 irrigation systems in ancient India led to the development of the complex urban societies and centres. The Indus
311 civilization was prominent in hydraulic engineering is known to have earliest known systems of flush toilets in
312 the world (Sharma and Shruthi, 2017). Kenoyer (2003) states that "... no other city in the ancient world had
313 developed such a sophisticated water and waste management system. Even during the Roman Empire, some 2,000
314 years later, these kinds of facilities were limited to upper-class neighbourhoods".

315 The Dholavira, an important city in the Indus civilization, contained sophisticated water management systems
316 comprising series of reservoirs, step wells and channels (Kirk, 1975; Sharma and Shruthi, 2017; Wright, 2010)
317 (Figures 3a and Figure 3b). The city is ringed with a series of 16 large reservoirs (7 m deep and 79 m long), some
318 of them interconnected and together, these storage structures account for about 10% of the area of the city (Iyer,
319 2019). The ability to conserve every drop of water in the parched landscape speaks volumes about the engineering
320 skills of the people of Dholavira. Recently, a rectangular stepwell has also been found at Dholavira which
321 measured 73.4 m long, 29.3 m wide, and 10 m deep, making it three times bigger than the Great Bath of Mohenjo-
322 Daro (<https://www.secret-bases.co.uk/wiki/Dholavira>).

323 The systems that Harappans of Dholavira city developed for conservation, harvesting, and storage of water, speak
324 eloquently about their advanced hydraulic engineering capabilities, given the state of technology (Baba et al.,
325 2018). The "Lothal" ("meaning *Mound of the dead*"), known as the harbour city of the Harappan civilization
326 (Bindra, 2003), is located at the *doab* of the Sabarmati and Bhogavo rivers. A roughly trapezoidal structure having
327 dimensions of 212.40 m on the western embankment, 209.30 m on the eastern one, 34.70 m on the southern one
328 and 36.70 m on the northern one (Rao, 1979) at Lothal is an example of advanced maritime activities in those old
329 days and is claimed by the archeologists to be the first known dockyard of the world (Nigam, 2016). Figure 4a
330 and Figure 4b show the dockyard at the Lothal after rains and the ancient Lothal as envisaged by the
331 Archaeological Survey of India (ASI). According to Nigam et al. (2016), the existence of the massive protective
332 wall (thickness up to 18 m) around the Dholavira city indicates the ancient Indians were aware of oceanic
333 calamities such as Tsunami/storm.

334

335 Agriculture was practised on a large scale having extensive networks of canals for irrigation (Nair, 2004). The
336 irrigation systems, different types of wells, water storage systems and low cost and sustainable water harvesting
337 techniques were developed throughout the region at that time (Nair, 2004; Wright, 2010). Mohenjo-Daro was one
338 of the major urban centres of the Harappan civilization receiving water from at least 700 wells and almost all
339 houses had one private well (Angelakis and Zheng, 2015). The wells were designed as circular to *pipal* (*Ficus*
340 *religiosa*) leaf shaped (Khan 2014). Canalising flood waters through ditches for irrigating the Rabi crops (crops
341 of the dry season) was also practiced at that time (Wright, 2010). The farmers of Harappa frequently used
342 "contouring, bunding, terracing, benching, *gabarbands* (dams) and canals for water management (Mckean, 1985).



343 The Gabarbands (stone-built dams for storing and controlling water) were also prevalent in these times for
344 irrigating agricultural lands during the dry seasons (Rabi crops) (Wright, 2010).

345

346 Agriculture and livestock rearing occupied a prominent role during Jainism and Buddhism period (600 B.C.) and
347 channel irrigation was in vogue (Bagchi and Bagchi, 1991). Field embankments were constructed surrounding the
348 fields to increase water holding capacity at strategic points with sluice gates to harness river water with proper
349 regulation facilities (*Arthshastra*, 400 B.C.) and irrigation through conduits was in practice to deliver water to the
350 irrigation field for attaining higher efficiency (Bagchi and Bagchi, 1991). Literature suggests that a large number
351 of hydraulic structures (dams, canals and lakes) were built during the Mauryan period in Indo-Gangetic plains and
352 other parts of the country for irrigation and drinking purposes (Shaw et al., 2007; Sutcliffe et al., 2011).
353 Surprisingly, many of these structures were equipped with the spillways to consider the flood protection measures.
354 During the Mauryan empire (400 BC-184 B.C), emperor Chandragupta Maurya constructed Sudarsana dam in
355 Girnar, Junagadh, Gujarat. Subsequent structural improvements involve the addition of conduits during the reign
356 of Asoka the Great, by his provincial governor the "Yavana Administrator (Greek Administrator)", Tusaspha
357 (Kielhorn, 1906; Shaw and Sutcliffe, 2001). In an excavation work conducted by Archaeological Survey of India
358 (ASI) during 1951-55, in Kumhrar (the site of ancient Pataliputra) a few miles south of Patna, Bihar "a canal 45
359 feet broad 10 feet deep and traced up to the length of 450 feet" was found of the Mauryan period. The canal was
360 linked with the 'Sone river' and also with the 'Ganges' for navigation purposes and also for the need of irrigation
361 to that area (Bhattacharya, 2012).

362 Here, it is instructive to quote Bhattacharya, (2012) : "... by the beginning of 300 B.C., a firm administrative set
363 up had taken shape. As a recognition of high position accorded to agriculture by the rulers as well as the people
364 at large, the construction of tanks and other types of reservoirs was considered to be an act of religious merit. The
365 king with the help and advice of his tiers of officials, ministers, consultants started acting as the "Chief trustee"
366 for optimizing, rationalizing and overall management of water resources. The *Arthasastra* of Kautilya gives us an
367 idea of principles and methods of management of irrigation systems ... that the Mauryan kings took keen interest
368 in the irrigation schemes, is borne at by the report of Megasthenes (a Greek traveller) who mentions about a group
369 of officers responsible for superintending the rivers, measuring the land as is done in Egypt and inspecting the
370 sluices through which the water is released from the main canals into their branches so that everyone may have
371 an equal supply ...".

372 Shaw and Sutcliffe, (2001) presented hydrological background of the historical development of water resources
373 in South Asia with particular emphasis on ancient Indian irrigation system at the Sanchi site (a well-known
374 Buddhist site and a UNESCO World Heritage site located in Madhya Pradesh). They investigated a 16-reservoir
375 complex located in in the Betwa river sub-basin (a tributary of Yamuna in Ganga basin) in Madhya Pradesh, India
376 during 1998 and 2005 (Shaw, 2000; Shaw et al., 2007; Shaw and Sutcliffe, 2001, 2003a&b, 2005). In addition to
377 Sanchi, four other known Buddhist sites of Morel-khurd, Sonari, Satdhara and Andher, all established between
378 300-200 B.C. (Cunningham, 1854; Marshall, 1940) were also surveyed by them. The heights of the dams were
379 found to vary from 1 to 6 m and their lengths from 80 to 1400 m with flat downstream faces; presumably designed
380 to reduce damage from overtopping. At least two of the larger dams were equipped with spillways, which could



381 pass floods of about 50 years' return period and it suggests that flood protection was also taken into account while
382 designing these structures (Shaw and Sutcliffe, 2003a). Their reservoir volumes range from 0.03 to 4.7×10^6 m³
383 and these estimates are closely related to the runoff generated by their catchments based on the present
384 hydrological conditions. These dams were constructed to a height sufficient to ensure that the reservoir volume
385 would be closely related to the volume of runoff from the upstream catchment of each site (Shaw and Sutcliffe,
386 2001). This indicates that these structures would have been constructed based on the detailed hydrological
387 investigations of the region. More or less identical spillways were also found with a group of much smaller
388 reservoirs in the neighbouring Devnimori area of Gujarat (Mehta, 1963). There are close similarities between the
389 Sanchi dams and well known Sudarsana dam (Shaw and Sutcliffe, 2003b). Sutcliffe et al., (2011) opines that it is
390 likely that some of the larger dams in the Sanchi area may have been fitted with similar spillways, which have
391 subsequently been obscured by siltation or erosion.

392 According to Shaw and Sutcliffe, (2001), a close relationship between runoff and reservoir volume in the Sanchi
393 area suggests a high level of understanding of water balance based on considerable period of observation and
394 understandings of local conditions. While excavating the area around the 'Heliodorus' pillar in Vedisa (present
395 day Vidisha, Madhya Pradesh), Bhandarkar, (1914) found the remains of a 300 B.C. canal, which would have
396 been drawing water from the river Betwa. However, Shaw and Sutcliffe, (2001) further mentions that a more
397 comprehensive understanding of ancient Indian irrigation would have been developed; had adequate attention
398 been paid to the Sanchi reservoir complex during the Vedisa excavations. Based on these findings, Shaw and
399 Sutcliffe (2003a&b) and Sutcliffe et al. (2011) conclude that the Sanchi Dam system would have been built on
400 the basis of a sound knowledge of the principles of water balance with detailed hydrological investigations and
401 by 'engineers with experience of reservoir irrigation' with a higher level understanding of the hydraulic
402 technology.

403
404 During the Sangam Period (300 B.C. to 300 A.D.), in the southern parts of India, the rainwater harvesting
405 structures such as tanks (*ery* in Tamil) were constructed for irrigating the paddy fields (Fardin et al., 2013; Sita,
406 2000) and fishing was also practiced in lotus ponds (*tamaraikulam* in Tamil) (Sita, 2000). The Grand Anicut
407 (Kallanai Dam) was constructed by the Chola King Karikalan during the 1st century A.D. on the river Cauvery for
408 protection of the downstream populations against flood and to provide for irrigation supplies in the Cauvery delta
409 region. The Grand Anicut is the world's oldest still in use dam and is also credited with being the 4th oldest dam
410 in the world and the first in India. In *Brihat Samhita* (550 A.D.), there are references regarding the orientation of
411 ponds, bank protection through pitching, plantation and also by providing sluicing arrangements. *Brihat Samhita*
412 contains many references regarding the orientation of ponds so as to store and conserve water efficiently (reducing
413 evaporation losses), plantation type for bank protection and proper sluicing to protect pond/reservoir from any
414 possible damage. Verse (54.118) mentions that a pond oriented in east to west direction retains water for a long
415 time while one from north to south loses invariably by the waves raised by the winds. Verse (54.120) suggests for
416 construction of spillway as an outlet for the water should be made on a side with the passage being laid with
417 stones.

418



419 **5 Wastewater Management in Ancient India**

420 The sanitation and wastewater management has always been one of the most important socio-environmental
421 challenges that the humankind has ever faced and the societies in the ancient India had developed state-of-the-art
422 technological solutions by utilizing their knowledge on hydraulic systems with the structural and materials
423 advancements. Apart from the detailed references on various aspects of hydrology as discussed earlier, we also
424 get some references to water quality in Vedas and other early literature, especially in *Atharvaveda*, *Charaka*
425 *Samhita*, and *Susruta Samhita* (both of pre- or early Buddhist era) (NIH, 2018). There are hymns in *Rigveda*
426 stating the role of forest conservation and tree plantation on water quality (Verse V, 83.4). The Verse V, 22.5 of
427 *Atharvaveda*, cautioned people from diseases living in a region with heavy rainfall and bad quality of water. There
428 are instances of classifying water based on taste in epic *Mahabharata* (Verse XII, 184.31 & 224.42). The *Brihat*
429 *Samhita* also discussed the relationship between soil colour and water quality (Verse, 54.104) and techniques are
430 mentioned for obtaining potable water with medicinal properties from contaminated water (Verses 54.121 &
431 54.122).

432 The Harappan cities were one of the very first and most urbanised centres developed with the excellent civil and
433 architectural knowledge in the old world. Even as early as 2500 BCE, Harappa and Mohenjo-Daro included the
434 world's first urban sanitation systems (Webster, 1962). The water and wastewater management systems have been
435 highly amenable to the socio-cultural and socio-economic conditions and religious ways of societies through all
436 the ages of the civilizations (Sorcinelli, 1998; Wolfe, 1999; De Feo and Napoli, 2007; Lofrano and Brown, 2010).
437 All through the ages, the wastewater management has been considered filthy (Lofrano and Brown, 2010;
438 Maneglier, 1994). The evolution process of wastewater management through the ages has been discussed by
439 several researchers worldwide, (e.g., Maneglier, 1994; Serner, 2007; Sorcinelli, 1998; Sori, 2001; Tarr, 1985;
440 Viale, 2000). Recently, Lofrano and Brown, (2010) presented an in-depth review of wastewater management in
441 the history of mankind and found that the 'Indus civilization was the first to have proper wastewater treatment
442 systems' in those ancient times. Wastewater management and sanitation were the major characteristics of the first
443 urban sites of the Harappan civilisation (Kenoyer, 1991). The sewage and drainage systems were composed of
444 complex networks, especially in Mohenjo-Daro and Harappa (Jansen, 1989). Latrines, soak-pits, cesspools, pipes
445 and channels were the main elements of wastewater disposal (Fardin et al., 2013).

446 All the houses were connected to the drainage channels covered with bricks and cut stones and the household
447 wastewater was first collected through tapered terra-cotta pipes into the small sumps for sedimentation and
448 removal of larger contaminants (primary wastewater treatment) and then into drainage channels in the street. This
449 most likely was the first attempt at treatment on record (Lofrano and Brown, 2010). These drainage channels were
450 having the provision of cleaning and maintenance by removing the bricks and cut stones (Wolfe, 1999). The
451 cesspits were fitted at the junction of the several drains to avoid the clogging of the drainage systems (Wright,
452 2010). Fardin et al., (2013) mention that almost all the settlements of Mohenjo-Daro were connected to the drain
453 network. However, at the same time, at Kalibangan, toilets and bathrooms outflows were connected in U-shaped
454 channels made of wood or terracotta bricks with decentralised sewage systems. These effluents poured into a jar
455 placed in the main street (Chakrabarti, 1995). The same model of wastewater collection was used in Banawali,
456 where effluents were channelled into drains made of clay bricks, before reaching the jars (Bisht, 1984).



457 In many other parts of the ancient India, e.g., Jorwe (Maharashtra), a similar drainage system was established
458 during 1375–1050 BC (Fardin et al., 2013; Kirk, 1975); at around 500 B.C., the city of Ujjain was also laid down
459 with the sophisticated drainage system having soak-pits built of pottery-ring or pierced pots (Kirk, 1975; Mate,
460 1969) and in Taxila around 300 B.C. very much similar drainage system to that of Mohenjo-Daro was in place.
461 (Singh, 2009). This shows that during the ancient times, modern concepts of sanitation and waste water
462 management technology were very well known to the Indians and were in their advanced stages during the Indus
463 valley civilization and later periods. Modern methods of wastewater disposal systems based on centralized and
464 decentralized concept as well as methods for wastewater treatments during Indus valley civilization were even
465 better than those used in the contemporary world.

466 **6 Summary and Conclusions**

467 This paper has explored the hydrological developments in ancient India starting from Harappa Civilization to the
468 Vedic Era and later, using references from Vedas, mythological epics such as *Mahabharata*, *Ramayana*, Jain and
469 Buddhist literature, and the references of *Arthshastra*, *Astadyayi* and many other Vedic text such as Puranas
470 (*Brahmana*, *Linga*, etc.), *Brihat Samhita*, and other ancient literature. The following conclusions can be drawn
471 from this exploration:

472

- 473 1. The Vedas, particularly the *Rigveda*, *Atharvaveda* and *Yajurveda* had specifically dwelt upon the hydrologic
474 cycle and various associated processes. The concepts of evaporation, cloud formation, water movement,
475 infiltration and river flow and repetition of cycle are explicitly discussed in these ancient texts. *Ramayana*
476 has also mentioned about hydrologic cycle and artesian wells. *Mahabharata* explains about the monsoon
477 seasons and water uptake process by plants. *Rigveda* also mentions about water lifting device such as
478 *Asmacakra/Ghatyanta* (similar to *Noria*), among others.
- 479 2. *Matsya Purana*, *Vayu Purana*, *Linga Purana*, and *Brahmanda Purana* also mention about the processes of
480 evaporation, formation of clouds due to cyclonic, convectional and orographic effects, rainfall potential of
481 clouds and many other associated hydrological processes.
- 482 3. The *Rigveda*, *Atharvaveda*, *Brihat Samhita*, *Susrutu Samhita* and *Charaka Samhita* have numerous references
483 of water quality and nature-based solutions (NBS) for obtaining potable water. The *Dakargalam* Chapter of
484 *Brihat Samhita* dwelt upon the occurrence and distribution of groundwater resources using geographical
485 pointers and soil markers.
- 486 4. The Harappa Civilization epitomizes the level of development in water sciences. Extensive network of canals,
487 water storage structures, different types of wells, and low cost and sustainable water harvesting structures
488 were developed during this period. These people had created sophisticated water and wastewater management
489 systems, planned network of sewerage systems through underground drains and also had the earliest known
490 system of flush toilets in the world. The Harappa Civilization is also credited with the first known dockyard
491 in the entire world. Indus people were also aware about the oceanic calamities such as Tsunami.
492
493
494



- 495 5. The first observatory for measuring rainfall using ‘*Varshamaan*’ (raingauge) was established during Mauryan
496 empire in India. The reservoirs, dams, canals equipped with the spillways were constructed for irrigation and
497 domestic supplies with adequate knowledge of water balance. Some structures were also constructed
498 considering 50 years’ return period. In ancient water history, the Mauryan period is also credited with the
499 first and foremost hydraulic civilization. Forecasting of rainfall and water pricing system was also prevalent
500 in this period.
- 501
- 502 6. The hydrologic knowledge in ancient India was contained in the *shlokas* of scriptures and very few people
503 are conversant with the languages of the scriptures. Hence, the knowledge and wisdom remained largely
504 unknown to the recent generations. Further, the script of the Harappans has not yet been deciphered. If further
505 research is carried out on ancient literature and when the script of the Harappans is deciphered, it is highly
506 likely that many more facts will emerge which may be much more fascinating than what we know so far.

507 **Data availability.** No data sets were used in this article.

508

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510 contributed to Sect. 5. PD also contributed to referencing and formatting the manuscript. SKJ and PPM reviewed
511 and supervised the content of the manuscript.

512

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514 **References**

- 515 Angelakis, A. N. and Zheng, X. Y.: Evolution of Water Supply, Sanitation, Wastewater, and Stormwater
516 Technologies Globally, *Water*, 7(2), 455–463, doi:10.3390/w7020455, 2015.
- 517 Baba, A., Tsatsanifos, C., El Gohary, F., Palerm, J., Khan, S., Mahmoudian, S. A., Ahmed, A. T., Tayfur, G.,
518 Dialynas, Y. G. and Angelakis, A. N.: Developments in water dams and water harvesting systems throughout
519 history in different civilizations, *Int. J. Hydrol.*, 2(2), doi:10.15406/ijh.2018.02.00064, 2018.
- 520 Bagchi, K. S. and Bagchi, S. S.: History of Irrigation in India I. Irrigation in Ancient India (From 2295 Bc upto
521 the 11th Century), *Irrig. Power J.*, 48(3), 69–76, 1991.
- 522 Baker, M. N. and Horton, R. E.: Historical development of ideas regarding the origin of springs and ground-water,
523 *Eos Trans. Am. Geophys. Union*, 17(2), 395–400, 1936.
- 524 Bhandarkar, D. R.: Excavations at Besnagar, Annual Reports, Archaeological Survey of India., 1914.
- 525 Bhattacharya, P. K.: Irrigation and Agriculture In Ancient India. Sectional President’s Address, Proc. Indian Hist.
526 Congr., 73, 18–34 [online] Available from: <https://www.jstor.org/stable/44156186> (Accessed 27 April 2020),
527 2012.
- 528 Bindra, S. C.: Lothal: A Harappan port town revisited, *Purātattva*, (33), 1, 2003.
- 529 Bisht, R. S.: Structural remains and town planning of Banawali, in *Frontiers of the Indus Civilization: Sir Mortimer*
530 *Wheeler Commemoration Volume*, pp. 89–98, Books & Books., 1984.
- 531 Biswas, A. K.: History of hydrology, North-Holland Publishing Company, Amsterdam., 1969.



- 532 Chakrabarti, D. K.: The archaeology of ancient Indian cities, Oxford University Press, USA., 1995.
- 533 Chase, B., Ajithprasad, P., Rajesh, S. V., Patel, A. and Sharma, B.: Materializing Harappan identities: Unity and
534 diversity in the borderlands of the Indus Civilization, *J. Anthropol. Archaeol.*, 35, 63–78,
535 doi:10.1016/j.jaa.2014.04.005, 2014.
- 536 Chow, V. T.: Handbook of Applied Hydrology: A Compendium of Water-resources Technology, 1st edition.,
537 McGraw-Hill Company, New York, NY., 1964.
- 538 Chow, V. T.: Contributions of Asian civilizations to the concept of the hydrological cycle, UNESCO [online]
539 Available from: <http://agris.fao.org/agris-search/search.do?recordID=FD7502194> (Accessed 27 April 2020),
540 1974.
- 541 Cunningham, S. A.: The Bhilsa Topes: Or, Buddhist Monuments of Central India, Smith, Elder and Company.,
542 1854.
- 543 De Feo, G. and Napoli, R. M. A.: Historical development of the Augustan Aqueduct in Southern Italy: twenty
544 centuries of works from Serino to Naples, *Water Supply*, 7(1), 131–138, doi:10.2166/ws.2007.015, 2007.
- 545 Dixit, Y., Hodell, D. A., Giesche, A., Tandon, S. K., Gázquez, F., Saini, H. S., Skinner, L. C., Mujtaba, S. A. I.,
546 Pawar, V., Singh, R. N. and Petrie, C. A.: Intensified summer monsoon and the urbanization of Indus Civilization
547 in northwest India, *Sci. Rep.*, 8(1), 1–8, doi:10.1038/s41598-018-22504-5, 2018.
- 548 Fardin, H. F., Hollé, A., Gautier, E. and Haury, J.: Wastewater management techniques from ancient civilizations
549 to modern ages: examples from South Asia, *Water Supply*, 13(3), 719–726, doi:10.2166/ws.2013.066, 2013.
- 550 Glücklich, A.: The Strides of Vishnu: Hindu Culture in Historical Perspective, Oxford University Press, Oxford,
551 New York., 2008.
- 552 Horton, R. E.: The field, scope, and status of the science of hydrology, *Eos Trans. Am. Geophys. Union*, 12(1),
553 189–202, doi:10.1029/TR012i001p00189-2, 1931.
- 554 Iyer, M.: The best laid plans, *Deccan Her.*, 20th January [online] Available from:
555 <https://www.deccanherald.com/sunday-herald/best-laid-plans-713650.html> (Accessed 27 April 2020), 2019.
- 556 Iyer, N. C.: Brihat Samhita of Varaha Mihira, Cent. Secr. Libr. [online] Available from:
557 <http://csrepository.nvli.in/handle/123456789/4675> (Accessed 28 April 2020), 1884.
- 558 Jain, S. K., Agarwal, P. K. and Singh, V. P.: Hydrology and Water Resources of India, Springer Science &
559 Business Media., 2007.
- 560 Jansen, M.: Water supply and sewage disposal at Mohenjo-Daro, *World Archaeol.*, 21(2), 177–192,
561 doi:10.1080/00438243.1989.9980100, 1989.
- 562 Jha, P. A.: Vrhat Sanhita (550 AD) by Varahmihira, Chow Khamba Vidyabhawan., 1988.
- 563 Jigyasu, B.: Ashtadhyayi (bhashya) prathamavrtti, three volumes., Ramlal Kapoor Trust Bahalgadh., 1979.
- 564 Kenoyer, J. M.: The Indus Valley Tradition of Pakistan and western India, *J. World Prehistory*, 5(4), 331–385,
565 doi:10.1007/BF00978474, 1991.
- 566 Kenoyer, J. M.: Ancient cities of the Indus valley civilization, *American Institute of Pakistan Studies.*, 1998.
- 567 Kenoyer, J. M.: Uncovering the keys to the lost Indus cities, *Sci. Am.*, 289(1), 66–75 [online] Available from:
568 <https://www.jstor.org/stable/26060364> (Accessed 27 April 2020), 2003.
- 569 Khan, S.: Sanitation and wastewater technologies in Harappa/Indus valley civilization (ca. 2600–1900 BC), in
570 Evolution of Sanitation and Wastewater Technologies through the Centuries, vol. 25, IWA Publishing., 2014.



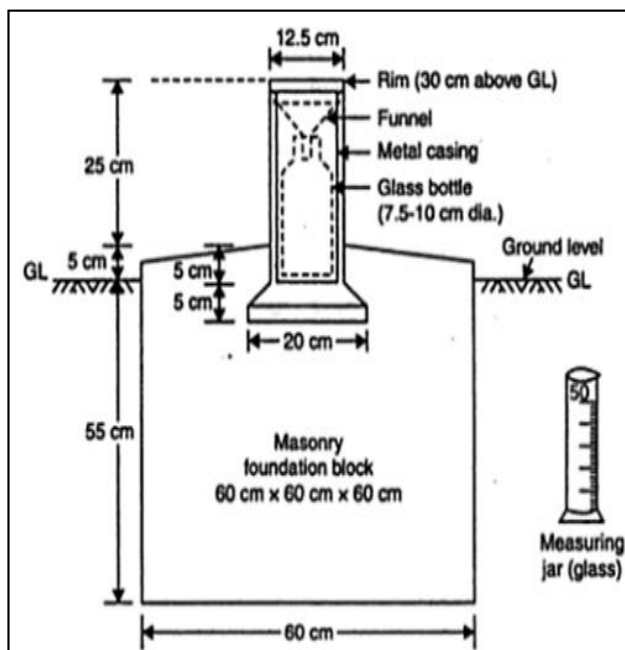
- 571 Kielhorn, F.: Junagadh rock inscription of Rudradaman: the year 72, Verlag nicht ermittelbar., 1906.
- 572 Kirk, W.: The Role of India in the Diffusion of Early Cultures, *Geogr. J.*, 141(1), 19–34, doi:10.2307/1796941,
573 1975.
- 574 Lofrano, G. and Brown, J.: Wastewater management through the ages: A history of mankind, *Sci. Total Environ.*,
575 408(22), 5254–5264, 2010.
- 576 Malik, S.: Conceptual Aspect of Hydrological Cycle in Indian Mythology of Kishkindha Kanda, Ramayana, J.
577 *Environ. Earth Sci.*, 6(4), 54–59 [online] Available from:
578 <https://www.iiste.org/Journals/index.php/JEES/article/view/30032> (Accessed 27 April 2020), 2016.
- 579 Maneglier, H.: *Storia dell'acqua*, SugarCo., 1994.
- 580 Marshall, S. J. H.: *The Monuments of Sanchi*, Swati Publications., 1940.
- 581 Mate, M. S.: Building in ancient India, *World Archaeol.*, 1(2), 236–246, doi:10.1080/00438243.1969.9979442,
582 1969.
- 583 McClellan III, J. E. and Dorn, H.: *Science and Technology in World History: An Introduction*, JHU Press., 2015.
- 584 Mckean, M. B.: *The Palynology of Balakot, a Pre-Harappan and Harappan Age Site in Las Bela, Pakistan.*, Ph.D
585 Dissertation, Southern Methodist University, Dallas, Texas, USA. [online] Available from:
586 <https://elibrary.ru/item.asp?id=7412156> (Accessed 27 April 2020), 1985.
- 587 Mehta, R. N.: Ancient bunds in Sabarkantha district, Gujarat, *J Orient. Inst. MS Univ. Baroda*, 10(4), 359–365,
588 1963.
- 589 Mujumdar, P. P. and Jain, S.K.: Hydrology in Ancient India: Some Fascinating Facets, in EGU General Assembly
590 Conference Abstracts, vol. 20, p. 8690., 2018.
- 591 Murty, K. S.: Varahamihira, the Earliest Hydrologist, *Water Future Hydrol. Perspect. IAHS Publ.*, (164), 1987.
- 592 Nair, K. S.: Role of water in the development of civilization in India—a review of ancient literature, traditional
593 practices and beliefs, *Int. Assoc. Hydrol. Sci.*, 286, 160–166, 2004.
- 594 Nigam, R., Dubey, R., Saraswat, R., Sundaresh, Gaur, A. S. and Loveson, V. J.: Ancient Indians (Harappan
595 settlement) were aware of tsunami/storm protection measures: a new interpretation of thick walls at Dholavira,
596 Gujarat, India, *Curr. Sci.*, 111(12), 2040–2043 [online] Available from: <https://www.jstor.org/stable/24911592>
597 (Accessed 27 April 2020), 2016.
- 598 NIH: *Hydrologic Knowledge in Ancient India*, National Institute of Hydrology, Jal Vigyan Bhavan, Roorkee,
599 India., 2018.
- 600 Orloff, C. R.: *Water engineering in the ancient world: Archaeological and climate perspectives on societies of*
601 *ancient South America, the Middle East, and South-East Asia*, Oxford University Press., 2009.
- 602 Possehl, G. L.: *The Indus civilization: a contemporary perspective*, Rowman Altamira., 2002.
- 603 Prasad, E. A. V.: *Ground water in Varahamihira's Vrhat Sanhita*. MASSLIT series No. 1, Sri Venkateswara
604 University Press, Tirupathi, India., 1980.
- 605 Prasad, E. a. V.: Bioindicators of Ground Water in Varahamihira's Brihat Samhita, *Groundwater*, 24(6), 824–828,
606 doi:10.1111/j.1745-6584.1986.tb01703.x, 1986.
- 607 Raghunath, H. M.: *Hydrology: principles, analysis and design*, New Age International., 2006.
- 608 Rao, S. R.: Lothal—A Harappan Port Town, vol. 1, *Mem. Archaeol. Surv. India*, (78), 83–84, 1979.
- 609 Sarasvati, S. P.: *Rig Veda*, DAV Publication Division., 2009.



- 610 Scarborough, V. L.: The Flow of Power: Ancient Water Systems and Landscapes, 1 edition., School of American
611 Research Press,U.S., Santa Fe, N.M., 2003.
- 612 Seneri, S. N.: The Construction of the Modern City and the Management of Water Resources in Italy, 1880—
613 1920, *J. Urban Hist.*, 33(5), 813–827, doi:10.1177/0096144207301452, 2007.
- 614 Shamasastri, R.: Kautīlya’s Arthaśāstra, Mysore Printing and Publishing House., 1961.
- 615 Sharma, S. and Shruthi, M. S.: Water in Hindu Scriptures: Thank You, Water!, in *Water and Scriptures: Ancient
616 Roots for Sustainable Development*, edited by K. V. Raju and S. Manasi, pp. 89–172, Springer International
617 Publishing, Cham., 2017.
- 618 Shaw, J.: Sanchi and its archaeological landscape: Buddhist monasteries, settlements & irrigation works in Central
619 India, *Antiquity*, 74(286), 775–776, doi:10.1017/S0003598X00060397, 2000.
- 620 Shaw, J. and Sutcliffe, J.: Ancient irrigation works in the Sanchi area: an archaeological and hydrological
621 investigation, *South Asian Stud.*, 17(1), 55–75, doi:10.1080/02666030.2001.9628592, 2001.
- 622 Shaw, J. and Sutcliffe, J.: Ancient dams, settlement archaeology and Buddhist propagation in central India: the
623 hydrological background, *Hydrol. Sci. J.*, 48(2), 277–291, doi:10.1623/hysj.48.2.277.44695, 2003a.
- 624 Shaw, J. and Sutcliffe, J.: Water Management, Patronage Networks and Religious Change: New evidence from
625 the Sanchi dam complex and counterparts in Gujarat and Sri Lanka, *South Asian Stud.*, 19(1), 73–104,
626 doi:10.1080/02666030.2003.9628622, 2003b.
- 627 Shaw, J. and Sutcliffe, J.: Ancient Dams and Buddhist Landscapes in the Sanchi area: New evidence on Irrigation,
628 Land use and Monasticism in Central India, *South Asian Stud.*, 21(1), 1–24,
629 doi:10.1080/02666030.2005.9628641, 2005.
- 630 Shaw, J., Sutcliffe, J., Lloyd-Smith, L., Schwenninger, J.-L. and Chauhan, M. S.: Ancient Irrigation and Buddhist
631 History in Central India: Optically Stimulated Luminescence Dates and Pollen Sequences from the Sanchi Dams,
632 *Asian Perspect.*, 46(1), 166–201 [online] Available from: <https://www.jstor.org/stable/42928709> (Accessed 27
633 April 2020), 2007.
- 634 Singh, U.: A History of Ancient and Early Medieval India: From the Stone Age to the 12th Century (PB), Pearson
635 Education India., 2009.
- 636 Sita, K.: Irrigation system of the Sangam Tamils, in *Irrigation system of the Sangam Tamils*, pp. 29–36, Rajesh
637 Publications, Nagercoil., 2000.
- 638 Sorcinelli, P.: *Storia sociale dell’acqua: riti e culture*, Pearson Italia Spa., 1998.
- 639 Sori, E.: *La città ei rifiuti: ecologia urbana dal Medioevo al primo Novecento*, Il mulino., 2001.
- 640 Srinivasan, T. M.: Measurement of Rainfall in Ancient India, *Indian J. Hist. Sci. Calcutta*, 11(2), 148–157, 1976.
- 641 Sutcliffe, J., Shaw, J. and Brown, E.: Historical water resources in South Asia: the hydrological background,
642 *Hydrol. Sci. J.*, 56(5), 775–788, doi:10.1080/02626667.2011.587425, 2011.
- 643 Tarr, J. A.: Historical perspectives on hazardous wastes in the United States, *Waste Manag. Res.*, 3(2), 95–102,
644 doi:10.1016/0734-242X(85)90068-0, 1985.
- 645 Tripathi, M. P.: *Development of geographic knowledge in ancient India*, Varanasi: Bharatiya Vidya Prakashan.,
646 1969.
- 647 Vālmīki and Goswami, C.: *Śrīmad Valmiki-Rāmāyaṇa: with Sanskrit text and English translation*, Gita Press.,
648 1973.

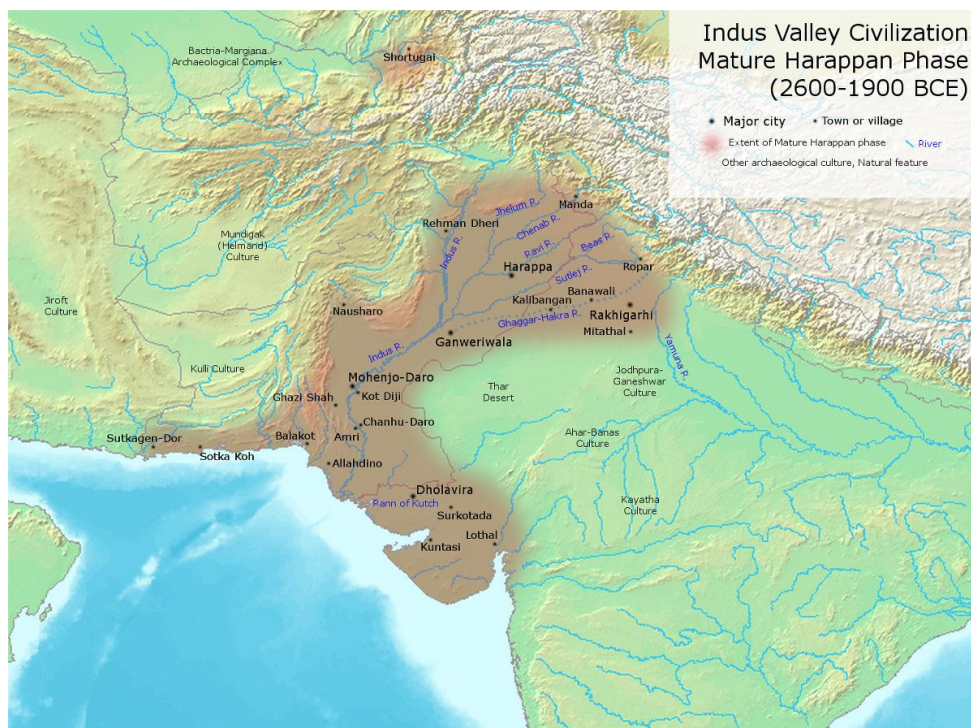


649 Viale, G.: Un mondo usa e getta. La civiltà dei rifiuti e i rifiuti della civiltà, Feltrinelli Editore., 2000.
650 Vuorinen, H. S., Juuti, P. S. and Katko, T. S.: History of water and health from ancient civilizations to modern
651 times, *Water Supply*, 7(1), 49–57, doi:10.2166/ws.2007.006, 2007.
652 Webster, C.: The Sewers of Mohenjo-Daro, *J. Water Pollut. Control Fed.*, 34(2), 116–123 [online] Available from:
653 <https://www.jstor.org/stable/25034575> (Accessed 27 April 2020), 1962.
654 Wolfe, P.: History of wastewater. *World of water 2000—the past, present and future*. Water World, Water
655 Wastewater Int. Suppl. Penn Well Mag. Tulsa OH USA, 1999.
656 Wright, R. P.: *The Ancient Indus. Urbanism, Economy and Society in South Asia*, Cambridge University Press.
657 [online] Available from: [https://nyuscholars.nyu.edu/en/publications/the-ancient-indus-urbanism-economy-and-](https://nyuscholars.nyu.edu/en/publications/the-ancient-indus-urbanism-economy-and-society-in-south-asia)
658 [society-in-south-asia](https://nyuscholars.nyu.edu/en/publications/the-ancient-indus-urbanism-economy-and-society-in-south-asia) (Accessed 27 April 2020), 2010.
659 Yannopoulos, S. I., Lyberatos, G., Theodossiou, N., Li, W., Valipour, M., Tamburrino, A. and Angelakis, A. N.:
660 Evolution of Water Lifting Devices (Pumps) over the Centuries Worldwide, *Water*, 7(9), 5031–5060,
661 doi:10.3390/w7095031, 2015.
662
663



664
665 Figure 1: The Symon's rain gauge [Source: Raghunath, (2006)].
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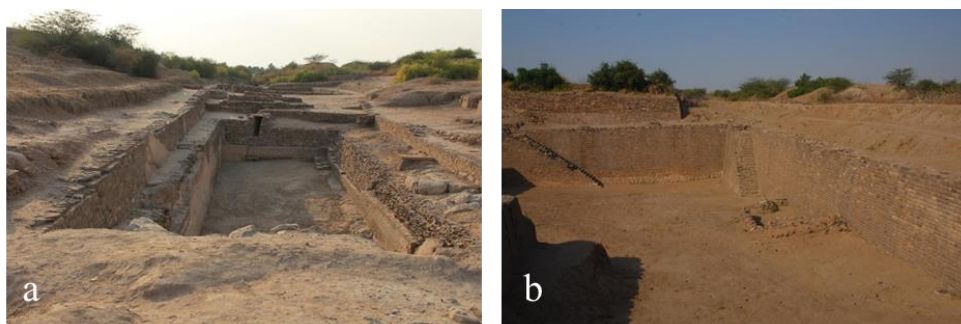
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Figure 2: Geographical extent of Indus Valley Civilization [Source: [https://commons.wikimedia.org/wiki/File:Indus_Valley_Civilization,_Mature_Phase_\(2600-1900_BCE\).png](https://commons.wikimedia.org/wiki/File:Indus_Valley_Civilization,_Mature_Phase_(2600-1900_BCE).png)].

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Figure 3: The southern (a) and eastern (b) reservoirs of Dholavira [Source: Iyer, (2019)].

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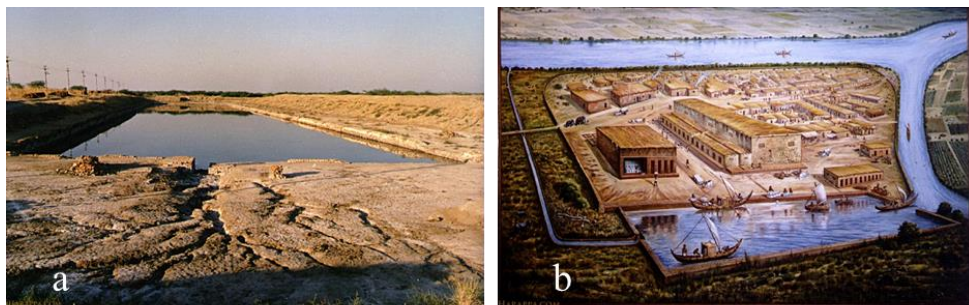
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678 **Figure 4: Dockyard (a) and ancient Indus port (b) of Lothal [Source: <https://www.harappa.com>].**