Abstract

The NGC region is characterized by a unique combination of geological, hydrological, tectonic and climatic features, namely, (i) two major deep seated faults, namely the East Cambay Basin Bounding Fault (ECBBF) and the West Cambay Basin Bounding Fault (WCBBF) defining the Cambay Graben with several other sympathetic faults parallel and orthogonal to these; (ii) more than 3 km thick sedimentary succession forming a regional aquifer system in the upper part; (iii) higher than average geothermal heat flow; (iv) intermittent seismicity; (v) emergence of thermal springs and thermal artesian wells in some cases with high helium concentrations; (vi) arid climate with high rate of evapotranspiration; and (v) significant mining of groundwater over the past few decades.

During the last couple of decades, along with declining piezometric levels a progressive increase in groundwater fluoride concentrations was observed. This prompted the belief that high fluoride in groundwater of the region was associated to long residence time of the mined groundwater and/ or subsurface injection of thermal waters. This study aimed to (i) determine the distribution of various geochemical tracers that could help identify the origin of groundwater fluoride; (ii) determine the direction and rate of movement of groundwater in the regional aquifer system; (iii) relate the reported high helium and temperature anomalies with the tectonic framework of the region; and (iv) search for hydrological proxies of past climates.

- A survey of dissolved groundwater fluoride and electrical conductivity (EC) was undertaken to identify areas of high concentration of fluoride, and to understand its origin. Dissolved fluoride and EC of modern rainfall were also measured to understand the role of dry deposition and/ or amount of rain in controlling the fluoride and EC of rainwater.

- A survey of dissolved helium and temperature of groundwater in the NGC region was undertaken to delineate areas with anomalies in these parameters and to understand their inter-relationship with the regional tectonics. Simple procedures were developed and standardized for (i) sample collection and storage, and (ii) measurement of helium concentrations in soil-gas and groundwater using commercially available helium leak detector.

- Groundwater dating was undertaken employing ^{14}C decay, ^{4}He accumulation and $^{4}He/ ^{222}Rn$ ratio methods to determine regional groundwater flow parameters. Laboratory and field procedures for carbonate precipitation (for ^{14}C method) and

water sample collection, storage and analyses for other groundwater dating methods were developed and standardized.

- Oxygen and hydrogen isotope ratios ($\delta^{18}O$ and δD) in thermal springs and groundwater samples were measured to identify the possible signatures of the past aridity and to identify the source of thermal spring water. Isotopic analyses of modern precipitation were also carried out to provide a reference for interpretation of the groundwater data.
- A groundwater CFC laboratory was set up as part of this study. Field and laboratory procedures for sample collection, storage, extraction of dissolved CFCs and injection for gas chromatographic analyses were standardized.

Important observations from the above investigations and conclusions drawn are summarized in the following.

The regional aquifer system of NGC region comprises a sequence of unconfined and confined sub-aquifers. The recharge area of the confined aquifers lies in the foot hills of the Aravalli Mountains in the east. The confinement of aquifers becomes effective only towards west of the ECBBF. Beyond the region of effective confinement, the groundwater in the aquifer system preserves the geochemical and isotopic characteristics acquired at the time of recharge in the recharge area. The groundwater ages progressively increase from <2 kaBP in the Aravalli foothills to > 35 kaBP in the low lying tract linking the Little Rann of Kachchh (LRK), the Nalsarovar (NS) and the Gulf of Cambay (GC). This defines the general flow direction along WSW.

Overlying the intersecting basement faults, deeper crustal fluids get injected into the aquifer system and significantly alter some of the geochemical properties of the groundwater of the region, namely, temperature, dissolved helium, water isotopes, fluoride and EC of groundwater in certain pockets. The localization of these pockets along intersecting deep seated basement faults on the two flanks of the Cambay basin is conceptualised in the form of a tectono-hydrothermal model of the NGC region. This model involves hydrothermal circulation of water of meteoric origin into deeper crustal layers, its interaction with deeper fluids and return flow to shallow depths, either into groundwater or as thermal springs. The faults and fractures provide the pathways for (i) downward percolation of shallow groundwater (of meteoric origin) as also (ii) for the upward migration of return flow with changed geochemical properties.

The high groundwater fluoride and EC in NGC region around an E-W trending line from around the thermal springs of Lasundra and Tuwa towards the Nalsarovar is explained by a continuous injection throughout Late Quaternary of hydrothermal fluids

and the regional groundwater flow in the aquifer system. This mechanism, however, does not explain the observed distribution of enhanced groundwater fluoride around the three nearly parallel lines trending NNW-SSE with intervening areas of low fluoride and EC. This distribution is explained by: (i) predisposition of this semi-arid region to high groundwater fluoride arising from mineral assemblage in surface soils and in aquifer matrix, aided by general aridity particularly in the recharge area; (ii) enhanced aridity around the LGM leading to recharge of groundwater enriched in fluoride resulting from enhanced evaporation as well as dry deposition and flow of this groundwater to its present location around a line within the Cambay Basin, during the past 20 ± 5 kaBP; and (iii) evaporative enrichment of stagnant surface water in the low lying LRK-NS-GC convergence zone and infiltration of a part of it into groundwater.

Additional hydrological signal of past aridity were also observed in the distribution of stable isotopes in the groundwater of the region in the form of high $\delta^{18}O$ and low *d*-excess nearly coinciding with the central belt of high fluoride and high EC. The ^{14}C ages of this belt around LGM (20 ± 5 kaBP) relate this to a period of enhanced aridity in the palaeoclimatic history of the NGC region.

Some additional studies as follow up of this work have also been proposed.