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Subsurface warming across the Veluwe area (Netherlands) driven by climate change, urbanisation, groundwater abstraction and aquifer energy storage

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Atmospheric warming, urbanisation, land-use changes, groundwater abstraction and aquifer thermal energy storage can induce significant changes in the subsurface thermal regime. These need to better understood and monitored in order for humanity to make efficient use of the subsurface as a thermal reservoir, but also to understand how this space acts as a heat sink during the current warming of the climate. This work aims to improve our understanding of the relative importance, spatiotemporal characteristics and mechanisms of how various environmental processes and anthropogenic activities control changes in subsurface thermal regimes. Such changes are poignantly illustrated by temperature-depth profiles recently obtained in ∼30 boreholes upto several hundreds of meters deep that are present in the unconsolidated sedimentary aquifer system of the Veluwe area, Netherlands. A comparison to similar data collected in 1978-1980 shows that since then across the entire study area subsurface warming has occurred to depths upto ∼250 m. The availability of historic land-use maps, hydrogeological and meteorological data for this area allow for a detailed analysis of the observed subsurface warming patterns, which is aided by numerical models of coupled groundwater and heat flow. On a regional scale and across the entire first 100-150 m into the subsurface, the classic thermal signatures of variations in land-use, groundwater recharge and discharge fluxes, are increasingly overprinted by those of regional atmospheric warming and urbanisation. In the topographically higher, forested groundwater recharge areas groundwater is significantly cooler (upto 6 K) than in the open agricultural lands where groundwater is discharging. The presence of a thick (upto 30-40 m) unsaturated zone in the recharge area probably enhances this striking contrast in groundwater temperature in addition to the effects of groundwater recharge and the presence of forest. Locally and at larger depths, however, aquifer thermal storage activities and groundwater abstraction have a strong and probably more immediate role in altering the subsurface thermal regime.