Journal of Hydrology (2008) **348**, 224–240

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

Assessment of exploitable groundwater resources of Denmark by use of ensemble resource indicators and a numerical groundwater—surface water model

Hans Jørgen Henriksen *, Lars Troldborg, Anker Lajer Højberg, Jens Christian Refsgaard

Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, DK-1350 Copenhagen, Denmark

Received 26 March 2007; received in revised form 14 September 2007; accepted 25 September 2007

KEYWORDS
Groundwater models;
Surface water;
Safe yield;
Environmental flow;
Water sustainability;
Ensemble resource indicators

Summary The trend towards construction of comprehensive dynamical numerical groundwater—surface water models to facilitate the examination of the quantitative status of groundwater resources by means of indicators is growing. A typical resource indicator is the assumption that the maximum abstraction should not exceed the groundwater recharge to an aquifer. From an aquatic, ecological point of view, the recommendation is only to exploit a small fraction of the recharge, in order to allow a significant fraction to supply wetlands and river systems. The paper proposes a set of four resource indicators for translating qualitative policy considerations on sustainable groundwater developments into quantitative criteria that can be evaluated by use of comprehensive hydrological models: (1) Indicator 1 is equal to a maximum abstraction of 35% of the pre-abstraction recharge; (2) Indicator 2 assumes a maximum 30% utilisation of current recharge; (3) Indicator 3 is identified as the abstraction at which mean river runoff is reduced by a maximum 10%, compared to pre-abstraction runoff; and (4) Indicator 4 is the abstraction at which baseflow is reduced by a maximum 5%, 10%, 15%, 25% and 50% aggregated for the reaches with the same environmental goal (e.g. a maximum 10% reduction of baseflow for salmonid spawning and nursery waters compared to pre-abstraction baseflow). The methodology for the design of the four ensemble resource indicators is described and the results of applying those indicators are demonstrated for assessment of the regional and national exploitable groundwater resources of Denmark.

* Corresponding author.
E-mail address: hjh@geus.dk (H.J. Henriksen).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2007.09.056

Introduction

With the European Water Framework Directive (WFD) the achievement of a good ecological status of surface waters and a good quantitative and qualitative status of groundwater has become compulsory. The ecological status of surface water is here defined by biological, chemical, morphological and hydrological criteria (Eisele et al., 2003). The WFD calls for combined management of surface water and groundwater, with proper assessment of the influence on groundwater quantity and quality of surface water ecology. Most rivers and other natural surface water systems (lakes and wetlands, etc.) derive their flow from surface runoff and groundwater discharges. The adverse impacts of groundwater abstraction on streamflow depletion define a limit to the exploitable groundwater resources. In addition, it is important to better understand the relationships between groundwater quality in shallow aquifers and deep aquifers, and possible negative effects of excessive groundwater abstraction on future groundwater quality in aquifers that are the backbone of drinking water and aquatic environment (Alley et al., 2002; Alley and Leake, 2004; Bredehoeft, 2002; Sophocleous, 1998, 2005; Konikow and Kendy, 2005; Custodio, 2002; Villholth, 2006; Llamas, 2004; Morris et al., 2003).

Model-based integrated assessment provides a vehicle for addressing key issues affecting the sustainability of aquifer and riverine systems (Jakeman et al., 2007; Letcher and Croke, 2007) by enabling effects of policy interventions, climate forcing and demographics to be predicted, and provides a means of expanding the understanding of river basin behaviour (Croke et al., 2004, 2006). Integrated assessment integrates knowledge and understanding from research areas, including social science, economics, ecology and hydrology, as well as from the community and managers to address real-world management issues. Evaluation of quantitative status by combined use of 'ensemble resource indicators' and numerical models should meet requirements of integrated assessment proposed by Jakeman and Letcher (2003):

- The combined ensemble resource indicators and numerical models must be problem-focused, iterative, adaptive and link research to policy.
- They must possess interactive transparency that enhances communication.
- They must be enriched by stakeholder involvement dedicated to adoption.
- They must take into account complexities between the natural and human environment, spatial dependence, feedbacks and impediments.
- They must attempt to recognise missing essential knowledge.

The combined use follows a trend in recent years which is to base water management decisions to a larger extent on modelling studies, and to use more sophisticated models (Refsgaard et al., 2005). Models have become an essential tool for analysing complexly managed basins (Grabert and Narasimhan, 2006). In Europe this trend is likely to be reinforced by the WFD due to its demand for integrating groundwater, surface water, ecological and economic aspects of water management at the river basin scale and due to the explicit requirement to study impacts of alternative measures (human interventions) intended to improve the ecological status in the river basin (Refsgaard et al., 2005). When such more sophisticated models become available, the understanding and assessment of sustainable groundwater abstraction can be further refined and adopted to policy making.

The Integrated Water Resource Management (IWRM) approach promotes the coordinated development and management of water, land and related resources in order to maximise the resulting economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (GWP, 2000). This approach is not only about 'managing physical resources' but also about 'reforming human systems to enable people to benefit from the resources'. WFD is a good first step towards this approach in terms of quantitative management of water.

The objectives of this paper are:

1. To translate qualitative policy considerations about sustainable developments into quantitative 'ensemble resource indicator' criteria for exchange flow components for groundwater bodies that can be evaluated by means of a comprehensive numerical hydrological model.
2. To test and critically evaluate these sustainability criteria (based on four ensemble resource indicators) in assessment of exploitable groundwater resource on regional and national scale for Denmark.

The journey from safe yield to numerical models and ensemble resource indicators

Historical review of the concepts of safe yield and sustainable yield

We aim to understand the adverse impacts of groundwater abstraction on streamflow depletion and groundwater quality to define a limit for the exploitable groundwater resource. In many cases groundwater discharges to streams constitute the major source of streamflow during dry periods, and baseflow reduction can thus be linked to groundwater abstraction.

Alley and Leake (2004) have provided a historical overview of how safe yield has been defined. The source of the following examples refers to citations in Alley and Leake (2004). Commonly, safe yield is defined as the attainment and maintenance of a long-term balance between the amount of groundwater withdrawn annually and the annual amount of recharge. The fundamental concept behind safe yield is to quantify the possible sustainable development of a groundwater basin. Lee (1915) defined safe yield as: ''*the quantity of water that can be pumped regularly and permanently without dangerous depletion of the storage reserve*''. Meinzer (1923) defined safe yield as: ''*the rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible*''. Over time the concept expanded, seeking more directly to include degradation of water quality and other factors.