EGU25-8126, updated on 21 May 2025
https://doi.org/10.5194/egusphere-egu25-8126
EGU General Assembly 2025

Analytical Estimation of Maximum Safe Pumping Rate in Sloping Confined and Unconfined Coastal Aquifers

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Coastal aquifers with sloping geometry (e.g., an inclined aquifer bed or confining layer) are common worldwide, yet most analytical models for pumping-induced seawater intrusion have assumed a horizontal setting (Lu et al., 2016). Building on our previously developed steady-state analytical solution for sloping unconfined coastal aquifers (Sun et al., 2023), this study extends the approach to both unconfined and confined aquifers under a fixed-flux inland boundary condition. Specifically, single potential theory is employed for unconfined aquifers, and finite Fourier cosine transforms are used for confined coastal aquifers. The proposed analytical solutions, corrected by an empirical factor, are validated against synthetic data generated by SEAWAT-based numerical simulations, demonstrating excellent agreement.

For unconfined aquifers, a positive sloping angle (i.e., higher aquifer bed toward inland) significantly increases the maximum safe pumping rate (MSPR) compared to an aquifer with a horizontal base. For instance, a slope of 0.01 yields a 42.6% increase in MSPR, whereas a slope of -0.01 leads to a 48.4% decrease relative to the horizontal case. In confined aquifers, the MSPR is governed by the slope of the upper confining layer and the angle difference between the upper and lower confining layers. A lower slope of the upper confining layer and a smaller angle difference lead to a higher head gradient, which suppresses seawater intrusion and thus enhances MSPR. For example, for an upper sloping angle of 0.05 combined with an angle difference of -0.01, as well as for an upper sloping angle of -0.01 combined with an angle difference of 0.01, the MSPR increases by 16.3% and decreases by 29.2%, respectively, in comparison to a horizontal aquifer.

These findings highlight that neglecting aquifer sloping geometry can introduce substantial errors in estimating MSPRs. Although the presented solutions offer a rapid assessment tool for pumping-induced seawater intrusion in sloping coastal aquifers, the flow field variations arising from inclined geometry and their implications for solute transport and biogeochemical reactions warrant further investigation, underscoring the need for ongoing research in their area.

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