An economic optimal control model of land subsidence (extended abstract)

Dewy Verhoeven[1], Suphi Sen[1], Hans-Peter Weikard[1]

1 Environmental Economics and Natural Resources Group, Wageningen University, Wageningen, The Netherlands
Contact: dewy.verhoeven@wur.nl

Background

Land subsidence is a common problem in delta regions due to soft soils and it is accelerated by human-induced processes such as intensive agriculture and urbanization (Koster and van Ommelen, 2015; Van den Born, 2016). Deltaic subsidence threatens the liveability of roughly half a billion people worldwide (Syvitski, 2009).

In this paper, we investigate how land subsidence can best be mitigated and managed. To keep subsiding land in deltas dry enough for human activity, groundwater levels are artificially lowered, in turn speeding up subsidence, depleting the fertile upper soil layer. The societal costs of subsidence are potentially very large, as it may damage the built environment and infrastructure, and increase flood risks, CO2-emissions and water management costs (Pelsma 2020; Van den Born, 2016). Maintaining higher water levels would slow down subsidence but also reduce land productivity. Thus, policy makers are faced with an intertemporal trade-off between the longer-term damage costs of land subsidence and short-term costs of mitigating subsidence through maintaining higher water levels. This paper is the first that develops a geophysical, economic model that integrates the dynamics of land subsidence and groundwater management with economic effects to derive socially optimal paths for water level control, through the application of optimal control theory. We focus on a paradigm example of subsidence management in agricultural areas inspired by the dynamics of peat soils in the Netherlands that are mainly used as grasslands. The objective of our model is to find the optimal path of the groundwater level over time that maximises the total discounted production value of the land minus the cost of water management over time. The model design allows for convenient additions (e.g. the nexus of subsidence and CO2 emissions) and modifications to be applicable to other settings (e.g. urban areas) in the future.

Our paper contributes to informed policy design and decision making by providing an economic analysis of land subsidence as a natural resource management problem. Earlier economic studies of subsidence assessed the societal damage costs of subsidence (Wade, 2018; Willemsen, 2020) or evaluated the costs and benefits of predetermined changes to water drainage regimes (van Hardeveld, 2017) or other sub-optimal policy scenarios (Kok, 2020; Pelsma, 2020) that reduce subsidence. In contrast, this study develops a bio-economic model that is able to derive long-term economically optimal groundwater management pathways in subsiding areas.

Our paper extends the literature that applies optimal control theory on water management and land issues, which has mostly focused on optimal groundwater extraction as a resource for agriculture and other uses (Gisser, 1980; Reinelt, 2020) with only limited attention to subsidence as either a constraint (Larson, 2001) or an extra cost factor (Chu, 2007). In contrast, our study treats the fertile soil itself as the scarce resource and models the unique trade-offs in groundwater management that apply to subsiding deltaic agricultural systems.

Model and method

Our model is set in the context of the drained peat grasslands of the Netherlands. We devise a schematic deterministic model for a single agricultural plot of land in which the groundwater level of that plot can be fully controlled by water pumping and other water management practices. We do not yet consider the external damage costs from subsidence.

We define S_t as the height at time t of the upper soil layer (consisting of peat and clay) above the sand or rock on which it lies. Let S_0 be the initial level of the soil surface. Land subsidence in our setting is defined as the vertical shrinkage of this upper soil layer such that S_t is declining over time. The decision maker can control the groundwater depth of the plot through the use of pumps, ditches, embankments and other water infrastructure. The control variable in our model is therefore the groundwater level g, measured as water height within the upper soil layer above the sand or rock. The difference between the soil thickness and the groundwater level is the groundwater depth, which we call the root zone $R_t = S_t - g_t$[1]. The speed of subsidence depends on the size of the root zone, such that $\dot{S} = \dot{S}(S, g)$. In the initial situation, groundwater levels are already artificially lowered below the natural water table to keep land sufficiently dry for cultivation. Figure 1 shows a schematic vertical cross section for a typical plot in our model, with the state and control variables depicted.

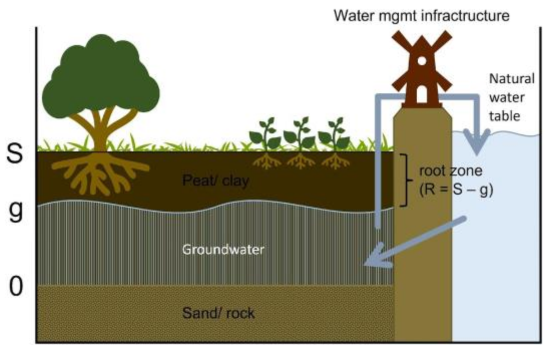


Figure 1 Schematic vertical cross section of a plot of peat land depicting the soil height S, groundwater level g and root zone R = S – g.

The farmer's net revenues from agriculture yt depends on the depth of the root zone, so $y = y(S, g)$, such that revenues are reduced when the plot is too wet (small root zone), but also when it is too dry (very large root zone). The costs of water management ct consist of the pumping effort and the investment in and management of the water infrastructure to reach a certain groundwater depth, which both increase by the depth of the groundwater level relative to the natural water table, such that $c = c(g)$ with $\frac{\partial g}{\partial c} < 0$.

The decision maker's objective is to find the optimal path for the artificial groundwater level over time that will maximise the production value of the land (agricultural net revenues) minus the cost of water management:

[1] In the remainder we drop time subscripts for ease of notation.

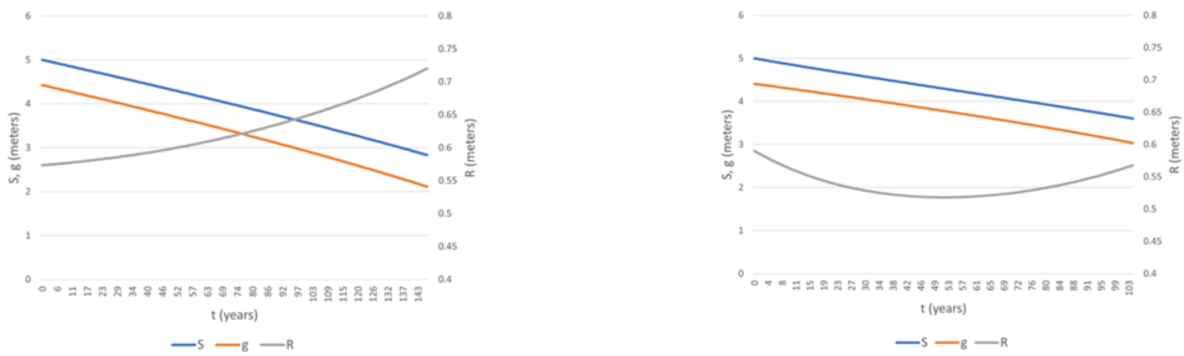
$$V^* = maxV\,[S, g, t] \;=\; \int_0^\infty \big(y(S,g) - c(g)\big)e^{-\delta t}dt \qquad (1)$$

Subject to:

$$\dot{S} = \;\dot{S}(S, g) \qquad (2)$$

with $S(0) = S_0 > 0$ given.

We rely on insights from soil and agronomic sciences to define the functional specification of our model, which we use to obtain analytical results to derive rules that describe the optimal behaviour of our control and state variable. Next, we use a number of data sets and existing model applications of subsidence studies in Dutch drained peat grasslands to assign values to the parameters in our model. Particularly, we use the 'Waterwijzer Landbouw' tool and WOFOST models for the relation between agricultural yields and groundwater levels, cost estimates from Van den Born et al. (2016) and the empirical subsidence relation for Dutch peat areas of Van den Akker et al. (2008). Our approach is similar to the work of van Hardeveld et al. (2017; 2018) regarding the integration of these geophysical and economic dynamics of subsidence for Dutch peat areas. The key difference is that in van Hardeveld et al.'s approach groundwater management strategies are externally determined as input for their Re:Peat model to run simulations of different policy options, while our work applies an optimization framework that endogenously determines the optimal policy path for groundwater management over time given the contextual parameter values. We provide sensitivity analyses with respect to water management costs, agricultural prices and the discount rate.



(a) linear marginal costs in depth

(b) quadratic marginal costs in depth

Figure 2 Model simulation of optimal groundwater and subsidence paths for a typical 1 ha grassland plot with a peat soil layer of 5m.

Results and discussion

Our analytical analysis shows that when water management costs are linearly increasing in depth, the optimal groundwater lowering is slower than when we would maximise agricultural yields. Consequently the optimal root zone is smaller and full subsidence of the peat soil is stretched out over a longer period. The optimal path reflects the fact that larger harvests in the near future come at the cost of reduced harvests later on. When marginal costs are increasing in depth, the optimal rate of groundwater lowering additionally slows down, reducing the root zone and therefore the rate of subsidence over time and we never fully deplete the peat soil.

Figure 2 shows the optimal paths for the groundwater and soil levels when these two variants of our model are simulated with the data described above and are applied to a typical 1 ha grassland plot with a pure peat layer of 5 meters. This simulation example reflects the same patterns and additionally shows that when costs are quadratic in depth, we should stop groundwater lowering after about 1.5 meters of subsidence as costs become too high. Sensitivity analysis shows that with lower discount rates and/or higher marginal pumping costs, groundwater tables are lowered less quickly and eventually kept at higher levels, resulting in a lower subsidence rate and less depletion of the soil.

What lacks in this model, but will be included in a future version of this paper, are the social damage costs of subsidence, particularly Greenhouse Gas (GHG) emissions. These are an important rationale for reducing subsidence in agricultural lands. This will allow us to calculate the welfare loss as a result of deviating from the optimal policy path for different policy scenarios typically considered in subsidence management. We also plan to adapt the model specification in the future so that it can be applied in an urban context. In addition, we propose a stochastic adaptation of the model that removes the assumption of full control of the groundwater level. In reality, there are external factors such as precipitation variability that lead to stochastic fluctuations in groundwater levels that affect subsidence.

Conclusion

Our results show that both the pure time preference trade-off between short-term and long-term production losses as well as water management costs can be rationales for slowing down land subsidence over time, even when we disregard the social damage costs of subsidence normally considered the main reason for subsidence mitigation. This analysis, together with the extensions proposed here, provide valuable input for decision-makers in the design of more efficient long-term policies for groundwater and subsidence management in the Netherlands.

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