A review of specific storage values from pore pressure response to passive in situ stresses:

Implications for sustainable groundwater management

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Outline

- Specific storage (S_s) values are important for ***analyzing the quantity of stored groundwater*** and for ***predicting drawdown*** to ensure sustainable pumping.

- This research ***compiled S_s values from many available studies*** including results based on pore pressure responses to passive stresses - barometric and earth tide signals.

- The range of values and maximum S_s values determined in situ from passive stresses, were ***significantly smaller*** than S_s values commonly applied including lab testing of cores, aquifer pumping tests and numerical groundwater modelling.

- Factors that results in ***overestimation or underestimation of S_s*** are considered with examples.

- In summary, ***poroelastic effects that are often neglected in groundwater studies are clearly important*** for quantifying water flow and storage in strata with changing hydraulic stress and loading conditions.

What is specific storage?

Specific yield Sy for unconfined aquifers is the volume of water draining from unit area per unit of drawdown (ie. watertable).

Specific storage Ss for confined aquifers, are much smaller than specific yields Sy, as water is stored under pressure (ie. below an aquitard).

Water volume released per metre of drawdown for specific storage S_s values:

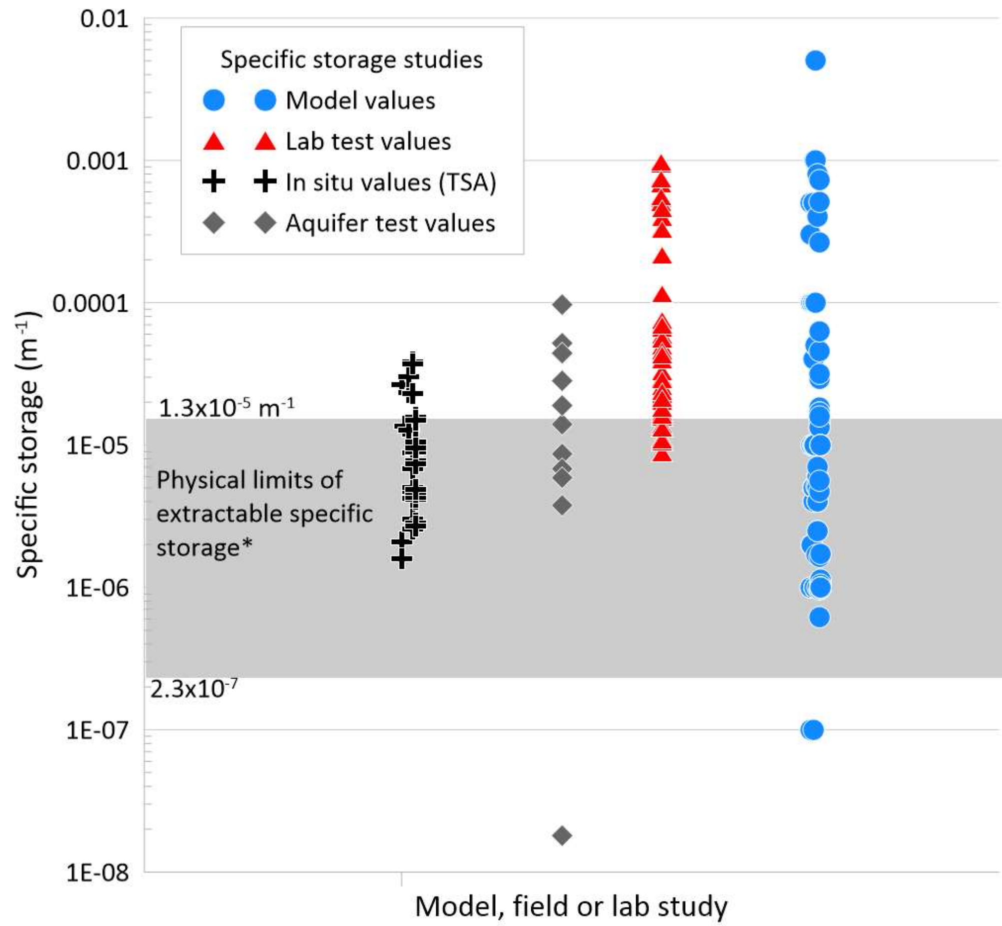
0.001 m^{-1}	1 L
$1x10^{-6}$ m^{-1}	0.001 L

Specific storage (S_s) values are important for analyzing the quantity of stored groundwater and for predicting drawdown to ensure sustainable pumping.

Compilation of S_s values

S_s values from pore pressure responses to passive in situ stresses ranged from 1.3×10^{-7} to 3.7×10^{-5} m^{-1} (geomean 2.0×10^{-6} m^{-1}, n=64 from 24 studies).

This large S_s dataset for confined aquifers included both consolidated and unconsolidated strata by extending two recent literature reviews. The dataset included several passive methods: Individual strains from Earth tides and atmospheric loading, their combined effect, and values derived from soil moisture loading due to rainfall events.

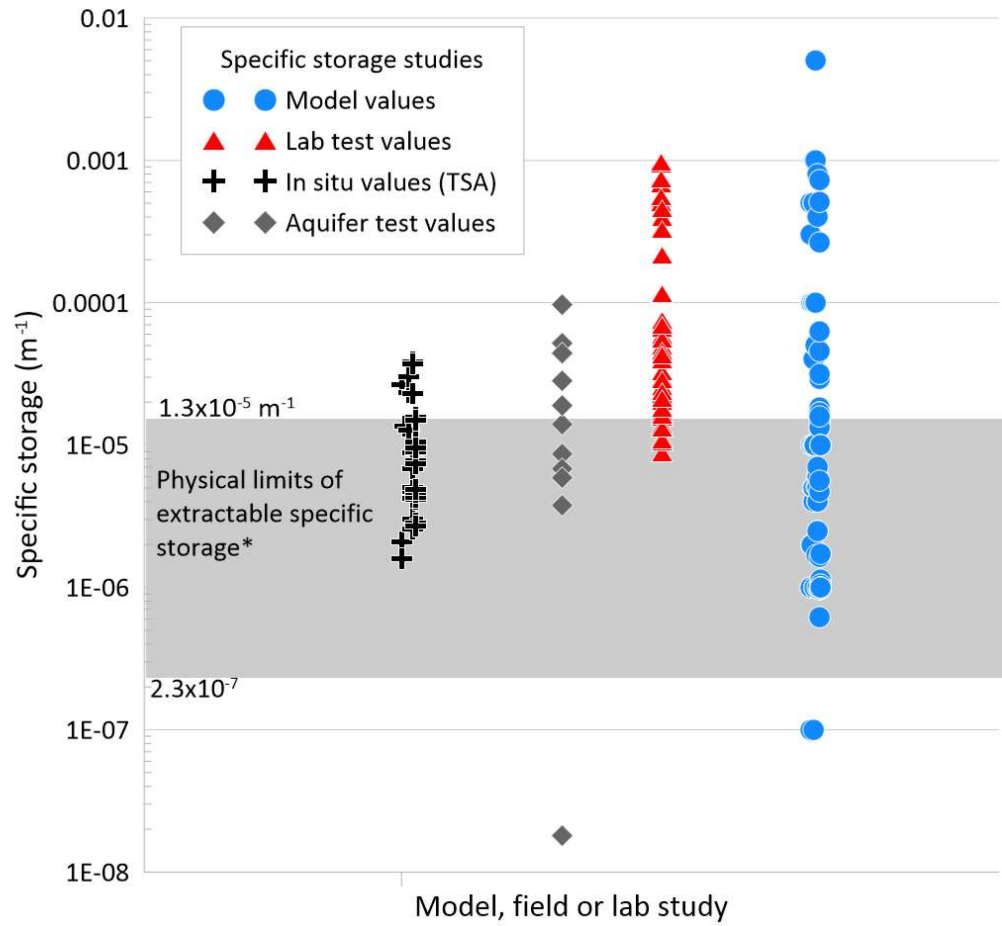


Compilation of S_s values

The range of S_s values spans approx. 2 orders of magnitude, far less than for hydraulic conductivity, a finding that has important implications for sustainable groundwater management.

Both the range of values and maximum S_s values in this large dataset were significantly smaller than S_s values commonly applied including

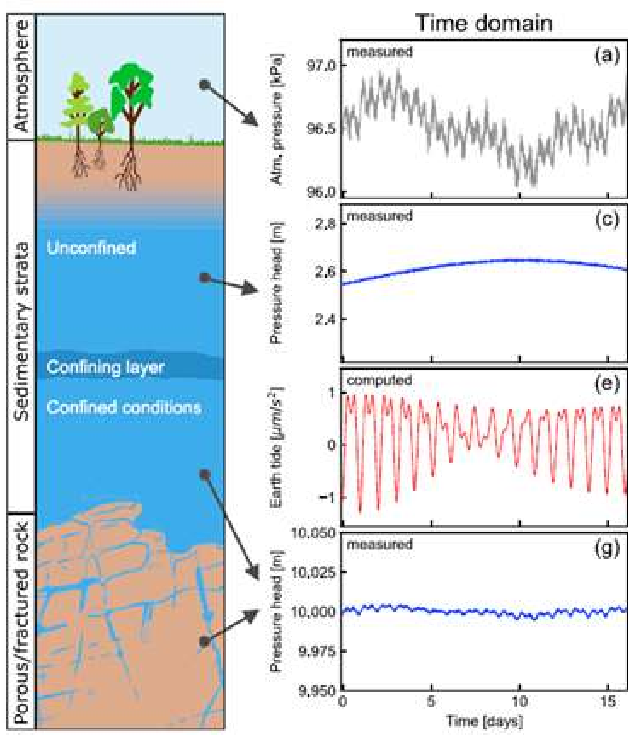
- laboratory testing of cores, aquifer pumping tests
- and numerical groundwater modelling



Why are passive measures of S_s apparently lower than aquifer pumping test S_s values?

What S_s values are reliable for use in transient 3D groundwater models?

Groundwater: tidal subsurface analysis (TSA), both barometric and earth tides



McMillan Rau Timms and Andersen (2019)
Reviews of Geophysics

Latest developments:

Gabriel Rau's presentation at EGU 2020
https://meetingorganizer.copernicus.org/EGU2020/session/35621

Millimetres and centimetres of groundwater level variation within a minutes to hours of barometric or earth tide effects. Twice per day for earth tides.

Passive, relatively inexpensive techniques that reduces the need for aquifer-aquitard pump testing and provides data on storage, ground compressibility and more.

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Groundwater: tidal subsurface analysis (TSA), both barometric and earth tides

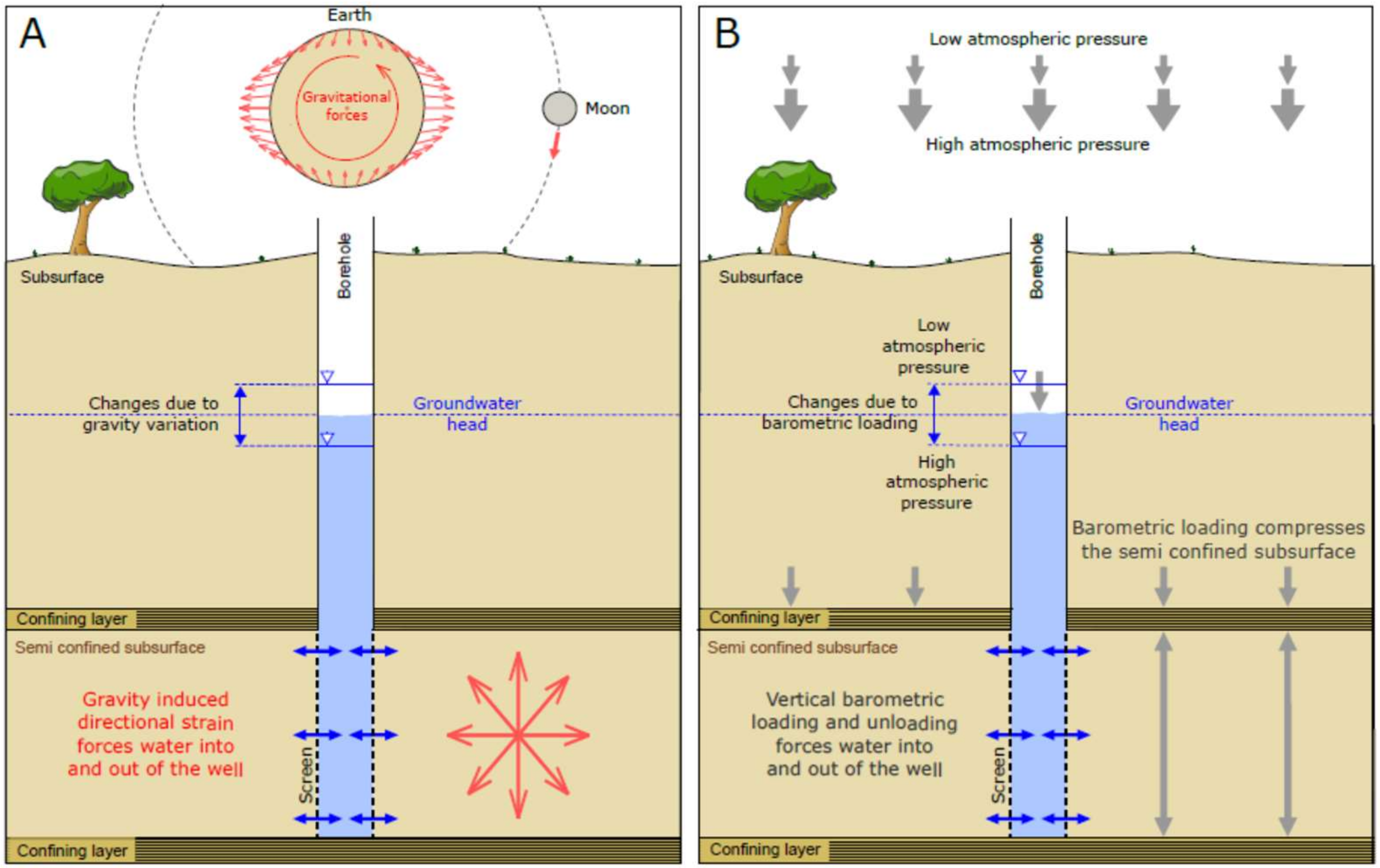

Figure 1: Representation of groundwater head measured in a well penetrating a semiconfined aquifer with a relatively rigid matrix subjected to A) strains caused by Earth tides (using the moon as an example celestial body) and B) barometric loading caused by atmospheric tides.

McMillan Rau Timms and Andersen (2019)
Reviews of Geophysics

Advancing methods

Reviews of Geophysics

REGULAR ARTICLE

10.1029/2018RG000630

Key Points:
- Earth and atmospheric tides occur globally, are predictable or observable, and induce groundwater oscillations under semiconfined conditions
- Tides, in combination with poroelastic theory, enable groundwater system characterization and hydrogeomechanical property quantification
- Analyzing groundwater responses to Earth and atmospheric tides is an underutilized passive technique to quantify subsurface properties

Utilizing the Impact of Earth and Atmospheric Tides on Groundwater Systems: A Review Reveals the Future Potential

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Abstract Groundwater extraction is increasing rapidly in many areas of the world, causing serious

Acworth Rau et al 2016 – ***objective barometric BE analysis*** based on 2 cpd signal that is (partly) disentangled from earth tide signal.

Acworth Rau Timms et al 2017 – applied objective BE analysis on 2 cpd signal to ***measure Ss changes with depth, verified with loading method*** of Timms and Acworth 2005. ***Phase lags demonstrated as a measure of aquifer confinement.***

Cook Timms et al 2017 - ***barometric response functions (BRFs) for monitoring bores in low K stra***ta, amplification of pore pressure response using packer shut-in of monitoring bores in low K strata

Rau et al 2018 – theoretical physical limits on extractable & uniaxial ***specific storage,*** new field techniques to combine cross-hole seismic surveys and head response to tides to calculate specific storage when given bulk density.

McMillan Rau Timms Andersen et al 2019 – ***review paper,*** good overview of advances to date.

Turnadge, Rau et al 2019 – compared BE methods in a confined sandstone aquifer, 6 x Ss values from TSA underestimated Ss values from 4x aquifer pump tests

Comparing stresses and conditions

	Tidal – barometric	Tidal – earth tide	Aquifer pumping test	Lab tests on cores	Groundwater model
In situ stresses	Yes	Yes	Yes	No	-
Dimensions	Vertical – area of influence above well screen depending on depth, and unconfined to confined conditions	Areal, horizontal plane	Depends on interpretation eg. Cooper method - areal horizontal plane	Uniaxial	3D Unconstrained
Conditions	Undrained	Undrained	***Drained*** to (initial) ***Undrained*** (steady state)	Undrained	
Issues to watch for	Local barometric measurement simultaneous with P_w data, thickness of vadose zone	High resolution P_w data, P_w time lags in low K strata, other factors, well screen/grout effects	Suitable P_w monitoring points, assumed boundary conditions & interpretation method	Disturbed sediment and rock samples, high strain rates in lab, ‘soil’ vs. ‘rock’ methods	

P_w is pore water pressure

Is S_s overestimated or underestimated?

Results confirm that ***S_s is overestimated by assuming incompressible grains***, particularly for consolidated rocks.

It was also evident that ***S_s that commonly assumes uniaxial conditions underestimate S_s that accounts for areal or volumetric conditions***.

Further research is required to ensure that ***S_s is not underestimated by assuming instantaneous pore pressure response to strains***, particularly in low permeability strata. However, ***in low permeability strata S_s could also be overestimated if based on total porosity*** (or moisture content) rather than a smaller free water content, due to water adsorbed by clay minerals.

Further evaluation is also required for influences on S_s from monitoring bore construction (ie. screen and casing or grouting), and ***S_s derived from tidal stresses (undrained or constant mass conditions) that could underestimate S_s applicable to groundwater pumping*** (drained or changing mass conditions).

Is S_s overestimated or underestimated?

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Common assumptions:

1. Incompressible grains
2. Total porosity can drain

Over-estimated S_s

3. Uniaxial (eg. Jacob 1940)
4. Instant P_w response to strain
5. Undrained conditions (constant mass, eg. tidal analysis)

Under - estimated S_s

Reality:

1. Compressible grains (clayey strata),
2. 'Extractable' free water drains (clayey strata)

3. 3D response (GW models),
3. Areal strain response (earth tides)
4. Time lag P_w response (low K strata)
5. Drained conditions (changing mass, eg. pumping)

Example of 2 - total or effective porosity

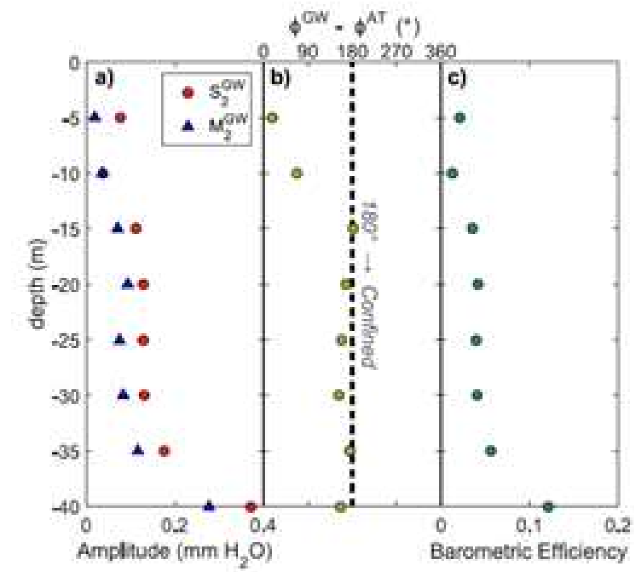
S_s is overestimated by using total porosity.

Extractable or effective porosity in clayey material is much lower that total porosity.

Eg. porosity 0.5 S_s 3.2×10^{-4}

porosity 0.02 S_s 1.3×10^{-5}

Phase lag of 180 degrees indicates confined conditions.



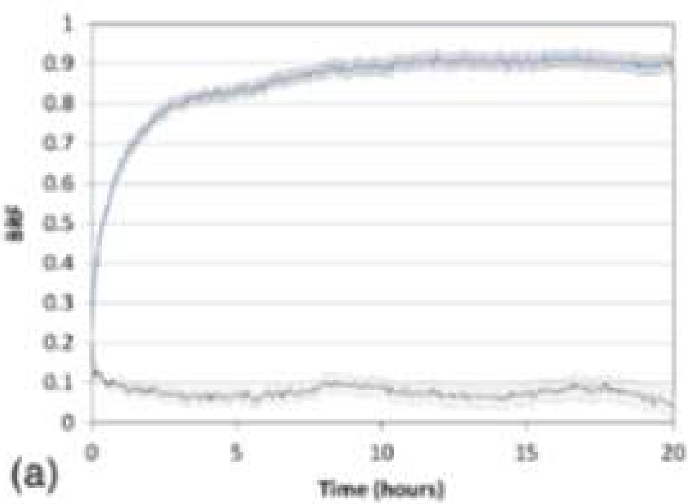
Acworth et al 2017, Cattle Lane clayey aquitard site

Table 1. Name of Piezometer or Bore, Barometric Efficiency, Total Moisture Derived From the Core, Specific Storage Estimates Based Upon Total Moisture Measurements Quantified Using Equation (5) (Column 4) and Then Repeated Based Upon Estimates of Specific Yield Rather Than Total Moisture Content (Column 6)

Piezo/Bore	Barometric Efficiency	Total Moisture θ	Specific Storage S_s	Effective Moisture S_y	Specific Storage S_s
CL-5	0.010	0.38	1.67×10^{-4}	0.05	2.20×10^{-5}
CL-10	0.007	0.50	3.16×10^{-4}	0.02	1.26×10^{-5}
CL-15	0.032	0.55	7.76×10^{-5}	0.08	1.06×10^{-5}
CL-20	0.039	0.52	6.06×10^{-5}	0.02	2.12×10^{-6}
CL-25	0.042	0.50	5.31×10^{-5}	0.02	2.12×10^{-6}
CL-30	0.042	0.45	4.83×10^{-5}	0.02	2.15×10^{-6}
CL-35	0.059	0.10	7.61×10^{-6}	0.01	7.61×10^{-6}
CL-40	0.121	0.20	7.42×10^{-6}	0.20	7.42×10^{-6}
GW 30061	0.138	0.20	6.50×10^{-6}	0.20	6.50×10^{-6}

Example of 4 - underestimated S_s by assuming instant pore pressure response

Bore	Time of response	LE	BE	Bm (/kPa)	Ss (/m)
High K strata	steady	0.85	0.15	1.04E-06	1.2E-05
Low K strata	initial	0.3	0.7	1.12E-07	**3.7E-06**
	early	0.4	0.6	1.74E-07	4.3E-06
	asymptote	0.8	0.2	1.04E-06	1.3E-05
	steady	0.91	0.09	2.64E-06	**2.8E-05**



Cook Timms et al 2017, Norman's Road site, aquitard + aquifer

High K monitoring bore, GW30476/5, porosity = 0.4
Low K monitoring bore, NMRDC1, porosity = 0.57

S_s value is most reliable after several hours of Pw response.

Realistic S_s value of 2.8×10^{-5} is ~8 times higher than initial estimate of S_s

Thanks, your comments, questions?

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Selected downloads available here: https://www.researchgate.net/profile/Wendy_Timms

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