General Report

Update of methodology of predicting gas- and aquifer pressures in the Waddenzee development area

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Table of Contents

1 Summary

This report describes the prediction of reservoir pressures versus time in the gas bearing part and underlying water bearing part of the reservoir (aquifer) as a result of gas production in the Waddenzee area. An assessment of gas and aquifer pressure depletion and its associated uncertainty range is an important input into for estimation of subsidence in the Waddenzee gas field development area.

This report is an update of the initial 2005 report “Prediction of reservoir pressures in the Waddenzee area” which was submitted prior to start of production in Waddenzee gas fields (Ref.1). The 2005 report was based on modeling of producing gas fields to the south of the Waddenzee area, which served as analogues for future depletion of Waddenzee gas fields.

The following updates have occurred in the period since 2005 to 2015:

- Inclusion of the Ameland gas field in the Waddenzee pressure depletion prediction area.
- Aquifer pressure depletion in lateral and vertical direction with respect to depleting gas reservoirs is in general lower than previously assumed. In 2005 it was conservatively assumed for prediction of aquifer pressures that no residual gas would be present in the aquifers. However the results of modeling of an aquifer production test are in agreement with the presence of residual gas. The presence of residual gas decreases associated pressure depletion of aquifers*.
- Aquifer pressure depletion in vertical direction with respect to depleting gas reservoirs (bottom aquifer) is likely much lower than previously assumed. Formation pressure measurements in infill wells in depleted reservoirs in the area since 2005 showed high bottom aquifer pressures. This is caused by the (sometimes fine) layered nature of the reservoirs, where thin tight streaks hamper vertical pressure transmission.

The following conclusions from the 2005 report remain valid:

- Permeability in aquifers is lower than in the gas bearing reservoir part leading to more restricted mobility of aquifer water. The lower permeability is caused for example by diagenetic growth of clay particles in the pore space. This means that aquifers are expected to remain at a more elevated pressure level due to the lower permeability of the aquifer. The pressure difference between gas reservoir and aquifer is forecasted to exist for a significant period of time beyond the end of gas production.

  N.B.: The presence of residual gas in aquifers and poorer vertical connectivity in aquifers significantly increases the time to pressure equalization between gas and aquifer reservoir, i.e. large pressure difference (or high pressure in the aquifer) can exists far beyond the time of interest.

- Watering out of gas production wells is not expected on an early and large scale. This will result in high recovery factors and low gas pressures at abandonment. However perforations close to the GWC with an adjacent connected lateral aquifer and good reservoir properties can water out prematurely. If water production negatively impact gas production the (partially) water producing perforations can be

shut off and depletion of the gas reservoir can continue via perforation higher up in the gas reservoir.

*Depletion of aquifers occurs due to aquifer water flowing into the lower pressured gas reservoir. The volume of aquifer water moving into the gas reservoir hardly changes whether residual gas in the aquifer is present or not. However, if residual gas is present in the aquifer the outflow aquifer water is strongly compensated by expansion of residual gas. This is in contrast to the very small expansion of water alone, leading to faster and deeper depletion, if no residual gas is present.

In summary this leads to the following conclusions with respect to depletion:

Depletion levels		
	Good reservoir	*Poor reservoir*
Gas reservoir	High	Medium/High
Lateral aquifer	High/Medium (close to the gas reservoir) Medium (farther from gas reservoir)	Low
Bottom aquifer	Low/Medium (close to gas reservoir) Low/None (deeper part of aquifer)	Low/None

Way forward

The following further work will be carried out to update prediction of depletion levels and uncertainty ranges in Waddenzee fields:

a) A numerical simulation study using a fine scaled representation of type aquifers in Waddenzee fields to assess/quantify impact of smaller scaled tight layers and presence of residual gas levels on aquifer depletion (bottom and lateral).

b) Based on the results of a) implement upscaled reservoir parameters in the individual full field reservoir model to match predicted aquifer depletion levels as predicted by the fine scaled model. The full field/reservoir pressure depletion results versus time will be used for updating subsidence models.

2 Reservoir simulation modeling - history

A summary of the reservoir model set up and assumptions for the 2005 report is given in the section below. Reference is made to valid findings. Updates and findings in the period 2005 to 2015 will be reported in the following section.

2.1 Model set-up 2005

The Anjum field was chosen as an analogue field for Waddenzee fields in 2005 given that no production from the Waddenzee was available for model calibration with observed production performance and pressure depletion.

Anjum (like the Waddenzee fields) is contained in the Upper Slochteren Sandstone Member (ROSLU) of the Rotliegend formation. The ROSLU consists of aeolian and fluvial/lacustrine sediments deposited in a desert environment. The depleting thickness of the ROSLU in this area varies between 85m and 110m, of which approximately 75 to 90% is gas bearing reservoir in Anjum. The Anjum field (and Waddenzee fields) are mainly fault closed structures at Base Zechstein (Rotliegend) level. Boundary faults are largely sealing as indicated by (slightly) different reservoir pressure gradients in adjacent fields.

A numerical simulation model of the Anjum field consisting of 3150 gridblocks (7 layers) was used for determining subsurface scenarios for the Waddenzee fields in 2005. At the time the field produced ca. 2/3rd of the gas initially in place (GIIP), which has allowed confident history matching of pressure and gas/water production data in order to fine-tune reservoir properties of the Anjum field.

Figure 1 shows the top reservoir depths and gridblock set up for the Anjum field as well as two cross-sections through the simulation model, which show gas and water bearing segments of the reservoir.

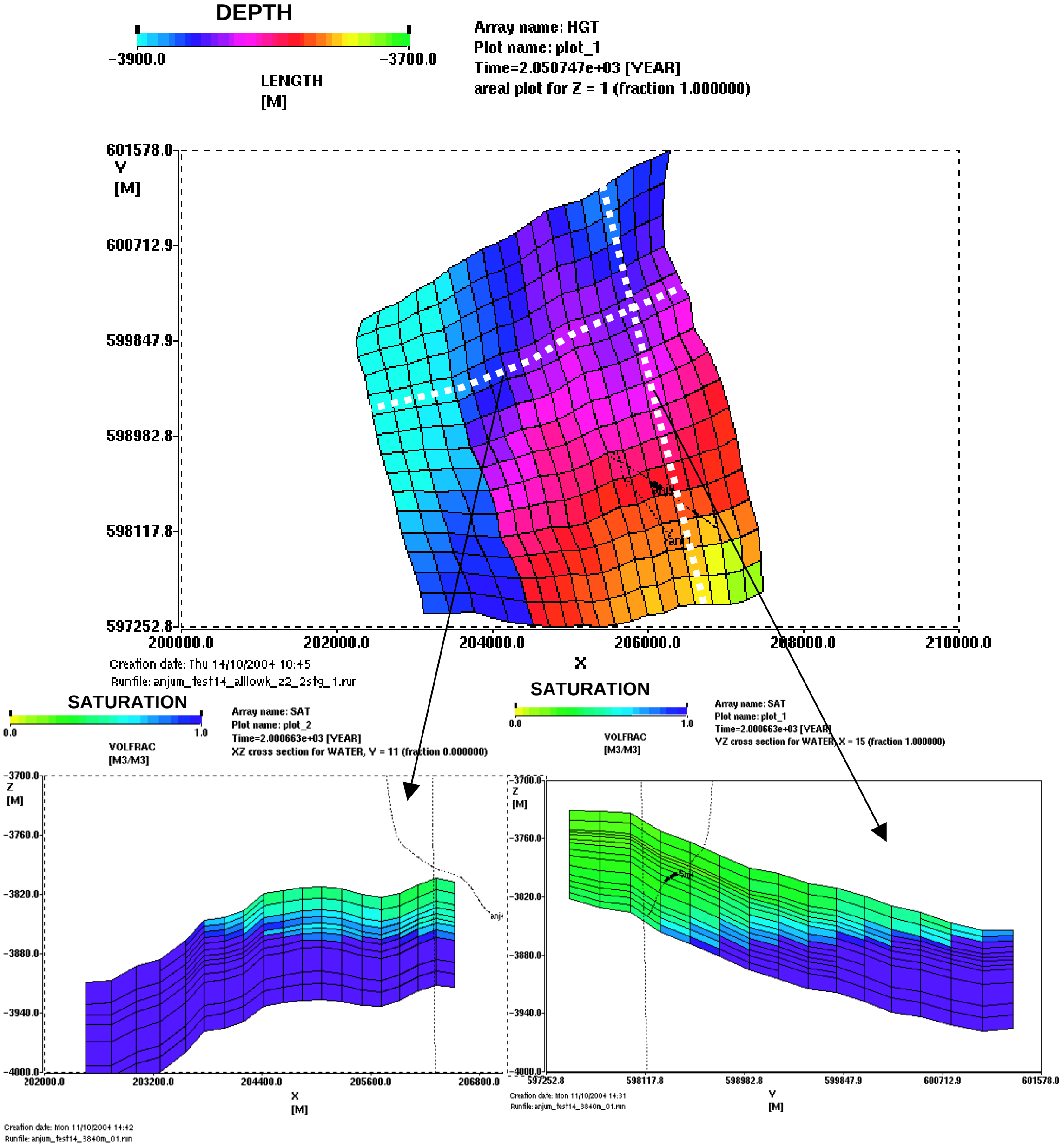


Figure 1 – Anjum Reservoir Model – top structure and gas saturation

Based on learnings from the fields in the area, which indicated that permeability in the aquifer can be lower than in the gas leg, core data for Anjum and the Waddenzee area were reviewed. Core data suggest that a difference between gas and aquifer permeability versus porosity functions exists in Anjum and the Waddenzee fields (Figure 2 showing measured air permeability core data at atmospheric conditions). Measured air permeability core data were in-situ stress corrected and gas- and aquifer “permeability versus porosity” functions were incorporated in the simulation model according to straight-line fits.

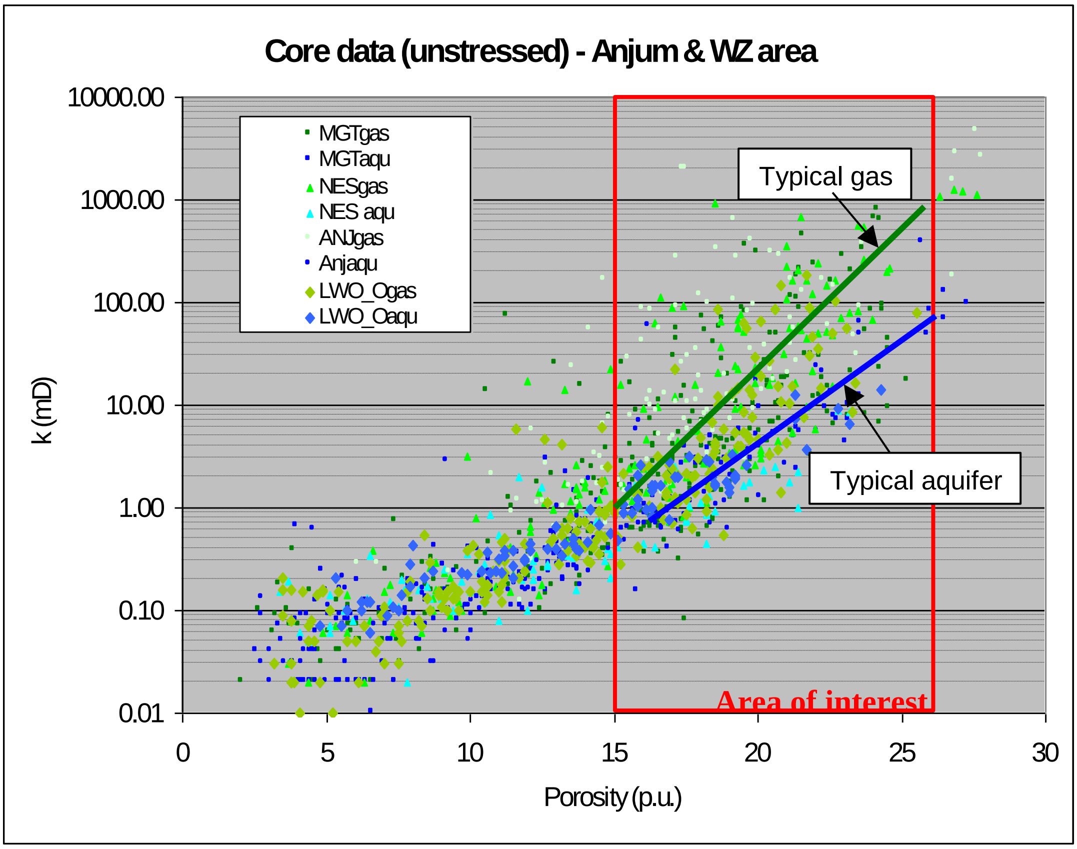


Figure 2 – Measured air permeability core data from gas and water bearing reservoir

Relative permeability functions for the gas - and water phases are based on special core analysis on core data in the area. These are supported by history matching production performance of fields in the area. An example for 18% porosity is shown in Figure 3.

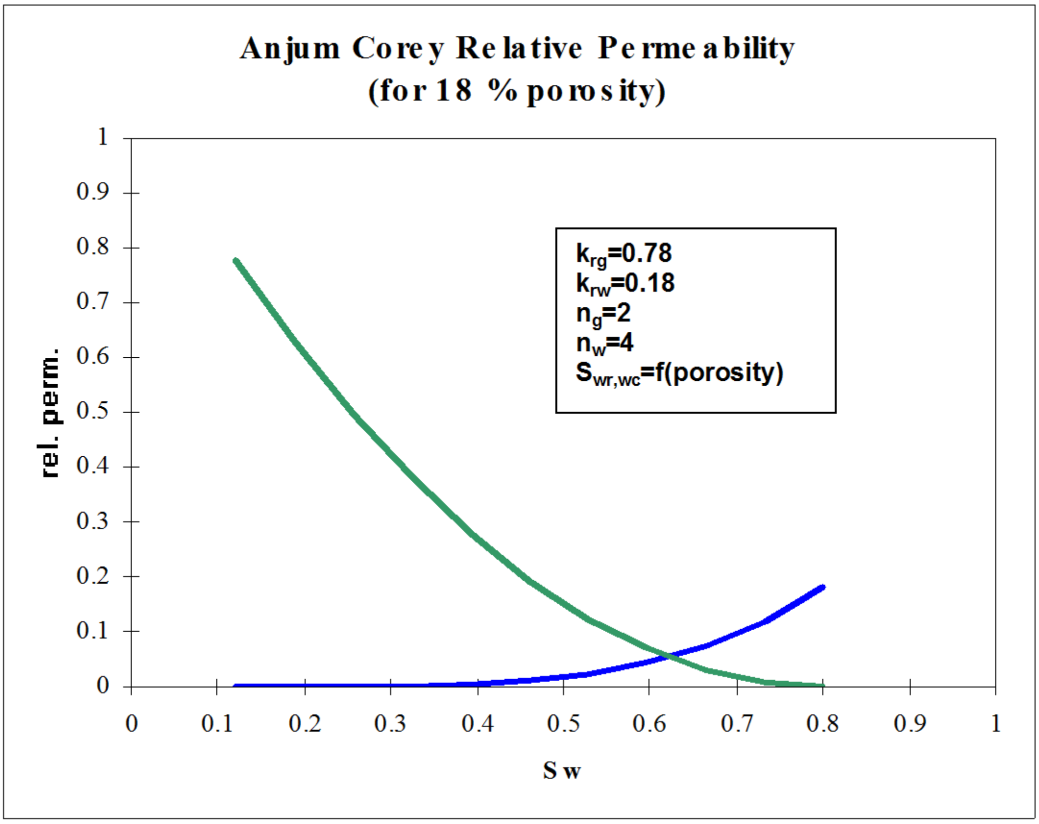


Figure 3 – relative gas and water permeability as a function of water (gas) saturation

Relative permeability is the reduction of gas and water permeability due to presence of water and gas, i.e. the higher gas/water saturation the lower water/gas relative permeability. Effective gas/water permeability is calculated by multiplying in-situ permeability with relative permeability.

2.2 History matching Anjum – impact of aquifer permeability

Modeled bottom hole pressure (BHP or prevailing pressure in the well at the sand face) in the well versus measured closed in bottom hole well pressures (black diamonds) for ANJ-1 is shown in Figure 4. Measured closed in pressures match with modeled/predicted closed in pressures indicating that a correct gas volume has been modeled within the structure. This gives confidence that also the correct (within reasonable limits) portion of the aquifer volume has been included in the model, as the structure is bounded by sealing faults and the total reservoir volume is well defined.

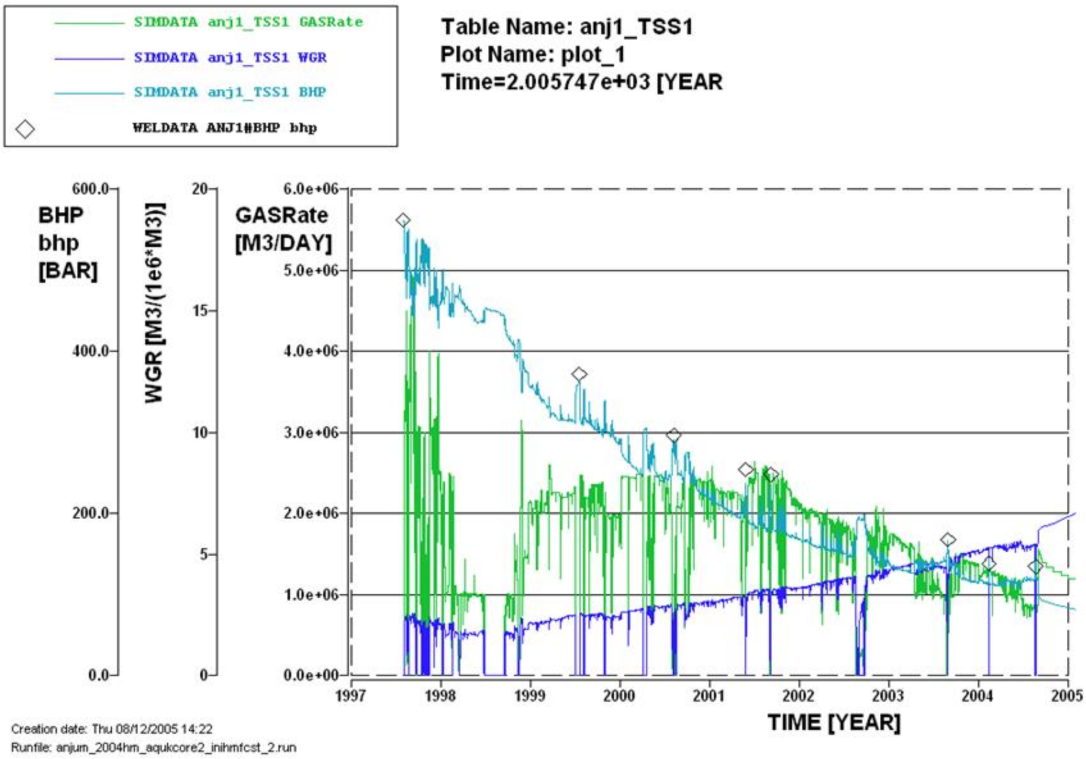


Figure 4– modeled gas pressure and WGR with reduced aquifer permeability.

Conclusions were that reduced permeability in the aquifer is required to model the correct volume of produced aquifer water. A model that uses a higher permeability in the aquifer results in a too high modeled aquifer water production, i.e. higher than actual water production that has been measured. This delays depletion of the aquifer even if no residual gas in the aquifer is assumed.

In summary, the model with reduced aquifer permeability (in line with core data) gives a better match of the modeled water production with actually observed water production. The observation that hardly any aquifer water production occurs in the field limits therefor the assumption of the maximum permeability in the aquifer. This also limits the maximum predicted depletion level of the aquifer for the worst case of no residual gas in the aquifer.

2.3 History matching Anjum – impact of residual gas in aquifer

The existence of residual gas in the aquifer was also investigated in 2005. Residual gas is interpreted on open hole logs run in wells in the Waddenzee area. However it was noted that quantification of residual gas saturations is difficult given the high sensitivity of log interpretation parameters. Therefore the presence of residual gas could not conclusively be determined in 2005. This was the reason that for subsidence calculations no residual gas was assumed until proven otherwise. No residual gas in aquifers results in a higher modeled aquifer depletion.

The possible impact of residual gas on the development of the Waddenzee would be twofold:

1) Residual gas will slow down aquifer depletion (i.e. result in a higher, final aquifer pressure) due to expansion, i.e. increasing the total aquifer compressibility. This would lead to less subsidence.
2) In certain parts (good reservoir, lateral aquifers) residual gas could partially become mobile due to aquifer depletion and expansion of the gas, resulting in (some) gas migrating to above the FWL. This would lead to a small additional recovery in the late stages of field life.

A residual saturation versus porosity function as used in the 2005 study is shown in Figure 5 below.

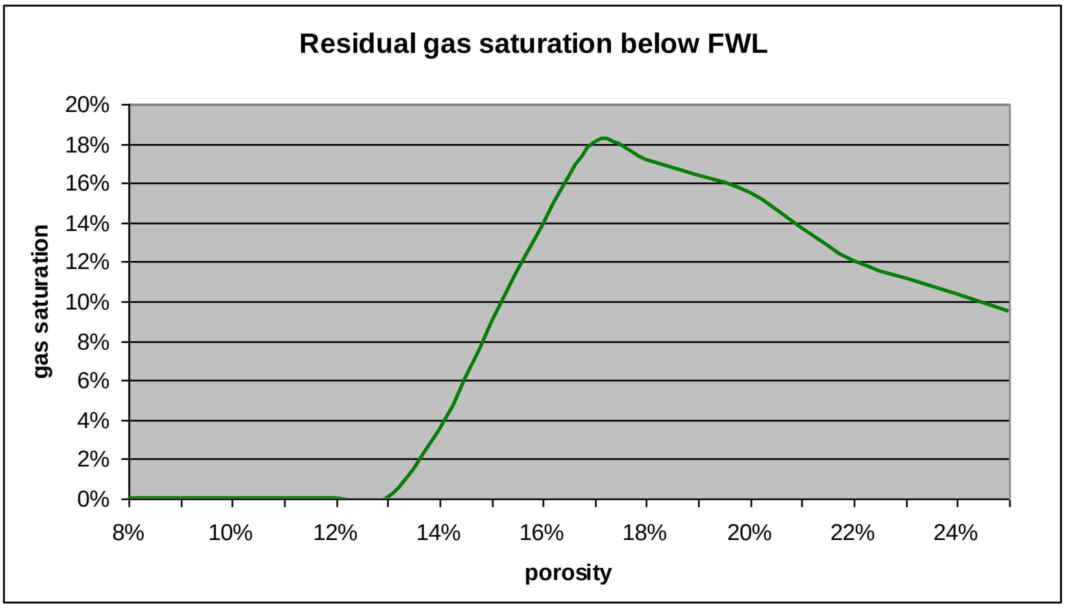


Figure 5 – Modelled residual gas function in aquifer versus porosity

Applying this function leads to a total average residual gas saturation below FWL of ca. 10% in the Anjum model.

Comparing the pressure history match with and without residual gas shows that the possible pressure support in the gas bearing part due to migration of residual gas into the gas part is still small (Figure 6a, 6b). Hence, the existence of gas migration from below FWL to above FWL will not be evident from history matching until a very late stage in the field life, if at all.

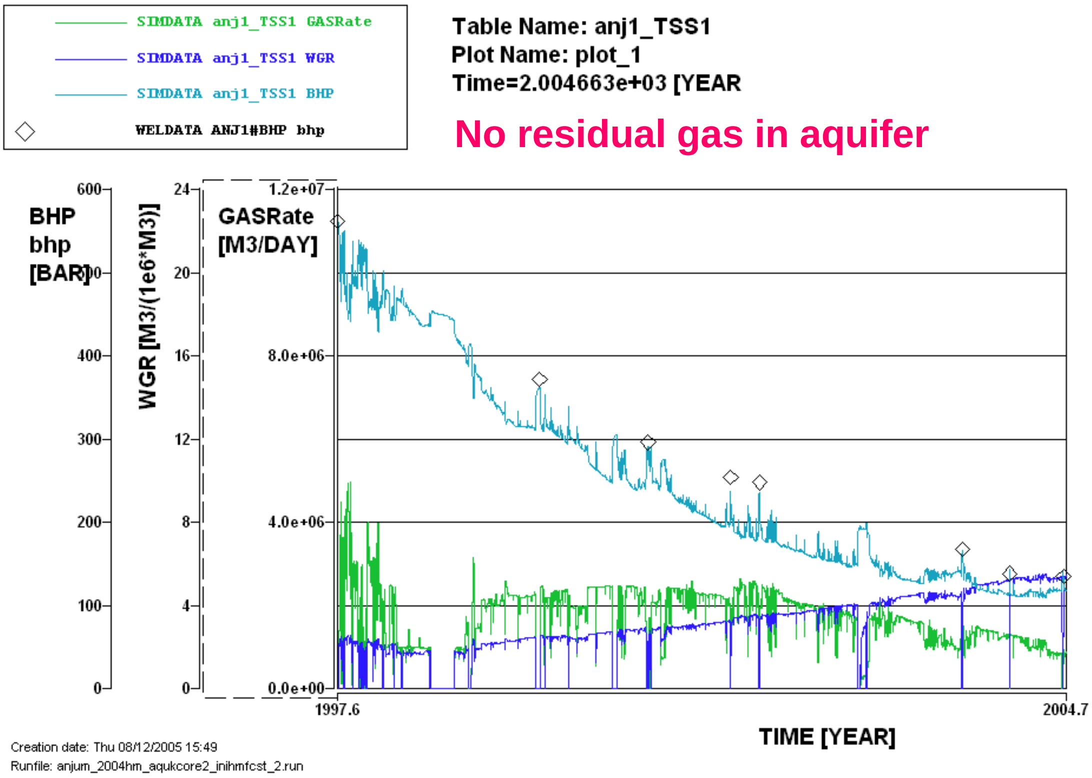


Figure 6a - Modelled gas pressure and WGR without residual gas in aquifer

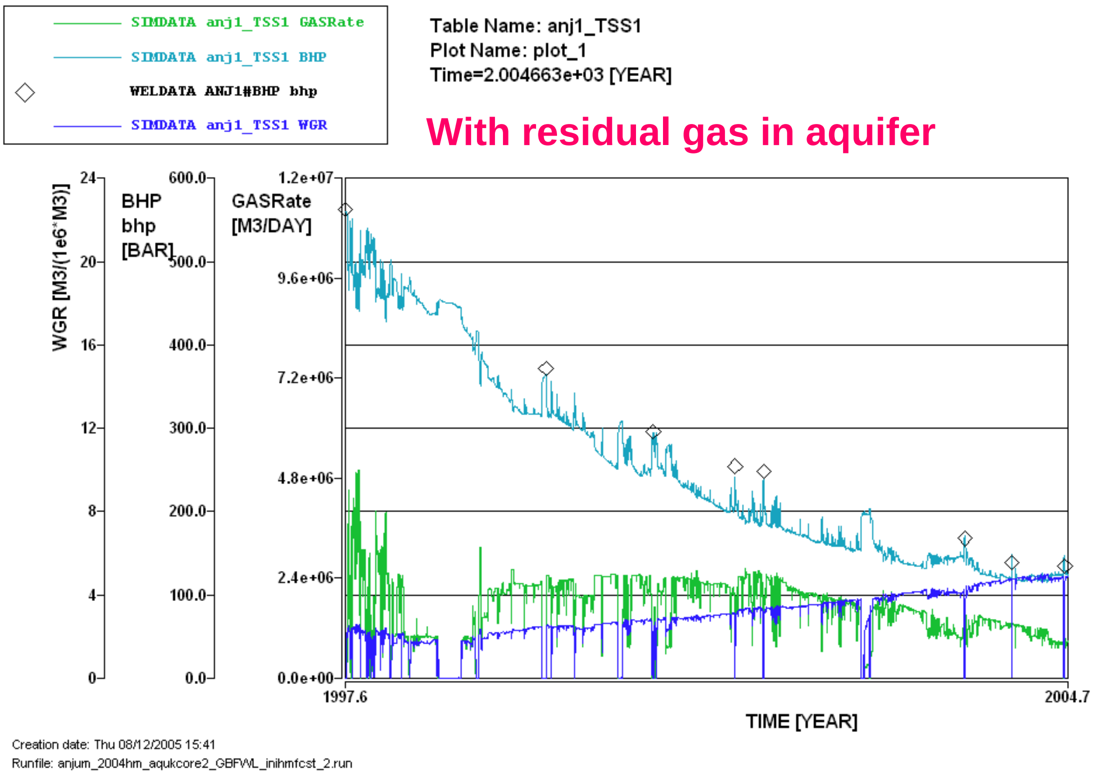


Figure 6b – Modelled gas pressure and WGR with residual gas in aquifer

Simulation runs show that the existence of residual gas in the aquifer cannot be proven by either matching pressure data or water production data given the small difference between the two scenarios. Hence the more conservative scenario (with respect to subsidence) of “no residual gas in the aquifer” was chosen as base case.

For subsidence calculations the average bottom aquifer (water bearing reservoir below gas bearing reservoir) and average lateral aquifer (entire reservoir column is water bearing) depletion in relation to the gas reservoir pressure were determined in the simulation model.

The impact of residual gas on average pressures per category (gas bearing, lateral aquifer and bottom aquifer) for the example of the Anjum field is shown in Figure 7 below. The cases with residual gas are marked as GBFWL (Gas Below Free Water Level). It should be noted that Anjum has a relatively small aquifer. Modelled average aquifer pressures in fields with a larger aquifer than the Anjum field will be higher than shown below.

The 2005 reservoir model also conservatively used a relatively high vertical connectivity, leading to relatively high depletion of the bottom aquifer.

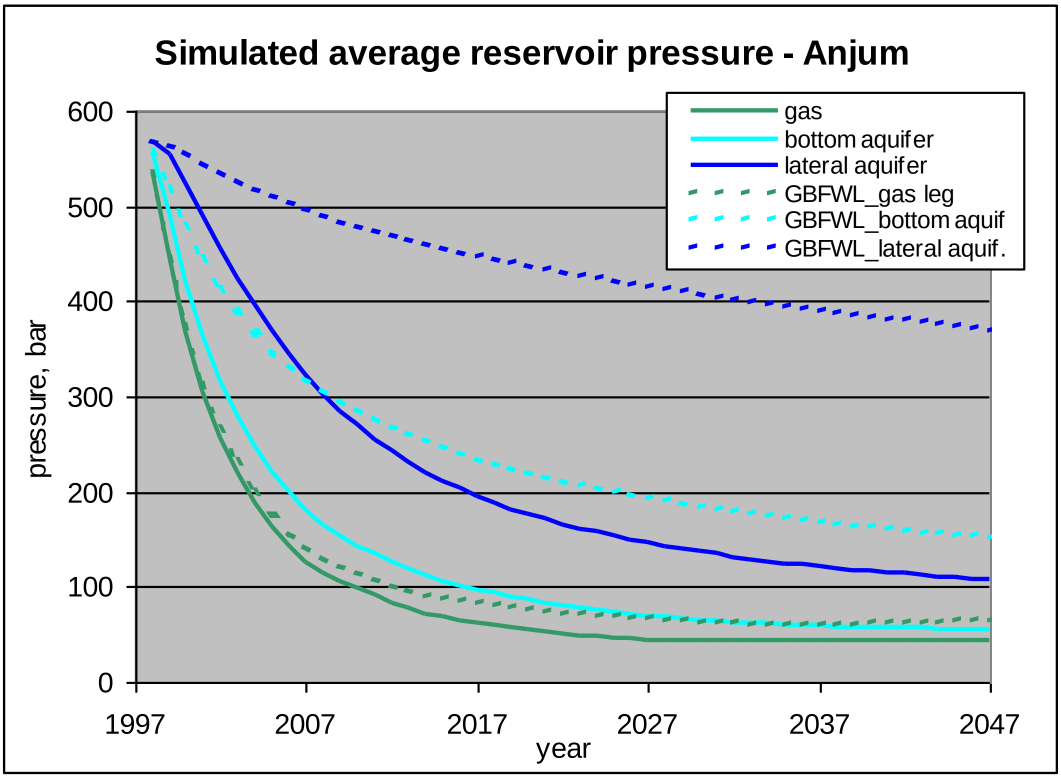


Figure 7 – 2005 model: gas and aquifer pressures with and without residual gas in aquifer

3 Reservoir simulation modeling updates 2005-2015

The following new information has become available since issuing of the 2005 report.

1) Formation pressure measurements in infill wells drilled since 2005 to assess vertical connectivity/depletion to improve prediction of bottom aquifer depletion.

2) A residual gas well test evaluation of a short production test of an aquifer zone with results being in agreement with the presence of residual gas in the aquifer.

3.1 Assessment of vertical connectivity

Several new infill wells have been drilled in producing gas fields in and near the Waddenzee area. In some cases it was possible to obtain formation pressure measurements at the sand face in various layers at variable distance from the producing wells. Formation pressures could be taken in
a) producing gas bearing layers of the reservoir,
b) gas bearing layers below perforated producing layers and
c) water bearing layers.

Infill formation pressure measurements in individual layers allowed an improved assessment of the lateral and vertical connectivity of the reservoir in the Waddenzee area by calibrating reservoir models to match the observed pressure distribution in the reservoirs.

The new formation pressure data revealed in general:
- poor vertical connectivity
- higher pressures in aquifers.

Examples of pressure taken in infill wells are shown in the figures below:

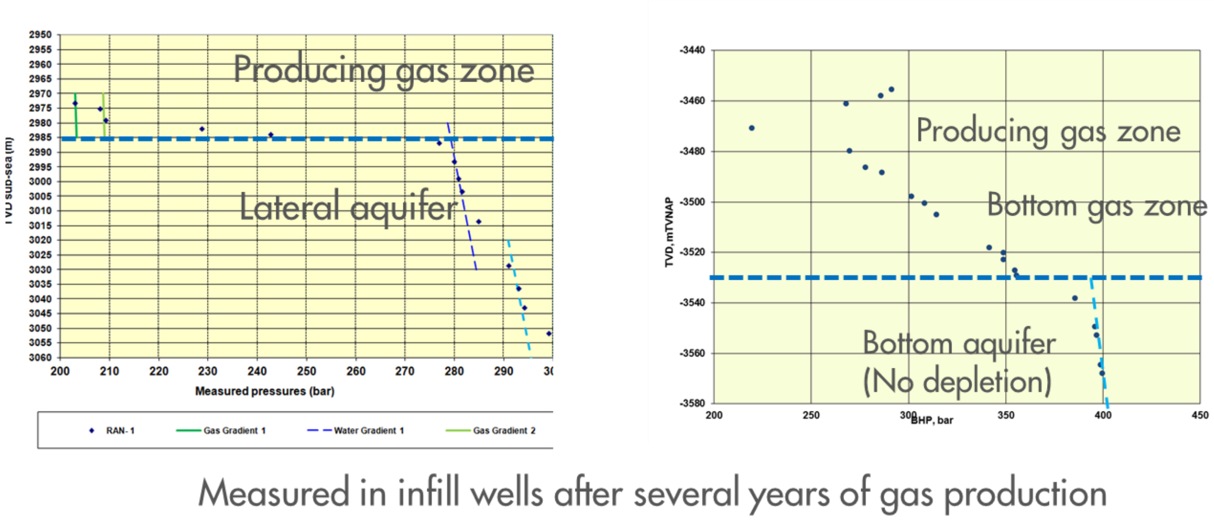


Figure 8a: measured formation pressures in infill wells near Waddenzee

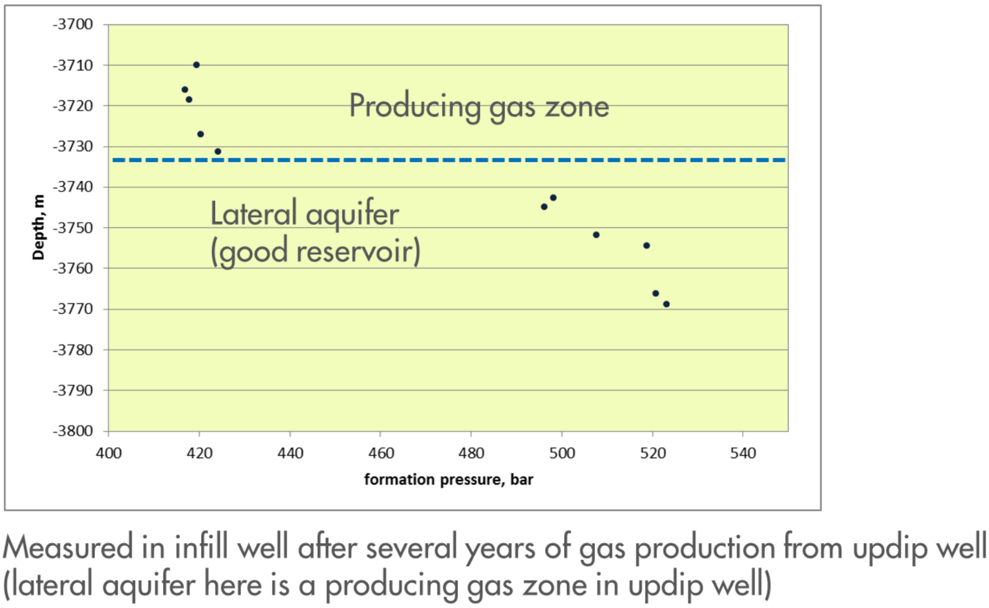


Figure 8b: measured formation pressures in an infill well in the Waddenzee

Poor vertical connectivity is also observed in the gas zone. This is for example indicated by delayed depletion as observed in the second well in Figure 8a. Poor vertical connectivity is likely caused by fine scaled layering. Tighter layers or even barriers can be observed on a scale ranging from meters to down to cm's. In general if layers become thinner, the likely extent of the layers becomes smaller. However the distribution and interconnection of these tighter layers is difficult to determine in situ.

Measured formation pressures allow calibration of vertical connectivity, i.e. the interconnection of small scale tight layers. This is usually expressed by the ratio of average horizontal permeability (k_h) to average vertical permeability (k_v). It was found that on average for package of a few meters thickness the average ratio of k_v/k_h can vary from ca. 0.01 down to 0.0001. This factor includes on average fine scaled layering but also reductions of relative permeability to gas and water in small tight layers. Such a low effective k_v/k_h ratio will severely slow down pressure diffusion (depletion) in vertical direction in deeper layers, which are not producing/perforated in wells.

It should be noted the k_v/k_h value will be a function of how much reservoir is averaged in the vertical direction. The values quoted above are indicative for averaging reservoir thicknesses of as of ~1m and higher. A typical k_v/k_h value for averaging of for example 2-3 cm will be more around 0.1.

Pressure diffusion (depletion) in lateral direction along the layering is determined by the average horizontal effective permeability, which can be significantly higher than vertical effective average permeability, i.e. k_v/k_h multiplier does not apply. Therefore depletion along layering/bedding can be faster than in vertical direction, provided (small scaled) faulting or changes in sand quality does not impose connectivity barriers in lateral direction.

3.2 Assessment of residual gas in aquifers

Presence of residual gas in aquifers changes the depletion behaviour of an aquifer due to much higher compressibility (ability to expand or compress at changing pressure) of gas as compared to water/brine.

Depletion of aquifers occurs due to aquifer water flowing into the lower pressured gas reservoir. The volume of aquifer water moving into the gas reservoir hardly changes whether residual gas in the aquifer is present or not. However, if residual gas is present in the aquifer the outflow of aquifer water (into the gas part) is strongly compensated by expansion of residual gas. The impact of the presence of residual gas is demonstrated in the depletion examples in Fig. 9 & 10 below.

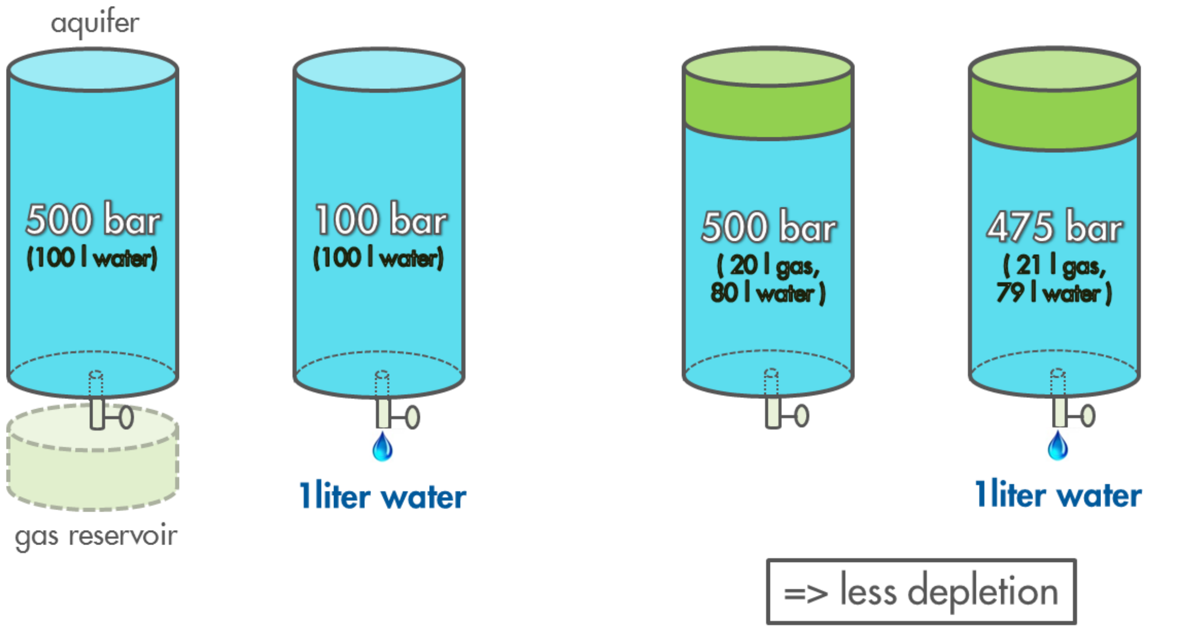


Figure 9 – Depletion example of removing 1% of fluid from a pressurized container with no gas and with 20% gas.

The outflow of fluid is synonymous for the flow of water from the aquifer into a depleted gas reservoir.

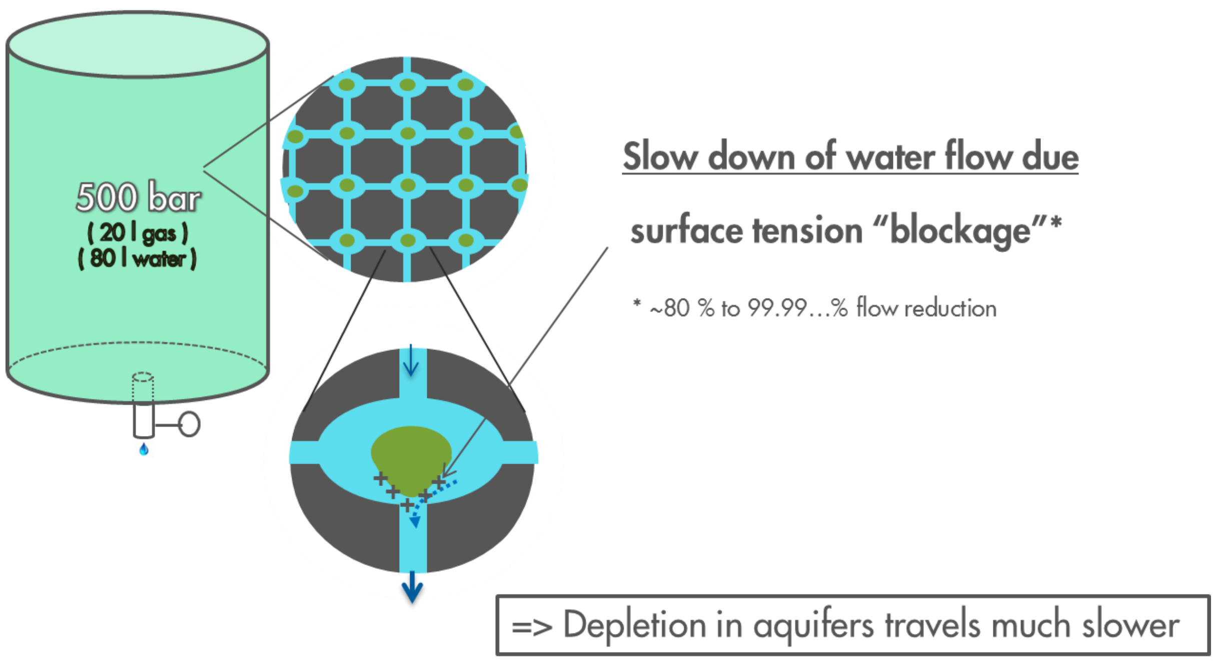


Figure 10 – Example showing water flow in the aquifer towards the low pressure gas part

Waterflow is hampered by the presence of residual gas in the aquifer due to interfacial tension between water and gas.

Speed of pressure diffusion (depletion) in the aquifer will depend on effective permeability in the flow direction. Pressure depletion at early time when the aquifer responds to pressure depletion in the connected gas reservoir will only occur near the gas water contact. Depletion will then slowly progress into the aquifer. Therefore pressure distribution in the aquifer will (slowly) change over the time of interest for subsidence estimation depending on the length and volume of the aquifer. This process is likely to extend far beyond the time of interest.

The level of depletion in the time of interest will depend on amount of residual gas saturation/percentage in the pore space and on the depletion direction (lateral vs. vertical):

- Depletion in lateral direction could still be sufficiently large to impact subsidence in the period of interest, if good reservoir quality is present in the aquifer.

- Depletion in vertical direction is likely to be extremely slow and it is possible that even no depletion in a bottom aquifer may occur over the time of interest.

The amount of residual gas present in aquifers is still uncertain as quantification of residual gas saturation from open borehole measurements (logs) is difficult at low gas saturations levels.

In the 2005 report a case with an average residual gas saturation of ca.10% was used – different residual gas was modeled for different porosities - to determine the impact on aquifer depletion. This showed that a relatively low residual gas volume or saturation will already decrease depletion in aquifers significantly (see earlier section).

Given the uncertainty of determining if residual gas is present from logs a production test of an aquifer interval in MGT-1 well was analysed. A type reservoir simulation model of an aquifer with residual gas was made to compare simulation response with test results. This showed that observed water and gas rates in MGT-1 are consistent with a residual gas situation. Gas is co-produced with water due to the local pressure drop around the well during the test. This leads to expansion of the residual gas, i.e. the residual gas bubble grows beyond it’s maximum residual value and a portion of the gas becomes mobile during the test. The figure below shows the simulation water and gas production rate versus reported values.

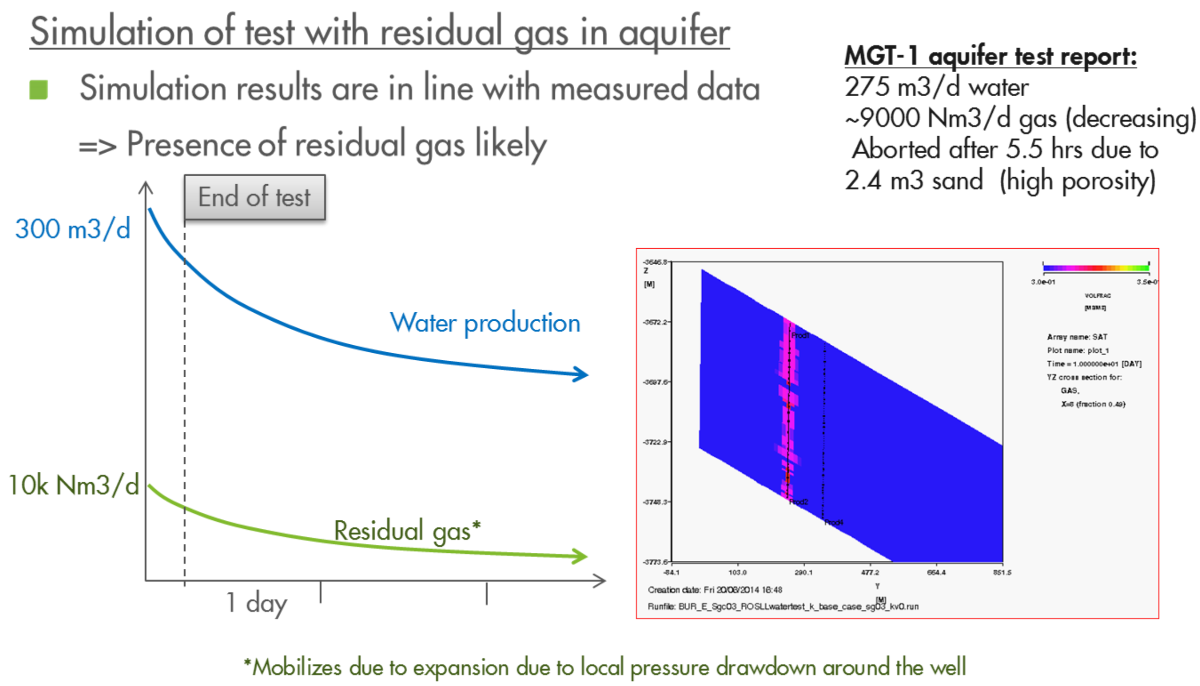


Figure 11: aquifer production test in MGT-1

Residual gas saturation levels remain uncertain. Currently typical average residual gas values of ca. 15% are been used for modelling aquifers in individual Waddenzee gas fields. Modelling assumes now uniform residual gas saturations for all porosities given the negligible impact of using different residual gas values for different porosities. Moreover it is difficult to establish a valid variation of residual gas per porosity.

In theory also higher (uniform) residual gas values are possible. However there is lack of evidence for such higher values at the moment and changes will only be implemented until conclusive evidence exists.

3.3 Conclusions period 2005-2015

In summary this leads to the following conclusions with respect to depletion:

Depletion levels		
	Good reservoir	*Poor reservoir*
Gas reservoir	High	Medium/High
Lateral aquifer	High/Medium (close to the gas reservoir) Medium (farther from gas reservoir)	Low
Bottom aquifer	Low/Medium (close to gas reservoir) Low/None (deeper part of aquifer)	Low/None

The following gives a general overview of depletion times that can be expected in respective reservoir parts of a typical Waddenzee reservoir as a result of gas production.

<u>Lateral direction</u>

- Gas bearing reservoir will deplete fast in Waddenzee reservoirs (<months)
- Water bearing reservoir with residual gas depletion will be very slow (tens of years to outside period of interest)

<u>Vertical direction</u>

- Gas bearing reservoir can deplete with some delay (months to years)
- Water bearing reservoir with residual gas is likely to deplete extremely slow (outside period of interest)

The cases of water bearing reservoir without residual gas have become less likely following evaluation of a water /residual gas test in MGT-1. In this case lateral aquifers would still deplete slower than gas reservoirs due to a reduction of the effective permeability for water flowing into the gas reservoir (years).
Bottom aquifers in the case of water bearing reservoir without residual gas would likely deplete very slow due to the reduced effective permeability in aquifers in combination with the likely poor vertical connectivity (years to tens of years)

For specific estimates of depletion levels and times for individual Waddenzee fields corresponding full field simulation models should be used. Ref. 2 describes the range of subsidence scenarios used for individual Waddenzee fields.

4 Reservoir simulation modeling – way forward

Based on the above updates the following has been implemented in existing full field/reservoir models, and has triggered the following further work:

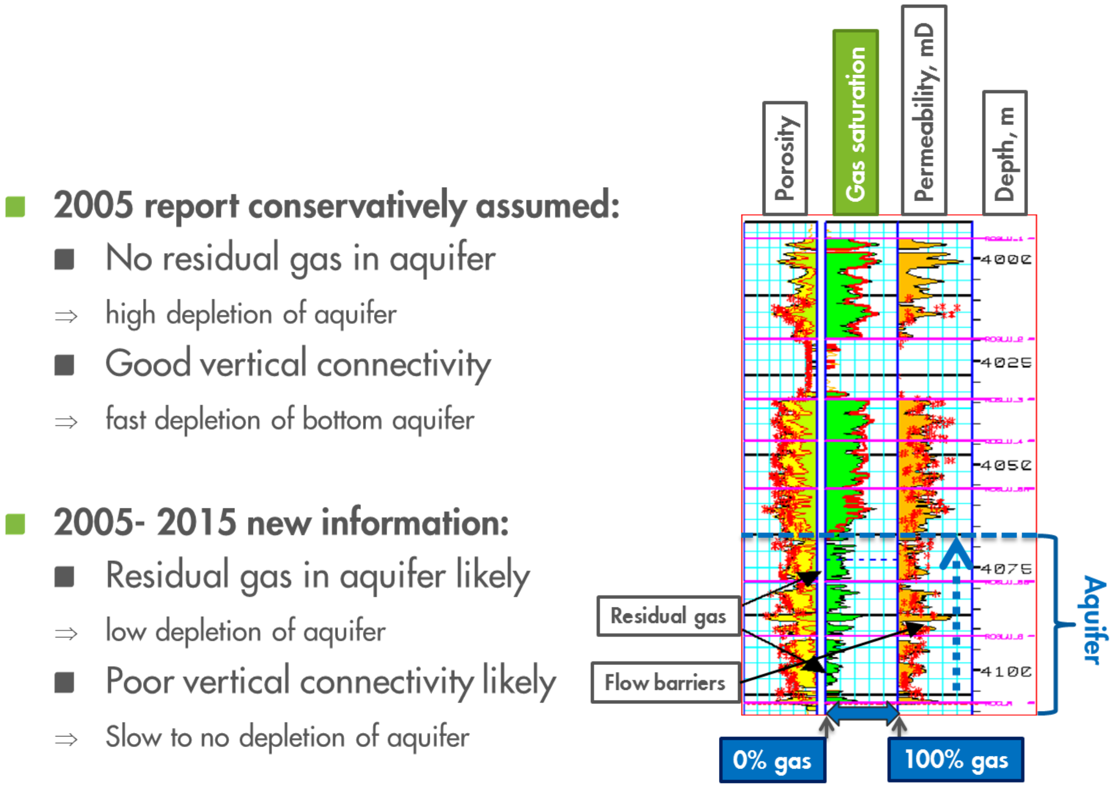
- Sensitivities for reduced vertical connectivity in field models were run to estimate impact on aquifer depletion levels. However the actual vertical connectivity range in Waddenzee field is still uncertain due to the absence of data points for calibration in many individual fields. Therefore the following further work will be carried out to further improve prediction of depletion levels and uncertainty ranges in Waddenzee fields:

  a) A numerical simulation study using a fine scaled representation of type aquifers in Waddenzee fields to assess/quantify impact of smaller scaled tight layers and presence of residual gas levels on aquifer depletion (bottom and lateral).

  b) Based on the results of a) implement upscaled reservoir parameters in the individual full field reservoir model to match predicted aquifer depletion levels of the fine scaled type model. The full field/reservoir models cover the entire depleting reservoir area in the Waddenzee. This expected to narrow the uncertainty range of pressure depletion results versus time, which are used for updating subsidence models.

- Reduced depletion in aquifers based on modeling of residual gas in aquifers or an equivalent severe reduction of aquifer permeability resulting in a similar reduced depletion level of the aquifer as for residual gas. Typical average residual gas values of ca. 15% are currently used.

Figure 12 shows the summary update for the period 2005 to 2015 and a type log of a Waddenzee reservoir.



5 References

Ref. 1) "Methodology of predicting gas- and aquifer pressures in the proposed Waddenzee development area", NAM B.V. *EP200512206995,* December 2005.

Ref. 2) "Gaswinning vanaf de locaties Moddergat, Lauwersoog en Vierhuizen Resultaten uitvoering Meet- en regelcyclus 2014" , NAM B.V., *EP201504206417*, May 2015

6 Figures