

# Watershed implications of shale oil and gas production in Vaca Muerta, Argentina

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## Key Messages

- A rapid increase in unconventional hydrocarbon production is underway in the Vaca Muerta region.
- Climate change threatens the timing and quantity of water that will be available for competing uses, including agricultural, municipal, hydroelectric, and shale oil and gas production.
- Shale oil and gas production could pose a water quality risk to water sources during both well completion and ongoing operations.
- Improvements in data collection and management systems can help build knowledge on how watershed conditions change over time and across the region, and how the watershed is impacted by climate change and other factors.
- A regulatory process that allows for collaboration and coordination among shale oil and gas producers and other water users can ensure that the hydrocarbon sector participates in and conforms with Integrated Water Resources Management (IWRM).

## 1. Introduction

As oil prices get closer to pre-pandemic levels, the likelihood increases that Vaca Muerta<sup>1</sup>, Argentina, will expand shale oil and gas production (Ministerio de Economía, 2020). This situation creates an opportunity to look in more detail at the environmental implications of shale oil and gas production on this region, and in particular on its water resources.

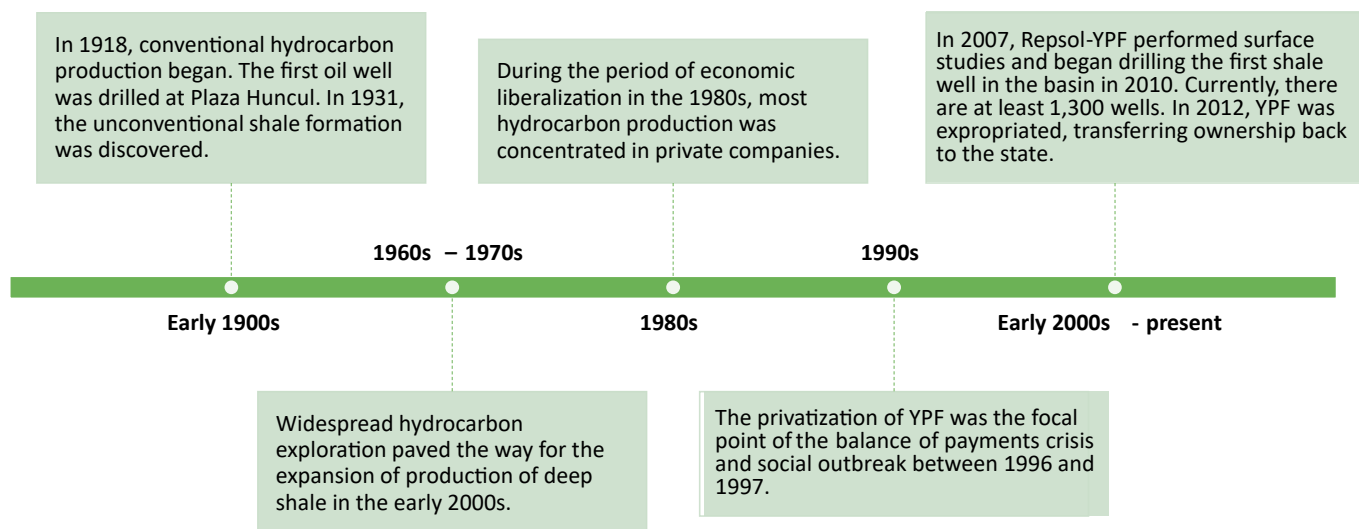
The objective of this paper is to increase understanding of the current state of knowledge and the potential risks of shale oil and gas production on water supply in the region, including current and projected water and wastewater implications, and to review the current policy environment. We examined the linkage between water (quantity and quality) and shale oil and gas production to understand the industry's impact on the watershed and on the long-term water security of the region. We reviewed over 57 documents in English and in Spanish. Of the documents in English, 77% are from peer-reviewed articles and 23% are from the grey literature. Of the Spanish documents, 29% are from peer-reviewed articles, and 71% are from the grey literature. In addition to the literature review, we used publicly available spatial data and results obtained from a water management study to produce a set of maps and graphics to understand these interconnections at a regional scale (Nadal et al., 2017).

This paper is organized as follows. First, we present a background on the relationship between shale oil and gas production and water use in the region, focusing on the present and future water uses in the watershed and water quality implications. We then discuss the current shale oil and gas governance in Vaca Muerta, focusing on the regulatory aspects. Finally, we present conclusions and potential paths for future water planning and policy development.

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<sup>1</sup> Vaca Muerta is a geological formation located in the Neuquén sedimentary basin in northern Patagonia, Argentina. It is well known as the host rock for major deposits of shale oil and shale gas.

Figure 1. Brief history of hydrocarbon development in Vaca Muerta (Spalletti et al., 2015)



## 2. Background

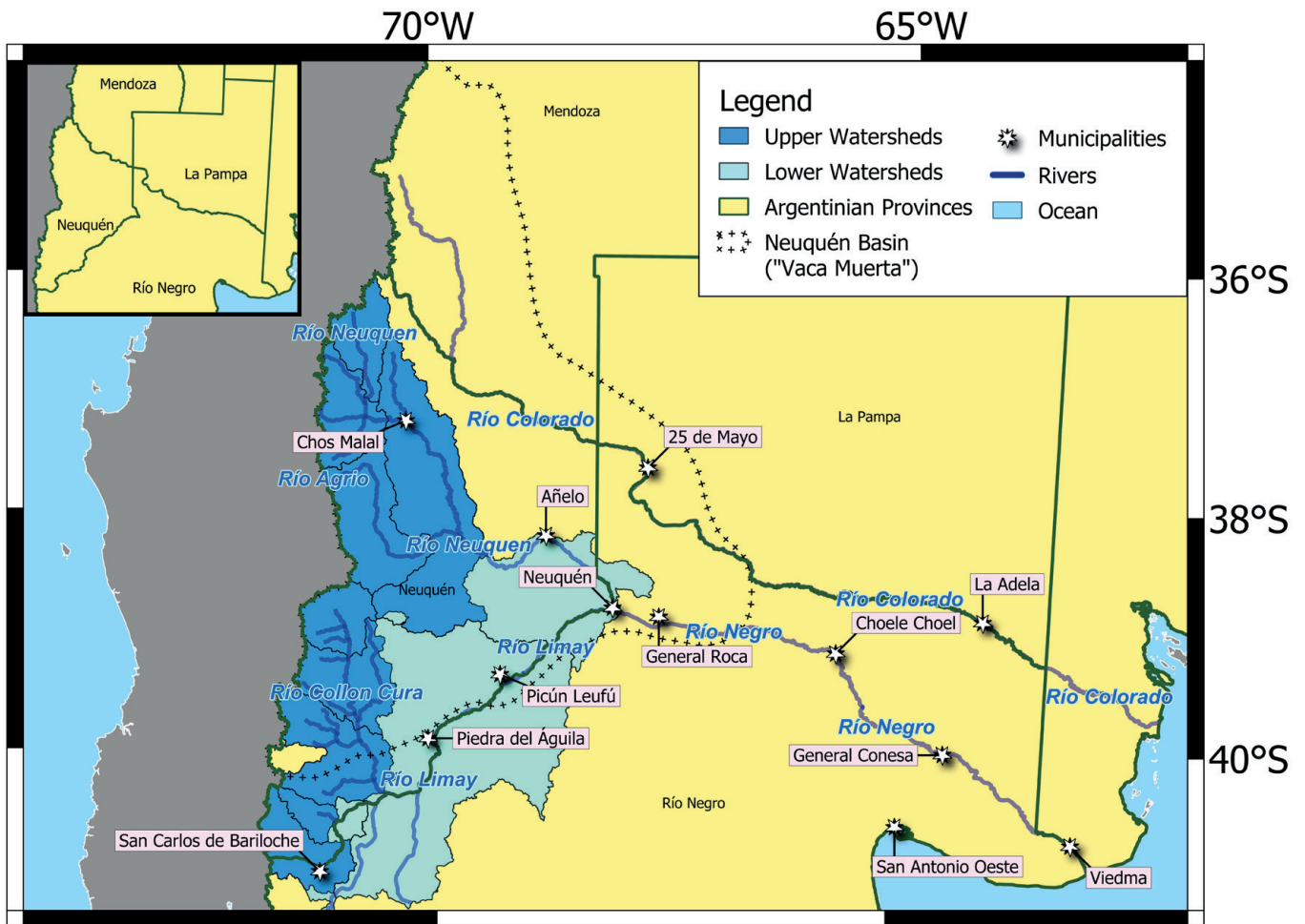
The Vaca Muerta region sits in northern Patagonia<sup>2</sup>, covering the provinces of Neuquén and Río Negro, as well as a smaller portion of the provinces of Mendoza and La Pampa (Figure 2). For this analysis, we studied the watersheds that overlap this region, fed by the Limay and Neuquén rivers, which meet at the Negro River. These watersheds support several hydroelectric plants (with more planned for the future), as well as provide irrigation for an estimated 150,000 hectares of farming, particularly fruits such as apples, pears, peaches, plums, and grapes for wine (Forni et al., 2018). They also support urban and industrial water uses in the region; in 2010, the estimated population was 968,338, which could reach 1,601,762 in 2050 (Nadal et al., 2017). Most of this population receives water from sources downstream of past and future hydrocarbon production areas.

Oil and gas production, closely followed by agriculture, form the pillars of the region's economy. Both draw on the same watersheds and plan expansions in the coming decades. The Food and Agriculture Organization (FAO) of the United Nations (2015a) estimates that the Neuquén province has 306,000 hectares (ha) of land available for agriculture, of which 278,000 ha are suitable for irrigation, with this number serving as the basis for anticipated irrigation development by 2050. The FAO (2015c) also notes that potentially irrigated areas close to the municipality of Ñeño (in the Neuquén province) could face strong pressure from increasing hydrocarbon activity. However, the current water infrastructure of these watersheds is insufficient even when just considering planned agricultural expansion; Forni et al (2018) estimate that under most future climate and irrigation expansion scenarios, current maximum canal capacity (combined maximum flow of 175 m<sup>3</sup>/s) would be met or exceeded in both the short- and long-term.

The Neuquén basin is rich in shale, and includes the Los Molles shale formation, and the shallower, hydrocarbon-rich Vaca Muerta shale formation, as well as a number of smaller formations, such as the Lajas formation (U.S. Energy Information Administration (EIA), 2015). The Vaca Muerta and Los Molles formations, combined, have an estimated 16.5 trillion cubic meters (m<sup>3</sup>) of shale gas and 19.7 billion barrels of shale oil in technically recoverable resources (Aloulou & Zaretskaya, 2019). Throughout this paper, we refer to both the Vaca Muerta and Los Molles formations as Vaca Muerta (Spanish for “dead cow”).

<sup>2</sup> See map of concessions and non-conventional exploitation in Vaca Muerta: [http://www.energia.gob.ar/contenidos/archivos/Reorganizacion/sig/mapas\\_tematicos/03\\_vaca\\_muerta/mapa\\_vc\\_2019\\_96dpi.pdf](http://www.energia.gob.ar/contenidos/archivos/Reorganizacion/sig/mapas_tematicos/03_vaca_muerta/mapa_vc_2019_96dpi.pdf)

Figure 2. A map of the Vaca Muerta region (dotted black border) showing major rivers (blue lines), upper and lower watersheds (blue and light blue areas), Argentinian province boundaries (inset map in top left corner), and major municipalities (white stars). Elaborated with data from Instituto Geográfico Nacional de Argentina (ign.gob.ar).



Repsol YPF, an oil and gas company, began drilling for shale oil in Vaca Muerta in 2010. In 2012, Argentina passed the Hydrocarbon Sovereignty Law, which declares hydrocarbon fields as part of the public domain; as part of this, the country bought back 51% of the shares in YPF. By 2018, Vaca Muerta represented 55% of Argentina's commercially recoverable natural gas reserves and 31% of its commercially recoverable oil reserves (Secretaría de Energía, 2019). About 1,000 wells were active in 2019, but the region can technically support the development of between 20,000 to 35,000 active wells (Reymundo 2019), or, by one estimate, even up to 60,000 wells over the next 25 years (Rosa & D'Odorico, 2019).

Motivated by the known and potential reserves, the national government promoted oil and gas development in the region, including through legislation; Vaca Muerta has subsequently seen growing production over the last decade. In 2014, Argentinian natural gas production reached 113.7 million cubic meters per day (MMm<sup>3</sup>/d), of which 56% was produced in the Neuquén Basin, and by 2018, those rates were 128.8 MMm<sup>3</sup>/d and 60%, respectively (Secretaría de Energía, 2019). The 2020 Energy Master Plan for Argentina outlines a number of investments and growth in current developments to result in 176 MMm<sup>3</sup>/d by 2030, including a ramp-up to the drilling of over 310 wells per year by 2024 (a more than 100% increase from 2017); the construction and expansion of railway capacity; and US\$157 million in allocated public funding in gas pipelines (Secretaría de Energía de Argentina, 2020). The total number of wells drilled each year will depend upon the price of oil in the global market, since the investment

to discover and exploit new reserves within the Vaca Muerta formation is feasible at different rates for different cases. The 2020 Master Plan details scenarios of 128, 143, and 174 MMm<sup>3</sup>/d production for low, medium, and high oil prices (Secretaria de Energia, 2019; Secretaria de Energia de Argentina, 2020).

The Argentinian federal government also recently passed legislation that subsidizes natural gas production to ensure a minimum production of 70 MMm<sup>3</sup>/d (67% from the Neuquén Basin) (Poder Ejecutivo Nacional (PEN), 2020). This support is meant to increase foreign investment, reduce reliance on foreign oil, and increase regional development through new jobs and technological advancement. In a region that has a long history of conventional oil and gas production, this push for unconventional shale oil and gas production represents a marked increase in overall hydrocarbon development.

With increasing hydrocarbon production, infrastructure, and transport comes increases in accidents and spills (Chen et al., 2019; da Cunha, 2016; Papadakis, 1999). In Vaca Muerta, there have been a number of documented cases of crude oil spills, improperly maintained oil and gas pipelines, and illegal dumping of hydrocarbon industry wastes and wastewater (Alvarez et al., 2017). In this context, it is important to understand the hydrologic stress that the region is already facing and will face in the future. On top of expected agricultural expansion, an increasing hydrocarbon industry and a growing municipal population will lead to increases in regional water demand. These demands exert pressure on the water supply system. In the next section, we discuss the importance of examining global climate change uncertainties in environmental planning.

### 3. Climate and hydrology

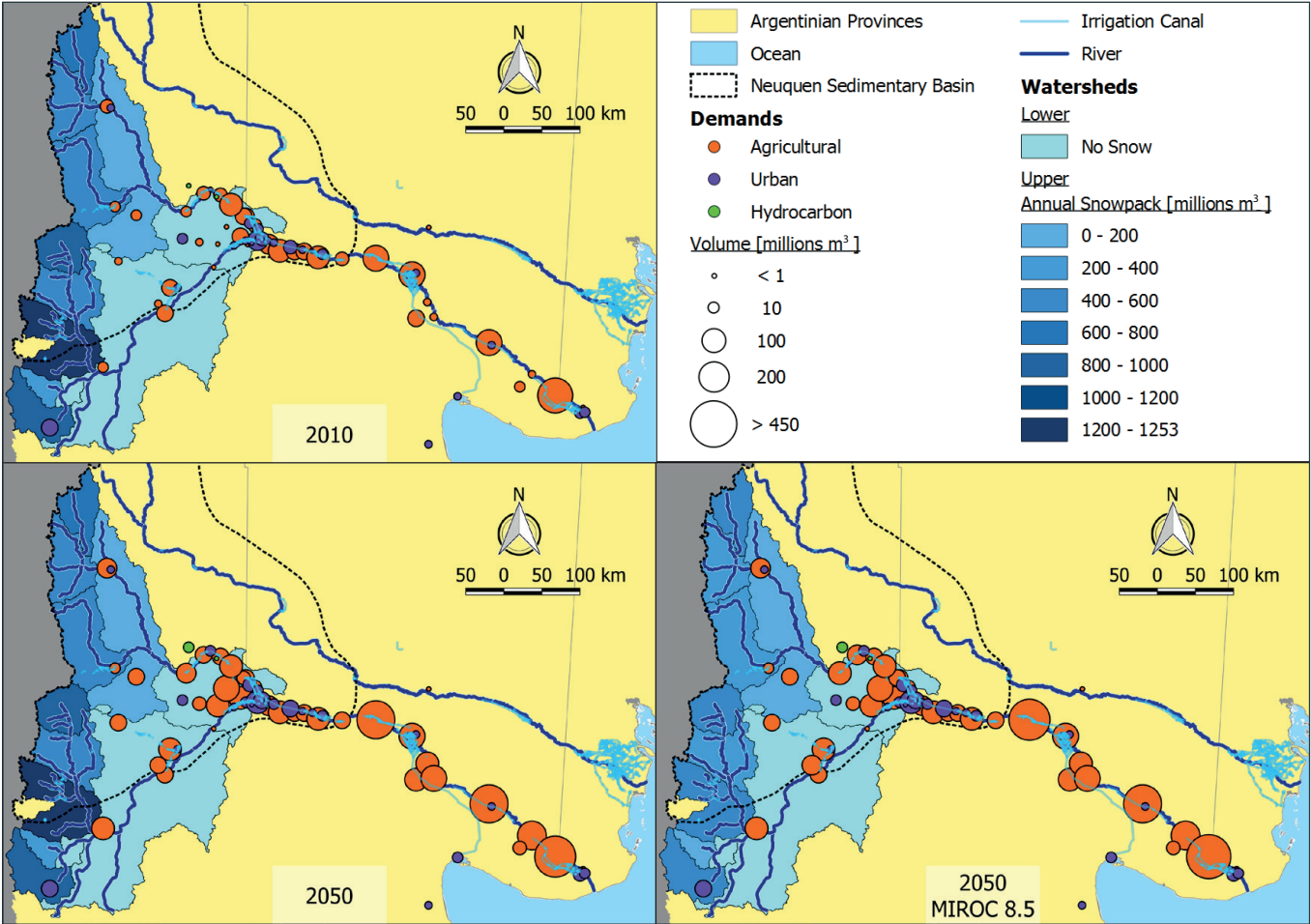
The Neuquén sedimentary basin overlaps with the Limay and Neuquén river watersheds, as shown in Figure 3. Most of the precipitation in the Neuquén river watershed (3,000 millimeters per year) occurs in the upper part of the mountain range, on the Chilean border. In the eastern part, the average annual precipitation drops significantly to about 200 mm (Ostertag & Cuellar, 2005). In the Limay river watershed, the reduction in elevation means humid air and higher rainfall, thereby supporting dense forests (FAO, 2015b). The flows of the Neuquén, Limay, and Negro rivers generally decrease significantly from early summer to early autumn (December to April), when they reach their minimum. Río Negro has a peak flow in July/August and a minimum around January, due to a peak in water demand requirements from irrigation and hydropower. The upper Limay river flows (at Villa Llanquin) have a double peak in August and November, with a minimum in April. The Neuquén river flows (at Paso del Indio) also have two peaks (August and November). These two peaks in flow could transform into one single peak in the future. Historical records on temperature indicate positive trends in average temperature (up to 1°C) between 1961-2004 and negative trends in average snow accumulation at high altitudes, influencing the timing of surface runoff and annual infiltration (Nadal et al., 2017). Fundación Torcuato Di Tella (2006) estimated a reduction in rainfall between 1967-1998 and prolonged drought events (lasting 5 to 9 years).

Future climate scenarios generated for the Limay and Neuquén basins – for the RCP4.5 (medium stabilization emissions scenario) and RCP8.5 (high emissions scenario) – show a generalized warming trend ranging between 1.5°C and 3°C at the end of the 21st century. RCP8.5 projections show a 20% decrease in precipitation for the Limay basin and a 30%-35% decrease for the Neuquén basin over the same period of time (See Figure 3). All scenarios evaluated show warming temperatures and decreasing precipitation in the second half of the 21st century, particularly in the RCP8.5 scenario (Nadal et al., 2017). These translate into lower spring/summer flows available due to earlier snowmelt and less rainfall. When combined with increasing irrigation, hydroelectric, and hydrocarbon water resource



needs, changes in climate will likely require trade-offs between preserving natural flows, developing agriculture, supporting hydroelectric energy production, and extracting and processing shale oil and gas (Forni et al., 2018). Water quality risks from the unconventional oil and gas industry – as described in the following section – will likely further complicate these water supply limitations.

Figure 3. Water supplies and demands in the study area. Supply is defined as annual snow storage in millions of cubic meters, since snow plays a vital role in the seasonal water supply. Demands are shown in circles according to annual millions of cubic meters: agricultural (orange), urban (purple), and hydrocarbon (green). The panels show different scenarios: 2010 (historical), 2050 with future projected demand, and 2050 with future projected demands and the projected climate change impacts from the MIROC earth system model. Elaborated with data from Instituto Geográfico Nacional de Argentina (2020) and Nadal et al. (2017)





## 4. Water use and wastewater management in shale oil and gas production

Unconventional oil and gas production could have major negative implications for water resources and quality (Villacis et al., 2019; Rahm & Riha, 2012; Soeder & Kappel, 2009; Vengosh et al., 2014). This section examines what we know about water use and water contamination in shale oil and gas extraction, to gain more understanding of what issues could arise in the Neuquén basin.

Shale oil and gas are extracted by injecting water with chemical additives and sand at high pressure to fracture the rock formation and release the gas (methane). Injection fluid typically comprises 90% water and 9% sand, with the rest a mixture of chemical additives, including friction reducers, biocides, scale inhibitors, surfactants, and acids (Karapataki, 2012). During the drilling process, a double or triple layer of cement and steel forms a barrier between the aquifer and the well (Ehlinger et al., 2014; He & You, 2014; Nicot & Scanlon, 2012).

The amount of water required for shale oil and gas production depends on the number of hydraulic fractures, the estimated recovery of gas from a well, the length of the horizontal portion of the well, the number of fracture stages, and the well's geologic characteristics. In Vaca Muerta, fracking is performed primarily in horizontal sections, with the well drilled to a depth of approximately 3,000 meters deep and then continuing horizontally for another 3,000 meters in length (IAPG, Nd).

Water is used throughout the process. About 1,800 cubic meters ( $\text{m}^3$ ) is used during the construction, stabilization, and access to the drilling pad (phase 1); about 700  $\text{m}^3$  is used during the drilling and cementation process of the well (phase 2); and about 47,850  $\text{m}^3$  is used during the hydraulic fracturing (phase 3), with 1,450  $\text{m}^3$  used during each of about 33 stages (with a stage indicating a series of fracking events within a single well, generally along a horizontal section) (Villacis & Prado, 2019). Therefore, the estimated total water consumption for hydraulic fracturing is 50,350  $\text{m}^3$  per well over the 30-year life of the well, with the majority of the water use occurring within the first six months of the well's existence (Clark et al., 2013; Villacis et al., 2019). Water use has increased over the last decade, as the length of the horizontal portions of the drilling process (phase 3 above) have increased the average number of stages per well (Kondash et al., 2018). Therefore, wastewater is expected to continue to increase, and if not managed properly, could potentially present environmental impacts in the future (Sosa, 2020).

In terms of absolute quantities, water use for shale oil and gas production is very small in the region, representing less than 1% of total water use; however, by sub-region, water use may be cause for concern. While surface water is abundant in some areas in the region, other areas rely entirely on groundwater or surface water transported in trucks for their water supply, such as the portion of the Mendoza province that overlays the Vaca Muerta formation. Development of shale gas and oil in the Mendoza province is still incipient, although many concessions for unconventional exploitation have already been granted (Sosa, 2020). As water shortages become more common in a changing climate, water resources planning will need to consider how water – particularly surface and potentially groundwater – is used and supplied in the mountain range, as indicated by Rosa and D'Odorico (2019).

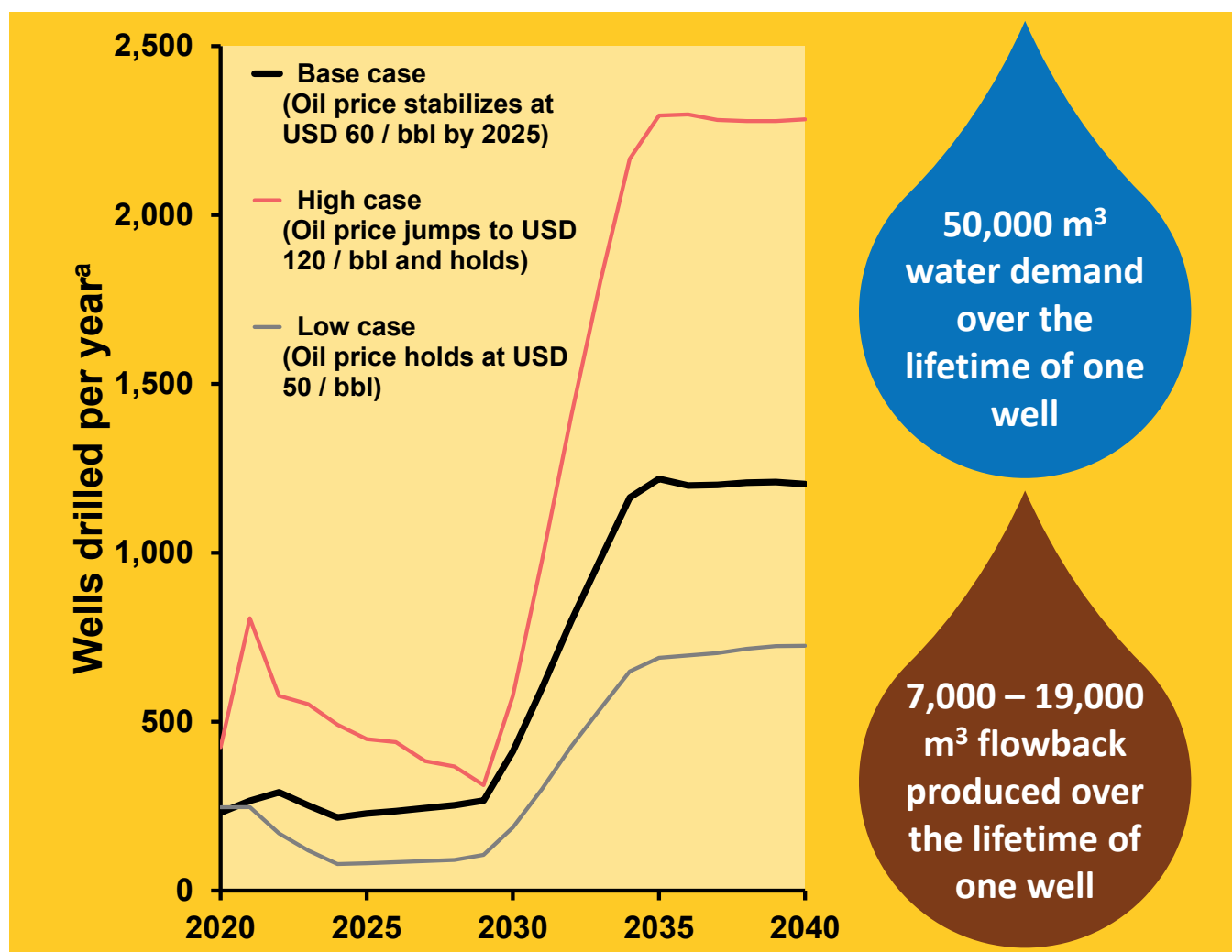
Figure 4 shows the expected increase in well drilling in Vaca Muerta for the base case (\$60 USD per barrel of oil, or bbl), as well as high (\$120 USD/bbl) and low (\$50 USD/bbl) projected oil prices, which depend on market forces. By 2025, these scenarios result in about 1,200, 2,300, and 700 wells drilled per year, respectively (Rystad Energy, 2019). Rosa and D'Odorico (2019) use similar future drilling scenarios, showing water consumption for fracking in Vaca Muerta will increase 2.2 times during 2017-2024, reaching 7.4 million  $\text{m}^3$  per year. If more than 1,000 wells are drilled annually after 2035, Vaca Muerta could require more than 50 million  $\text{m}^3$  of water per year, approximately 1.3% of the total projected water demand from all sources.

The shale oil and gas industry thus may only pose a low risk to water supply in the Vaca Muerta region. However, wastewater from shale gas and oil production could increase the risk of pollution to surface freshwater and groundwater resources, as described in the next section.

## 5. Wastewater and water quality implications

Given the increasing pressures on regional water supply in Vaca Muerta, the quality of the available water resources is of the utmost importance. Specifically, downstream domestic and agricultural water users require water that meets water quality standards meant to protect public and environmental health. Wastewater from shale oil and gas production can contain heavy metals, salts, and volatile compounds that pose risks to both humans and the natural environment (Werner et al., 2015). These compounds come from both the injection fluid and naturally occurring water in the rock formation. There are two types of wastewater: *flowback*, or the mixture of injection fluids and naturally occurring water that is recovered during the initial perforation of the well, and *produced water*, or the naturally occurring water that continues to flow to the surface during the life of the well (Gao & You, 2014). In this document, we use wastewater to indicate both, as their composition is similar despite their distinct sources.

Figure 4. Expected number of wells, per year, based on base, high, and low cases of oil prices (Rystad Energy, 2019). Icons to the right show water consumption and flowback water produced over the 30-year average lifetime of a single well (Villacis & Prado, 2019).



The amount of wastewater per well depends on the amount of water injected, and is greatest in the well's first month of production; the amount then decreases in the six months after the drilling process is complete. As an example, one company in Vaca Muerta expects 110 shale gas wells to create produced water at a rate of 11,000 m<sup>3</sup>/day during the first month of production, decreasing to 1,600 m<sup>3</sup>/day by the sixth month (Villacis & Prado, 2019).

The adequate management of wastewater is critical in reducing environmental and health risks. This includes wastewater capture at the wellhead, installation of protection elements to prevent leakage, proper wastewater transport and treatment, and final disposition (Sosa, 2020). This section reviews the composition of the injection fluids, the composition of naturally occurring formation water, and wastewater disposal practices, in order to better understand the water quality implications of shale gas and oil production that should be considered in regional governance.

### Injection fluid and wastewater

Several articles offer an overview of injection fluid components in the US (Rahm & Riha, 2012; Soeder & Kappel, 2009; Vengosh et al., 2014), where over 90% of global shale production has occurred and has been best studied (Rystad Energy, 2019). Although different types of chemicals are used in the well completion stage than in the flowback water, both contain hazardous components due to their concentrations and/or chemical makeup. Between eight and 15 chemical additives are used in the injection fluid for Vaca Muerta shale oil and gas extraction, including anticorrosive, bacterial growth inhibitory, and gelling agents, according to IAPG (IAPG, Nd)<sup>3</sup>.

In addition to the injection fluid, return flows from shale gas and oil production also include substances naturally occurring within the Vaca Muerta geologic formation, such as mudstones, marlstones (locally called Marga), and limestone (Chebli et al., 2011). For environmental and human health reasons, it is important to have a record of the quantities and chemical composition of both the injection fluid and the flowback (Rahm & Riha, 2012; Rowan et al., 2011; Soeder & Kappel, 2009). Pichtel (2016) indicates that flowback contains "[injection] fluids, naturally occurring salts, radioactive materials, heavy metals, and other compounds from the formation such as polycyclic aromatic hydrocarbons, alkenes, alkanes, and other volatile and semivolatile organics." Although the above studies were not conducted on the Vaca Muerta formation, similar wastewater composition is expected from the combination of injection fluids and return flows in this region.

### Treatment and disposal of wastewater

The above contaminants – and the associated high salinity – precludes the wastewater of shale gas and oil production from being used for other purposes or discharged to surface water directly. Instead, it must be transported to disposal wells for injection, transported to a commercial wastewater facility for treatment, or treated onsite for reuse (Gao & You, 2014; Sosa, 2020). The vast majority of shale gas and oil production wastewater worldwide and in Vaca Muerta is stored in deep injection wells indefinitely. In the United States, there is an increasing number of cases of water supply and soil contamination from shale oil and gas production wastewater, particularly from poor pre-injection storage practices in surface tanks and trucks, and from the failure of injection well casings (Akob et al., 2016; Vengosh et al., 2014). In Vaca Muerta, there are concerns that wastewater and wastewater storage facilities are not following government regulations: a 2016 audit of conventional gas wells found that 432 wastewater storage pools were sealed without treatment, against government requirements for remediation,

<sup>3</sup> Sosa (2020) presents a list of chemicals used in the injection fluid (as detailed in environmental impact studies). These are: 1,2,4-trimethylbenzene, acetic acid, alcohols (C10-16 ethoxylated with 6.5 EO), ammonium chloride, ammonium persulfate, crystalline silica (quartz), diesel 2, ethanol (acetylenic alcohol), ethoxylated alcohol, ethylene glycol, glutaraldehyde, guar gum, heavy aromatic petroleum naphtha (aromatic solvent), hemicellulase enzyme, methane, methanol, naphthalene, light hydrodistilled oil, tergitol, polyacrylamide, potassium carbonate, potassium hydroxide, sodium carbonate, sodium hydroxide, sodium persulfate, sulfonate, tetramethyl ammonium chloride, and tributyl phosphate.

according to a hydrocarbon industry union official (Alvarez et al., 2017). However, there is currently very little publicly available data both globally and in Vaca Muerta on the quality of groundwater and surface water near wastewater injection wells.

A number of studies have shown that there is the potential for the industry to treat and reuse produced water as injection water, or for treated water to be used in agricultural applications and as surface disposal. Treatment onsite for reuse can help reduce the amount of freshwater used in the process, since treated wastewater can be used in place of surface water for injection fluids (Gao & You, 2014; Oetjen et al., 2018). Rosa and D'Odorico (2019) estimated that wastewater from unconventional oil and gas production in the Vaca Muerta formation increased from 0 to 1.15 million m<sup>3</sup>/year between 2009 and 2017 – and that less than 5% of this is currently treated and reused in hydraulic fracturing. Although hydrocarbon companies project treatment of up to 80% of produced water (Rosa & D'Odorico, 2019), only a few companies recycle the wastewater and water management is sometimes unsatisfactory (Sosa, 2020). Similarly, many studies have found that using treated wastewater to irrigate crops has negatively affected crop yields – sometimes resulting in no crop yield at all – even when the wastewater was diluted or conventionally treated; this is because of the complex interaction of the contaminants present in flowback and produced water (Chorghe et al., 2017; Oetjen et al., 2018; Sedlacko et al., 2020). Unfortunately, the few studies that have been conducted in the region are generally in disagreement and rely on data that is not easily accessible to the public (Alvarez et al., 2017; Mendia et al., 2018; Migueles et al., 2019).

Detailed, publicly available data is necessary for urban, municipal and academic study of the water quality risk posed by the extraction and injection of untreated wastewater in existing and future shale production wells. Data on water quality is sparse – both temporally and spatially – making it difficult to understand how surface and groundwater quality evolve over time, as well as how casings degrade and how injected wastewater migrates when it is improperly contained within target formations. It is still early in Vaca Muerta's shale oil and gas development. However, the region's history of spills and illegal waste dumping from conventional hydrocarbon production raise a cause for concern, as the quantities of wastewater produced in unconventional gas and oil production are orders of magnitude larger. Similarly, research in other parts of the world has shown that strict treatment regulations are necessary for the wastewater created during the production process. These studies clearly show a need for better reporting of the specific impacts of fracking on water quality in Vaca Muerta.

## 6. Regulatory environment

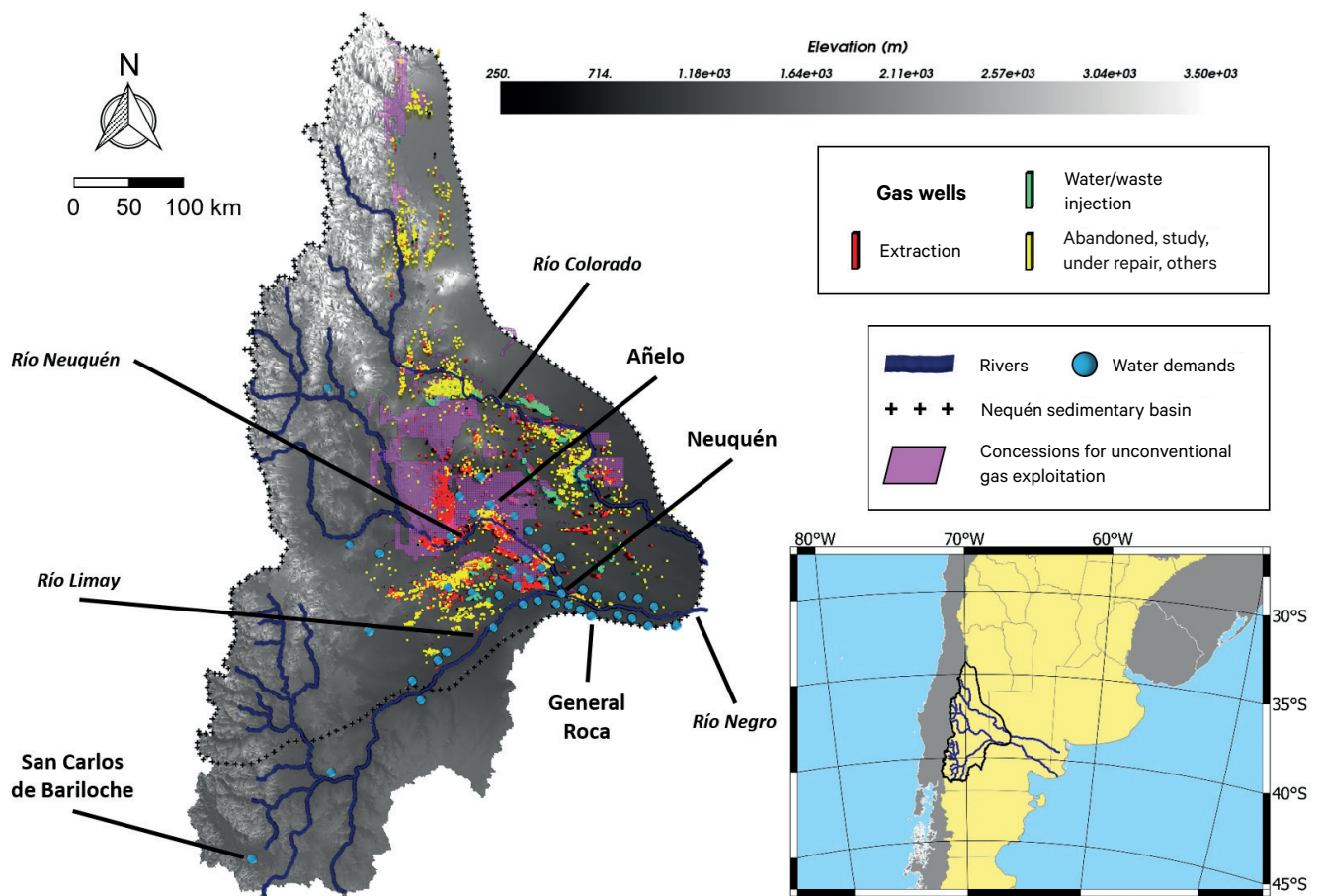
Figure 5 shows a geographical representation of the different components discussed in this brief, emphasizing the importance of integrated regulatory policy and water management planning. Here we can clearly see the different elements of supply and demand, and how they interact at the basin level with the overlay of future shale gas concessions (magenta). This physical context shows the interdependency of the supply and demand elements with the shale gas production infrastructure, highlighting the importance of an integrated policy and regulatory context for water planning in the region. Shale oil and gas production are not isolated from the rest of the watershed and should be regulated with such considerations in mind. Each province has its own environmental legislature, each individually delimiting water supply quantities and use (Law 25.688), as well as regulating oil and gas (Law 48, Law 17.319 and Law 26.197). In the case of Neuquén, Article 5 of the Water Code of the Province of Neuquén (Law 899) establishes the priority of uses (e.g., human, irrigation, industry) and imposes restrictions “limiting the use of groundwater for human consumption or irrigation, and for unconventional hydrocarbon activity.” In other words, groundwater is not authorized for shale oil and gas production use (Laurenzano, 2019; Sosa, 2020).

Oil and gas exploration permits are granted at the province level. Petroleum companies perform environmental impact assessments and send them to the province-level environmental institutions

(Dirección de Ambiente de las provincias). Despite the policies for managing water resources and the interjurisdictional committees of basins, the differences between the regulatory frameworks and the provinces' technical and financial capacity result in the fragmented management of the resource (OECD, 2020). We did not find publicly available reports from companies on the water quality of deep injection wells that, by law, need to be sent to the province.

Regional and provincial governmental institutions have water quality monitoring programs. The Interjurisdictional Basin Authority (AIC) aims to monitor water quality and hydrocarbon levels three times per year. However, capacity is tight; the Neuquén province, for example, has only one inspector for every 100 active wells, compared to one inspector for every 10 active wells in the United States (Alvarez et al., 2017, citing Bercovich & Rebossio, 2015). An environmental assessment of Río Negro recommended an increase in monitoring on 15 sites affected by Vaca Muerta activities: four in the Neuquén river basin, five in the Limay river basin, and six in the Río Negro river basin (Migueles et al., 2019). Some of these sites still do not have sufficient monitoring, and of those that do, the data management systems are not accessible online.

Figure 5. A combined view of hydrologic catchments, the Neuquén hydrocarbon sedimentary basin, and water demand in the Vaca Muerta region. Demand points are shown as blue spheres for agricultural, urban, and hydrocarbon uses. Wells associated with natural gas production are shown as rectangular columns (squares in plan-view): red for extraction, aqua/green for water or waste injection, and yellow for abandoned, in repair, under study, or unknown. Major rivers are shown in dark blue. The extent of the Neuquén sedimentary formation that has been defined for exploration is shown in black crosses, while unconventional hydrocarbon concessions are shown in pink on the land surface—elaborated with data from Instituto Geográfico Nacional de Argentina (2020), Secretaría de Energía de Argentina (2017), and Nadal et al. (2017).



The unpredictability of global oil prices can complicate effective regulation of wells and water quality, when such price changes result in large scale abandonment and bankruptcy; in the U.S., for example, federal and state regulation of unconventional gas well maintenance and proper well abandonment have historically been unable to keep pace (The Texas Tribune, 2016). Consistent regulation and monitoring by regional and federal actors would help to avoid this potential pitfall. On a hyper-local level, stakeholders could benefit from specific technical interventions, such as water sampling at critical points upstream and downstream of wells, in order to better understand whether and to what degree hydrocarbon production has affected water quality (Migueles et al., 2019). This stream sampling could complement onsite monitoring of wells and water sampling.

Ensuring the sustainability of ecosystems and livelihoods requires more refined data and monitoring, as well as an integrated interprovincial regulatory system to generate environmental plans. Existing regional water management schemes, such as the integrated regional water management (IRWM) effort in California, have shown the importance of frameworks that reach across local geographies and institutions to improve cross collaboration (Cain et al., 2020; Conrad, E. C., 2015; Hughes & Pincetl, 2014).

## 7. Conclusions

This study details the linkages between shale oil and gas production in the Vaca Muerta region and regional water management considerations, including surface and groundwater sources, climate change, wastewater treatment, water quality, land use, and water demand.

Shale oil and gas production poses a water quality risk during both well completion and operation. Expected shale oil and gas well expansion in Vaca Muerta would result in a significant increase in wastewater from the industry; this is especially concerning given that the region treats only 5% of its current shale production wastewater. Studies of shale sites around the world show that carcinogens and contaminants are in both injection fluids and the naturally occurring water within the shale formations. This poses health and environmental risks, and in the absence of treatment plants, shale production expansion will increase pressure for surface storage and the disposal, by underground injection, of wastewater.

Water quality risks can be magnified in drought years and during dry months. The shale industry's growth will come as urban areas expand and irrigation needs grow; this will mean increased water demand in a region that sees more frequent droughts and water shortages as the climate changes. Though shale oil and gas production uses a proportionally small amount of water, the industry's wastewater practices could risk the quality of the region's broader water supply, at a time when that supply becomes increasingly limited.

To ensure environmental and public health protections, an analysis should look beyond the average annual water supply. A more holistic analysis that looks at water supply under future scenarios – including ones with a range of climate impacts, economic expansion, and ecological constraints – would better inform successful regulation of water and oil resources.

Integrated water resource management – at the regional scale – can best tackle this complex web of needs and challenges. The regulatory system in Vaca Muerta is currently managed individually at the provincial level, which may prevent adequate integration of environmental regulations to mitigate potential risks. An integrated cross-sectoral analysis could help to ensure that both economic and environmental objectives are met through the planning process (Nadal et al., 2017). Along with more refined spatial and temporal monitoring data and greater coordination across sectors (i.e., energy, agriculture, and urban), a more comprehensive examination of future implications can ensure that regulatory measures can protect existing economic interests, energy security, provincial character, threatened habitats, and public health.

In short, the hydrocarbon industry should participate in and conform with an IWRM process that investigates the water quality and quantity in a watershed – both over time and geographically. This would help ensure people's well-being, regional economic health, and environmental sustainability. As an immediate step, the region should gather key actors in a participatory process to collect the spatial and temporal information required for a technical analysis that addresses the future reliability of watershed-level water quality and quantity.



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