Assignment 1

TPM802A Model-Based Water Systems Assessment

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The Nile River Basin

1.1. Geographical context and topological scheme

Figure 1.1 highlights the administrative and natural boundaries of the Nile River Basin in the form of a geographical map as well as its topological representation. What immediately becomes clear is that the administrative boundaries do not dictate the Nile River Basin. Rather, the natural boundaries determine the use of water resources.

The use of water resources from the Nile River Basin is heavily dependent on the geographical location of users. Whereas upstream users such as Ethiopia have the benefit of using the water resources first, Egypt as downstream user is highly dependent on the quality and quantity of the water left by upstream users. Placing a dam, such as the Grand Renaissance Dam (GERD), may have detrimental affects on the water management of downstream users. To ensure the quality and quantity of the Nile River Basin water for all users, collaboration between countries seems inevitable.

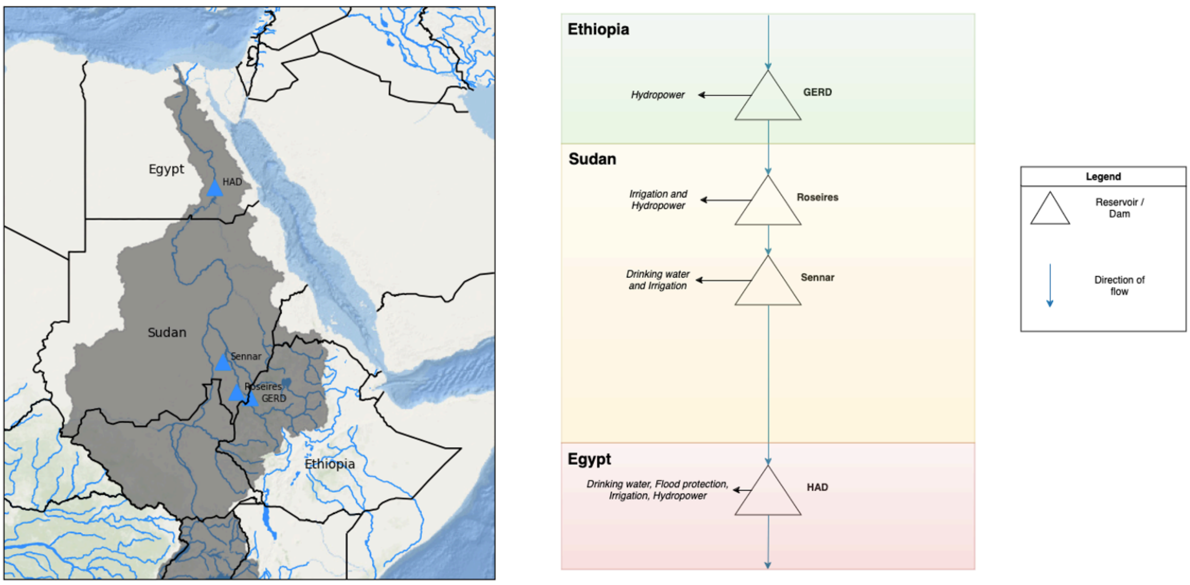

Figure 1.1: Geographical map and topological scheme of Nile River Basin.

1.2. Geopolitical Context

The Nile basin has a long and dynamic history, with the valley also being called *the cradle of civilization* (Swain, 2011). Flowing through 10 countries in Africa, with Egypt, Sudan and Ethiopia as its main consumers, the Nile is one of the longest international river systems of the world and serves many people (Swain, 2011). Yet, compared to other river systems, its annual discharge, runoff, and flow is quite moderate (Swain, 2011). Along with high flow variations between wet and dry seasons, fast-growing population and unequal distribution of flow, the Nile river basin region is vulnerable for geopolitical friction (Swain, 2011). After all, as water is a condition for life, access to water equals access to power and countries facing a shortage find themselves in a vulnerable position.

Historically, Egypt has long been a superpower. The 1929 Nile Water Agreement appointed Nile autonomy and certain water shares to Egypt and Sudan (Mbaku & Kimenyi, 2015), with a larger share for Egypt due to the presence of colonial power(Swain, 2011). After a period of unrest, these shares were re-divided in the 1959 Nile Water Agreements (Mbaku & Kimenyi, 2015) (Swain, 2011). Interestingly, Ethiopia was not considered in these agreements. Despite a period of 'water peace' characterised by cooperation between Egypt and Sudan, tensions arose in the 1990s due to increased water demands of Sudan and Ethiopia (Swain, 2011). These tensions further drove the already existing fear of a 'water war' in the region, with Sudan going as far as witholding water from further downstream Egypt (Swain, 2011). These tensions led to the signing of the Nile Basin Initiative in 1998, signed by 8 out of 10 riparian states (Swain, 2011).

Yet, despite this Nile Basin Initiative, tensions still exist today and are even becoming more complex due to megatrends of climate change en urbanisation. The most recent example and one that is highly discussed in existing literature is the Grand Renaissance Dam (GERD) in Ethiopia. As Ethiopia is located upstream, downstream Sudan and Egypt are dependent on Ethiopia's water supply. When Ethiopia unilaterally started building GERD, this resulted in a dispute between Egypt and Ethiopia, with Sudan in the middle of it. From the perspective of Egypt, Ethiopia had no right to start building the dam, as Egypt historically has Nile autonomy (Press, 2020). However, from the perspective of Ethiopia, the historical Nile autonomy of Egypt and Sudan is unjust as upstream countries were never involved (Lazarus, 2018). Because of their long history, the dispute has become more than 'just' a dispute on water, but one of power, respect and honour (Hall, 2023). As if this isn't complicated enough, other world powers China, America, Russia and Europe are using their power to influence the Nile Basin region, who each have their own geopolitical history with each other (Swain, 2011).

2

Pareto Optimal Tradeoffs across multiple conflicting uses

Figure 2.1 below highlights, for each objective in the Nile problem, the best policy solution parallel coordinates for one objective as well as two compromise policy solutions for all objectives. Figure 2.1 was made using the plotter.py file. Several adjustments have been made to the orginal plotter.py file, of which an overview is presented in appendix A.

Figure 2.1 shows different trade-offs between objectives, both between the different countries' objectives as well as between Egypt's objectives themselves.

First, there is a trade-off between the objectives of Egypt and Ethiopia. Despite both Egypt's objectives and Ethiopia's hydropower having relatively desirable values, Figure 2.1 shows that the solution in which Ethiopia's hydropower production is maximized, Egypt's irrigation deficit objectives are not minimized and Egypt's HAD level is low in approximately 40 percent of the time. The trade-off between the two countries is especially present between Egypt's objective to minimize the percentage of low HAD levels and Ethiopia's objective of maximizing hydropower. Higher Ethiopian hydropower production shows a higher percentage of low HAD levels, which is undesirable for Egypt.

Moreover, there is a trade-off between Egypt's objectives and Sudan's objectives. Again, this trade-off mainly exists between Egypt's to minimize the percentage of low HAD levels and Sudan's irrigation objectives. Low Sudanese irrigation deficits show high percentages of undesirable low HAD levels for Egypt.

Interestingly, Figure 2.1 shows a clear trade-off between Egypt's objectives themselves. Lower, desirable, Egyptian irrigation deficits show higher, undesirable, percentages of low HAD levels. Yet, this trade-off seems understandable as part of Egypt's irrigation demand is extracted from the HAD.

From Figure 2.1 , no large trade-off between Sudan's objectives and Ethiopia's objective can be observed. Yet, a smaller trade-off is observed between Ethiopia's 90th irr deficit objective and Ethiopia's hydropower objective.

Another interesting observation from Figure 2.1 regards the variability of Ethiopia's hydropower objective and Egypt's HAD objective values. As the figure shows, both objectives show a large surface of outcomes (grey areas). This suggests that there might be other factors or uncertainties impacting these objectives.

Figure 2.1 also shows two compromise solutions, which differ mostly in their HAD levels. Compromise 1 (red) shows a higher percentage of low HAD levels than compromise 2 (blue). With compromised solutions, trade-offs are reduced.

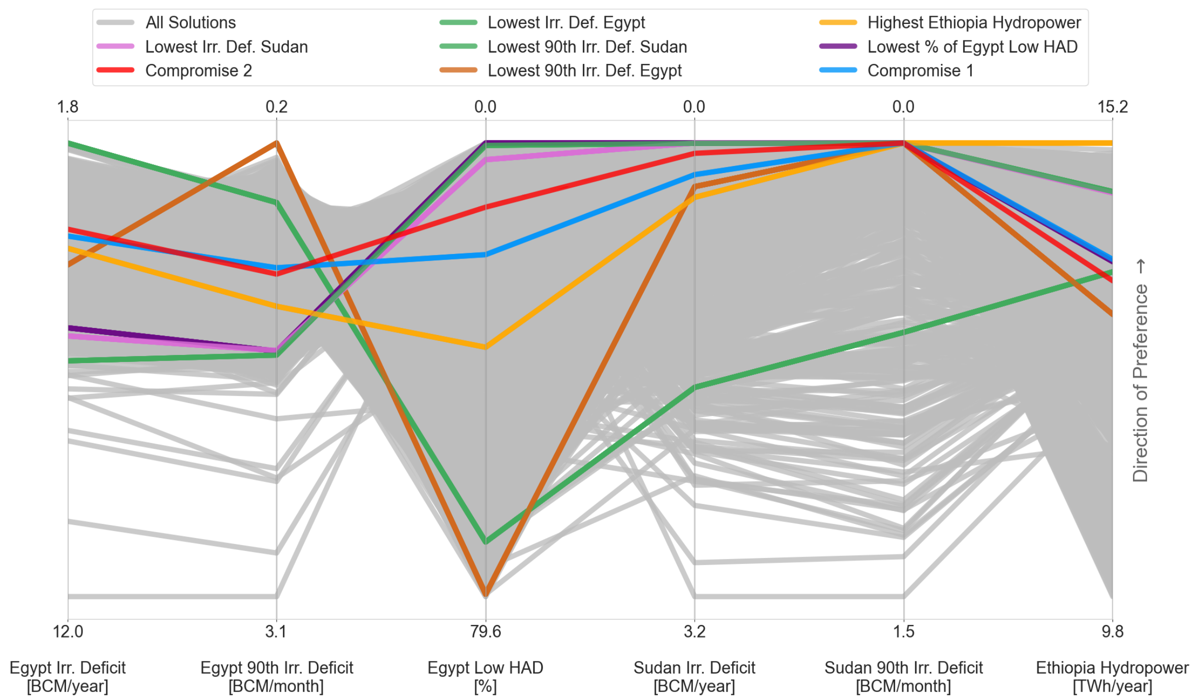

Figure 2.1: Parallel coordinates solutions. For each objective in the Nile problem, the best policy solution parallel coordinates for one objective as well as two compromise policy solutions for all objectives are highlighted.

First, threshold values for each objective were calculated using quantile values in the "*set threshold*" function. This function takes three arguments: "*objectives df*" , which is a DataFrame with the objectives outcomes; *" columns list"* , which is a List containing the column names of which thresholds need to be calculated; and *"quantile"* , which is a Float that indicates what percentage quantile should be used as a threshold. Threshold values are calculated by taking the set quantile value for each objective. The choice was made to use the same quantiles for the objectives with the same direction (i.e. minimize or maximize), to prevent bias in finding compromise policies. The function returns a Dictionary object containing the threshold values for each column. As a result, two dictionaries were made: *" min threshold dict" and " max threshold dict"* to account for objectives that need to be minimized (Egypt Irr. Deficit, Egypt 90th Irr. Deficit, Egypt low HAD, Sudan Irr. Deficit and Sudan 90th Irr. Deficit) and maximized (Ethiopia Hydropower) respectively.

Consequently, a new DataFrame " df compromise" was created using the "*get compromise solutions"* function. This function takes three arguments: "*objectives df*", which is a DataFrame with the objectives outcomes; "*min dict*" and "*max dict*" , which are Dictionaries with the thresholds for the objectives to be minimized and maximized respectively. The function returns a DataFrame with the found solutions that fit within the set threshold boundaries. This way, solutions are found that, for all objectives, adhere to the registered threshold levels. Note that if threshold levels are know beforehand or calculated differently, these can be used in this function as well by specifying the input dictionaries. As a result, a DataFrame was created, "*df compromise*" , containing two compromise solutions.

To extract two compromise solutions, the process described above was iterative to choose the right quantile values. Ultimately, the quantile value for the dictionary with all the objectives to be minimized was set to 0.54 and the quantile value for the dictionary with the objective to be maximized was set to 1-0.54 = 0.46 to ensure the same range for each threshold was used.

The two compromise solutions represent a good compromise for the system as threshold levels are indicated using the same quantiles for each objective . This way, the variability in ranges of different objectives is taken into account whilst ensuring that each objective is evaluated in the same scale. Whereas other distributions are possible, the choice for a more egalitarian distribution was explicitly made to prevent bias and view all objectives in a similar light. Moreover, the quantile percentages for which the thresholds have been set and the two compromise solutions have been found are located in the upper half of the distribution, which ensures that each objective is met on a minimal level. This is also visualized in Figure 2.1, which shows that for all objectives both compromise solution 1 (blue) and compromise solution 2 (red) are located in the upper half of the direction of preference.

The trade-off analysis above underlines the necessity for transboundary river basin management. The clear trade-offs between multiple objectives of Egypt, Sudan and Ethiopia show that the countries are dependent on each other. Yet, the analysis also shows that compromise solutions are possible. This asks for cooperation between the countries to ensure good transboundary river basin management.

3

Sensitivity and Vulnerability Analysis

3.1. Global Sensitivity Analysis

In order to understand the sensitivities across the outcomes of interest driven by parameter inputs, feature scoring is conducted. The results of the feature scoring are shown in Figure 3.1. In general, Figure 3.1 highlights that all objectives are driven by the Blue Nile mean inflow. Hence, the inflow of the Blue Nile, which starts in Ethiopia, determines irrigation deficits and hydro-power production to a large extent. In contrast, the Blue Nile deviation coefficient as well as the Black Nile (Atbare) and White Nile mean and deviation coefficients contribute the least to the variability of the outcomes of interest.

With regard to the irrigation deficit for Egypt, the annual worst case irrigation deficit is determined by the Blue Nile inflow to some extent. However, the annual demand growth rate has more impact on this deficit compared to this inflow coefficient. Contrary, the 90th percentile worst month is largely determined by the inflow coefficient rather than the yearly demand growth rate.

Interestingly, the Sudan irrigation deficit is determined by the Blue Nile inflow coefficient and the yearly demand growth rate to a lower extent compared to the Ethiopian irrigation deficit. Nonetheless, Ethiopia is the upstream user of the Blue Nile, whereas Sudan is the downstream user. This difference in geographical location might explain the higher sensitivity of Ethiopian irrigation deficit compared to Sudan's irrigation deficit, with regard to the inflow coefficient and growth rate.

In addition, Sudan's annual worst case irrigation deficit is driven by the policy selection to some degree. While not highlighted in the trade-off analysis conducted as part of section 2 of this report, the policy selection, between the two compromise solutions, shows some variation with regard to the deficit. Contrary, the policy selection is not able to contribute a lot to the variability of the other objectives.

Lastly, both the level of reliability of the High Answar Dam (HAD) and the hydro-power production of the Grand Ethiopian Renaissance Dam (GERD) are highly driven by the Blue Nile mean inflow coefficient. In addition, the level of reliability of the HAD can also be attributed to the White Nile mean inflow coefficient to some degree. These sensitivities of the HAD's reliability and the GERD's hydro-power production to the inflow coefficients of both the Blue and White Nile may well be related to the geographical locations of the dams. For instance, the GERD is geographically located on the Blue Nile, while the HAD is dependent on the inflow of both the Blue and the White Nile.

3.2. Vulnerabilities and Opportunities

Based on the feature scoring analysis, we conclude that the inflow of the Blue Nile has a significant effect on irrigation deficits and hydroelectric power production for all parties involved. Ethiopia is eager to use the inflow for their hydropower production, yet Sudan and Egypt are highly dependent on this water flow as well. While the yearly worst case for both countries is determined to a lesser extant by

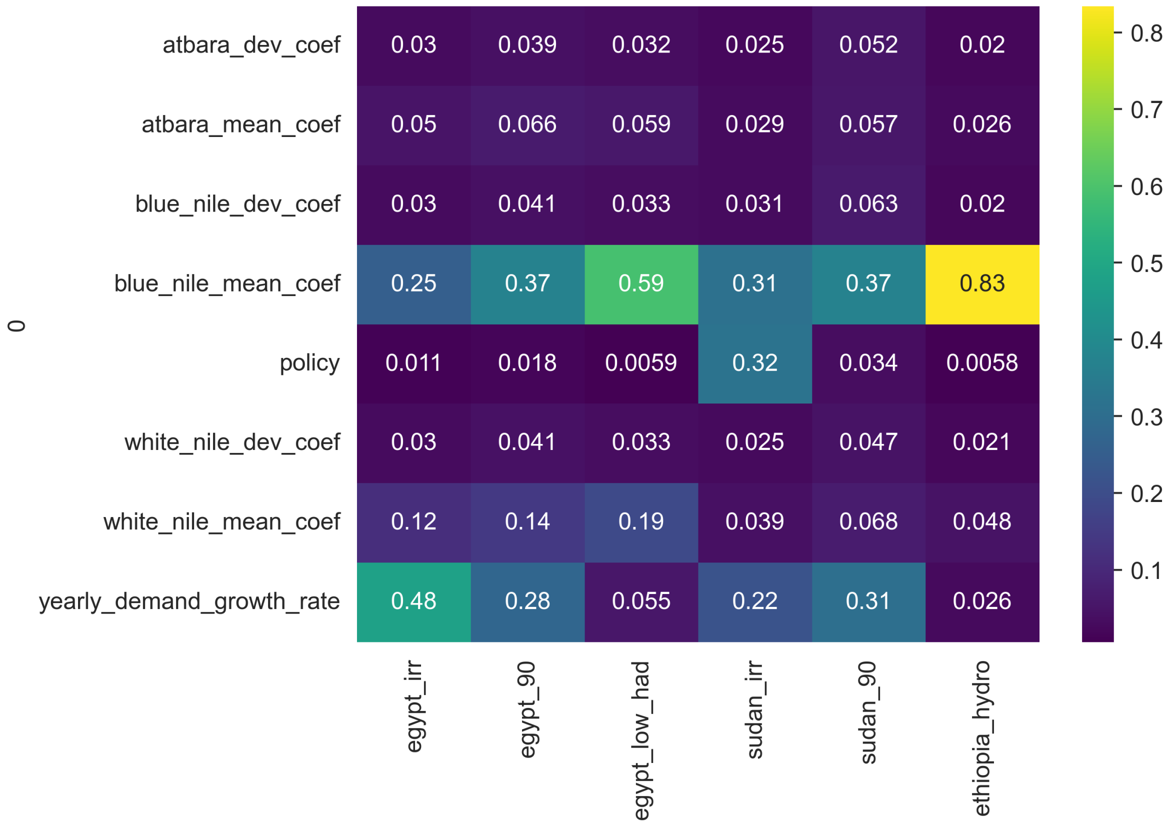

Figure 3.1: Feature scoring results for the Nile River Basin case.

this inflow, the 90th percentile worst month depends on the Blue Nile inflow to a large degree. This highlights the vulnerability within the system; Ethiopia may use the inflow of the Blue Nile to such an extent that this results in a reduced inflow for Sudan and Egypt. In such a case, irrigation deficits and a lower reliability level for the HAD are inevitable. Hence, the feature scoring analysis shows that collaboration between all three parties is principal in limiting this dependency between upstream and downstream Blue Nile users.

4

Reflection

Tensions between Egypt, Ethiopia and Sudan are risen due to recent megatrends such as climate change and urbanisation as well as the new GERD in Ethiopia. Hence, Egypt and Sudan have become more dependent on Ethiopia's water supply. Due to the geographical location of these three users of the Nile, friction exists between their objectives. Upstream Ethiopia aims to maximize its hydropower production from GERD, whereas more downstream countries Egypt and Sudan want to minimize their irrigation deficits. Moreover, Egypt aims to minimize the percentage of low HAD levels. By analyzing the conflicting uses, three clear trade-offs have been observed. First, a trade-off between Egypt's and Ethiopia's objectives, especially for Egypt's HAD level objective and Ethiopia's hydropower objective. Second, a trade-off is also observed between Egypt's HAD level objective and Sudan's irrigation objectives. Interestingly, a trade-off between Egypt's irrigation objectives and its HAD level objectives is observed.

These trade-offs underline the (historical) inter-dependencies between the different countries within the Nile system. Due to the positioning of the GERD in Ethiopia, the risk exists that both Egypt and Sudan have higher irrigation deficits or that Egypt's HAD has a higher percentage of low levels. As a result, millions of people could be affected. Also, a risk exists for Egypt where maintaining higher water levels for its HAD, the country could face higher irrigation deficits. These risks do not only bring forward economic and humanitarian challenges, but also ecological challenges. Moreover, from a geopolitical perspective, the risk of a 'water war' is evident when the current tensions reach a tipping point. Considering the countries' history together, the rising demand for water across all countries, and their conflicting uses, the risk for further tensions rises if no feasible solution is found in which all parties' needs are (partially) met.

Yet, there are also opportunities for cooperation within the Nile system. The sensitivity analysis has showed that the inflow of the Blue Nile, which starts in Ethiopia and ends in the main Nile river stream, does determine the outcome of objectives to a large extent. Keeping this in mind, two compromised solutions have been identified, which optimize the objectives across all parties. Of these two solutions, compromised 2 has been put forward as the most favourable. While the hydropower production for Ethiopia is somewhat lower compared to compromise 1, the increase in level of reliability for Egypt's HAD is significant for compromise 2. For all other objectives, the solutions are somewhat similar. By implementing this compromised policy, and by facilitating collaboration between Nile River Basin users, sufficient water flow for all users is ensured.

While the analysis put forward two compromised solutions and insights in the sensitivity of the system, several impacts of modelling and experimental choices on the policy recommendations are identified. Firstly, the threshold used to evaluate solutions and to retrieve 2 compromised solutions is based on an iterative process to get the right quantile value. Another approach might yield different results, and thus policy recommendations. Secondly, the analysis used 1000 scenarios to evaluate the sensitivities within the system, yet one could debate that this number of scenarios is not enough. Increasing this number may have an impact on the policy recommendation, while not evaluated in this analysis. Thirdly, feature scoring has been conducted as sensitivity analysis. Other approaches, such as Sobol, are not examined. By identifying differences in outcomes between these approaches, a more robust solution may be put forward. Fourthly, the analysis only applied one problem framing, while other alternative problem framings may result in different outcomes. In line with this, the number of objectives per country is unbalanced. Whereas three objectives are included for Egypt, only one objective has been evaluated for Ethiopia. Whether this distribution does justice to the complexity of the problem is open to debate too.

Besides effect of modelling choices on the policy recommendations, possible improvements in modelling efforts are also identified. One improvement could be to disaggregate the irrigation deficit of Sudan, due to several agricultural users of the Nile that can be identified. Additional modelling of other problem framings may be considered as well. Also, distributing objectives across parties in a more balanced way may be explored in future attempts too.

To end, several sensible investment opportunities that may be considered to better manage the water resources of the Nile River Basin are identified. These include agricultural and hydropower investments to increase the efficiency of water usage. In line with this, one could also consider investments in water use campaigns along the Nile.

A

Additional code alterations

Here, we discuss our modifications to the plotter.py script in order to use the plotting functions for the trade-off and vulnerability analysis. Whereas Figure A.1 shows the original lines used in the plotter.py file, Figure A.2 shows the new lines. The main difference is that in the original file the 'append' method of Pandas is used, whereas the new file uses 'concat' instead. The 'append' method is deprecated since Pandas version 1.4.0.
Another small modification is the use of colors in parallel plots to ensure visibility of different solutions. This is also noted in the corresponding notebooks with the parallel plots.

```
        norm_df["Name"] = "All Solutions"
        for i, solution_index in enumerate(solution_indices):
            norm_df.loc[solution_index, "Name"] = solution_names[i]
            norm_df = norm_df.append(norm_df.loc[solution_index, :].copy())
```

Figure A.1: Original lines in plotter.py

```
        norm_df["Name"] = "All Solutions"
        concat_rows = []
        for i, solution_index in enumerate(solution_indices):
            norm_df.loc[solution_index, "Name"] = solution_names[i]
            #print(norm_df.loc[solution_index, "Name"])
            concat_rows.append(norm_df.loc[solution_index, :].copy())
            norm_df = pd.concat([norm_df, pd.DataFrame(concat_rows)])
```

Figure A.2: New lines in plotter.py

Bibliography

Hall, N. (2023). Guardians of the Nile: No Interstate War, No Peace. https://www.csis.org/analysis/guardians-nile-no-interstate-war-no-peace

Lazarus, S. (2018). Is Ethiopia taking control of the River Nile? https://edition.cnn.com/2018/10/19/africa/ethiopia-new-dam-threatens-egypts-water/index.html

Mbaku, J. M., & Kimenyi, M. S. (2015). The limits of the new “Nile Agreement”. https://www.brookings.edu/articles/the-limits-of-the-new-nile-agreement/

Press, A. (2020). Egypt wants UN to avert unilateral fill of dam. https://www.voanews.com/a/africa_egypt-wants-un-avert-unilateral-fill-dam/6191557.html

Swain, A. (2011). Challenges for water sharing in the Nile basin: changing geo-politics and changing climate. *Hydrological Sciences Journal*, *56*(4), 687–702. https://doi.org/10.1080/02626667.2011.577037