Section 5. Technical sciences

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DEVELOPMENT OF A MODEL TO PREVENT DROUGHT OF LAKE MEAD WATER RESERVOIR

Abstract. Climate change has been a prominent subject in recent decades as it silently alters our lives. Droughts have become more common, resulting in the decrease of the Lake Mead water reservoir in the United States. To keep track of the situation, we'll need to simulate the trend in elevation, surface area, and volume, which collectively define the water level. To combat the drought, we'll need to develop drought criteria for Lake Mead, as well as feasible programs and techniques for measuring the impact.

In this paper, we will finally develop a time series model to predict the water level and help people and government to prepare in advance for the drought period.

Keywords: climate change, combat the drought, time series model, Lake Mead, water level, water recycle technology.

1. Introduction

1.1 Background

Droughts, exacerbated by climate change, have wreaked havoc on water reservoirs throughout the world, particularly Lake Mead, for which the Bureau of Reclamation has issued the first-ever water shortage declaration.

The federal government declared a water shortage on the Colorado River on Aug. 16, 2021, in response to low water levels in Lake Mead. Beginning in January 2022, the scarcity will restrict the quantity of water Southern Nevada will be able to drain from Lake Mead. Millions of people will be affected in the coming years and decades by the Colorado River shortage alone, researchers say, with some being forced to make painful water cuts.

Our modeling team has access to the surface area and volume associated with water elevation, as well as data on water elevation at Lake Mead at the end of each month from 1935 through 2021, as well as the maximum and lowest elevations by year.

1.2 Research Objectives

Our objective is to use this information to analyze the drought's effects on reservoirs, identify alternative remedies to the water crisis, and provide a method for measuring the plan's effectiveness. In order to achieve the research goals, we will utilize the mathematical and statistical models including linear regression, time series analysis and curve fitting methodologies.

1.3 Assumptions

Several assumptions will help us clarify and simplify the model.

First, we assume that the sea level is always the same. We overlook the possibility of rising mean sea level as a result of climate change.

Second, the amount of Lake Mead below mean sea level is assumed to be modest enough to be omitted in the calculations.

Thirdly, we assume all the data available is accurate and there are no outliers in the dataset.

2. Study of the Inflow, Outflow, and Loss

2.1 Factors of Inflow

The continuous dryness in the upper Colorado River basin, which generates over 96 percent of the inflow, is one of the culprits. Water availability in the Colorado River has been progressively decreased since 2000, since it is more dependent on seasonal precipitation. As a result, the ongoing drought will continue to reduce the inflow to the River Mead.

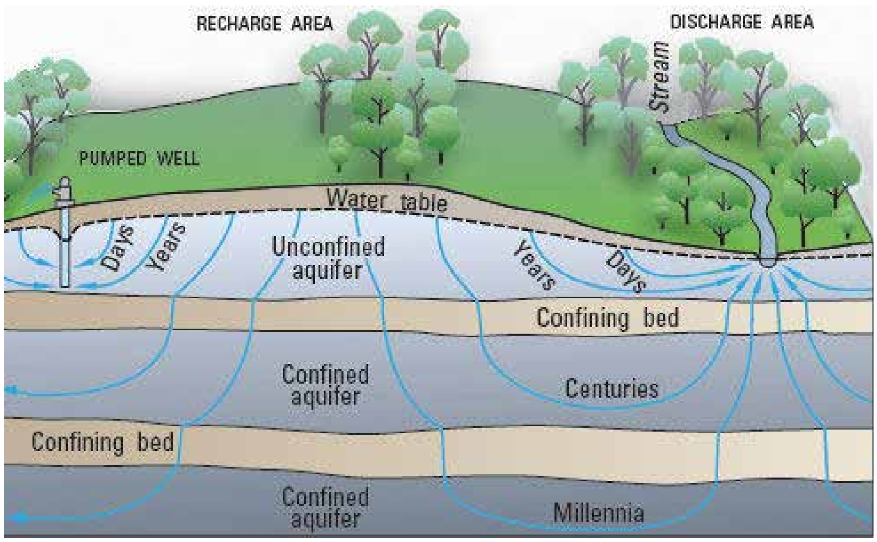

Figure 1. Groundwater flow

Some of the rain that falls on the ground seeps into the earth and becomes groundwater. Water may travel both vertically and horizontally when it contacts the water table (below which the soil is wet). Water flowing downward can collide with more thick and water-resistant nonporous rock and soil, causing it to flow horizontally, usually towards streams, the ocean, or deeper into the ground.

2.2 Factors of Outflow

Water withdrawals, or water abstractions, are defined as freshwater taken from ground or surface water sources, either permanently or temporarily, and conveyed to a place of use.

Water source	Water volume, in cubic miles	Water volume, in cubic kilometers	Percent of total water	Percent of total freshwater
Fresh groundwater	2,526,000	10,530,000	0.8%	30.1%
Groundwater	5,614,000	23,400,000	1.7%	--
Total global water	332,500,000	1,386,000,000	--	--

Figure 2. Global Water Distribution Estimation

This can be one of the main reason of the water outflow of Lake Mead. The water withdrawals can include abstractions for public water supply, irrigation, industrial processes and cooling of electric power plants.

Another source of water outflow can be the formation or dissipation of glaciers, snowfields, and permafrost, which means the water cycle itself is part of the reason of outflow. Even though the water in ice and glaciers travels very slowly, they are part of the water cycle. The weather is also influenced by ice caps. White reflects more sunlight (heat) than darker hues, and since ice is so white, sunlight is reflected back out to the sky, aiding in the formation of weather patterns. Continue reading to learn about the role of glaciers and ice caps in the water cycle.

2.3 Factor of Loss

The intensity of the drought is one aspect that contributes to the loss; varying degrees of dryness result in varied evaporation rates. The surface size of Lake Mead is also a role in the loss. Lake Mead's evaporation rate would be lower if its surface area was smaller, decreasing the amount of water lost. However, we may disregard the extent of the loss in the preservation of Lake Mead in this study since only a tiny surface area could avoid evaporation loss. Nonetheless, we want Lake Mead's water level to rise to help ease the drought. Because a bigger water surface area has a larger water storage, the somewhat higher loss associated with the larger water surface area is inconsequential in this study.

3. Water Level Time Series Exploration

3.1 Definition of Drought Period

A drought is a period of time when an area or region receives less rain than usual. Reduced soil moisture or groundwater, reduced stream flow, agricultural damage, and a general water scarcity can all result from a lack of appropriate precipitation, whether rain or snow. Droughts, after hurricanes, are the most expensive weather occurrences.

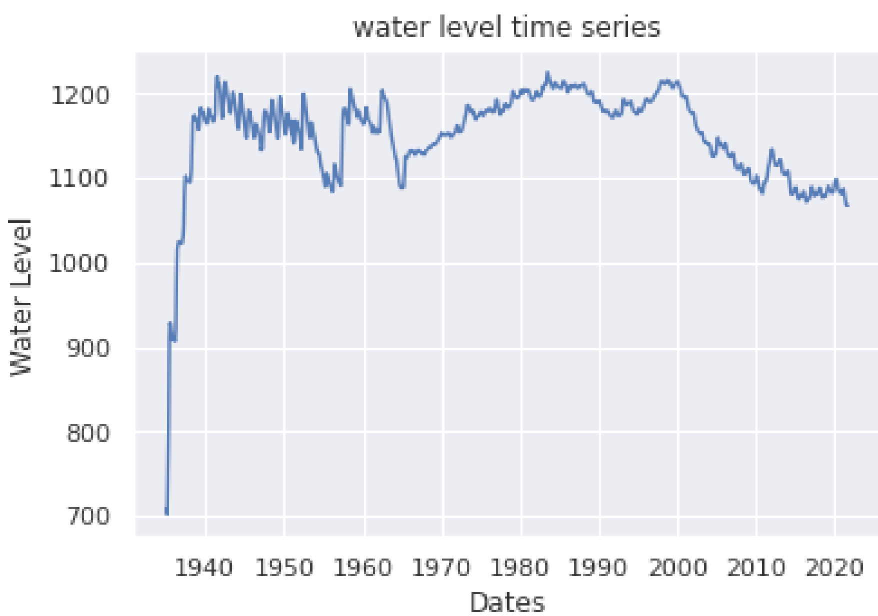

Figure 3. Lake Mead Water Level

Droughts, unlike other severe weather disasters like hurricanes, tornadoes, and thunderstorms, are notoriously difficult to predict when they begin and end. Because the early consequences of a drought might be difficult to detect, it could take weeks or months to confirm that a drought has begun. For the same reason, the end of a drought is difficult to predict. A dry spell might last weeks, months, or even years.

In this paper, we will define the drought period as the continuous at least 14 days (two weeks) which the water level of the lake is below the 25% position over the recent years.

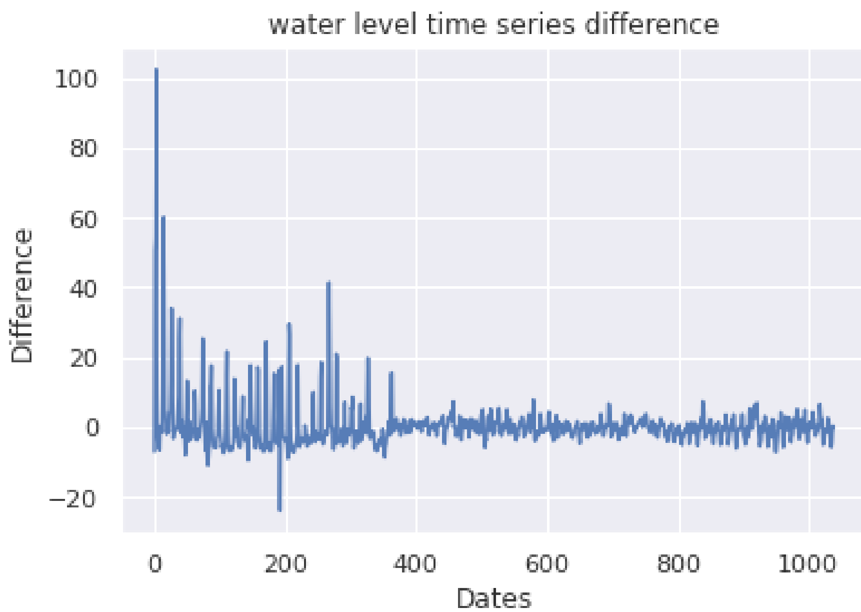

Figure 4: Water Level Difference

3.2 Water Level Time Series

The plot shows that since 1940 the Lake Mead keeps the water level above the 1100 level. There was a big inflow before 1940 to keep the water level high. During 1940 to 2020, the water level fluctuates a lot but it shows a clear declining trend since 2000.

The below chart is displaying the water level delta (difference) time series. Positive delta means the inflow is larger than the outflow, causing an increase of the water level (ignoring the effect of water loss). Obviously the first 380 days the Lake Mead was having frequent large water inflow but since the 400 days, it shows a small inflow and outflow change comparing to the first 380 days. It can be one of the sign the severe drought period is affecting the overall water level.

4. Water Level Prediction

4.1 Stationary Time Series And ADF Test

The features of a stationary time series are independent of the time at which the series is seen. As a result, time series containing trends or seasonality are not stationary, as the trend and seasonality will alter the value of the time series at different points in time. A white noise series, on the other hand, is stationary – it should seem the same regardless of when you examine it. Stationary series means the statistical features of a time series (or, more accurately, the process that generates it) do not vary with time, which is known as stationarity. Stationarity is significant since it is required by many valuable analytical tools, statistical tests, and models.

The testing procedure for the ADF test is the same as for the Dickey-Fuller test but it is applied to the model

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \delta_1 \Delta y_{t-1} + \cdots + \delta_{\rho-1} \Delta y_{t-\rho\perp 1} + \varepsilon_t ,$$

where α is a constant, β is the coefficient on a time trend and p is the lag order of the autoregressive process.

Imposing the constraints $\alpha = 0$ and $\beta = 0$ corresponds to modelling a random walk and using the constraint $\beta = 0$ corresponds to modeling a random walk with a drift. The unit root test is then carried out under the null hypothesis $\gamma = 0$ against the alternative hypothesis of $\gamma < 0$. Once a value for the test statistic:

$$DF_\gamma = \frac{\gamma}{SE(\hat{\gamma})}$$

Is computed it can be compared to the critical value of DF test.

The following is the ADF test results for water level first order difference:

```
ADF Statistic: -6.654371
p-value: 0.000000
Critical Values:
        1%: -3.437
        5%: -2.864
        10%: -2.568
```

The p value is nearly zero meaning that the difference series are stationary and we can build time series model based on it.

4.2 ARIMA Model

We get a non-seasonal ARIMA model when we mix differencing with autoregression and a moving average model. ARIMA stands for AutoRegressive Integrated Moving Average (integration is the inverse of differencing in this context). The entire model may be written as follows:

$$y'_t = c + \phi_1 y'_{t-1} + \cdots + \phi_p y'_{t-p} + \\ + \theta_1 \varepsilon_{t-1} + \cdots + \theta_q \varepsilon_{t-q} + \varepsilon_t,$$

where y'_t is the differenced series (it may have been differenced more than once). The "predictors" on the right hand side include both lagged values of y'_t and lagged errors. We call this model an ARIMA(p, d, q) **model**, where:

- p: the order of autoregressive part;
- d: the order of integration part;
- q: the order of moving average part.

5. Prediction Model Results

5.1 Model Output

The following shows the ARIMA model parameter outputs form python results.

```
                              ARIMA Model Results
==============================================================================
Dep. Variable:           D.waterlevel   No. Observations:                 1039
Model:                 ARIMA(10, 1, 1)  Log Likelihood               -3055.311
Method:                       css-mle   S.D. of innovations              4.568
Date:                Mon, 15 Nov 2021   AIC                           6136.623
Time:                        22:14:30   BIC                           6200.921
Sample:                             1   HQIC                          6161.015

=========================================================================================
                           coef    std err          z      P>|z|      [0.025      0.975]
-----------------------------------------------------------------------------------------
const                    0.8796      1.060      0.830      0.407      -1.198       2.957
ar.L1.D.waterlevel       1.1916      0.038     31.050      0.000       1.116       1.267
ar.L2.D.waterlevel      -0.4272      0.051     -8.413      0.000      -0.527      -0.328
ar.L3.D.waterlevel      -0.1759      0.051     -3.443      0.001      -0.276      -0.076
ar.L4.D.waterlevel       0.2458      0.058      4.223      0.000       0.132       0.360
ar.L5.D.waterlevel      -0.1168      0.063     -1.861      0.063      -0.240       0.006
ar.L6.D.waterlevel       0.0089      0.063      0.141      0.888      -0.115       0.133
ar.L7.D.waterlevel      -0.0088      0.063     -0.139      0.889      -0.132       0.115
ar.L8.D.waterlevel       0.1005      0.063      1.595      0.111      -0.023       0.224
ar.L9.D.waterlevel      -0.3389      0.059     -5.732      0.000      -0.455      -0.223
ar.L10.D.waterlevel      0.4694      0.037     12.846      0.000       0.398       0.541
ma.L1.D.waterlevel      -0.6176      0.032    -19.231      0.000      -0.681      -0.555
                                    Roots
==============================================================================
                  Real          Imaginary           Modulus         Frequency
------------------------------------------------------------------------------
AR.1            1.0180           -0.0000j            1.0180           -0.0000
AR.2            0.8835           -0.4994j            1.0149           -0.0819
AR.3            0.8835           +0.4994j            1.0149            0.0819
AR.4            0.5147           -0.9197j            1.0539           -0.1688
```

```
AR.5              0.5147          +0.9197j            1.0539            0.1688
AR.6             -1.0885          -0.0000j            1.0885           -0.5000
AR.7             -0.8802          -0.7465j            1.1542           -0.3881
AR.8             -0.8802          +0.7465j            1.1542            0.3881
AR.9             -0.1217          -1.1166j            1.1232           -0.2673
AR.10            -0.1217          +1.1166j            1.1232            0.2673
MA.1              1.6192          +0.0000j            1.6192            0.0000
-------------------------------------------------------------------------------
```

Figure 5. ARIMA Output

Here we used the ARIMA [10; 1,1] for the total 1039 model input. In order to check the validation of the results, we plot the residual density, which is concentrated near zero, meaning that our model is performing a good fit (Figure 6).

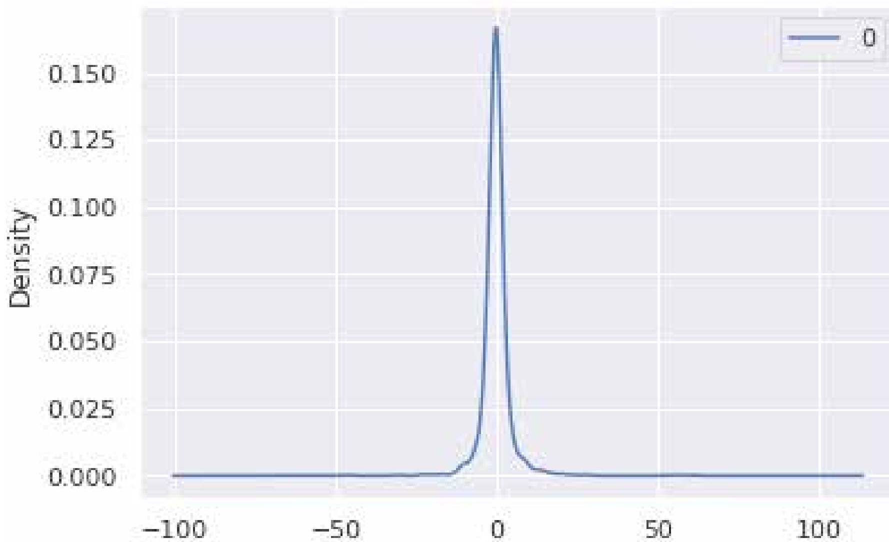

Figure 6. Residuals Density Plot

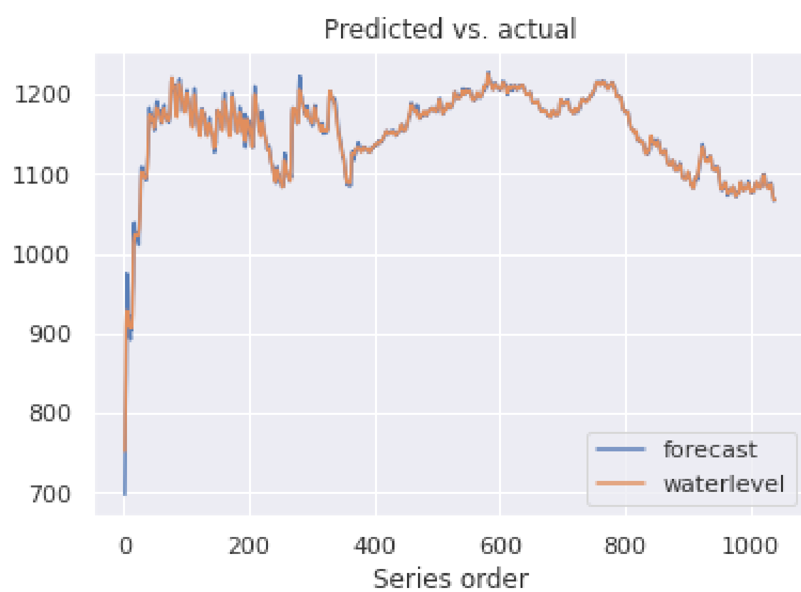

Figure 7. Prediction and True Water Level

5.2 Long-Term Time Series Prediction

The next step is that we want to predict the water level till 2050. In general, in time series analysis, you look for stationarity, which allows you to forecast both short and long term outcomes (think for example of an AR process that has a long term expected mean and variance because it is less persistent than an ARIMA and tends to forget past shocks with an exponential decay in the ACF). Particularly, if your process is linear and you can only analyze the first two moments, stationarity in mean and variance. As a result, both short- and long-term stationary processes are predictable. Remember, however, that short-term predictions are usually associated with lower MSE (prediction error): for example, one-step-ahead predictions are less noisy than two-step-ahead predictions: this is because conditional variance is compounded over time for each step ahead, making your forecast noisier if you try to predict the distant future.

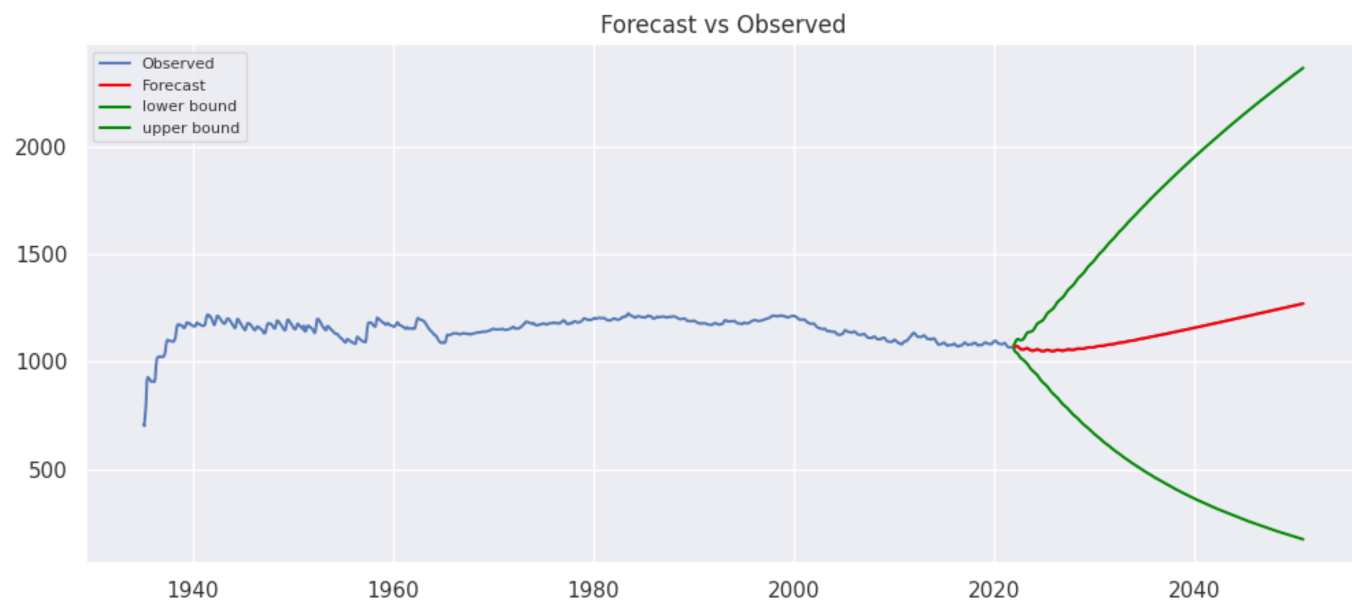

Figure 8. Water Level Prediction

Based on our ARIMA model, considering the noise for long term forecasting, here the plot shows the future prediction (the red line) as well as the prediction 95% level confidence interval (the green lines).

Obviously it indicates that the further your prediction is, the nosier the results will be. The prediction of 2050 water level will have a big confidence interval ranging from 400 to over 2000. In average, for the incoming 30 years, the Lake Mead water level will be around 1000 and has a slight increasing pattern according to our model prediction.

6. Discussions

6.1 Water Drought Crisis

Water is a holy resource that is needed to feed families, cultivate crops, protect animals and the environment, and run agricultural companies. Unfortunately, drought conditions in the West are worsening, and water allocations in places like the Klamath River Basin and the Colorado River Basin are at historic lows.

Drought has an urgent need to be mitigated and a long-term strategy developed to assist conservation and economic growth, because drought affects everyone, from farmers and ranchers to city inhabitants and Tribes.

By collaborating with partners throughout the federal government, providing aid to afflicted areas, and researching long-term climate change solutions to address this rising catastrophe, the Interior Department is helping the administration's whole-of-government approach to drought mitigation.

6.2 How Our Model Can Help?

The long term prediction in the previous part of paper has indicated the stable water level for the incoming decades. However, people are expecting a faster economic growth and resources supply in the future thus the government should prepare for the increasing amount of water usage in the future.

Also, the model shows the possibility that the water level in 2050 will drop to a very alarming level. Other back up plans should be available in case of such extreme drought periods happened.

6.3 Potential Solutions and Water Recycle Technology

The possible solutions and suggestions are just in the water inflow, outflow and loss analysis. There are three aspects we can prepare for the drought periods: increase inflow, decrease the outflow and loss.

However, we here want to address the decrease of water outflow which is also the most controllable aspects that government can perform. The outflow is mainly due to the water distribution, meaning that an efficient water distribution system would help a lot to prevent lake drought.

Technology and reasonable distribution can help decrease the usage of water and the water loss during the distribution. Therefore, the water recycle is kicked to improve the water usage system.

According to Katz, what's new in water reuse/ recycling technology isn't so much the technology itself as it is how it's being utilized. Many factors influence the choice of water reclamation technology, according to the National Academies Press study. The type of water reuse application, reclaimed water quality goals, source water wastewater characteristics, compatibility with existing conditions, process flexibility, operating and maintenance requirements, energy and chemical requirements, personnel and staffing requirements, residual disposal options, and environmental constraints are all important factors to consider. Water rights, economics, institutional concerns, and public confidence all influence treatment design decisions.

A few major high-level industrial transformations are now ongoing. What was formerly considered trash is now being re-evaluated for its worth, with the emphasis shifting to resource recovery.

Organic fuel, nutrients, and water are commonly found in wastewater streams. The industry is working to extract these valuable products more efficiently, and new technologies are being developed to help.

7. Conclusion

In this paper, we first discussed about the factors that can affect the Lake inflow, outflow and loss. Then some statistical tests and model are implemented to predict the Lake Mead future water level time series. From the prediction results we foresee a possibility that the water level of Lake Mead will drop drastically by the year of 2050 although the average predictions show that the future water level will not change too much for the decades. However, with the growing economy development, resources usages and population growth, the government should be prepared for the stressed scenarios of lake long and severe drought periods.

We proposed the drought period forecast and meanwhile the potential solutions and preparation for such drought periods are also summarized: use the technology to improve the water recycle efficiency, and as a result the water inflow and outflow stream will be more efficient.

References:

1. Kwiatkowski D., Phillips P. C. B., Schmidt P., & Shin Y. Testing the null hypothesis of stationarity against the alternative of a unit root: How sure are we that economic time series have a unit root? Journal of Econometrics, – 54(1–3). 1992. – P. 159–178.
2. Wei W. W. Time series analysis. In The Oxford Handbook of Quantitative Methods in Psychology: – Vol. 2. 2006.

3. Keddy P. A., & Reznicek A. A. Great Lakes vegetation dynamics: the role of fluctuating water levels and buried seeds. Journal of Great Lakes Research, – 12(1). 1986. – P. 25–36.
4. Brook A. J., & Woodward W. B. Some observations on the effects of water inflow and outflow on the plankton of small lakes. The journal of Animal Ecology, 1956. – P. 22–35.
5. Anderson J. The environmental benefits of water recycling and reuse. Water Science and Technology: Water Supply, – 3(4). 2003. – P. 1–10.
6. Angelakis A. N., Bontoux L., & Lazarova V. Challenges and prospectives for water recycling and reuse in EU countries. Water Science and Technology: Water Supply, – 3(4). 2003. – P. 59–68.
7. Sorjamaa A., Hao J., Reyhani N., Ji Y., & Lendasse A. Methodology for long-term prediction of time series. Neurocomputing, – 70(16–18). 2007. – P. 2861–2869.
8. Karakoyun E. S., & Cibikdiken A. O. Comparison of arima time series model and lstm deep learning algorithm for bitcoin price forecasting. In The 13th multidisciplinary academic conference in Prague. – Vol. 2018. – May, 2018. – P. 171–180.
9. Hall A. Testing for a unit root in time series with pretest data-based model selection. Journal of Business & Economic Statistics. – 12(4). 1994. – P. 461–470.
10. Mitchell V. G., Mein R. G., & Mc Mahon T. A. Modelling the urban water cycle. Environmental Modelling & Software. – 16(7). 2001. – P. 615–629.
11. Lucchetti G. L., & Gray G. A. Water reuse systems: a review of principal components. The Progressive Fish-Culturist. – 50(1). 1988. – P. 1–6.
12. Barnett T. P., & Pierce D. W. When will Lake Mead go dry? Water Resources Research. – 44(3). 2008.
13. Harbeck G. E. Water-loss investigations: Lake Mead studies (Vol. 298). US Government Printing Office. 1958.
14. Achhami A., Kalra A., & Ahmad S. Dynamic simulation of Lake Mead water levels in response to climate change and varying demands. In World Environmental and Water Resources Congress 2018: Watershed Management, Irrigation and Drainage, and Water Resources Planning and Management May, 2018. – P. 260–268. Reston, VA: American Society of Civil Engineers.