STUDY AND PREDICTION OF THE PARAGUAY RIVER LEVEL BY HARMONIC ANALYSIS AND NEURAL NETWORKS

Li Weigang & Daniel J. R. Nordemann

Neural networks and harmonic analysis by iterative regression are implemented for the prediction of the level of Paraguay River. The selected neural networks include Feed-forward Neural Networks with Backpropagation learning law and Time Delay Neural Network. Using the 1145 monthly mean values, the trained networks predict the levels of the 12 next months with Normalized Mean Squared Error NMSE < 0.06 and Negative Average Log Likelihood NALL.< 9.0. On the other hand, the determination of the most important sine functions embedded in the same series allows to reconstruct the main features of the variations of the river level and to predict yearly mean values for the next two decades (assuming no major change of the environment). The results obtained show that both methods seem to be efficient to process time series related to phenomena influenced by complex climatic and geophysical processes, even not dealing with causal relationships involved in the phenomena studied. They may be used to predict future behavior of such phenomena, at ranges depending specifically on the method used, interval, size and quality of data available.

Key words: Prediction; Neural networks; Harmonic analysis; Iterative regression; Paraguay river; Paraguay river level.

ESTUDO E PREVISÃO DO NÍVEL DO RIO PARAGUAI USANDO ANÁLISE HARMÔNICA E REDES NEURAIS - *Redes neurais e análise harmônica por regressão iterativa foram usadas para a previsão do nível do Rio Paraguai. As redes neurais selecionadas para este trabalho compreendem a rede neural "Feed-forward" com lei de aprendizagem com retropropagação e rede neural com atraso de tempo. A partir de 1145 valores mensais médios, a rede neural treinada prediz o nível dos doze meses seguintes com erro médio normalizado ao quadrado NMSE < 0.06 e probabilidade logarítmica média negativa NALL < 9.0. Além disto, a determinação das mais importantes funções senoidais embutidas na mesma série permite a reconstrução das principais variações do nível do rio e a previsão dos valores médios anuais para as duas décadas seguintes (supondo nenhuma mudança importante do meio ambiente). Os resultados obtidos mostram que ambos os métodos parecem ser eficientes para processar séries temporais influenciadas por processos climáticos e geofísicos complexos, mesmo sem considerar as relações causais envolvidas nos fenômenos estudados. Eles podem ser usados para prever o comportamento de tais fenômenos em escalas de tempo que dependem especificamente do método usado, do intervalo de tempo e do tamanho e da qualidade dos dados disponíveis.*

Palavras-chave: *Previsão; Redes neurais; Análise harmônica; Regressão Iterativa; Rio Paraguai; Níveis do Rio Paraguai.*

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INTRODUCTION

The Paraguay River (length: 2550 km) rises in the Mato Grosso region of Brazil, at 300 m above sea level, and runs southward between highlands at the west and the Brazilian plateau at the east. Its basin, with an area of approximately 500000 km^2, consists of a series of huge alluvial plains drained by a complex network of rivers interspersed with marshes, in a region called Pantanal. In this region, many areas suffer a succession of droughts and severe floods with their obvious economic and social consequences. Paraguay River levels are influenced by several different factors from micro to macro scales. Therefore, predicting the level of the Paraguay River with convenient antecedence (and so estimating the area to be flooded) is a relevant scientific goal. In this paper, Feed-forward Neural Network, Time Delay Neural Network and harmonic analysis with iterative regression are implemented for the reconstruction and prediction of the level of the Paraguay River at Ladário near Corumbá (Mato Grosso do Sul State, Brazil). The harmonic analysis with iterative regression was used to investigate the most important periodicities of the time series of the Paraguay River levels. The neural networks method was further used to predict the future behavior of the levels which were measured up to the present time. As shown in the following parts of this work, the neural networks can treat all the involved factors simultaneously, which was an incentive to apply this method to complex time series such as river levels. The daily data of the series studied in this work were collected from 1900 to June of 1995. About 1145 monthly mean data are used to train the neural network, which in return gives the monthly predictions. The initial results show successful predictions within three to four month scale.

PERIODICITIES ANALYZED BY ITERATIVE REGRESSION ANALYSIS

Variations of the Paraguay River (Fig. 1) clearly show a complex behavior with long periods of drought and flood. Periodicities are not evident and it also may be seen that the flow rate is not stationary. For these reasons, these data were analyzed by several mathematical methods including Fourier analysis, periodogram/cyclogram, dynamic spectral analysis and iterative regression and a methodology developed for this purpose (Nordemann, 1995). In spite of the river level (Fig. 1) not being stationary, (DNOS/UNESCO-PNUD, 1974; Nordemann, 1995), an attempt was done to select the most important periodicities embedded in the signal and to use them in order to predict the near future of the river level.

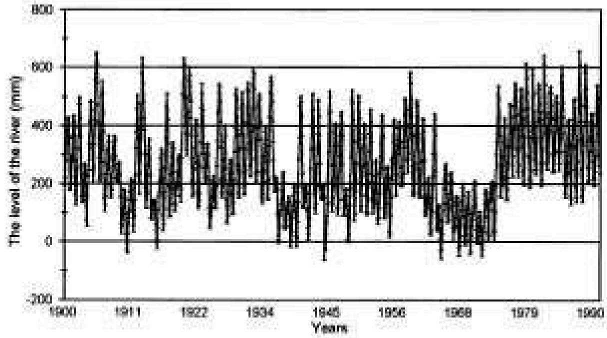

Figure 1 - The observed monthly means of the level of Paraguay River.

Figura 1 *- Médias mensais dos níveis do Rio Paraguai.*

METHODS

In order to analyze geophysical time series, it is recommended to use methods which are more adequate to the problem and which are chosen within computational tools and software compatible with available hardware and processing time (Dettinger et al., 1995). Several algorithms were developed by us within *Mathematica* for Windows environment (Wolfram, 1991; Nordemann, 1994). All treatments were processed by a 486DX4 100 MHz machine with 16 MB RAM and 500 MB hard disk.

In order to study better River Paraguay behavior, the iterative regression method was chosen among the methods previously used and applied to the 1900-1995 level value series (Nordemann, 1995). Most of classical harmonic analysis are performed on the time series using methods such as Fourier transform. Here, we used a different method which searches one by one the 3-parameter sine functions which fit better with data by a minimum square iterative regression fit (Wolberg, 1967). For a better accuracy on the period values, the method may be applied through the sweep of allowed frequencies or periods. In our case a preliminary search using periodogram restricts the search only to the most important sine function embedded in the signal as detected by the maxima of periodogram. Following this step, the iterative regression method is applied to the regions of the maxima, in decreasing order of their amplitude. This iterative regression was applied for every sine function to the initial time series stripped of the reconstructed function from the previously detected periodicities.

RESULTS FROM ITERATIVE REGRESSION

These determinations gave convergence for about 50 sine functions with amplitude greater than the corresponding standard deviation. Tab. 1 presents the most important periodicity parameters. The major amplitudes correspond to 1-year period (Earth orbital revolution) followed by the 28-year period and several amplitudes for periods 2 to 4 years (Quasi Biannual Oscillation/El Niño Southern Oscillation QBO/ENSO) and others.

Period (yr.)	Amplitude ± s.d. (cm)	Observation
1.0000 ± 0.0002	130.0 ± 5.2	Orbital revolution
28.4 ± 0.77	77.0 ± 13.7	
14.6 ± 0.34	44.5 ± 12.0	
8.9 ± 0.16	33.7 ± 11.4	
7.8 ± 0.14	33.6 ± 12.8	
6.6 ± 0.12	20.7 ± 10.2	
3.8 ± 0.03	32.6 ± 10.9	QBO/ENSO
4.8 ± 0.06	23.9 ± 10.7	
2.8 ± 0.02	22.7 ± 10.5	
2.3 ± 0.02	17.3 ± 10.1	
...	...	

Table 1 - Most important periodicity parameters (Paraguay river, 1900-1995).

Tabela 1 *- Parâmetros das periodicidades mais importantes (Rio Paraguai 1900-1995).*

Of course, the most important periodicity found in the studied time series corresponds to one year period, being due to the orbital revolution of the Earth. But it may be seen that the amplitude which corresponds to 1-year period represents only a small fraction of the total amplitude of the river height variations (half difference between extreme heights [657-(-61)]/2 = 359 cm). For this reason, components of the following periods play a very important part. It may also be seen that the sum of the nine major amplitudes is about 400 cm, which means that, in the case of this study, about nine amplitudes may be enough to account for the observed extreme values. With the method used, about 50 periodicities present an amplitude greater than their respective standard deviation. This means that besides the first nine periodicities quoted, others may be significant and that there may be other natural cycles which may also influence the river height.

To show tendencies embedded in the time series, a dynamic spectral analysis was also performed as "classical" dynamic spectral analysis with constant length samples and also as "wavelet style" dynamic spectral analysis with constant number of periods per sample (Farge, 1995). It showed clearly the evolution of the 2 to 5 years periodicity (ENSO-QBO), stronger from 1900 to 1950 than for the rest of the series as well as other features of the evolution of the river behavior. Among these features is the higher amplitude of the 28.4 year period versus time during the last decades of the series.

The 28.4 year period is within the 28-32 yr interval periodicity shown by Kane & Teixeira (1990) in air temperatures for both hemispheres, but the remaining periodicities at 5-6 yr, 10-11 yr, 15 yr 20 yr and 55-80 yr detected by these authors do not appear or appear only as small signals in the 1900-1995 Paraguay River series.

As a preliminary effort, and in spite of the recognized evolution of the series, the reconstruction, for each hydrological year, was made after the determination by iterative regression analysis of the sine functions embedded in the whole series. The results obtained are presented in Fig. 2 which shows the reconstruction of the Paraguay River height using the nine most significant sine components (Tab. 1). It may be seen that, for this model, some large amplitude floods (before 1920) or droughts (1963 to 1974) are not described with fidelity, which corresponds to their exceptional occurrence, opposed to the hypothesis of being stationary. An attempt was also made using the same functions to predict the behavior of the annual means of the Paraguay River during the next 20 years, assuming no important change in the regional and global environment for this interval. Drastic change in the environment such as land use in the Pantanal and adjacent regions or works to improve the navigability of the Paraguay River should invalidate such medium or long term forecasting. It may be seen that this model predicts a large amplitude drought for the near future, up to about year 2000, followed by alternate periods of normal level and mild flood.

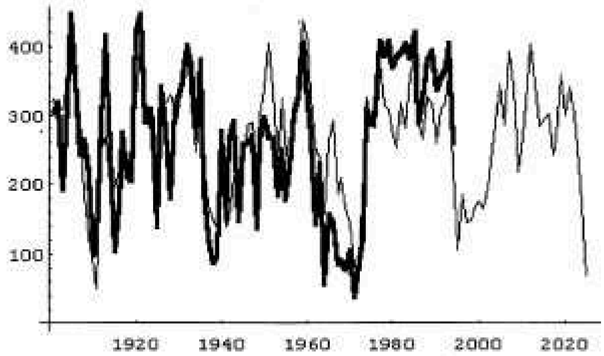

Figure 2 - Yearly means of the level of the Paraguay River at Ladário 1900 to 1994 (thick curve) and prediction based on 9 most important periodicities up to 2025 (thin curve). A rather good fit may be observed between observed and reconstructed values except in the case of several periods of flood or drought after 1950, which characterize their exceptionallity. This model predicts a rather long period of lower than mean values from present to about 2005 and variable values higher than mean after 2005.

***Figura 2** - Médias anuais dos níveis do Rio Paraguai, em Ladário, de 1900 a 1994 (traço grosso) e previsão baseada nas nove mais importantes periodicidades até 2025 (traço fino). Uma razoável concordância é notada entre os valores observados e os previstos, exceto em casos dos vários períodos de inundação ou seca após 1950, o que caracteriza a sua excepcionalidade. Este modelo prediz um período bem longo de níveis mais baixos do que a da média, do presente momento até aproximadamente o ano de 2005, e valores variáveis maiores do que a média após 2005.*

APPLICATION OF THE NEURAL NETWORKS

Prediction of time series is an exciting recent application of neural networks. There are a number of prediction methods available for this kind of problem (Casdagli, 1989). Neural networks were found to be useful and competitive with the best recent approximation methods (Lapedes & Farber, 1987; Gallant & White, 1992; Gershenfeld & Weigend, 1993; Li et al., 1995a; 1995b). To predict the future behavior of the Paraguay River level time series, the Feed-forward Neural Network (BPNN) and Time Delay Neural Network (TDNN) were used and both of them were implemented in the neural networks simulator SNNS (Zell et al., 1995). To analyze the prediction quality, we used a simple method-independent technique (Gershenfeld & Weigend, 1993; Nordemann & Li, 1996).

Feed-forward neural network

The most popular network is the Feed Forward Network with backpropagation learning law (Rumelhart et al., 1986). For one hidden layer, the input values of time series $x(t-1)$, $x(t-2)$,...$x(t-d)$ are received through d input units, which simply pass the input forwards to the hidden units u_j, $j = 1,2,...,q$. Each connection performs a linear transformation determined by the connection strength w_{ij}, so the total input for every hidden unit u_j is $\Sigma_{i=1}^{d} w_{ij}\, x(t\text{-}i)$. Each unit performs a nonlinear transformation on its total input, producing the output:

$$u_j = \Psi\left(W_{0j} + \sum_{i=1}^{d} W_{ij} X(t-i)\right).$$

The activation function Ψ is the same for all units. Here, Ψ is a sigmoid function with limiting value 0 and 1 as $u_j \to -\infty$ and $u_j \to +\infty$, respectively:

$$\Psi(u_j) = \frac{1}{\left(1 + e^{-u_j}\right)}.$$

The hidden layer outputs u_j are passed along to the single output unit with connection strength β_j, which performs an affine transformation on its total input. Then, the network's output $x(t)$ can be represented as:

$$x(t) = \beta_0 + \sum_{j=1}^{q} \beta_j . \Psi . \left(w_{0j} + \sum_{i=1}^{d} w_{ij} .\ x(t-i)\right),$$

for d inputs and q units in the hidden layer.

Time Delay Neural Network

The Time Delay Neural Network is a layered network in which the outputs of a layer are buffered by several time lags and then fed fully connected to the next layer (Waibel et al., 1989; Wan, 1993). The activation of an unit is normally computed by passing the weighted sum of its inputs to an activation function, usually a threshold or sigmoid function. For TDNN, this behavior is modified through the introduction of delays (Zell et al., 1995). Training for this kind of network is performed by a procedure similar to backpropagation, that takes the special semantics of coupled links into account. To enable the network to achieve the desired behavior, a sequence of patterns has to be presented to the input layer with the feature of interest shifted within the patterns.

The results from neural networks

The selected prediction methods include Feed-forward Network with Backpropagation (BPNN) and Time Delay Neural Network (TDNN). We used the notation input units:hidden units:hidden units:... :output units to describe the structure of the network. For BPNN, the selected structure is 12:48:48:1; for TDNN, the selected structure is 36:9:1. In both networks, the training rate used was 0.2. Fig. 3 shows the reconstruction (from 01/90 to 06/95) and the predictions (from 07/95 to 06/96) of the monthly level of Paraguay River. The trained networks gave the next 12 months prediction values. For the period 07/95 to 12/95, the predictions from two networks gave very similar results; for the next 6 months, the differences between predictions were slightly higher. The confidence one may have in such prediction is shown with prediction error bars which characterize the probability of having the result of a future measurement within a given interval (one standard deviation) near the predicted value. Figs. 4 and 5 show the prediction error bars (from 06/95 to 07/96) obtained by using Feed-forward Neural Network with Backpropagation and Time Delay Neural Network.

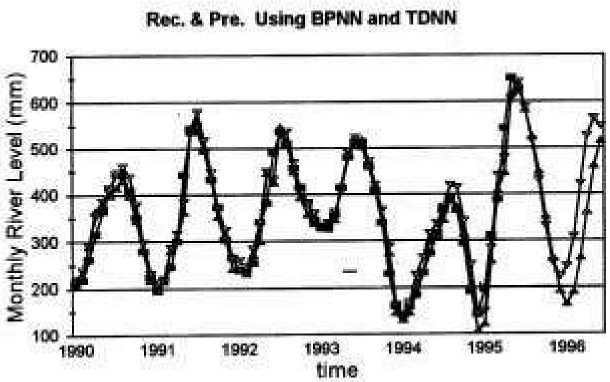

Figure 3 - Reconstruction (01/90-06/95) & prediction (07/95-06/95) of the monthly level of Paraguay River.

Figura 3 - *Reconstrução (01/90-06/95) e previsão (07/95-06/95) dos níveis mensais do Rio Paraguai.*

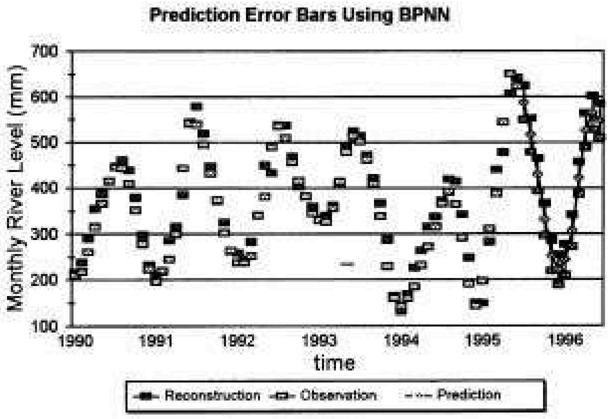

Figure 4 - Prediction error bars (06/95-07/96) using BPNN.

Figura 4 - *Barras de erro das previsões (06/95-07/96) utilizando BPNN.*

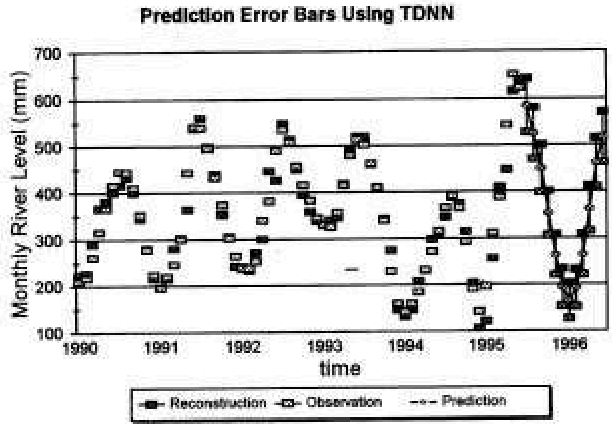

Figure 5 - Prediction error bars (06/95-07/96) using TDNN.

Figura 5 - *Barras de erro das previsões (06/95-07/96) utilizando TDNN.*

Tab. 2 shows the prediction quality of two neural networks using 1000 monthly mean data with 2000 training cycles. The index *nmse1* and *nall1* denote the quality of the reconstruction and the index *nmse2* and *nall2* denote the quality of the prediction (Nordemann & Li, 1996). The results in Tab. 2 show that Time Delay Neural Network gave the best reconstruction, *nmse1* = *0.0305* and *nall1* = *8.2288*, and Feed-forward Network with Backpropagation was located in second, *nmse1* = *0.1114* and *nall1* = *9.5082*. For the future prediction, Time Delay Neural Network also gave the best results, *nmse2* = *0.0588* and *nall2* = *8.5317* and and Feed-forward Network with Backpropagation was located in second, *nmse2* = *0.0584* and *nall2* = *8.5498*.

Net models	Training time	Reconstru. quality		Prediction quality	
		nmse1	nall1	nmse2	nall2
Backpropagation (BPNN)	2 hours	0.1114	9.5082	0.0584	8.5498
Time Delay Network (TDNN)	20 min.	0.0305	8.2288	0.0588	8.5317

Table 2 - Prediction quality of two neural network models.

***Tabela 2** - Qualidade de previsão dos dois modelos de redes neurais.*

COMPARISON BETWEEN NEURAL NETWORKS AND ITERATIVE REGRESSION METHOD

For further evaluation of the prediction results, the same prediction has been done by means of the iterative regression method and neural networks (Nordemann et al., 1995).

Comparison of the methods used

Common Points

Neural Networks	Iterative regression
Using the minimization of the mean-square (ms) error as prediction error criterion.	Using the minimization of the mean-square (ms) error as prediction error criterion.
More data, better prediction	More data, better prediction

Differences

Neural Networks	Iterative regression
Parallel processing	Series processing
Using exponent function	Using sine function
Using the learning technique	Using the successful iterations
Taking long time for training neural networks (days)	Short processing time if considering only the most significant periodicities
Good fit of reconstructed data to observed data	Medium quality reconstruction
Good prediction for short range	Prediction supposed to be satisfactory for the middle range (about or less than 20% of the sampled interval, depending on the most significant periodicities)

Comparison of the prediction results

Short range (Months)	March/95	April/95	May/95	June/95
Observations (cm)	543	650	622	588
TDNN	446	605	637	83
Relative error (%)	7.76	5.34	2.5	0.7
BPNN	477	606	641	567
Relative error (%)	12.0	6.0	3.0	0.21
Iterative regression	310	332	336	331
Relative error (%)	42.77	48.88	45.95	43.65

Long range (Years)	1996—2001	2002—2023
Neural Networks	381	
Iterative regression	152	299

Analysis of comparison

From the above analysis, we may draw the following conclusions:

1) Both methods are suitable to predict the level of the Paraguay River;

2) For short time period, the predicted results from Neural Networks are better than those from iterative regression;

3) For medium range period, the iterative regression shows better potential for prediction.

CONCLUSIONS

Feed-forward Neural Network, Time Delay Neural Network and iterative regression methods are suitable tools for mathematical reconstruction and prediction of natural multiple cause complex phenomena such as the level of the Paraguay River. Comparing both methods used, the predictors gave acceptable results for different duration ranges. Although the results presented are preliminary, they are promising. Improving the prediction with the help of predictors carefully chosen and investigating theoretical aspects of the predictability of such geophysical and climatologic phenomena will be the objects of further works.

ACKNOWLEDGMENTS

This research was supported by CNPq, under contracts 300585/94-2 and 300031/94-7, FAPESP under contract 93/2715-1.

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Submetido em: 12/03/96
Revisado pelo(s) autor(es) em: 04/06/96
Aceito em: 10/06/96

ESTUDO E PREVISÃO DO NÍVEL DO RIO PARAGUAI USANDO ANÁLISE HARMÔNICA E REDES NEURAIS

Os níveis do Rio Paraguai são influenciados por diversos fatores geofísicos complexos que atuam em várias escalas. Torna-se, portanto, bastante relevante, nos aspectos científicos, sociais e econômicos, a previsão do nível do Rio Paraguai (na cidade de Ladário) com uma certa antecedência (e assim pode-se estimar a área a ser inundada). Neste artigo, redes neurais e análise harmônica por regressão iterativa foram usadas para a previsão do nível do Rio Paraguai. As redes neurais selecionadas para este trabalho compreendem a rede neural "Feed-forward" com lei de aprendizagem com retropropagação e rede neural com atraso de tempo. Ambas foram implementadas no simulador de redes neurais SNNS (Zell et al., 1995). Para analisar a qualidade da previsão nós usamos uma técnica simples independente do método empregado (Gershenfeld & Weigend, 1993; Nordemann & Li, 1996). A partir de 1145 valores mensais médios, a rede neural treinada prediz o nível dos doze meses seguintes com erro médio normalizado ao quadrado NMSE < 0,06 e probabilidade logaritma média negativa NALL < 9,0. Nós comparamos os resultados obtidos pelos dois modelos de redes neurais, de acordo com a análise da qualidade da previsão. O resultado preliminar indica que a TDNN produziu a melhor reconstrução e previsão. Por outro lado, variações no nível do Rio Paraguai baseadas em determinações diárias em Ladário, de janeiro de 1900 até o presente (médias mensais), foram estudadas para se obter o histórico do clima e a relação com fenômenos geofísicos. Estas variações mostram de maneira bem clara, o comportamento complexo dos longos períodos de seca e de inundações. As periodicidades não são evidentes e também pode ser observado que a taxa de vazão não é estacionária. Por estas razões, estes dados foram analisados por diversos métodos matemáticos incluindo a análise de Fourier, periodogramas/ciclogramas, análise espectral dinâmica e regressão iterativa.

Além disto, a determinação das mais importantes funções senoidais embutidas na mesma série permite a reconstrução das principais variações do nível do rio e a previsão dos valores médios anuais para as duas décadas seguintes (supondo nenhuma mudança importante do meio ambiente). Os resultados obtidos mostram que ambos os métodos parecem ser eficientes para processar séries temporais influenciadas por processos climáticos e geofísicos complexos, mesmo sem considerar as relações causais envolvidas nos fenômenos estudados. Eles podem ser usados para prever o comportamento de tais fenômenos em escalas de tempo que dependem especificamente do método usado, do intervalo de tempo e do tamanho dos dados disponíveis.

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  1957-1970 and 1974-1979 - French Atomic Energy Commission - CEA at Low Radioactivity Center - CFR, France
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