ASSESSING THE EFFECTS OF LAND USE CHANGES ON FLOODS IN THE MEUSE AND ODER CATCHMENT

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Abstract

Recently, dramatic flooding occurred in several regions of the world. To investigate the causes of the flooding and the influence of land use, soil characteristics and antecedent catchment moisture conditions, the distributed catchment model LISFLOOD has been developed. LISFLOOD simulates runoff in large river basins. Two transnational European river basins are used to test and validate the model: the Meuse catchment (France, Belgium, Germany and The Netherlands) and the Oder basin (The Czech Republic, Poland and Germany). In the Meuse and Oder catchment, land use change information over the past 200 years is processed at the moment. The LISFLOOD simulation model is used to simulate the effects of these land use changes on floods. Some influences of land use and vegetation on the water balance are clear, such as the changing vegetation cover (leaf area index) which will influence evapotranspiration. However, not so much is known about the influences of vegetation on soil properties, which influence infiltration, soil water redistribution, throughflow and groundwater recharge.

1. Influences of land use on floods

The hydrologic effects of land use changes have been thoroughly described by Calder (1993). The major changes in land use that affect hydrology are afforrestation and deforestation, the intensification of agriculture, the drainage of wetlands, road construction and urbanization.

The most obvious influence of land use on the water balance of a catchment is on the evapotranspiration process (Calder, 1993). Different land use types have different evapotranspiration rates, because different crops have different vegetation cover, leaf area indices, root depths and albedo. During storms, interception rates are different for different land-use types. Although it is recognized, that interception losses represent a significant net addition to catchment evaporative losses (Ward & Robinson, 1990), the influence of interception is noticeable only during small storms and influences only surface runoff rates: they are of minor importance in the largest storm and flood events (Calder, 1993).

Land use also influences the infiltration and soil water redistribution process, because especially saturated hydraulic conductivity is influenced by plant roots and pores resulting from soil fauna (Ragab & Cooper, 1993). An extreme example is the influence of build up areas and roads on overland flow.

Finally, land use influences surface roughness, which controls overland flow velocity and floodplain flow rates.

2. The quantitative effect of land use on soil and land-use parameters

Although the precise effect of deforestation on a catchment water balance is still unclear (Bonell, 1993), there seems to be no doubt that land-use influences hydrologic processes. However, not so much is known on the quantitative effects of vegetation on the above mentioned processes. One of the key questions is how vegetation influences the processes of evapotranspiration, infiltration and soil water redistribution and their controlling parameters.

For example, the hydraulic conductivity of a soil is often measured from samples on soils with only little vegetation, or in between crops. As a result, a relation is obtained between soil texture and conductivity. When there are too many roots or macropores in the soil sample, samples are often abandoned or these samples are never taken at all... So how do we know the influence of vegetation on

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hydraulic conductivity? Within the framework of a soil erosion project in The Netherlands, Ritsema et al. (1996) measured hydraulic conductivity in loess soils for different land use types and soil tillage operations and found some significant differences. These studies are rare, however. There is a need for more detailed information on the effect of land use on hydraulic conductivity.

Information that can be found in literature, are pedo-transfer functions relating soil texture to soil hydraulic properties (Rawls and Brakensiek, 1985) (Wösten et al., 1998). However, influences of vegetation on these properties is not mentioned. Since different vegetation types or crops develop different root systems, the hydraulic properties will be different. Added to that, there is an influence of soil tillage, which is different for each crop.

In the simulation model we have used to study the influence of land use on floods – LISFLOOD, discussed below -, we use leaf area index as an input parameter for interception and evapotranspiration simulation. However, leaf area index values reported in literature for several vegetation and crop types vary enormously (Table 1).

Landuse	Maximum Leaf Area Index
Pine forest	**3.8 - 14.0**
Broad leaved forest	**2.3 - 10.0**
Grassland	**3.5 - 12.9**
Arable land	**4.0 - 18.0**

Table 1. Reported variations in Leaf Area Index for several land use types (BfG, 1995)

Thus, it is clear that the number of field and laboratory measurements on the parameterization of the effects of land use change on floods is currently insufficient.

3. The LISFLOOD simulation model

To assess the influence of land use on flooding and to examine the major source areas of recent European floods, the distributed catchment model LISFLOOD is being developed (De Roo, 1999; De Roo et al., 1999; Bates & De Roo, 2000; De Roo et al., 2000). LISFLOOD simulates runoff and flooding in large river basins as a consequence of extreme rainfall. LISFLOOD is a distributed rainfall-runoff model which takes into account the influence of topography, precipitation amounts and intensities, antecedent soil moisture content, land use type and soil type. LISFLOOD simulates flood events - typically with a 1.5 month duration and includes the pre-flood period of typically a 1 year duration - in catchments using various pixel sizes (1 km or smaller) and with various time steps (1 hour or shorter). A flowchart of the model showing the main processes simulated in the model is shown in Figure 1. A summary of the processes that are simulated is given below:

- Precipitation data from individual stations can be used in LISFLOOD, which are then interpolated using an inverse distance method of the 5 closest stations. Precipitation is corrected for altitude effects, based on precipitation-altitude relations found in the catchment to be simulated.
- Snowfall is simulated when the average daily temperature is lower than 1.0 degree Celsius. Minimum and maximum daily temperature values from stations are interpolated using an inverse distance method of the 5 closest stations, and on each pixel are corrected for altitude.
- Interception of rainfall by the vegetation is simulated using the method of Von Hoyningen-Huene (1981) for all land use except forests, for which the approach of Shuttleworth and Calder (1979) is used. The equations are based on the Leaf Area Index of the vegetation. Seasonal changes of LAI are taken into account.
- Evapotranspiration is simulated using the Penman-Monteith method, as applied in the WOFOST model (Supit et al., 1994, Van Der Goot, 1997). For forests, the Priestley-Taylor equation is used, as modified by Shuttleworth and Calder (1979). Meteorological variables used are temperature, wind speed, sunshine duration, cloud cover and actual vapor pressure, which are all interpolated from station data using an inverse distance method and where appropriate corrected for altitude. The Leaf Area Index of each simulated pixel is used to calculate actual evapotranspiration from potential evapotranspiration.
- Snowmelt is simulated using a degree-day method (Baumgarter et al., 1994), when the average daily temperature is above 0 degrees Celsius.
- Infiltration is simulated using the Smith-Parlange equation (Smith and Parlange, 1978). The capillary drive value is based on topsoil texture. Saturated hydraulic conductivity values are based on topsoil texture and land use. In city areas and on water bodies no infiltration takes place. A correction factor is applied to account for land use influences on infiltration. For example in city areas and on open water surfaces no infiltration takes place.
- Soil freezing is simulated using a degree-day method (Molnau and Bissel, 1983). If the soil is frozen to a certain degree, infiltration is reduced to zero
- Vertical transport of water in the two soil layers is simulated using a one-dimensional form of the Richard’s equation. Soil water retention and conductivity curves are described by van Genuchten's (1980) relationships. Pedotransfer-functions from the HYPRES project (Wosten et al, 1998) are used to calculate the water retention and conductivity curves from soil texture. Both soil texture and soil depth are derived from the European Soils Database (Finke et al., 1998) or local soil maps.
- Percolation to the groundwater store is calculated using the Darcy equation.

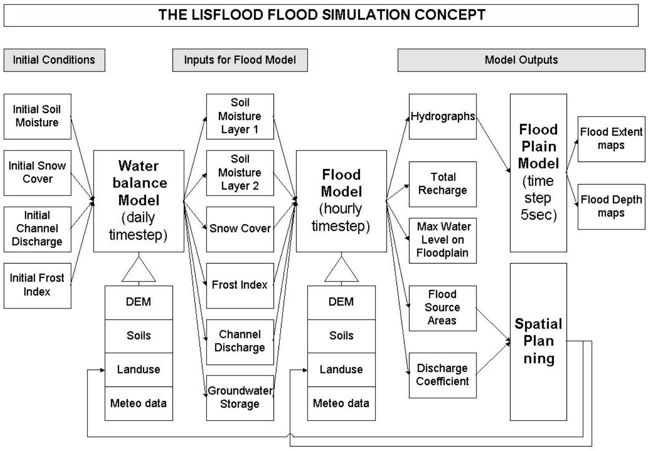

Figure 1. Flowchart of the LISFLOOD water-balance, flood simulation and flood inundation model.

- Groundwater storage and transport to the channel system are simulated with an upper and a lower groundwater zone, and groundwater is then routed using a response function similar to the one adopted in the HBV model (Lindström et al., 1997).
- Overland flow and transport to the channel system is simulated using a four-point finite-difference solution of the kinematic wave (Chow et al. 1988) together with Manning's equation.
- Channel flow is also simulated using a four-point finite-difference solution of the kinematic wave (Chow et al. 1988) together with Manning's equation. The channel and floodplain dimensions (width and depth) are used to calculate the wetted perimeter. A correction of the Manning roughness value is applied to simulate the momentum exchange, which occurs across the shear layer between main channel and floodplain flows.
- Special structures such as water reservoirs and retention areas can be simulated by giving their location, size and in- and outflow boundary conditions (maximum storage volume, minimum and maximum outflow, reservoir management parameters).

Digital elevation data (75 m - MonaPro. and 1 km – GTOPO30), Corine land cover data, soil parameters from the European Soils Database (texture, soil depth, parent material, soil hydraulic parameters) and meteorological parameters from the MARS Meteorological database (precipitation, temperature, vapour pressure, sunshine duration, wind speed, cloud cover) are used for input data to run the model. The actual river network is used together with the DEMs to obtain an accurate flow network in the catchments. LISFLOOD consists of a water balance model, run with a daily timestep, and a flood simulation model, run with an hourly or 15 minute timestep. The flood model starts just a few days before a flood. Outputs from the water-balance model are used as input for the flood model.

4. Deriving Leaf Area Index time series for land use types from satellite data

In order to correctly simulate the effect of vegetation on interception and evapotranspiration, information is needed how vegetation cover varies in the year for each crop type. Based on the Corine land cover classification (44 land use classes), Normalized Difference Vegetation Index (NDVI) profiles were constructed using a series of IRS-WIFS satellite images (180 m resolution) from 1998 (Figures 2 and 3).

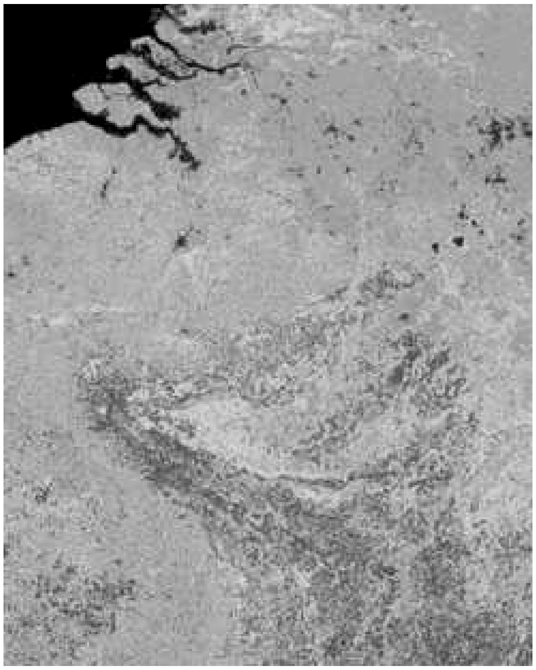

Figure 2. NDVI image for the Meuse catchment, obtained with an IRS-WiFS satellite image.

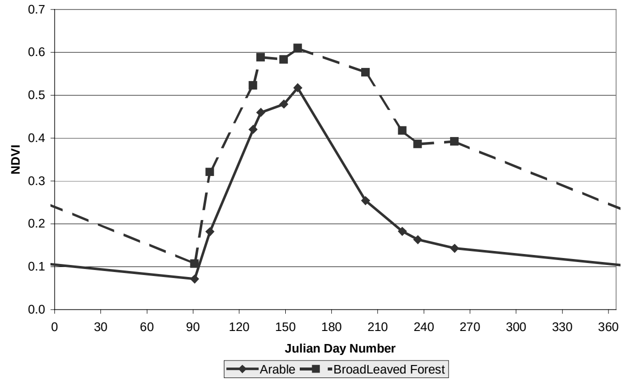

Figure 3 NDVI profiles for arable land and broad-leaved forest, obtained using IRS-WIFS images.

The NDVI is converted to Leaf Area Indices (LAI) by applying a linear scaling technique, because no better results could be obtained by using empirical, exponential

NDVI-LAI relations (Chen and Cihlar, 1996; Wiegand et al., 1992). Linear scaling is applied as follows:

$$LAI = \frac{NDVI}{NDVI_{\max}} \times LAI_{\max}$$

The LAI maxima are derived from literature. Using the NDVI profiles, we then obtain LAI-profiles of the 44 Corine land cover classes. Values in between two satellite images are linearly interpolated. In Figure 4 it is shown how the Leaf Area Index is used in LISFLOOD to calculate actual evapotranspiration from potential evapotranspiration (PET).

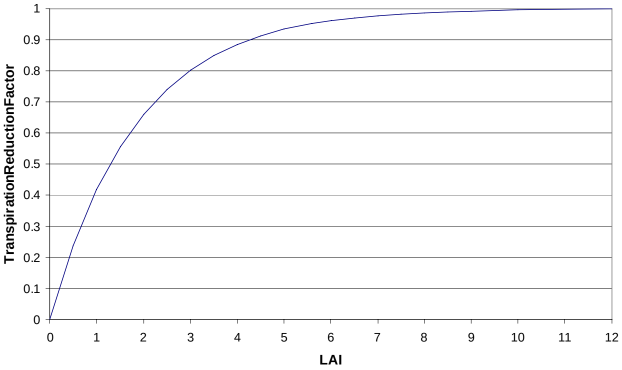

Figure 4. The influence of LAI on reducing the potential evapotranspiration to the actual value.

From Figure 4 it can be seen that LAI values above 6 do not have an additional effect on evapotranspiration. Evapotranspiration will be reaching its potential value, provided that enough moisture is available. This will be the case for forests. Uncertainties in LAI values below 5 will have an effect on the evapotranspiration calculations and thus on the results of any water-balance model. Thus, the reported variations in LAI (table 1) do result in uncertainties in the simulation results. Figure 5 shows the effect of an overall increase and decrease of LAI with 1 and 2. LAI changes of 1 result in a 5% change in the total yearly evapotranspiration and to a 2% change in the average soil moisture storage capacity.

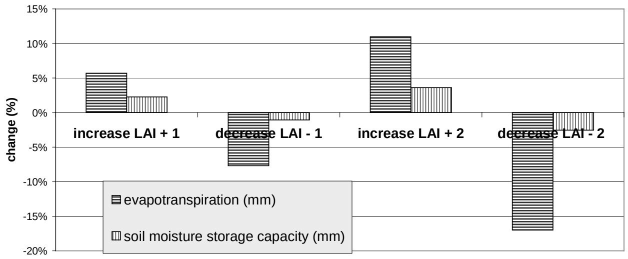

Figure 5. Sensitivity of evapotranspiration and soil moisture capacity in the Oder catchment to uncertainties in Leaf Area Index (LAI) values.

5. Validation

Before we can apply LISFLOOD to simulate the effects of land use changes on floods, the model needs to be validated. At present, LISFLOOD is being tested in the two pilot catchments, the Meuse (32457 km2, upstream of the Biesbos) and the upper-Oder catchment (59162 km2, upstream of Warta confluence). Both catchments are discretized into 1km pixels. However, sub-grid information of land use (100 m resolution) and elevation (75 m resolution) is used to calculate effective parameters at the 1 km scale. In each of these catchments, sub-catchments are selected to run and test the model with a finer special resolution: 100 m. In the Meuse catchments, LISFLOOD is tested and applied to 10 flood events: 5 for calibration, and 5 for validation. These flood events include the 1993 and 1995 floods. For the Oder catchment, 3 historic floods are available for validation and testing: summer 1977, summer 1985 and the summer 1997 flood. The water-balance model is always run over the two years before the flood, so 1976-1977, 1984-1985 and 1996-1997. Because the validation has started recently, only preliminary results can be shown.

For the Meuse catchment 58 stations with hourly rainfall data are used for the flood model and 33 stations with daily meteorological parameters are used for water balance modelling. Figure 6 shows a comparison between measured and simulated discharge in January 1995 in the Meuse catchment (station Borgharen, the Netherlands), showing a good agreement. These are preliminary results (before calibration! and further validations) and no conclusions can be made. However, the results appear promising.

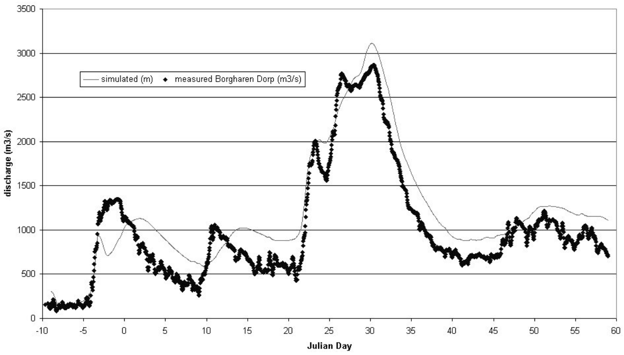

Figure 6. Measured and simulated discharge at Borgharen-Dorp (Meuse catchment, The Netherlands), during the January 1995 flood (measured data provided by the Dutch Water Authorities, RWS Maastricht).

For the Oder catchment, currently 100 stations with daily and hourly rainfall are used for the flood model, and 90 rainfall stations and 18 stations with other meteorological parameters are used for water balance modelling. Initial results for the Oder catchment show that the simulation of the flood hydrographs in the upstream section of the Oder and in the tributary catchments is reasonably good, but the simulation of flood hydrographs in the downstream section of the main river Oder is a problem. During the 1997 Oder flood many dike breaks occurred, and these, together with human influences such as water reservoir operations in the Czech and Polish mountains, combine to complicate the simulation of the flood hydrograph in the Oder river. Figure 7 shows a comparison of measured and simulated discharge at Miedonia (Poland), close to the Czech border. In Figure 7 and several other hydrographs, the peak time is simulated earlier than measured. A possible explanation for this might be storage of water in reservoirs during the initial phase of the flood. In the version of LISFLOOD presented here, reservoirs were not yet simulated. The reservoirs had a small flood storage potential, and shortly after the beginning of the flood the outflow rates had to be set at maximum to prevent reservoir overtopping.

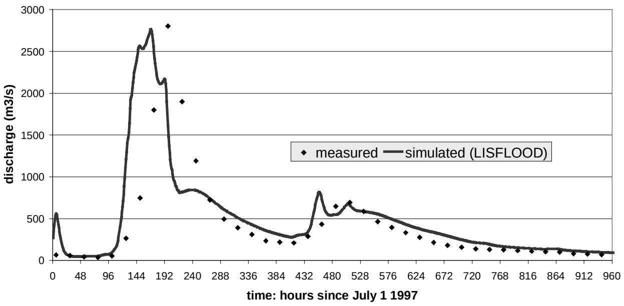

Figure 7. Measured and simulated discharge at Miedonia (Oder catchment, Poland), during the July 1997 flood. Measured data provided by IMGW, Wroclaw, Poland.

For the Oder catchment, validation and testing of the water balance model is performed using daily discharges and a series of calculated potential evapotranspiration data provided by the IMGW Polish water authorities using the Jaworski method (Wozniak, 1999).

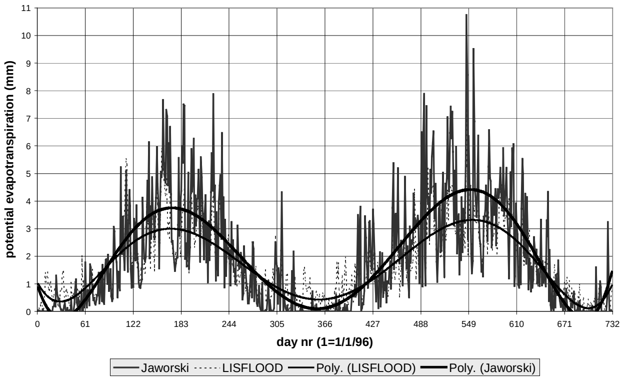

Figure 8a Potential daily evapotranspiration values (mm) as calculated with LISFLOOD and with the Jaworski method (Tomaszúw Gúrny station, Poland).

Current analysis shows that the LISFLOOD simulations of potential evapotranspiration are in general lower than the Polish calculated evapotranspiration data (Figure 8b): in winter LISFLOOD values tend to be higher, whereas in summer LISFLOOD values tend to be lower (Figure 8a). The probable explanation for this is the influence of advection in summer. Also, the daily discharge values showed that LISFLOOD was over-estimating discharges. The differences in potential evapotranspiration calculations can be caused by several factors: the algorithms used, and the source data used. At the moment LISFLOOD is being calibrated on the potential evapotranspiration calculations to better fit the Jaworski calculations and improve the water-balance discharge simulations.

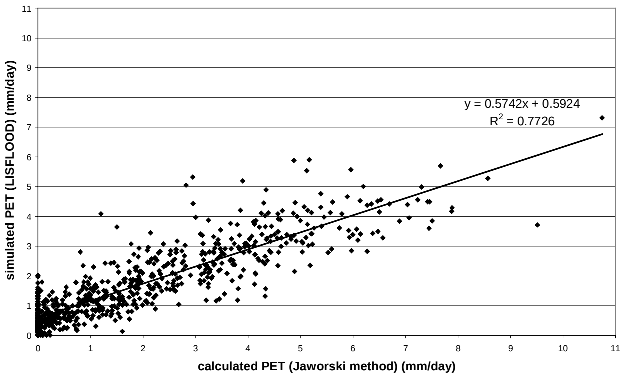

Figure 8b. Potential daily evapotranspiration values (mm) as calculated with LISFLOOD and with the Jaworski method (Tomaszúw Gúrny station, Poland).

6. The effect of catchment land use changes on floods in the Meuse and Oder catchment

Although it has been discussed above that there are many uncertainties in parameter estimation to simulate the effects of land use changes on floods, and although the validation and testing of LISFLOOD are not yet completed, several simulations have been carried out with LISFLOOD in the Meuse and Oder catchment.

For the Oder catchment, CORINE land cover information of 1992 is available. Landsat MSS images of 1975 have been used to obtain a similar land cover classification of 1975. At the moment, work is ongoing to obtain recent land use changes (CORINE 2000) and historic land use changes over the past 200 years. Analysis showed that between 1975 and 1992 no major changes in land use occurred and therefore no hydrologic changes were simulated by the LISFLOOD model.

For the Meuse catchment, also CORINE 1975 and 1992 data were available. Also here, work is ongoing to obtain historic land use over the past 200 years (Stam & De Roo, 1999). In the Meuse catchment, there have been slight changes in land use between 1975 and 1992. To simulate the effect of land use changes on floods, the 1995 flood event has been simulated both with the 1992 land use and with the 1975 land use. Differences occur especially in the initial conditions before the flood, obtained with the daily water-balance model. On average, soil moisture storage capacity just before the flood period is reduced from 210 mm using the 1975 land use, to 198 mm using the 1992 land use because of evapotranspiration differences: a decrease of 5.85%. When these initial conditions are used to run the flood simulation model, the peak discharge as a result of the 1992 land use is 0.20 % higher than the peak discharge simulated using the 1975 land use. The total volume of water simulated during the flood is 4.06% larger. The peak water level at Borgharen is 1 cm higher when the 1992 land use is simulated as compared to the 1975 landuse.

LISFLOOD output	landuse1975	landuse1995	change (%)
peak discharge (m3/s)	3099	3105	0.2
total discharge (M m3)	7621	7930	4.1
cumulative evapotranspiration before the flood (mm)	486	429	-11.7
initial soil moisture storage capacity (mm)	210	198	-5.9

Table 2. Hydrological changes in the Meuse catchment – simulated with the LISFLOOD model - as a consequence of land use change

7. Conclusions

The influence of land use and land use changes on hydrological processes and process parameters is not yet well quantified. Therefore, simulating the effects of land use change on hydrology leads at present to results that carry quite a bit of uncertainty. Obvious effects are that a forest cover will increase the evapotranspiration, and that urbanization will reduce evapotranspiration and infiltration and increase surface runoff. From simulations in this paper with the LISFLOOD model, no changes in land use and thus hydrology are found in the Oder catchment between 1975 and 1992. In the Meuse catchment, land use has changed from 1975 to 1992 such that the flood risk has become slightly larger. The initial soil moisture storage capacity just before the flood is reduced by 12 mm (6%), the peak discharge is increased by 0.2% and water level is 1 cm higher. Considering the uncertainty of several input parameters used in the model, the results should be interpreted with care.

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