LANDPINE – A Hydrological Model to Simulate the Influence of Land-Use Changes on Runoff

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Margins: This paper describes a distributed hydrological model, LANDPINE, which has been developed and used to study how changed land-use may affect the runoff from catchments. The model was implemented within a simulation framework called PINE, Rinde [1998], on WindowsNT platform, and it operates in integration with a geographical information system, which is used for preparation of input data, and analysis and presentation of simulation results. The model accounts on a distributed basis for interception in high and low vegetation, storage of water on the ground surface, evaporation and transpiration, accumulation and melting of snow, infiltration, retention of water in the soil, and generation of surface runoff and outflow from the soil. Water movement in rivers and outflows from ground water reservoirs are described by help of an aggregated response function. The model was used to simulate runoff from one large catchment (1200 km^2) with varied land-use, and three smaller catchments (<10 km^2) characterised by relatively homogeneous land-use. For the large catchment several historical periods, characterised by different land-use, were used as a common calibration data set. Land-use effects was afterwards investigated by re-simulating the periods while switching land-use situations. This indicated that changed forest conditions due to use of clear-cutting instead of selection felling as logging practice, had increased total runoff by 4%. The smaller catchments were calibrated to the present land-use situation. Then hypothetical scenarios of afforestation and deforestation were run. These showed a change in runoff dynamics towards higher and more violent flood events, and earlier onset of melt floods.

1. BACKGROUND

In the spring of 1995 Norway suffered the biggest flood of this century. The flood created damage in the order of 235 mill. USD and was caused by a combination of large snow pack, late spring, high air temperature and unusual although not extreme precipitation. After the flood, the Norwegian government agreed to fund a 3-year research programme, called HYDRA, whose main objective was to investigate how human activities may affect flood regimes in rivers. Four topics were selected as particular areas for research. These were: (1) effects of hydropower regulation, (2) effects of urbanisation, (3) effects of changed land use, and (4) effects of river embankments and other flood-protection structures. The largest river in Norway, the Glomma River (42,000 km^2), was selected as study area.

The participants in the HYDRA-project were organised into working groups. Four groups studied the effects of man-made encroachments within the defined research areas. These groups were assisted by a fifth group that provided database services and GIS support. The results from the separate studies were finally brought together in a sixth group, which performed integrated river-system modelling. Each of the working groups have reported on the connections between natural resources and human activities on the one hand and floods and flood damages on the other. Measures has further been proposed to prevent damaging floods and flood damages in the future.

One result of the project has been the development of modelling tools that can facilitate improved decision making, operation, and analysis of river systems. A modelling framework has been developed, which allows river-system models to be established as assemblies of sub-models for different system components, Killingtveit et al. [1998]. A distributed hydrological model particularly designed to simulate the effects of land-use changes on runoff has also been developed. This model is presented below.

1.1 Introduction

The working hypothesis of the HYDRA-project was that: "*the sum of man-made encroachments in Norwegian river-systems has increased the risks for floods*". In order to test this hypothesis, it was decided to make quantitative estimates of the effects of the various encroachments with the help of simulation models. Among the encroachments that were believed to be significant, was land-use changes. During the last 100 years such changes have emerged from agricultural development, afforestation and deforestation, drainage of wetlands, and community development and urbanisation. A hydrological model was therefore needed, that could explicitly represent catchment characteristics which are influenced by such activities.

1.2 Basis for the model development

No model was found to fulfil these requirements to a full extent. It was therefore decided to develop a new model for the simulation of land-use effects. Two requirements were put on the model that was to be developed: (1) it should contain an explicit representation of the catchment characteristics that will change if land-use is changed and which are relevant to runoff, and (2) it should not require more input data than what is generally available for operational modelling in Norway, i.e. only precipitation and temperature data. The challenge thus became finding process descriptions which had a sufficient physical basis and at the same time were enough parsimonious in their input requirements. The PINE-system, developed by Rinde [1998], was selected as basis for the model development.

2. THE LANDPINE MODEL

The resulting model, the LANDPINE-model, accounts on a distributed basis for interception in high and low vegetation, storage of water on the ground surface, evapotranspiration, accumulation and melting of snow, infiltration, retention of water in the soil, and generation of surface runoff and outflow from the soil. Water movement in rivers and outflows from ground water reservoirs are described by help of an aggregated response function. Figure 1 shows the general model structure of the LANDPINE-model, whereas Figure 2 shows the representation used in the grid-cells. The various processes in it are described below.

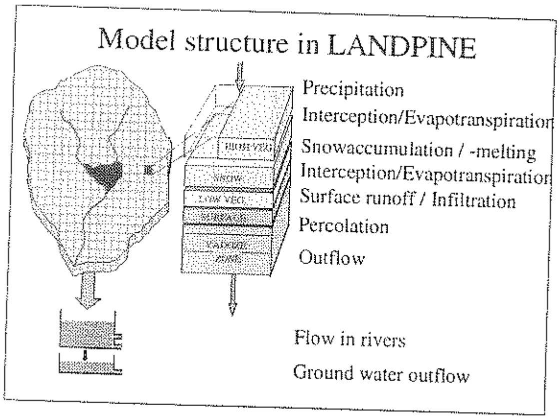

Figure 1 Model structure of LANDPINE.

2.1 Meteorological input

Temperature and precipitation input can be imported to the model either as records of point measurements from a number of gauging stations, or as distributed values, e.g. as generated by a meteorological model. In the case of point measurements, the recorded precipitation is first corrected for inaccuracy of the measurement device by multiplying it by a correction factor. A threshold temperature is used to classify the precipitation as rain or snow, and a different correction factor is used for the two cases. Then a spatial interpolation is performed to produce the temperature and precipitation distributions. Both temperature and precipitation values are here adjusted for difference between local surface elevation and the elevation to which the input values refer. For temperatures different lapse rates are used for time steps with and without precipitation.

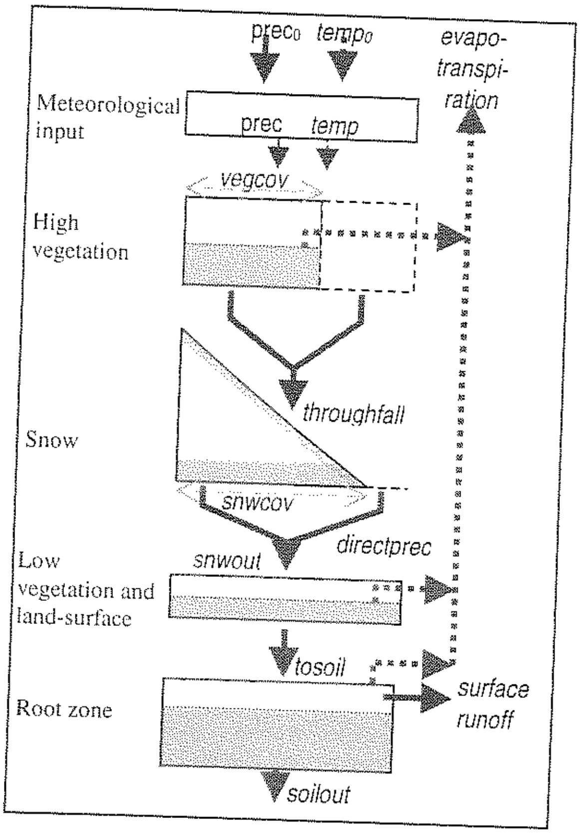

Figure 2 Representation of grid-cell processes.

2.2 High vegetation

High vegetation is represented in the model in terms of five parameters. These are the maximum and the minimum seasonal leaf-area index, the specific storage capacity per leaf-area index unit, the vegetation coverage factor, and the average height of the vegetation stand. In each timestep an interception capacity and a potential evaporation rate is calculated along with actual values for interception and evaporation. To account for the fact that a stand may not be fully grown, and for variation in canopy development in the course of the year, the interception capacity is modified by two other factors which are functions of vegetation height and accumulated temperature degrees above a selected threshold for canopy growth, respectively. These factors ensure a proper progression in interception capacity as trees grow or are removed, and in the transitions between winter and summer periods.

Potential evaporation is calculated from monthly values for normal potential evaporation per day. These values refer to average climatic conditions, and a standardised surface type. If temperatures deviate from their normals, a linear function is used to adjust the potential evaporation rate up or down. In periods with precipitation, air humidity is assumed higher than normal, and a reduction is imposed on potential evaporation. Potential evaporation rates can also be adjusted for deviations in wind speeds from their monthly means. Vegetation height influences potential evaporation in that the exchange of air masses generally occurs more efficiently high above the ground than close to it. High vegetation therefore lead to higher potential evaporation than low vegetation. This effect is dealt with by an adjustment factor being the ratio of actual vegetation height to the defined standard height for vegetation, restricted by a maximum and a minimum boundary. Actual evaporation from interception in high vegetation is taken as the potential evaporation rate multiplied by the vegetation coverage factor. If the intercepted water is in the form of snow then the evaporation rate is reduced by a factor specified by the user. In each time step, incoming precipitation is used to fill up the interception storage. When the interception capacity is reached, excess precipitation forms throughfall to the ground or the snow surface.

2.3 Snow

If local air temperature is lower than the rain / snow threshold, the throughfall from high vegetation goes to increase the snow layer. If the temperature is higher, the throughfall instead goes to increase the liquid water content in the snow, or, if no snow is present, it passes on to the lower interception storage. In each grid-cell, the snow distribution can be linearly biased. A distribution factor is then used to specify the relative magnitudes of the maximum and minimum storage values in the cell. If the distribution factor is set to unity, the snow pack becomes homogeneous. If it is set equal to 2.0, the maximum value becomes twice the average value, and the minimum value becomes zero. If it is set higher than 2.0, only partial snow cover will be simulated. The three situations are illustrated in Figure 3 a to c.

Snow melt is calculated as a melt factor times the temperature degrees above a melt threshold, i.e. according to the degree day principle. In forested and partly forested areas the melt factor is reduced. This causes reduced melt intensity and hereby delayed snow melting in forested areas compared to open land. If air temperature is lower than the melt threshold, refreezing of liquid water in the snow is calculated as a refreeze factor times the temperature degrees below the threshold. Snowmelt, as well as refreezing, is assumed to be homogeneous across the snow surface. Melted snow is added to the liquid water content in the snow. A separate parameter specifies the maximum relative amount of such water that can be withheld in the snow. If the relative amount becomes larger than this fraction, the excess forms outflow from the snow. Throughfall on the snow-free parts contributes directly to the outflow.

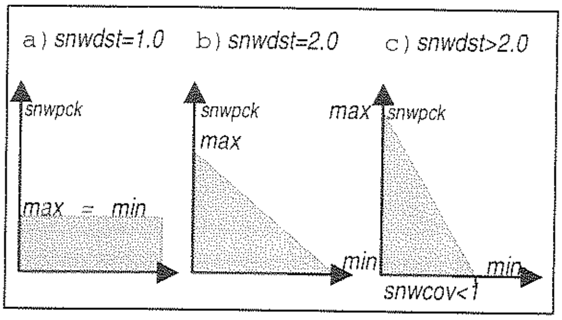

Figure 3 Snow distribution inside grid-cells.

2.4 Low vegetation and land-surface

An interception storage given by a leaf area index value times the specific storage capacity per leaf area index unit is also considered for low vegetation. The storage is lumped together with a wetting storage for the land surface. The storage is filled by outflow from the snow routine. When the storage capacity is exceeded, excess water may infiltrate to ground, or form surface runoff if the infiltration capacity is also exceeded. As for the high interception storage, actual evaporation is also here assumed to occur at a potential rate. This rate is now however reduced according to the actual evaporation that has already occurred in the high interception storage.

2.5 Root-zone

Inflow to the root-zone is limited by an infiltration capacity. Any throughfall or outflow from snow above this threshold forms surface runoff. The storage of water in the zone is similarly limited by a field capacity. If the root-zone is fully saturated, any incoming water will simply pass directly through and form river runoff. If the zone is partially filled, the entering water is split into two fractions. The first will increase the moisture content in the zone itself, and the second contributes to runoff. The relative magnitudes of the two fractions are given by a non-linear relationship as shown in Figure 4. It shows that a larger portion of incoming water will be retained in the zone if the soil is dry than if it is wet.

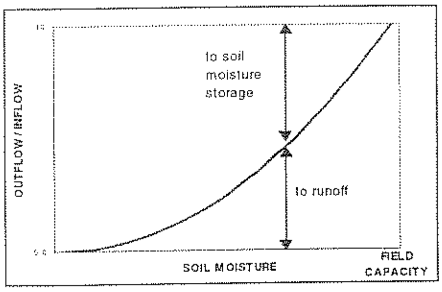

Figure 4 Non-linearity in root-zone

Depletion of water in the root-zone can only happen through transpiration. Under wet conditions transpiration is assumed to occur at a potential rate, which now is reduced according to the actual evaporation that has already taken place in the high and the low interception storage. As the soil dries out the transpiration rate is also reduced according to the soil saturation deficit. However, since a certain saturation deficit must be reached before plant uptake of water becomes noticeably hindered, this reduction is first considered when the relative soil moisture content falls below a specified threshold value. A reduction factor is finally used to account for the fact that transpiration intensity is lower for small trees than for fully grown stands.

2.6 Ground-water and surface-water

Outflow from ground water reservoirs and flow through rivers and lakes is not described in a distributed manner. Instead the sum of soil and surface runoffs from all the grid-cells are provided as input to a lumped response routine consisting of two linear tanks (see lower part of Figure 1). In the response routine, which is similar to the one used in the HBV-model, Bergstrøm [1976], the upper tank accounts for the retention of water in rivers, whereas the lower tank describes outflow from ground water reservoirs.

3. LARGE SCALE SIMULATIONS

In order to study the effects of land-use changes on runoff, the model was first calibrated to the sub-catchment Osensjøen ($A=1178$ km^2), in the Glomma river. Here land-use data was available all the way back to 1920. The periods 1920-30, 1960-70, and 1985-95, were used as a common basis for calibration and verification of the model. Maps of vegetation type, coverage, and height were digitised from historical records on forestry and agriculture. Together with soil information, these were used to generate interception capacity and field capacity distributions. Surface types, such as forests, bogs, fields, urban areas, and lakes were also digitised. These showed little change between the periods and were assumed constant in the simulations.

The most significant land-use change that was identified in the period of study was caused by the changes in forest management practice which took place around 1950. Compared to 1920, the introduction of clear-cut areas lowered the average tree height by 24 % in 1960. At the same time, however, the average vegetation density increased by 5 %, and most for the highest stands. In sum a 12 % increase in total interception capacity resulted. From 1960 to 1990, the clear cutting practice was extended, but without causing significant further increase in the interception capacity. Figure 5 shows some of the geographical data that were used for the Osensjoen catchment, and also the development in vegetation height between the three time periods. The calibration results are shown in Figure 6 and in Table 1.

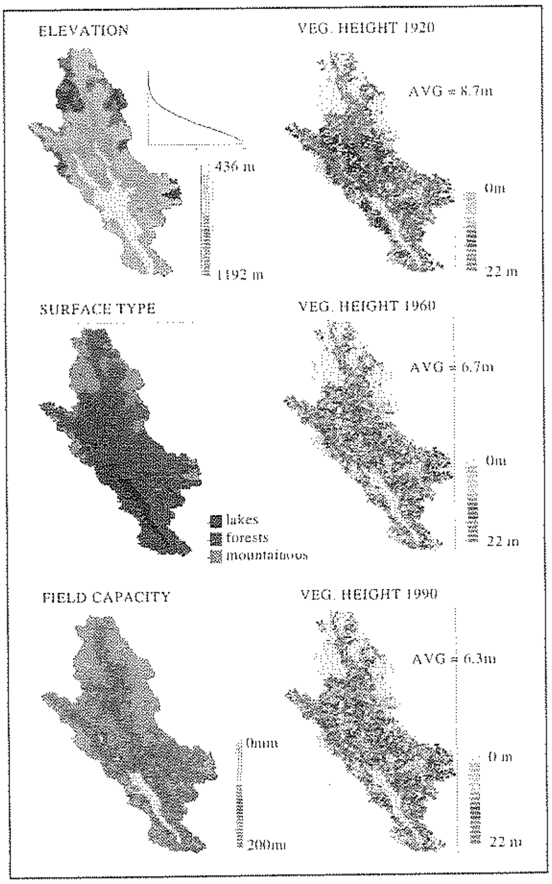

Figure 5 Geographical data for Osensjøen.

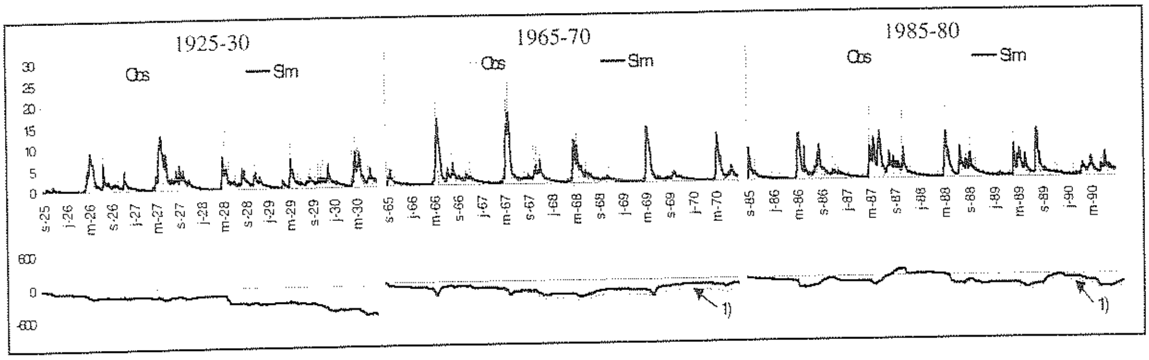

Figure 6 Simulated runoff from Osensjøen.

Simulation Period	R^2 Calibration	R^2 Verification	Vol. error [mm] Sim. – Obs.
1920-25		0.51	-777
1925-30	0.64		-519
1960-65	0.62 (0.63[1])		49 (-87[1])
1965-70		0.69 (0.68[1])	-75 (-177[1])
1985-90		0.59 (0.54[1])	-121 (-194[1])
1990-95	0.71 (0.71[1])		-300 (-402[1])

[1] Re-simulation with land-use situation from 1920.

Table 1 Calibration results for Osensjøen.

To investigate whether the land-use changes that had occurred during the period of study had affected on runoff, the periods 1960-70 and 1985-95 were re-simulated, using the land-use situation from 1920 as input. An average of 4 % reduction in total runoff volume was found (see lines and figures marked [1] in Figure 6 and Table 1). At first glance this could seem contradictory to the increase that was found in interception capacity from 1920 to 1960, which would suggest less runoff for the 1960 situation than for that of 1920, since a larger interception storage gives rise to higher evaporation loss. However, the clear cutting practice had also lowered the average tree height in the catchment. This influences the calculation of potential evaporation, and thereby also the evaporation from interception storage and transpiration from the root-zone. A closer look at the simulation results revealed that this effect by far exceeded the first one. On average, the total evapotranspiration loss was 14 % higher for the land-use situation of 1920 compared to those of 1960 and 1990. Figure 7 shows the calculated actual transpiration on a certain day when the two different land-use situations are used as input to the model.

4. SMALL SCALE SIMULATIONS

For the Osensjøen catchment, no noticeable changes could be observed in the dynamics of the simulated runoff, when switching the land-use of the two latter periods with that of 1920. For that, the actual land-use changes were too small. The model was therefore calibrated to a number of smaller catchments, characterised by having relatively homogeneous land-use conditions. Hypothetical land-use changes, such as total deforestation or afforestation, were afterwards introduced, in order to see how that influenced on the dynamics of the simulated runoff. Figure 8 shows the catchments that were calibrated and Table 2 summarises the calibration results.

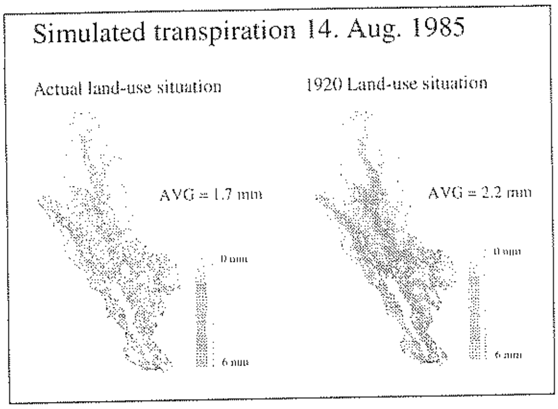

Figure 7 Simulated transpiration for different land-use situations.

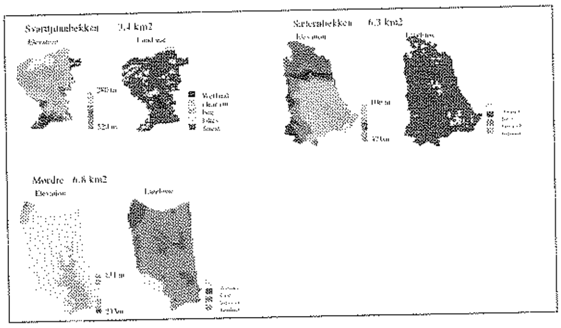

Figure 8 The small catchments used.

	R2	Vol. error [mm] Sim. – Obs.
Svarttjønnbkn. (1982-87)	0.78	-26
Skuterud (1993-98)	0.53	-71
Mørdre (1991-96)	0.59	-49

Table 2 Calibration results for small catchments.

For Svarttjønnbekken, a reduction from 88 % to zero % forest cover was considered. This was found to increase runoff by an average of 165 mm (7 %) per year, due to a corresponding reduction in evapotranspiration loss. It also had a remarkable impact on the runoff dynamics. Spring floods in average increased by 60 % in peak value, and they also came earlier and more abruptly. This was cause by the intensified melting in open areas compared to forested areas. Floods in summer and in autumn on the average increased by 35 %. Also these showed a more abrupt behaviour. Some small floods even showed an increase of more than 150 %. This was mainly caused by a higher soil moisture filling due to reduced transpiration, and thus lead to less buffering capacity in the soil prior to the precipitation events.

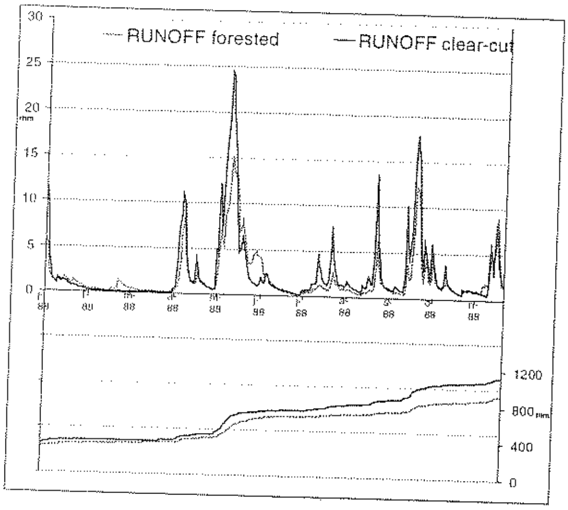

Figure 9 Simulated runoff if deforestation in Svarttjønbekken.

For the Mørdre and the Skuterud catchments, which are characterised by 65 % and 61 % agricultural land, respectively, a scenario of complete afforestation was run. The simulated effects on runoff was an average reduction of 220 mm in annual volume. The general effects on the runoff dynamics were opposite to those obtained in the deforestation scenario that was run for Svarttjønnbeken.

5. DISCUSSION AND CONCLUSIONS

In the HYDRA-project, modelling tools are used to analyse the effects of man-made encroachments on runoff in river-systems. The tools should be applicable to catchments in general, and facilitate operational use after the project. This has limited the data that could be available for hydrological modelling. In practice, only precipitation and temperature data are recorded, sometimes along with wind speeds. LANDPINE was developed to simulate the effects of land-use changes on runoff. The simulations have shown that LANDPINE is able to this adequately. Land-use characteristics may be explicitly specified in simulation setups, which allows for "what if" scenarios for changed land-use.

For Osensjøen LANDPINE was able to simulate three periods of different land-use situation, using a common set of parameter values. Re-simulating the periods for the initial land-use situation indicated that the actual land-use changes have lead to a 4 % increase in total runoff. Scenario simulations of afforestation and deforestation in the small catchments, indicated that deforestation leads to increased runoff and higher flood peeks because evapotranspiration loss is reduced. It also leads to earlier onset of spring floods since melt rates are higher for open compared to forested areas. The simulated effects of deforestation and afforestation on runoff agrees with what was presented by Brandt et.al. [1988].

The LANDPINE-model requires distributed vegetation data, which is cumbersome to extract from maps or other non-digital sources. Within a research project called ARSGISIP, Fluegel & Mueschen [1998], an attempt is presently made to acquire the distributed vegetation parameters from remote-sensing techniques.

6. REFERENCES

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