River parameters and discharge estimation at the Otemma glacier forefield

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Measurement goals

Projects being conducted in the Glacier d'Otemma proglacial margin required time-series at high resolution for stream discharge, water temperature, electrical conductivity. The time-series were needed for three gauging stations : (1) at the glacier snout (upstream of the main proglacial braidplain); (2) downstream of the braidplain and (3) 1.2 km downstream at the limit of selected catchment boundary.

Choice of gauging station locations and monitoring approach

Three gauging stations were installed and maintained from July 2019 to October 2021 (Figure 1). Sites were chosen where the river flow was confined to a single channel, collecting all stream water. At all gauging stations, two sensors for discharge estimation and one sensor for suspended sediment concentration estimation were installed.

The first gauging station (**Station 1**, WGS84 coordinate: 7.419497642° East, 45.937451950° North) was located about 140 m from the glacier snout at a place where all subglacial drainage channels had converged to form a single channelized river. This site allowed for discharge estimation. The second sensor for discharge estimation at gauging station 1 was installed at the first suitable site downstream, a distance of 120 m, and was designed to provide a check on the gauging station 1 discharge estimations.

The second gauging station (**Station 2**, WGS84 coordinate: 7.407790045° East, 45.931758075° North) was installed at the downstream end of the braided outwash plain and was composed of two sites separated by 75 meters, similar to site 1. Both sites are located outside the braided channel system so that the total flow is confined to a single channel.

The third gauging station (**Station 3**, WGS84: 7.39673° East, 45.92446° North) was installed at the selected catchment boundary were the river is strictly constrained by steep bedrock valley sides. This station was not used for discharge estimation.

The equipment installed at each gauging station comprised: (1) a **Campbell** Scientific CR.200 datalogger, a CS451 pressure transducer to measure flow depth and a temperature sensor, located at the upstream; (2) a **Keller** DCX-22AA-CTD logger and pressure transducer, located to the downstream.

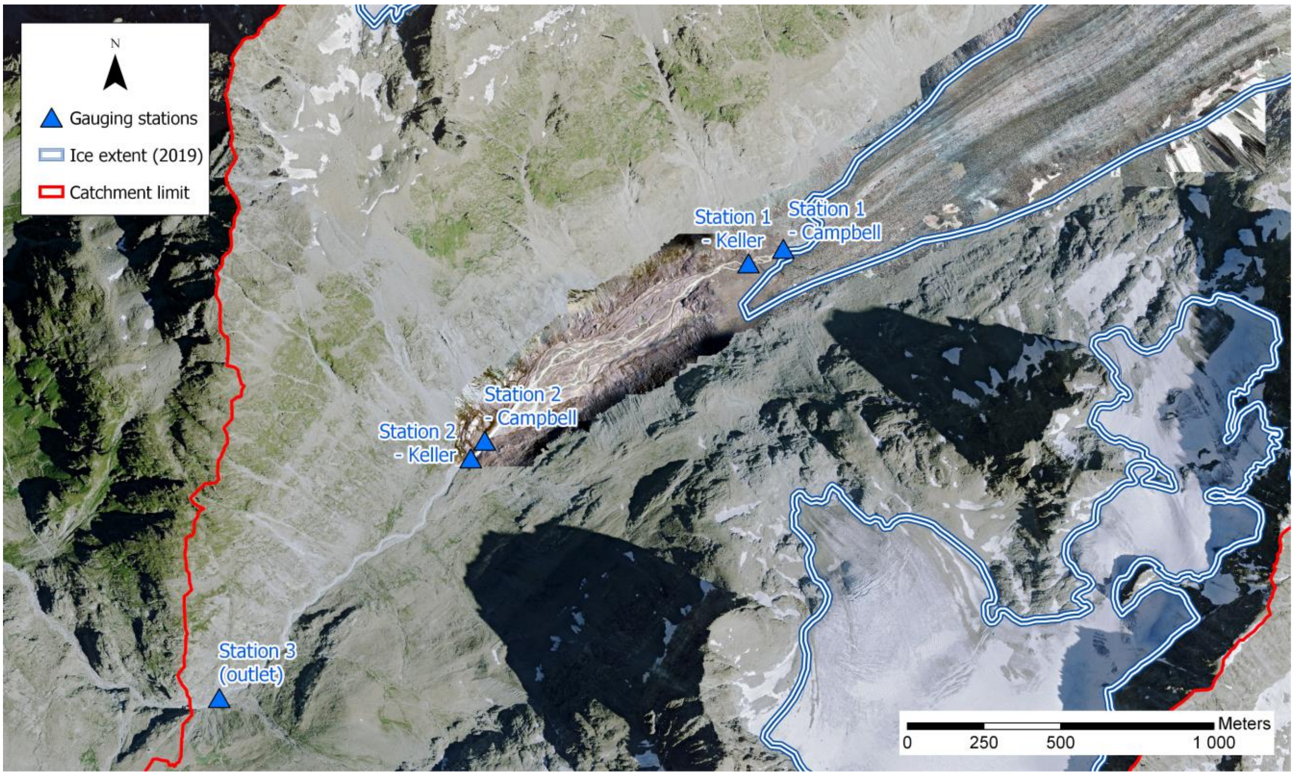

Figure 1: Location of gauging stations in the glacier forefield of the Otemma glacier.

Sensor characteristics, data availability and resolution

The Campbell system involved a pressure transducer being mounted in the lower end of aluminium tubes, which were anchored to the bedrock or large boulders along the river bank. Data recorded from July 2019 to September 2021 only during the summer months (July to September). Measurement frequency varied across the years but was mainly set to a 2-minutes interval based on single measurements.

The Keller system measured stage using the built-in Absolute-Absolute difference method, consisting in one atmospheric absolute pressure sensor and one submersible absolute pressure sensor. Total Error Band of the sensor for stage (according to manufacturer) is 0.0075 meters H_20. No temperature dependence is observed between -10°C to 40°C. Sensor precision was manually verified and cleaned every 2 weeks. Data were collected from July 2019 to September 2021. Measurement frequency varied across the years but was mainly set to a 5 or 10 minutes interval during the summer and 30 minutes during the rest of the year to guarantee sufficient data storage space.

A detailed representation of data availability and measurement frequency for stage records is provided in Figure 2.

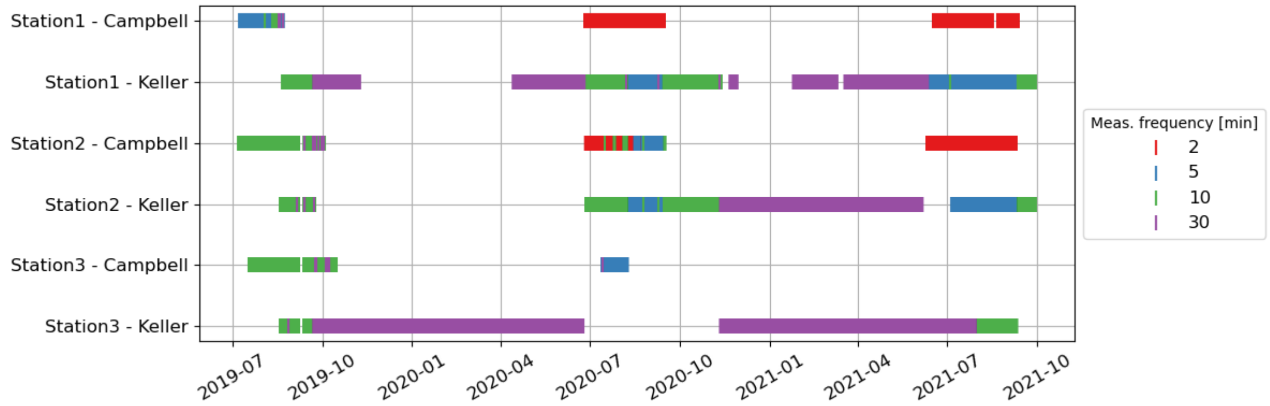

Figure 2: Data availability for river stage and measurement frequency for each stations from 07.2019 to 10.2021

River parameters measured were stage and water temperature for the Campbell stations. Electrical conductivity (EC) was also recorded at the Keller stations. Electrical conductivity measurements failed more regularly than stage records due to clogging of the sensor by fine sediments. The probe was regularly cleaned and recalibrated using a 100 µS/cm calibration solution (every 2 weeks in summer, once in January). Discharge estimation was only conducted at Station 1 and Station 2. Sensor type, parameters and accuracy are summarized in Table 1.

Table 1: Description of sensors installed at each gauging station. Measured parameters as well as accuracy are also detailed. Dates at which each sensor was used for discharge estimation is also described.

Station location	Company	Sensors type	River parameters	Full scale (FS) measurement band	Accuracy (total error band)	Discharge estimation
Station 1	Campbell	CS451 pressure transducer	Stage Temperature	0… 1.0 bar 0… 60 °C	±0.1% FS (0.01 mH_2O) ±0.2 °C	summers 2020 & 2021
	Keller	DCX-22AA-CTD	Stage Temperature Electrical conductivity	0… 1.5 bar -10… +40 °C 0…200 µS/cm	± 0.05 %FS (0.0075 mH_2O) ±0.5 °C ± 2.5 %FS (5 µS/cm)	July 2020 to October 2021
Station 2	Campbell	CS451 pressure transducer	Stage Temperature	same as above	same as above	summers 2020 & 2021
	Keller	DCX-22AA-CTD	Stage Temperature Electrical conductivity	same as above	same as above	July 2020 to October 2021
Station 3	Campbell	CS451 pressure transducer	Stage Temperature	same as above	same as above	no
	Keller	DCX-22AA-CTD	Stage Temperature Electrical conductivity	same as above	same as above	no

Discharge measurements for calibration – year 2020

The next sections describe the discharge estimation procedure for 2020. Discharge was also estimated in 2021, following a similar procedure and only be briefly discussed.

48 river discharge measurements were performed at both stations (27 for Station 1 and 21 for Station 2) approximately twice per week when weather conditions permitted, at varying intervals during the rising limb of the diurnal hydrograph. Discharge was not estimated at Station 3.

Between 19 July and 09 September 2020, dilution gauging was based on fluorescence dye tracing using commercially available Rhodamine WT 20% and an Albillia Fluorometer GGUN-FL30 which recorded single measurements at 5 second intervals following dye slug injection. The sensor has a linear detection range between 0.2 – 400 ppb and can correct for turbidity up to 400 NTU as well as for temperature (Dahlke, 2014).

Salt dilution gauging was used for discharge lower than 0.5 m^3/s later on, using a WTW Multi 3510 IDS logger with a IDS TetraCon® 925 water conductivity probe with temperature correction, recording single measurements at an interval of 1 second. Water conductivity was converted to salt concentration using an onsite calibration.

Tracer solution were always injected upstream of the gauging stations while sensors were located downstream, at approximately 50 m distance from the injection site to ensure full mixing of the tracer.

Stage-discharge rating curves : year 2020

River stage data processing

In order to reduce measurement noise, we used a light smoothing algorithm for each datasets based on the Savitzky-Golay filter (from python's *scipy.signal* library), using a window of 10 points and a third order polynomial. This filter allowed for a good representation of short-scale (minutes to hours) fluctuations, while efficiently removing random noise.

Every stage dataset was plotted against all other datasets to detect any deviations which may have occurred due to slight displacement of the probe after cleaning and were manually corrected where necessary.

Discharge calibration

The stage-discharge rating curve is shown in Figure 3. The relationship between stage (h) and discharge (Q) was defined by a typical power law function of the form $Q = a + b \cdot h^c$. Because the sensor is never located at the exact river lowest point, the curve is not constrained to pass by the origin, allowing a residual discharge when the stage is null. The best fit was calculated directly with the power function using the Levenberg – Marquardt algorithm, which is used to solve non-linear least squares problems by iteratively minimizing the sum of the squares of the deviations.

In order to assess the uncertainty, the algorithm also provides the confidence interval (CI) of the fit on the estimated parameters (a,b,c), which error can be propagated on the discharge (red area in Figure 3).

Moreover, because there is a significant uncertainty in the point discharge measurements, as well as in the stage measurements, we defined a normally distributed error for both stage and discharge. For stage, we defined a Gaussian distribution with a standard deviation (σ) of ±5mm for each point. For discharge, we used a standard deviation of ±5% of the measurement, but a minimum of 0.125 m^3/s. This error is illustrated by the whiskers around each data point, representing 2σ on Figure 3.

We then randomly picked values in their respective distributions for all stage-discharge pairs and recalculated the best fit and related uncertainty. We created 5000 realizations using this random picking method and then computed the mean, median and standard deviation of all the realizations.

This procedure led to a somewhat larger error (light blue line in Figure 3) than the one calculated without taking into account the uncertainty on the data points (red area). We finally used the relationship defined by the median of all realizations as the ultimate best fit of the stage-discharge rating curve.

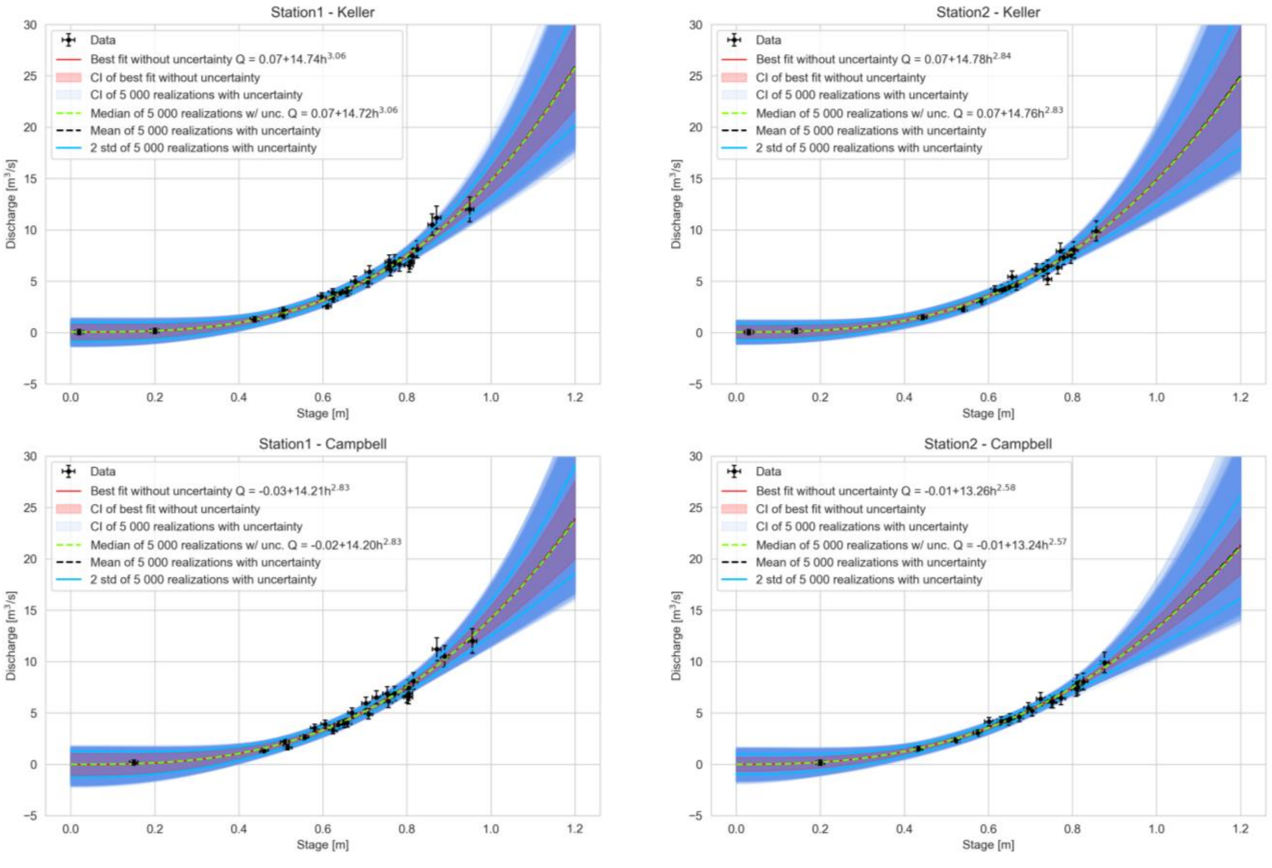

Figure 3: Stage-Discharge relationship estimation for both stations and sensors for year 2020. The best fit without defining uncertainty on the data is represented by the red line. The red area shows the confidence interval used by propagating the error of the fitted parameters on discharge. The blue area represents the total spread of 5000 realizations when considering an error on the data points, and the blue lines represent 2 standard deviations of the 5 000 realizations, which was used for estimation of the final discharge uncertainty.

Overall, the discharge calculated with the Campbell sensors seems slightly more reliable due to its finer measurement frequency and less displacement / clogging of the sensor during the season. However, the sensor at Station 2 was out of the river during low flows and the results are only available until September 14. The Keller sensors performed better for lower discharge due to their deeper position in the river and where then used for the whole cold season from September 2020 to June 2021.

It was finally decided to merge both discharge estimations at each station to create a single, clean dataset. For both stations the same procedure was applied and is detailed in Table 2. Essentially, the Campbell data were used entirely except for the low flows in early September and after mid-September.

Table 2: Sensor data used for the final discharge dataset for each station in 2020.

Date	Station 1	Station 2
26.06.2020 – 29.08.2020 23:55	Campbell	Campbell
30.08.2020 – 04.09.2020 23:55	Keller	Keller
05.09.2020 – 14.09.2020 11:55	Campbell	Campbell
14.09.2020 12:00 – 04.06.2021	Keller	Keller

Discharge estimation : year 2021

A similar independent procedure was performed for year 2021 starting on 11 June 2021. An independent stage-discharge rating curve was built for summer 2021, as changes modification of the river bed at the measurement locations may have occurred. 15 dilution gauging measurements were performed to estimate discharge for Station 1 and 13 measurements for Station 2. The stage-discharge rating curve results are shown in Figure 4.

For year 2021, the Keller sensors were mainly used (see Table 3).

Table 3: Sensor data used for the final discharge dataset for each station in 2021.

Date	Station 1	Station 2
11.06.2021 – 04.09.2021 14:55	Keller	Campbell
04.09.2021 15:00 - 28.09.2021	Keller	Keller

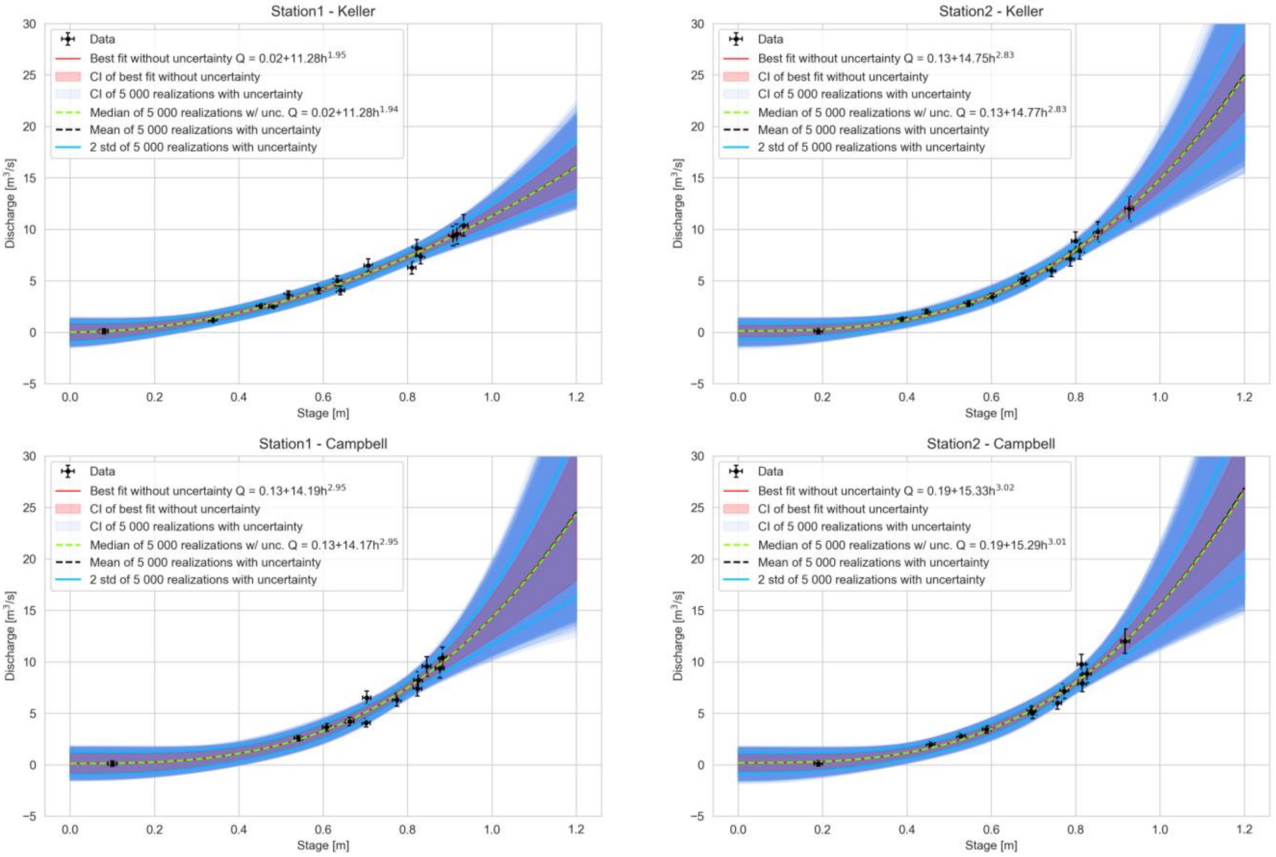

Figure 4: Stage-Discharge relationship estimation for both stations and sensors for year 2021. The best fit without defining uncertainty on the data is represented by the red line. The red area shows the confidence interval used by propagating the error of the fitted parameters on discharge. The blue area represents the total spread of 5000 realizations when considering an error on the data points, and the blue lines represent 2 standard deviations of the 5 000 realizations, which was used for estimation of the final discharge uncertainty.

Notes on uncertainty propagation

The error on discharge was calculated by computing the variance of the 5000 realizations, and the confidence interval was then defined as two standard deviations (95.45% confidence).

While the error on stage for each time step is independent (measurement uncertainty), the error for each time step for discharge is not. This is due to the fact that the estimated error on discharge is bound to the estimated error on the power fit which is applied on the whole time series. For instance, if the power fit overestimates discharge, then the discharge is overestimated over the whole time series. Thus, the error on discharge is dependent. Finally, the error on discharge of two different datasets is considered independent.

When calculating discharge differences, errors are independent, so that standard deviation is calculated using the subtraction (or summation) rule as follows:

[1] $$\sigma_{Q_{diff}} = \left(\sigma_{Q_1}{}^2 + \sigma_{Q_2}{}^2\right)^{0.5}$$

Daily discharge is calculated by the sum of individual discharge multiplied by the time step (t_i). In this case, the error is dependent and the propagation of error is calculated as a simple sum:

[2] $$\sigma_{Q_{daily}} = \sum_i^N (t_i * \sigma_{Q_i})$$

Available data sets

Two data sets are available.

The first one (*River_2019_2021_10T.csv*) contains all river data collected between July 2019 and October 2021 by the Campbell and Keller sensors at all gauging stations (1, 2 and 3). This includes stage records in [meters], water electrical conductivity (EC) in [μS/cm], water temperature [°C]. All data provided were averaged with a 10-minutes interval and were re-arranged in tidy data structure with a consistent 10-minutes time-step, including gaps. Dates are provided in local time (UTC+01 with daylight saving time) and with UTC timezone.

The second data set (*Discharge2020_10T.csv* & *Discharge2021_10T.csv*) contains the discharge data in [m^3/s] presented above with the related errors, corresponding to 2 standard deviations. All data provided were averaged with a 10-minutes interval and were re-arranged in tidy data structure with a consistent 10-minutes time-step, including gaps.

River_2019_2021_10T.csv:

Headers :	**date**	**name**	**sensor**	**variable**	**value**	**dateUTC**
Description	Local date (UTC+01)	Station number	Sensor type	Measured parameter	Measurement	Date in UTC
Range of values	-	Station1, Station2, Station3	Keller, Campbell	T, EC, Stage	-	-
Type of data	String	String	String	String	Double	String

Discharge2020_10T.csv & Discharge2021_10T.csv:

Headers :	**date**	**station**	**discharge**	**error**	**dateUTC**
Description	Local date (UTC+01)	Station number	Calculated discharge	Error (2 std)	Date in UTC format
Range of values	-	Station1, Station2	-	-	-
Type of data	String	String	Double	Double	String

References:

Dahlke, H.E., 2014. Discharge measurement using the fluorescent dye dilutionmethod with the FL30 field fluorometer. http://ucce-plumas-sierra.ucanr.edu/files/197836.pdf